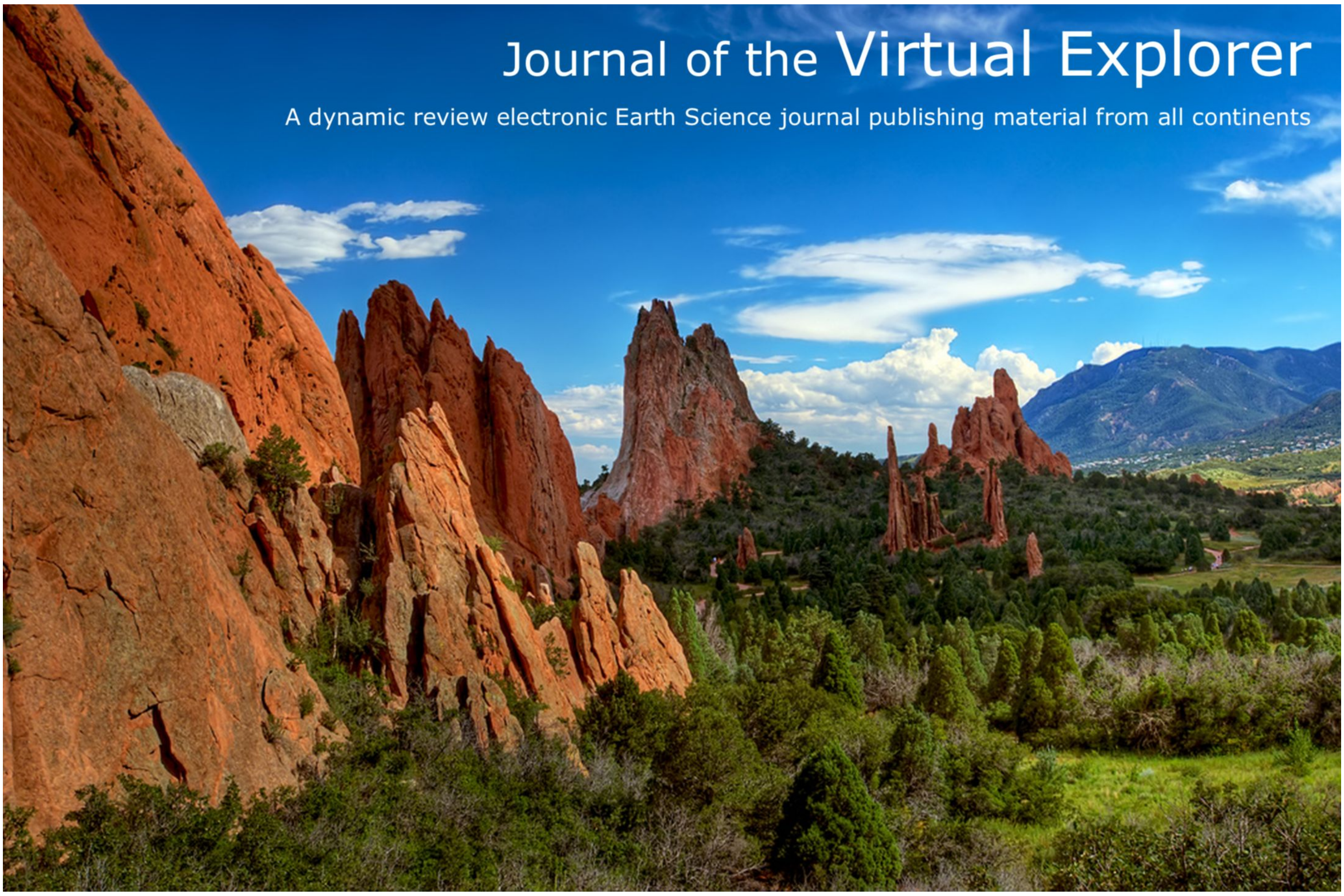

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Seismicity and deep structure of the northern-central Apennines

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Abstract: In this paper, we report on the velocity structure and seismicity of the northern-central Apennines. Recent seismological studies elucidate the crust and uppermost mantle structure in this peculiar and controversial portion of the central Mediterranean region. Quaternary extension develops on a main NW-trending seismic belt located along the Apennines range, at the boundary between the Adria and Tyrrhenian lithospheres, i.e. a complex setting in a more general framework of the Africa-Eurasia collision. This boundary is well defined at Moho depth by tomographic P-wave velocity models and receiver function analyses. The characteristics of the mantle vary between the Tyrrhenian and Adria domains, suggesting that the Tyrrhenian wedge is widely permeated by fluids due to the presence of subducted lithosphere at depth.

The seismic belt is fragmented into adjacent and laterally offset segments, whose length is in the order of tens of kilometres. This feature is consistent with the occurrence of moderate and large (M>6.0) normal faulting earthquakes. We hypothesize that the fragmentation derives from the extreme complexity of the pre-existing structure, where subsequent tectonic inversions, from the Mesozoic Tethys extension to the Neogene compression and then to the presently active extension, created a puzzling scenario of faults in the crust. Deep fluids formerly released by the subduction process and broadly stocked in the mantle wedge up-raise in the crust favouring the re-activation of the pre-existing structures in the extending Apennines range.

