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# Deepening of the Adriatic Moho beneath the central Apennines (Italy) along the CROP 11 seismic profile: indications from geologic, seismologic and gravity data and tectonic implications

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**Abstract**

Geologic and seismic evidence from the eastern half of the CROP 11 seismic reflection profile, running across the central Apennines, indicates that the Adriatic Moho deepens gradually from 34 km in the foreland areas to 47 km beneath the core of the belt. This is in agreement with local Moho depths estimated from receiver functions of teleseismic events recorded at several stations installed close to the CROP 11. Unlike the Moho trend imaged by DSS data, the Moho deepening illustrated in this paper supports the hypothesis of a westward downgoing of a portion of Adriatic crust. The deepening of the Adriatic Moho is consistent with the regional gravity anomaly field provided that very high-density rocks, not involved in thrusting deformation, are present beneath the core of the central Apennine belt. The alternative models of delamination and subduction of the Adriatic crust are discussed and compared with geophysical and geologic data.

Key words: Moho depth, crustal structure, CROP 11, central Apennines, Italy

## 1. Introduction

A rich literature was produced in the last three decades based on the geophysical investigations of the Italian crust. Wide-angle refraction profiles (DSS) (Cassinis, 1983; Nicolich, 1989; Locardi and Nicolich, 1992; Nicolich and Dal Piaz, 1992; Scarascia et al., 1994; Cassinis et al., 2003) and analysis of Bouguer gravity anomalies (Carrozzo and Nicolich, 1977; Corrado and Rapolla, 1981; Bigi et al., 1992; Scarascia et al., 1998) allowed geophysicists to infer the crustal structure of the Italian peninsula and offshore areas. Different types of crust are recognized (Figure 1):

1) a Paleozoic to Mesozoic European continental crust below the Alps and the Sardinia and Corsica major islands;

2) a Paleozoic to Mesozoic African-Adriatic continental crust in the Adriatic foreland of the Apennine belt and Alpine retro-belt (i.e., the southern Alps);

3) a Neogene to Quaternary transitional crust along the Tyrrhenian coast line and along the western border of the Apennine belt (peri-Tyrrhenian areas), including remnants of European crust;

4) a Neogene to Quaternary oceanic or sub-oceanic crust in the southern Tyrrhenian Sea and in the Ligurian Sea.

The map of the Moho discontinuity redrawn in Figure 1 after Cassinis et al. (2003) shows that the depth of the crust-mantle transition ranges between 30 and 37.5 km beneath the European block of Sardinia and the Adriatic foreland of the southern Alps and Apennines. The thickness of the crust decreases to 20-27.5 km along the central and northern Tyrrhenian coasts and peri-Tyrrhenian continental areas and reaches a minimum value of 10 km beneath the Tyrrhenian abissal plain, where a young oceanic crust is present (e.g. Sartori, 2001). Crust is thicker below the Alps (45-55 km) and in some axial zones of the Apennine belt: east of the border of the Tyrrhenian crustal domain (thick dashed line in Figure 1), Moho depth exceeds 40 km only in the northernmost part of the Apennines and in Sicily, while in the central and southern Apennines the maximum depth is 37.5 and 40 km, respectively (squared numbers in Figure 1).

The crustal structure of the Apennine belt was investigated onshore by three CROP (CROsta Profonda) near vertical reflection profiles crossing the chain from the Tyrrhenian to the Adriatic coasts: from north to south the CROP 03, CROP 11 and CROP 04 (see inset in Figure 1). The CROP Project started in the middle 80's and was initially joined and funded by the CNR (National Research Council), AGIP Oil Company and ENEL (National Electric Company). The CROP seismic profiles were recently released (Scrocca et al., 2003).

Recent studies of teleseismic receiver functions questioned the results of the DSS experiments and showed that the Moho is significantly deeper than 40 km in the northern Apennines, along the

CROP03 (Mele and Sandvol, 2003) and in the central Apennines, along the CROP 11 (Mele et al., 2006). (Mele and Sandvol, 2003) found that the depth of the crust-mantle transition increases from about 30 km beneath the northern Adriatic coast to about 50 km beneath the northern Apennines, within a distance of 100 km. In central Italy (Mele et al., 2006) estimate a maximum Moho depth of about 47 km beneath the axial zone of the Apennines.

The main geologic and geophysical constraints necessary to the interpretion of the CROP 11 profiles are extensively discussed in Patacca et al. (2007): the Authors identify the main shallow geologic sequences and related seismic facies, and discuss about the deformation ages and mechanisms and the relationship between tectonics and sedimentation.

The contribution of the present paper is to focus on the deepest crustal levels of the eastern part of the CROP 11, from the Adriatic coast to the Fucino Basin (Figure 2), and in particular on the crust-mantle transition. We extended the time-to-depth converted section of Patacca et al. (2007) to the lowermost crustal levels. This operation was done adopting for the central Apennine belt a velocity model of the Adriatic crust consistent with the geologic literature and the results of the DSS experiments.

In addition, we compare the geologic crustal section of the central Apennines to the seismologic data and the regional Bouguer anomalies. Geologic and geophysical data are finally discussed within the frame of delamination and subduction models of the Adriatic continental crust.

## 2. Geologic and geodynamic framework of the area crossed by the CROP11 profile

The Apennine mountain belt, running along the Italian peninsula and western Sicily, formed mainly during the Neogene along the collisional boundary between the European and the African-Adriatic plates (Malinverno and Ryan 1986; Dewey et al., 1989; Patacca and Scandone, 1989;

Doglioni 1991; Doglioni et al., 1999).

The CROP 11 profile runs E-W throughout the central Apennines crossing several tectonic units formed by E to NE-verging thrust sheets emplaced between the Late Tortonian and the Early Pleistocene (Bally et al., 1986; Patacca and Scandone, 1989; Patacca et al., 1991; Bigi et al., 1998; Patacca et al., 2007): the Sabina and Simbruini units, east of Plio-Quaternary volcanic deposits; the Velino-Sirente, Marsica, Morrone-Porrara, Gran Sasso and Queglia units in the central areas; the Maiella Unit near the Adriatic coast (Figure 2). The sedimentary sequences involved in the building of the central Apennines were deposited in carbonate platform, slope and basin environments. These geologic domains differentiated since Early Jurassic and further developed during the Mesozoic and Cenozoic above an African-Adriatic continental crust (Mostardini and Merlini, 1986; Patacca et al., 1991). The thrusting of the sedimentary units during the Neogene was simultaneous with extensional processes along the internal peri-Tyrrhenian sectors of the belt (Patacca et al., 1990).

The westward subduction of the Adriatic lithosphere during the Neogene is testified along the Apennines by the eastward migration of the foreland-foredeep-belt system, as a consequence of the slab roll-back (Malinverno and Ryan, 1986; Royden et al., 1987; Patacca and Scandone, 1989; Gueguen et al., 1998). In the central Apennines, Mio-Pliocene foredeep deposits lying above the pre-orogenic sequences are younger towards the Adriatic foreland (Patacca et al., 1991; Cipollari and Cosentino, 1995a, 1995b). Since the end of the Lower Pleistocene the flexural subsidence and the eastward retreat of the subduction hinge have decreased and the Apennine belt has begun to extend and uplift (Patacca et al., 1990; Cinque et al., 1993; D'Agostino et al., 2001). Earthquake mechanisms and borehole breakout analysis show that central Apennines are presently experiencing a NW-SE extension (Montone et al., 2004 and references therein) with shallow seismicity; along the Italian peninsula subcrustal earthquakes occur only beneath the northern Apennines and the Calabrian Arc (Giardini and Velonà, 1991; Selvaggi and Amato, 1992; Chiarabba et al., 2005).

## 3. The Adriatic foreland imaged by the CROP 11 seismic profile

A detailed image of the foreland crust beneath the Adriatic coastline is given by the easternmost section of the RAP (Real Amplitude Preservation) version of the CROP 11 profile already presented in Patacca et al., 2007 (Figures 3a,b).

The Adriatic foreland is characterized by the geologic sequence of the Apulian Platform Unit, drilled by several exploration wells. It is composed by Triassic dolomites and evaporites, Jurassic-Cretaceous shallow-water carbonates, Neogene ramp calcareous deposits and evaporites. This sequence is overlain by a Plio-Pleistocene clastic, terrigenous sequence that reaches a thickness of 2.0-2.5 km at the eastern termination of the CROP 11 profile (Mostardini and Merlini, 1986; Patacca et al., 1991; 2007).

The Apulian Platform Top (APT) is imaged on the RAP section by a pair of low-frequency, very high-amplitude reflectors lying at 1.7-1.8 s TWT right beneath the Adriatic coastline. This horizon gently dips westwards depicting the regional foreland monocline (Royden et al., 1987; Mariotti and Doglioni, 2000). The Gargano 1 and Puglia 1 deep wells (see Figure 1 for locations and Patacca et al., 2007 for a detailed stratigraphy) drilled the entire Apulian carbonate sequence in the foreland and revealed a Permo-Triassic terrigenous, clastic sequence at its base (Ricchetti et al., 1988; Mazzoli et al., 2000). In particular, Puglia 1 encountered, below a 6100 m thick sequence of Triassic-Lower Cretaceous shelf carbonates and evaporites, 900 m of Lower Triassic clays and silty clays with intercalations of breccia beds and Upper Permian sandstones with rare mudstones (Figure 4a).

The litho-stratigraphy of Puglia 1 shows a good correspondence with the seismostratigraphy of the Apulian Platform Unit along the CROP 11 (Patacca et al., 2007). Moreover, the terrigenous sequence unconformably overlain by the Apulian Platform is a heterogeneous sedimentary

multilayer that may generate a reflective seismic facies. Therefore, the uppermost part of the reflectors package between 4.0 and 5.6 s TWT in the RAP section is considered the seismic evidence of the Permo-Triassic sequence (Figure 3b).

The Apulian Platform is imaged by a transparent seismic facies with few reflections at well known stratigraphic levels (as the Triassic dolomites) and delimited upwards by the clear signal of the APT (Figures 3a). The Apulian Platform has an almost constant time-thickness of 2.2-2.4 s TWT at regional scale (Patacca et al., 2007), which corresponds to a thickness of 6.5-7.0 km if we assume a mean P-wave velocity (Vp) of 6.0 km/s.

Between 6.5 and 7.6 s TWT the upper crust is characterized by other organized reflections, interpreted by Patacca et al. (2007) as the lowermost part of a metamorphosed Paleozoic-Triassic sedimentary sequence having a time thickness not smaller than 3.0 s TWT. Beneath this interval, the Adriatic crust is featured by an almost reflections-free interval between 7.6 and 9.3 s TWT, interpreted as a crystalline basement composed of metamorphic and/or igneous intrusive rocks.

The RAP section has a good resolving power for the crust-mantle transition (Figure 3a). The reflective interval between 9.3 and 11.4 s TWT is interpreted as the layered Adriatic lower crust. The Moho discontinuity is placed at the base of this interval (Figure 3b). Assuming a mean P-wave velocity of 6.1 km/s for the foreland crust, a Moho depth of about 34 km can be estimated; this value is consistent with the results of the DSS acquired in central Italy (Cassinis, 1983; Nicolich and Dal Piaz, 1992; Scarascia et al., 1994; Anelli et al., 1995; Biella et al., 1997; Morelli, 1998; Cassinis et al., 2003).

## 4. The velocity model of the Adriatic crust

In this chapter we describe the velocity model adopted for the Adriatic crust (Figures 4b,c) that we use to reconstruct the lowermost crustal levels of the Apennine chain in the crustal section of

Figure 5a.

A Vp ranging from 2.5 to 3.0 km/s is assigned to the Plio-Pleistocene terrigenous sequence on the easternmost part of the line and to the basin-derived Molise nappes, featured by a high clay/carbonate ratio (see Patacca et al., 2007). For the Apulian Platform we adopt a mean Vp of 6.0 km/s, which is consistent with the time-thickness of about 2.2-2.4 s TWT imaged on the CROP 11 and with the thickness of the entire Triassic-Messinian carbonate sequence ranging between 6500 and 7000 m at regional scale.

Due to its lithology, the Permo-Triassic sediments cause a velocity inversion within the Adriatic upper crust. This hypothesis is supported by the interpretation of DSS profiles (see inset of Figure 1 for location) given by Nicolich (1981), that located a low-velocity layer (5.0 km/s) between 10 and 20 km of depth in the foreland areas. Similarly, Scarascia et al. (1994) hypothesized a low-velocity layer (Vp=6.2 km/s) between 11 and 22 km beneath the Adriatic coast and comparable values are proposed for the low-velocity layer beneath the northern Apennines by Morelli (1998). On the contrary, the models of Anelli et al. (1995) and Biella et al. (1997) do not show a low-velocity layer within the Adriatic crust.

In agreement with Patacca et al. (2007), the top of the low-velocity layer of Nicolich (1981) and Scarascia et al. (1994) is identified with the top of the Permo-Triassic sequence underlying the Apulian Platform (Figures 4a, b). Consistently, the velocity function of the Puglia 1 well (VanDijk, personal communication) shows that Vp abruptly decreases from 6.7 km/s within the Triassic evaporites of the Apulian Platform to 4.5-5.0 km/s entering the Permo-Triassic sequence. Vp then rapidly increases to about 6.0 km/sec within few kilometres from the stratigraphic boundary (Figure 4c).

The extension of the low-velocity layer at depths of 20-22 km suggests that the P-wave velocity of 6.7 km/s, hold by the Triassic evaporites, is regained only close to the transition between the upper and lower crust (about 25 km in the section of Figure 5a). In our model we adopt a mean

velocity of 6.0 km/s for the seismic interval between the base of the Apulian Platform and the top of the crystalline basement. Finally, we use Vp of 6.7 for the Adriatic crystalline basement and 7.0-7.3 km/s for the lower crust, according to DSS data.

As for the shallower levels, we assign a mean Vp of 6.0 km/s to the shelf sequences of the Maiella, Morrone-Porrara and Marsica tectonic units (6.3 km/s where overthrusted) and to the slope-to-basin sequence of the Gran Sasso-Genzana Unit, featured by a very low clay/carbonate ratio.

## 5. The crustal geologic section

We use the velocity model of Figure 4c to draw the deepest crustal levels in the easternmost and axial sectors of the central Apennines and to extend the geologic section of Patacca et al. (2007) down to the crust-mantle transition (Figure 5a). The upper portion of the geologic section is a simplified version of the CROP11 profile after Patacca et al. (2007). The Apulian Platform Unit in the foreland is indicated as UAP (Undifferentiated Apulian Platform). Although they belong to the Apulian geologic domain, the Casoli Bomba (CA-BO) and Maiella (MAI) tectonic units are distinguished from the UAP since they form the easternmost part of the central Apennines, built between the Middle Pliocene and the Early Pleistocene (deformed Apulian Platform *sensu* Mostardini and Merlini, 1986). Finally, the shallow tectonic units described in Patacca et al. (2007) in the axial zone of the belt have been simplified and grouped as Upper Miocene-Pliocene Belt (UMPB).

The geologic section of Figure 5a shows the main tectonic units emplaced in an east-verging thrust system organized as a fan structure in the axial zone of the chain (Marsica areas and Sulmona Plain) and as a duplex structure in the easternmost areas (Maiella Massif and Molise Mts) (Patacca et al., 1991; 2007). The thrust system is detached along a sole-thrust lying within the Permo-

Triassic sedimentary sequence found at the base of the Apulian Platform in the Adriatic foreland, according to a thin-skin style of deformation.

Using the velocity model of Figure 4c we depth-converted the foreland part of the CROP 11 in Figure 3. Beneath the Apulian Platform we reconstruct a geologic sequence about 11.0 km thick corresponding to the reflective interval between 4.0 and 7.6 sec TWT; the uppermost part of this sequence corresponds to the Permo-Triassic deposits found at the base of the Puglia 1 and Gargano 1 wells. The remarkable thickness of the Paleozoic-Triassic sequence, likely affected by metamorphic imprinting, closely matches the thickness of the low-velocity layer of Nicolich (1981) and Scarascia et al. (1994) (Figure 4c). Below it, the crystalline basement would have a thickness of about 6.0 km and the lower crust would extend for about 8.0 km down to the Moho discontinuity.

The thickness of the main crustal layers obtained for the Adriatic foreland was adopted for the inner part of the belt, since along the CROP 11 there is no clear evidence of pre-Alpine tectonic structures that may reveal the Permian paleogeography. Assuming a constant-thickness style of deformation, we have drawn the Paleozoic-Triassic sequence and the lowermost crustal levels following the dip of the regional monocline (trend of APT) and of the base of the Apulian sequence (Triassic levels) as in Patacca et al. (2007). The APT has a dip of 3° in the Adriatic foreland, 5° east of the Casoli-Bomba structure and 7-9° at the eastern edge of the Maiella Massif. These values are in agreement with Mariotti and Doglioni (2000). The dip of the main geologic boundaries reconstructed between the Adriatic coast and the Maiella Massif, where the CROP 11 is roughly perpendicular to the geologic structures, were extrapolated beneath the Sulmona and Marsica areas where the trace of the profile is oblique to the trend of the Apennine structures.

The geologic section of Figure 5a shows the deepening of the main geologic boundaries of the Adriatic crust from the foreland toward the core of the belt. The Moho discontinuity, called "CROP11 Moho" hereinafter, deepens from about 34 km beneath the Adriatic coast to 35-36 km below the Casoli-Bomba structure and 38-39 km below the Maiella Massif. Moho depth exceeds 40

km west of the Sulmona Plain and reaches 47 km beneath the Fucino Basin. The geologic section proposed in this paper ends at the western edge of the Fucino Basin where DSS experiments image the transition from the Adriatic continental crust to the Tyrrhenian transitional crust (Figure 1).

## 6. Seismologic data: teleseismic receiver functions

Seismologists use receiver functions of teleseismic events (epicentral distance ranging from 30° to 90°) to estimate the depth of the Moho discontinuity beneath a recording station. Teleseismic receiver functions are time series computed by deconvolving the vertical from the horizontal components of 3D broadband recordings of earthquakes. This technique allows to remove source and propagation path effects from the recordings and enhances, in the coda of the first arrival (i.e., the direct P-wave), the PS waves converted at the Moho and other first-order discontinuities. The delay of the arrival of the $PS_{Moho}$ with respect to the direct P wave depends on the depth of the Moho and on the velocity structure (Vp and Vs) between the Moho and the surface (the receiver). In the simplest approach, Moho depth can be estimated by inverting the $PS_{Moho}$-P delay, assuming a bulk crustal velocity and an average Poisson's ratio (Zandt and Ammon, 1995). The depths computed with this method are local (within 10-15 km from the station) and average values. With respect to Italy, the majority of the events that can be used for this kind of studies are from the NE quadrant, which means that the Moho interface is mostly "sampled" from the NE.

Local Moho depths have been computed by Mele et al. (2006) beneath 14 stations that were installed along the CROP 11 profile during a temporary experiment (Amato et al., 1998). In the present work we use the receiver functions computed by Mele et al. (2006) at stations 6 to 12, located in the study area, and add data from station FRES (Figure 5c). This station operates since 2004 as a permanent recording site of the National Seismic Network run by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and is located about 10 km south of the CROP 11 trace.

While in Mele et al. (2006) a mean crustal Vp of 6.5 km/s was used for stations 6 to 12, in the present study we reconstruct a crustal litho-stratigraphic column for each station site (Figure 5b) to compute an in-situ bulk crustal Vp and re-estimate Moho depths from the $PS_{Moho}$ delay. For station FRES we used the litho-stratigraphic column of Figure 4b, referred to the Adriatic foreland. Local Moho depths estimated from seismologic data match the Moho discontinuity drawn in the geologic section (Figure 5a) except at station 8. For this station, in spite of the low number of data available (Figures 6a,b), we used the slant stacking method of Zhu and Kanamori (2000) and obtained a best solution for a crustal thickness of 42.5 km (black cross in Figure 6c). With respect to Mele et al. (2006), this value is more consistent with the depth of the nearest station 7 and with a trend of westward deepening. However, the presence of another maximum in Figure 6c suggests that some complexity possibly characterizes the crustal structure beneath this station. In Table 1 the results of this work are summarized and compared with those of Mele et al. (2006). Local Moho depths are then projected on the geologic section after subtracting the altitude of the recording sites: black circles indicate stations projected following the local structural axis, mainly NW-SE and N-S, white circles indicate stations projected along the minimum-distance path to the trace of the CROP 11.

## 7. Gravity data: Bouguer anomalies

The 2D gravity model computed by Tiberti and Orlando (2006) is carried out picking up regional gravity anomaly values along a rectified trace of the CROP 11 profile (Figures 2, 7a). The regional gravity data are obtained through a 'stripping off' technique (Tiberti et al., 2005). This technique consists in the 3D removal of the gravity effect produced by the geologic bodies shallower than the Apulian Platform from the Bouguer anomaly database of the Italian Geologic Survey (which has a grid cell size of 3 km).

This 2D model takes into account constraints provided by seismic data both from the DSS

experiments (Cassinis et al., 2003) and from the CROP profile. It also considers geologic data by Parotto et al. (2004) which consist in a preliminary version of the geologic profile along the line. Density values are assigned to the not-investigated portion of the crust and the upper mantle according to literature data (e.g. Pasquale et al., 1997; Gualtieri and Zappone, 1998) and then the density distribution was progressively changed by means of a trial-and-error procedure in order to reach the best fitting between the observed and the calculated gravity. The final geologic model by Patacca et al. (2007) shows slight differences that anyway would not significantly affected the general trend of the gravity curve calculated from the model. The best fit between the regional gravity anomaly curve and the computed curve is obtained by a trial and error procedure.

In the gravity profile, the Tyrrhenian and Adriatic domains are characterized by gravity highs, whereas a prominent gravity low occurs in the central Apennines beneath the Fucino Basin and the Marsica area (Figure 7b).

The results of the modelling of Tiberti and Orlando (2006) show that the architecture of the Adriatic crust between the coastline and the Fucino Basin imaged in Figure 5a is consistent with gravity data except for a gravity low east of the Maiella Massif (Figures 7b, c). Within the model a distinction is made between the upper part of the Paleozoic-Triassic sequence (that is involved in thrusting deformation) which has been attributed of a density value of 2.57 g/cm$^3$ and the lower part of the same sequence considered together with the crystalline basement at a density value of 2.75 g/cm$^3$. Gravity data exclude the presence of tectonic slices of high-density rocks at shallow depths beneath the trace of the CROP 11 profile; also the mid-crustal antiformal structure recognised by Billi et al. (2006) beneath the inner part of the belt (and showed in Figures 7, 8) is supposed to be made of “light” materia. Finally, a lower density is proposed for both the uppermost crust and the mantle in the western half of the CROP 11 profile (Figure 7c).

The gravity low in the central part of the gravity anomalies profile (Figure 7b) could be compensated with the combined effect of a regional deepening of the Moho discontinuity and the

top of the crystalline basement. Nevertheless, the gravity model is not fully consistent with the trend of the Adriatic Moho illustrated in Figures 5a. To fit gravity data the Adriatic Moho should have an intermediate deepening trend ("gravity Moho") between the one derived from the geologic section along the CROP11 profile ("CROP 11 Moho") and the one imaged by DSS ("DSS Moho"). Moreover, a density of 3.10 g/cm$^3$ has to be assigned to part of the Adriatic lower crust above the "gravity Moho" (Figure 7c) to better fit the observed anomalies: similar density values were measured by Rey et al. (1990) in exposed crustal rocks in the western Alps (Ivrea-Verbano zone).

## 8. Discussion

The geologic section of Figure 5a shows the architecture of the central Apennine belt and the westward deepening of the Adriatic Moho. The style of deformation of the more external part of the central Apennines is typical of a thin-skin tectonics; the gravity model of Figure 7 excludes the presence of high-density rocks at shallow depths within the Apennine thrust belt and thus supports this hypothesis.

The deepening of the Adriatic Moho is consistent with local Moho depths estimated at stations 6, 7, 9÷12 and FRES using seismologic data. With respect to Mele et al. (2006), we assign to station 8 a depth of 42.5 km that is the best solution obtained from the slant stacking analysis. This value fits the trend of the Moho between station 9 and the much closer station 7. The Moho trend is in agreement with the gravity model in the foreland and in the outermost sector of central Apennines (Figure 7c). West of the Maiella Massif, in the axial zone of the chain, the Moho deepening accounts for the gravity low (Figure 7a), but it is excessive to fit the regional gravity anomaly trend (Figure 7b). To fit the observed gravity anomaly, Tiberti and Orlando (2006) have hypothesized a portion of "heavier" (3.10 g/cm$^3$) Adriatic lower crust and a position of the Moho lower than the "DSS Moho", i.e., the "gravity Moho" of Figure 7c. The "CROP 11 Moho", proposed in the present

work on the basis of geologic and seismologic evidence, would be consistent with the gravity anomaly field only assigning a mantle density (about 3.32 g/cm$^3$) to the lower crust beneath the core of the belt (Figure 7c).

These geophysical constraints were considered in two alternative tectonic models illustrated by the regional cross-sections of Figure 8, drawn along the rectified CROP 11 trace with indication of the density values. Both in the crustal delamination (Figure 8a) and subduction (Figure 8b) models we draw the different Moho discontinuities and interpret the "lighter" Tyrrhenian mantle as the asthenospheric wedge hypothesized beneath the Apennines on the basis of regional shear waves attenuation (Mele et al., 1997). In Figure 8a the Tyrrhenian asthenosphere wedges the delaminated Adriatic lower crust. The delamination model is consistent with the gravity model since the asthenospheric material would partly fill the mantle-like density zone needed to fit the "CROP 11 Moho". Nevertheless, a delamination of the crust would imply a much deeper sole-thrust for the central Apennines but the gravity model does not support the presence of tectonic slices of high-density materials in the upper crust.

In Figure 8b the deepening of the "CROP 11 Moho" allows the undeformed Adriatic crust to subduct beneath the Tyrrhenian domain (e.g. Doglioni, 1991; Doglioni et al., 1999). Nevertheless, if "light" Adriatic continental crust is subducted, the gravity low observed beneath the core of the central Apennine should be larger (Figure 7b). The subduction model would fit the gravity data only considering processes like eclogitisation that may account for mantle-like density within the subducting continental lower crust.

The role of eclogitisation in mountain building has been widely discussed (Austrheim, 1990; 1991; Kay and Kay, 1991; Nelson, 1991; Laubscher, 1990; Andersen et al., 1991; Bousquet et al., 1997; Jackson et al., 2004). Eclogites are high-pressure, dry metamorphic rocks having an original gabbroic-like composition and therefore developed within oceanic crust in $PH_2O << PTot$ conditions. However, the term "eclogites" can be referred also to acid or intermediate rocks

metamorphosed in "eclogite-facies" conditions (T > 500 °C and P > 1.2 GPa, corresponding to a depth > 40 km) and is used by Laubscher (1990) and Bousquet et al. (1997) for the granulitic rocks of the continental European lower crust subducted beneath the Alps. Although the original composition of the Adriatic lower crust is substantially unknown, the transition from a former metamorphic rock to eclogite implies a dramatic increase in the rock density. Bousquet et al. (1997) proposed a density similar or even higher than the upper mantle, i.e., 3.37 g/cm$^3$, for andesitic, intermediate eclogites.

An eclogitisation of the lower crust beneath the axial zone of the central Apennines makes the subduction model consistent with the regional gravity anomalies and reduce (if not invert) the buoyancy contrast with respect to the surrounding mantle. In this scenario, the "gravity Moho" in Figure 7c might correspond to the upper boundary of the eclogitised zone.

Finally, the eclogitisation of the lower crust beneath the axial zone of the central Apennines could also explain the poor reflectivity of the lower crust observed by Patacca et al. (2007). Moreover, since a transition to eclogite implies a weakening of the rock mass strength (Jackson et al., 2004), eclogitisation could also account for the absence of subcrustal seismicity beneath the central Apennines.

## 9. Conclusions

Geologic and seismologic data along the eastern half of the CROP 11 profile shows that the Adriatic Moho deepens westward beneath the central Apennines from 34 km along the Adriatic coast to 47 km beneath the Fucino Basin. The deepening of the so-called "CROP 11 Moho", that we propose in this paper, is consistent with gravity data only from the Adriatic coast to the eastern edge of the Maiella Massif, but does not fit the gravity model between the Sulmona Plain and the Fucino Basin. This inconsistency between geologic-seismologic and gravity evidence is overcome if a

mantle-like density is present beneath the core of the belt. Delamination of the lower Adriatic crust makes the "CROP 11 Moho" acceptable for the gravity model since the Tyrrhenian asthenosperic wedge would partly fill the required mantle-like density zone. However, delamination of the Adriatic crust contrasts with the thin-skin tectonic style of deformation of the easternmost part of the central Apennines.

To be consistent with the gravity model, the subduction of the entire undeformed Adriatic crust, allowed by the "CROP 11 Moho" deepening, requires the presence of very high-density crustal rocks beneath the axial zone of the central Apennines. This can be explained if we hypothesize an eclogitisation-like process in the lower crust. This would reduce the slab buoyancy contrast and could explain both the disappearance of seismic reflectivity in the lower crust and the absence of subcrustal seismicity beneath the central Apennines.

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FIGURE CAPTIONS

**Figure 1**. Map of Italy and surrounding areas showing the Moho isobaths (km) redrawn after Cassinis et al. (2003) and the main tectonic features. Legend: 1) European continental crust; 2) African-Adriatic continental crust; 3) Tyrrhenian and peri-tyrrhenian transitional crust including remnants of European crust; 4) oceanic or sub-oceanic crust; 5a) border between European and Adriatic crustal domains; 5b) border between Adriatic and Tyrrhenian crustal domains; 6) fragmentation lines in the upper mantle; 7) Moho isobaths; squared numbers indicate the maximum depths of the Adriatic Moho east of the Tyrrhenian crustal domain; 8) isobaths of the subducted Moho; 9) Apennine thrust front; 10) trace of the CROP 11 profile in the central Apennines (CA); 11) wells: GA1=Gargano 1; PU1= Puglia 1. In the inset: DSS profiles acquired in the central Apennines and traces of the CROP 03 and 04 profiles.

**Figure 2**. Geologic-structural map of the study area (S.P.=Sulmona Plain; F.B.=Fucino Basin). Open circles indicate seismic stations of Mele et al. (2006) used in this work (Table 1). Segments of the CROP 11 profile funded by different public and private companies are indicated.

**Figure 3**. a) CROP 11 RAP stack section and b) line drawing. Legend: APT=Apulian Platform Top; MN=Molise nappes; P-T sequence: Paleozoic-Triassic sequence. Vertical lines indicate position of wells projected on the CROP 11 profile (see Patacca et al., 2007).

**Figure 4**. a) Schematic litho-stratigraphic log of the Puglia 1 deep well drilled in the Adriatic foreland (TD=total depth; LVL=low-velocity layer); b) crustal section (mean Vp values in km/s are indicated for each crustal layer) and c) velocity model of the Adriatic foreland.

**Figure 5**. a) crustal geologic section along the CROP 11 profile from the Adriatic foreland to the axial zone of the belt (Fucino Basin). From surface to the dashed line the section is a simplified version of Patacca et al (2007). Legend: CA-BO=Casoli-Bomba Unit; MAI=Maiella Unit; MN=Molise nappes; UAP=Undifferentiated Apulian Platform; UMPB=Undifferentiated Mio-Pliocene belt; P-T Paleozoic-Triassic sequence; C.B.=Cristalline Basement; L.C.=Lower Crust; Moho depths estimated from receiver functions are projected on the CROP 11 following the shallow structural axis (black circles) and the minimum-distance path (white circles); b) litho-stratigraphic columns (depths are in km) beneath the seismic stations 6 to 12 and FRES. The average Vp is indicated in km/s for each crustal layer. FD= Foreland Domain; c) stacks of teleseismic receiver functions computed at stations 6 to 12 Mele et al. (2006) and at station FRES (this work). Arrows indicate the $PS_{Moho}$ phase.

**Figure 6.** a) Azimuthal projection of the earthquakes (stars) used to compute receiver functions. Triangle indicates the recording station; b) slant stacked receiver functions sorted by increasing epicentral distance; c) results of the slant stacking analysis: black cross indicates the best estimate of crustal thickness (42.4 km) and Vp/Vs (1.76).

**Figure 7**. a) Gravity anomalies map of central Italy from Tiberti et al. (2005) and rectified trace of the CROP 11 profile (as in Figure 2); b) gravity anomaly profile along the trace of (a) from Tiberti and Orlando (2006); c) density distribution in the central Apennine and Adriatic crust and upper mantle (modified from Tiberti and Orlando (2006)). Density values are in $g/cm^3$. Legend: 1) "stripped units"; 2) Tyrrhenian upper crust; 3) Apulian Platform units; 4) other carbonate units (or having similar density); 5) upper part of the Paleozoic-Triassic sequence, involved in thrusting deformation; 6) lower part of the Paleozoic-Triassic sequence, undeformed, and crystalline

basement; 7) lower crust; 8) high-density (3.10 g/cm$^3$) lower crust; 9a) Tyrrhenian upper mantle; 9b) Adriatic upper mantle.

**Figure 8.** Tectonic models of (a) crustal delamination and (b) subduction of the Adriatic continental crust. Legend: 1) "stripped units" in the gravity model; 2) Tyrrhenian upper crust; 3) Apulian Platform units; 4) other carbonate units (or having similar density); upper part of the Paleozoic-Triassic sequence, involved in thrusting deformation; 6) lower part of the Paleozoic-Triassic sequence, undeformed, and crystalline basement; 7) lower crust; 8) Apennine sole-thrust. Density values (g/cm$^3$) and distribution are from the gravity model of Figure 7c. Circles indicate local estimates of Moho depth from stations 6-12 and FRES projected on the CROP 11 profile.

**Table 1.** Sesimic stations location, with indication of the geologic domain, and mean crustal Vp and Moho depth (in km) estimated in this work for each station site. Moho depths estimated by Mele et al. (2006) are listed for comparison. Depths include the elevation of the recording sites (h). CaBo=Casoli-Bomba Unit; MAI=Maiella Unit; MAR=Marsica Unit; MPQ=Morrone-Porrara and La Queglia units; S.P.=Sulmona Plain.

| Station | Lat, N | Long, E | h (km) | geologic domain | Vp (km/s) | Moho depth this work | Moho depth (Mele et al., 2006) |
|---|---|---|---|---|---|---|---|
| **6** | 42º 08.40’ | 13º 19.92’ | 1.0 | MAR | 6.3 | 46 | 47 |
| **7** | 42º 06.78’ | 13º 28.02’ | 1.2 | MAR | 6.3 | 42 | 42 |
| **8** | 42º 08.28’ | 13º 32.22’ | 1.5 | MAR | 6.3 | 42 | 39 |
| **9** | 42º 07.20’ | 13º 48.72’ | 0.6 | S.P. | 6.3 | 39 | 40 |
| **10** | 42º 08.88’ | 13º 56.88’ | 0.9 | MPQ | 6.2 | 40 | 40 |
| **11** | 42º 09.18’ | 14º 11.34’ | 0.7 | MAI | 6.4 | 38 | 39 |
| **12** | 42º 06.60’ | 14º 16.98’ | 0.4 | CaBo | 6.2 | 3 | 40 |
| **FRES** | 41º 58.63’ | 14º 40.23’ | 0.4 | Foreland | 6.1 | 34 | - |

**Figure 1**

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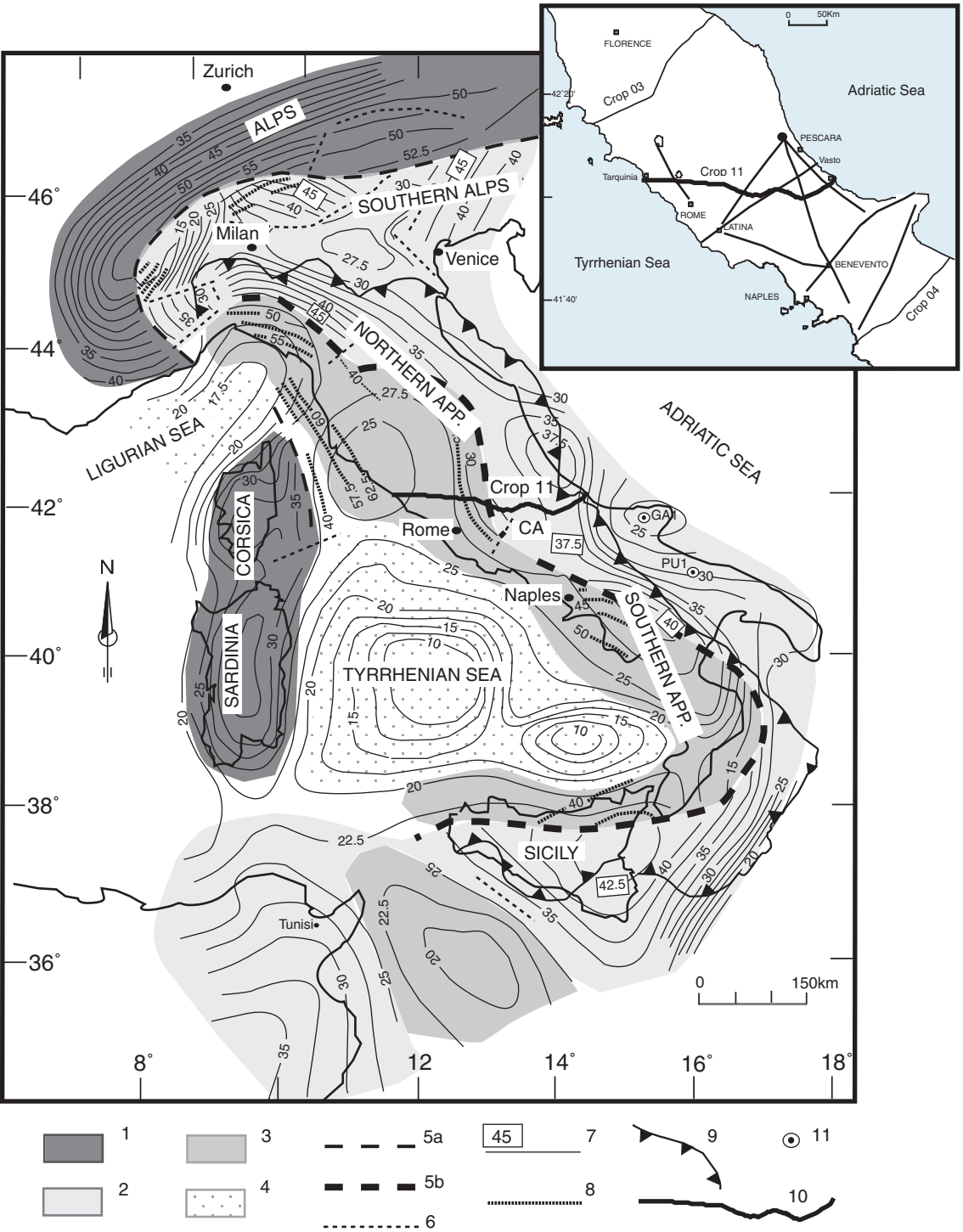

**Figure 2**

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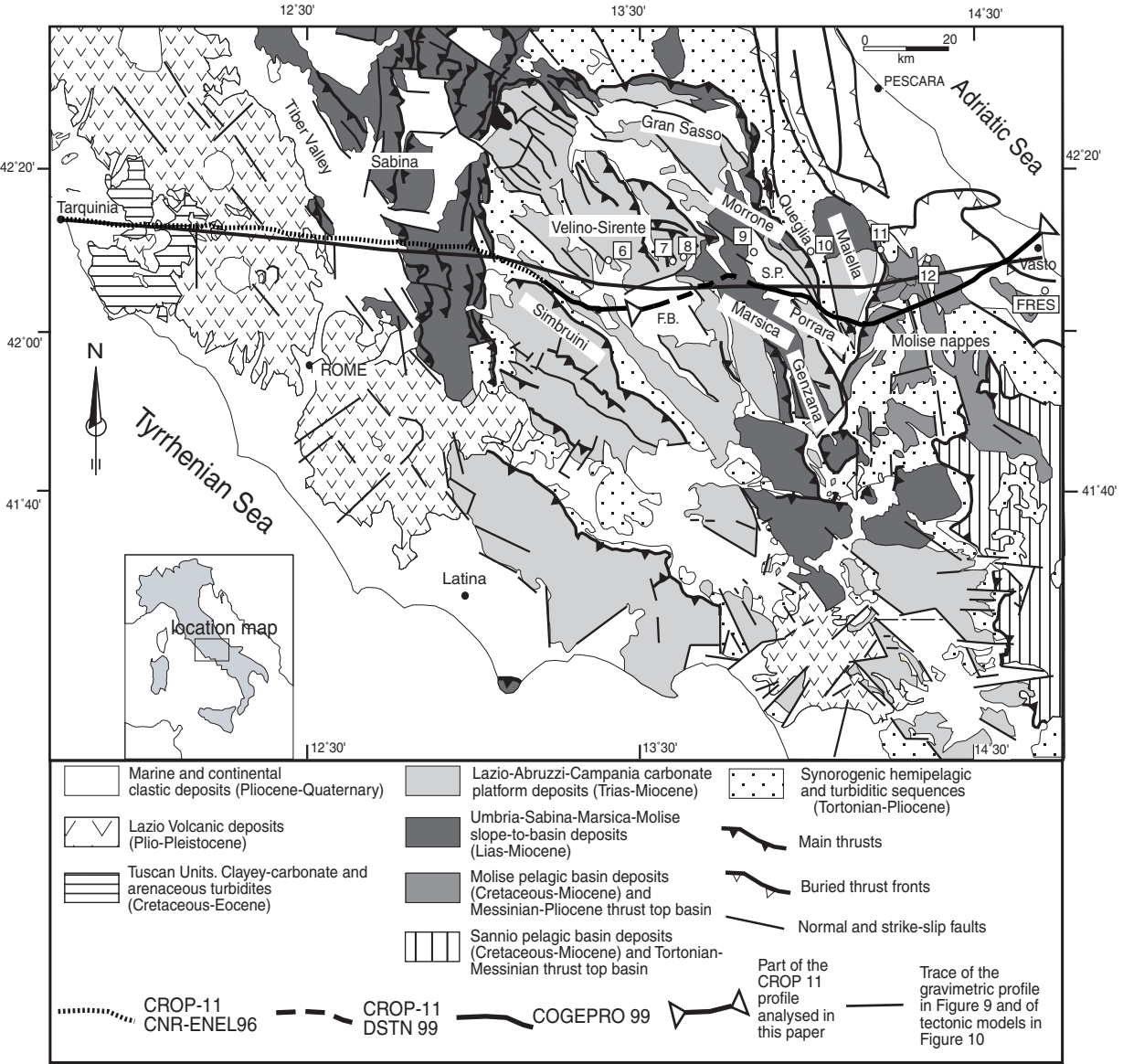

**Figure 3**

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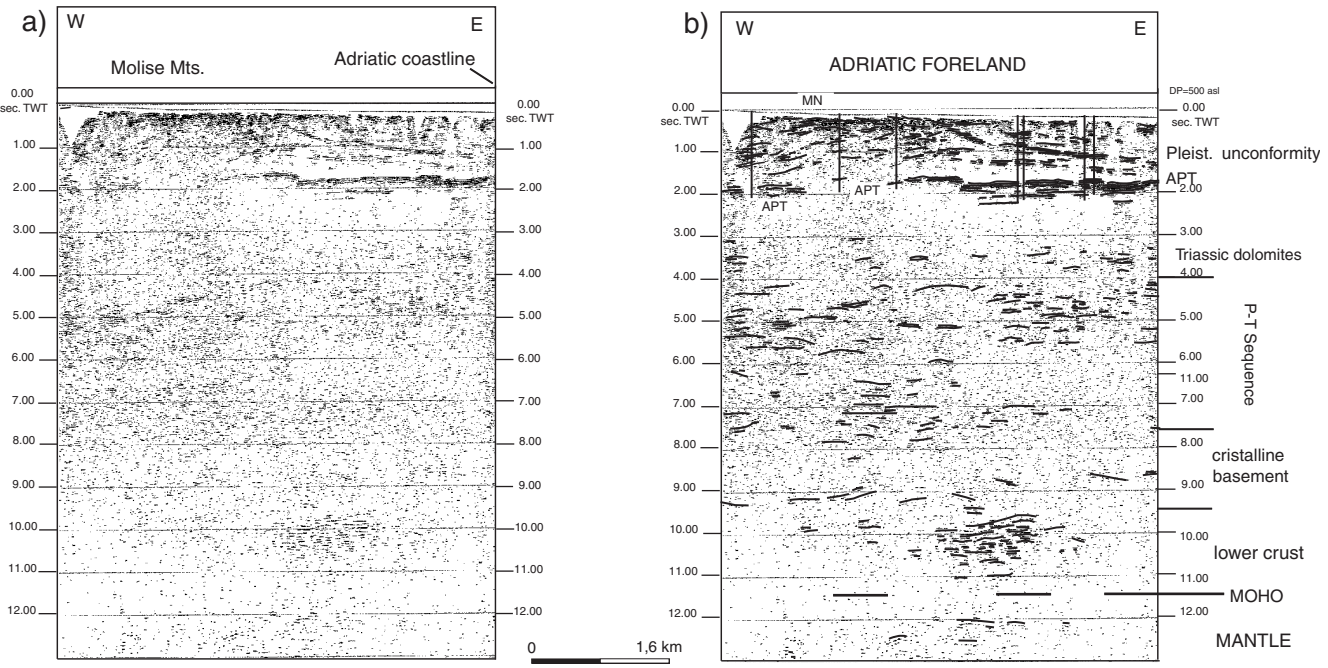

**Figure 4**

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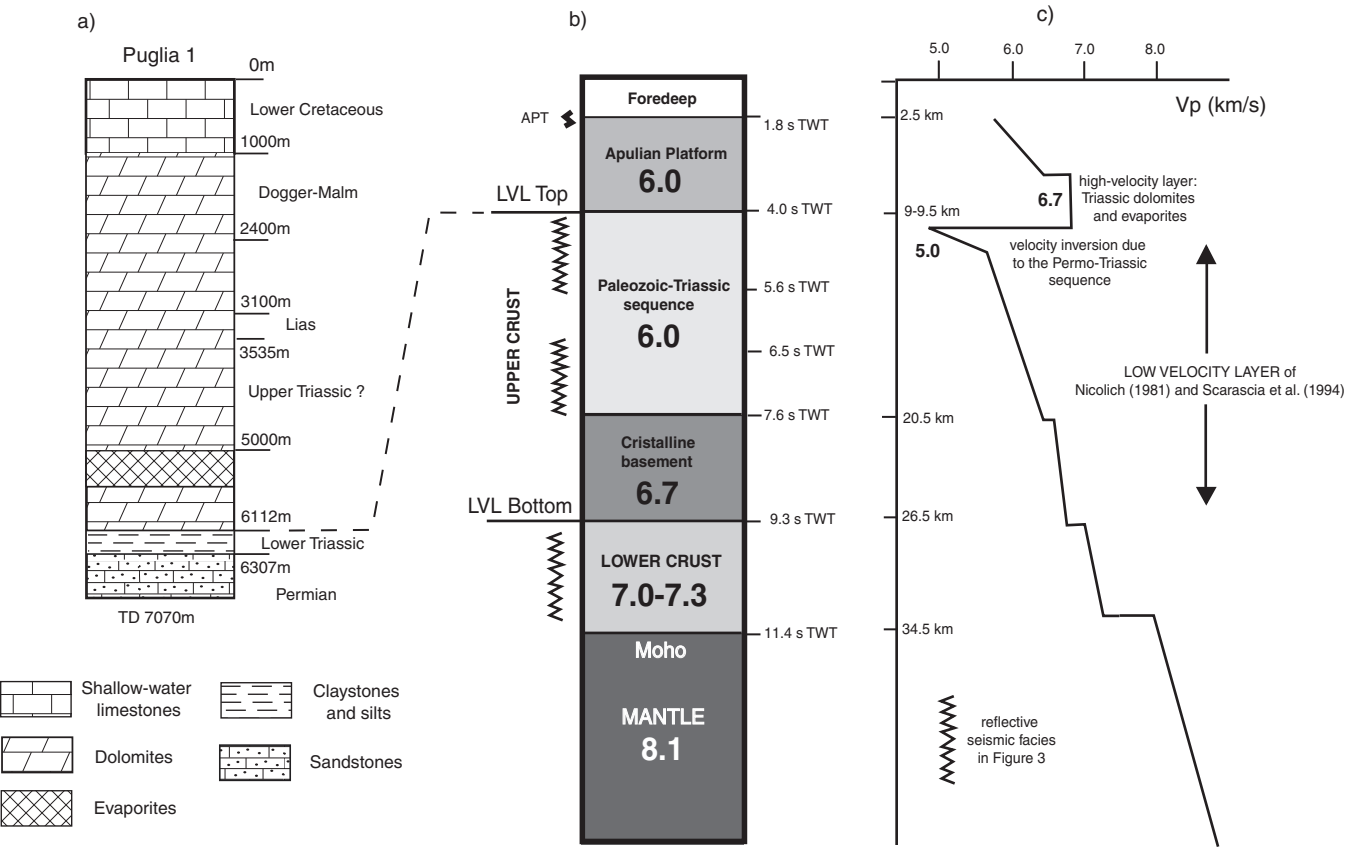

**Figure 5**

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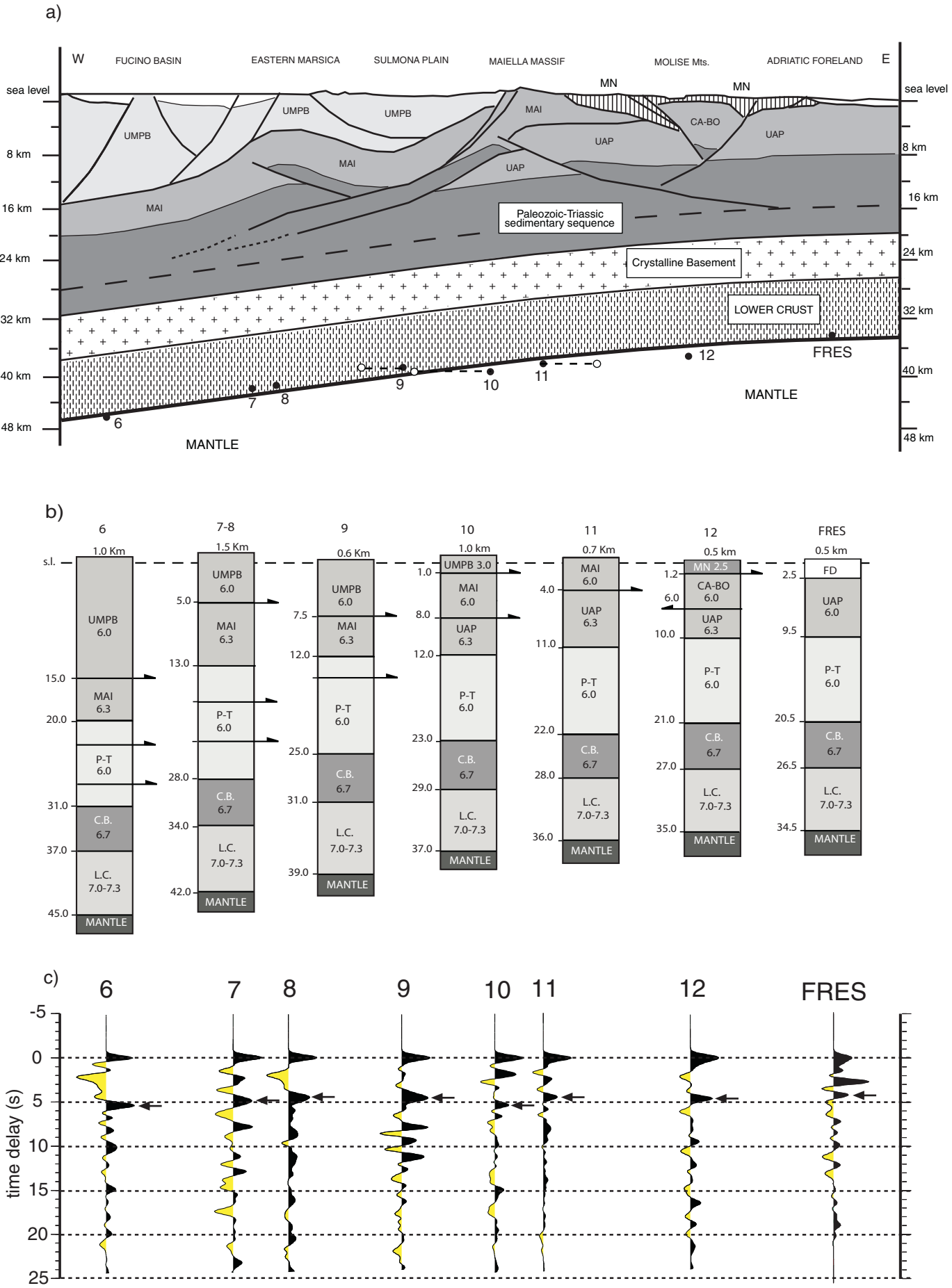

**Figure 6**

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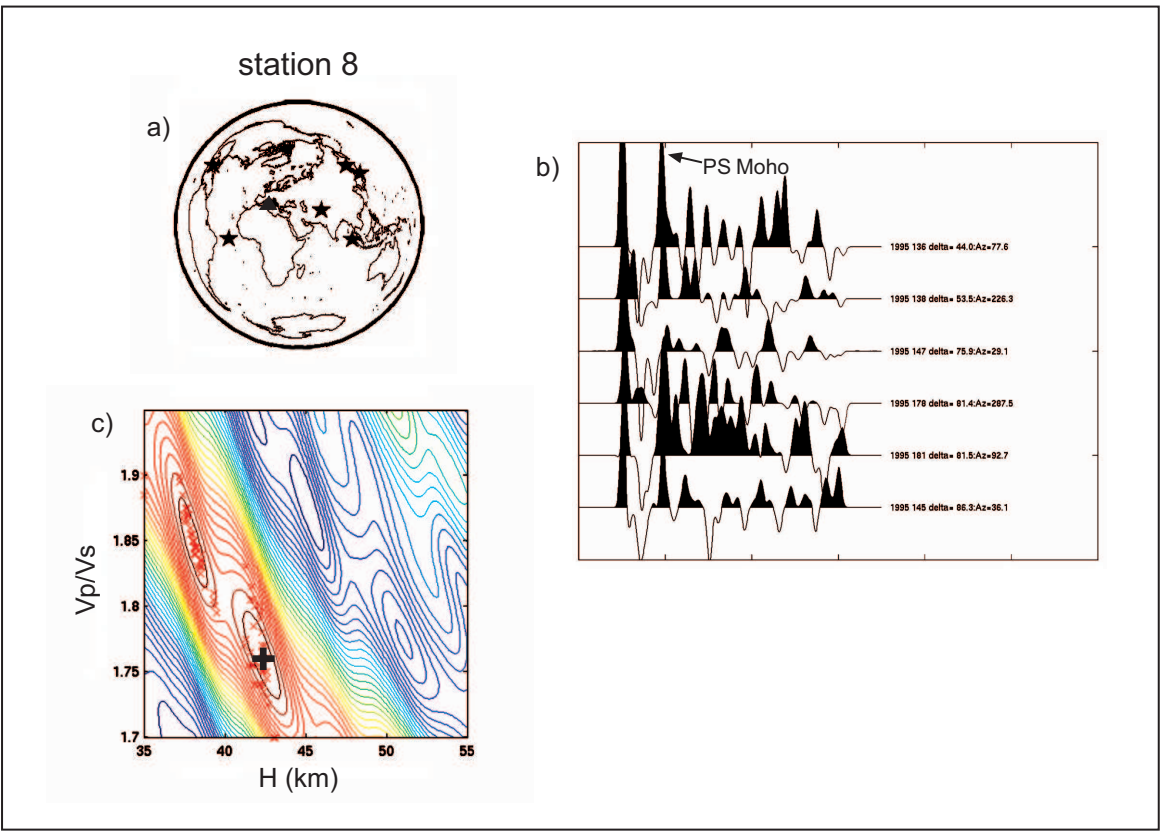

**Figure 7**
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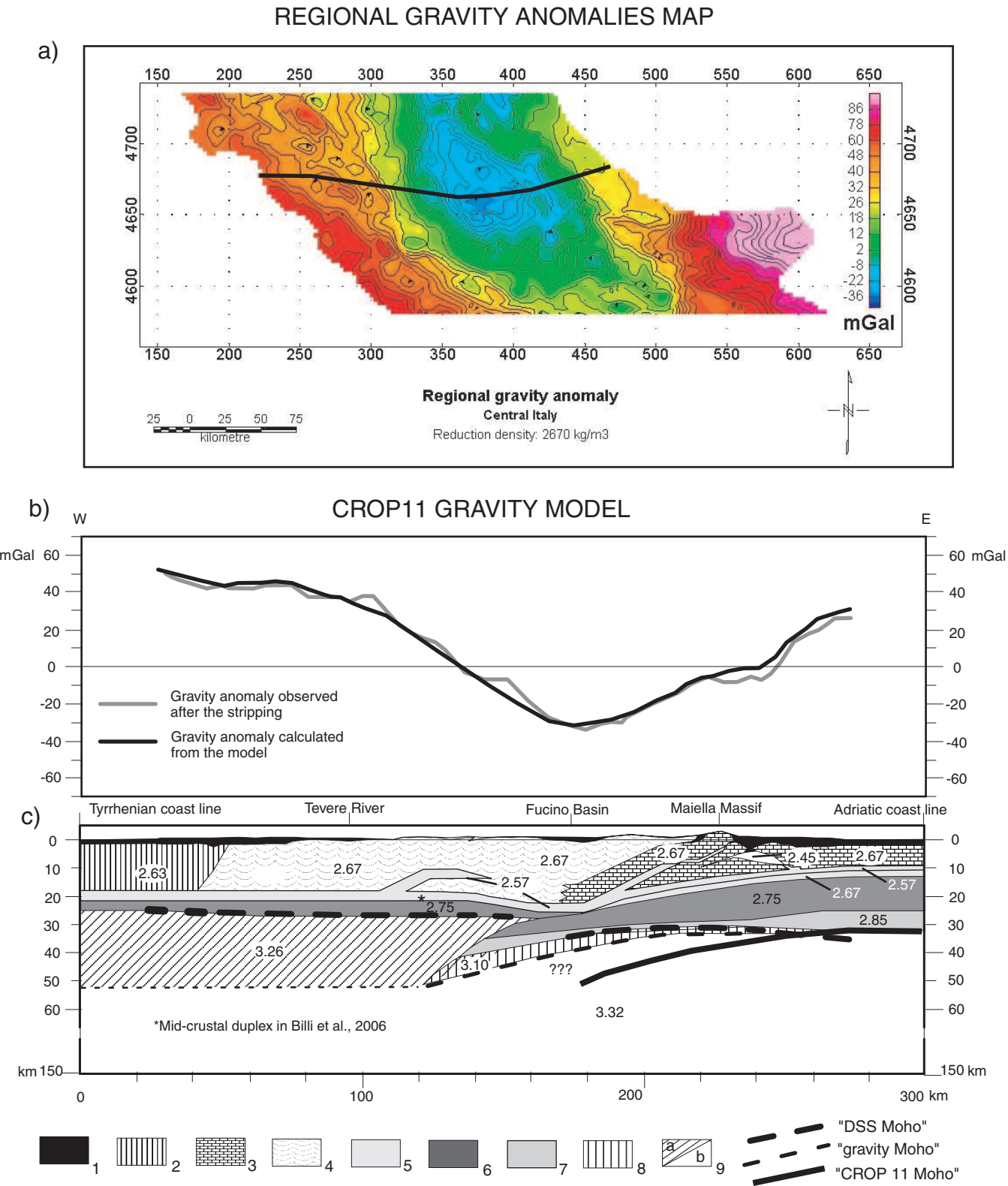

**Figure 8**
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