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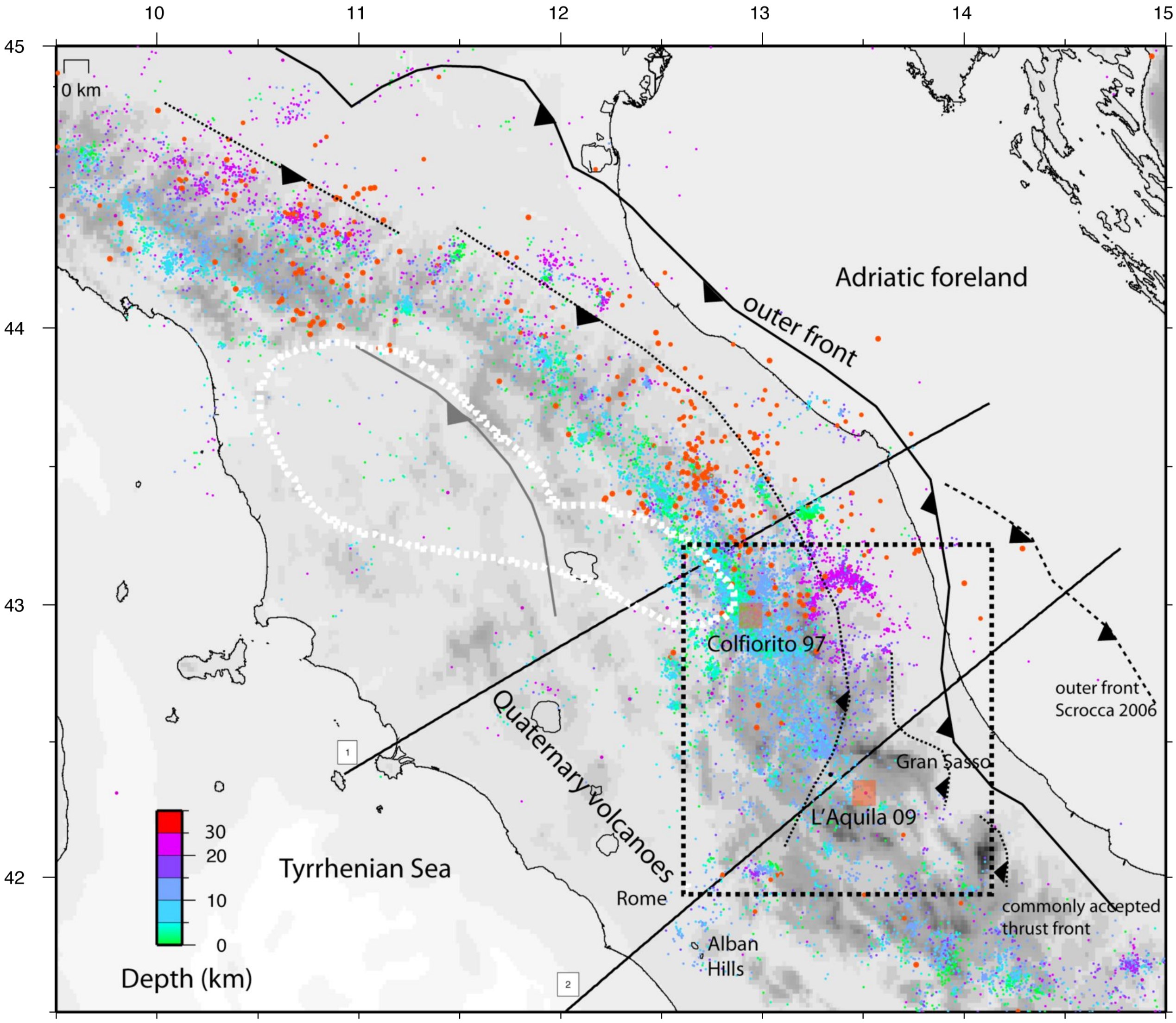
Introduction

The Apennines of Italy is an outstanding example of syn- and late-orogenic extension spreading over and after the collision between the continental Africa and Eurasia plates (Dercourt *et al.*, 1986). Although the paired extension and compression appear to be common to other Tethys regions (Hymalayas, Molnar *et al.*, 1993 and the Aegean, Jolivet *et al.*, 1998a), this process is still a debated feature of continental deformation. Well documented for the Apennines is a progressive eastward migration of a coupled pair of compression and extension, from the Tyrrhenian to the Adriatic regions (Elter *et al.*, 1975; Bally *et al.*, 1986). Barchi *et al.* (2006) proposed three main rules for the northern Apennines, for which the compression and extension are always tightly related in space and time.

Figure 1. Instrumental seismicity of northern-central Apennines.



Seismicity of northern-central Apennines in the period 1980-2008 /locations form the CSI catalog. The colour scale is relative to the depth of earthquake. A schematic representation of the thrust fronts is shown. The white dashed line is the limit of the high velocity anomaly in the mantle revealed by Giacomuzzi *et al.*, 2010. The rectangle indicates the region zoomed in Figure 2, the black lines the traces of sections in figures 7 and 8.

The present-day outer compressive front runs broadly along the Adriatic coast of the Italian peninsula (Figure 1) and shows a curved and irregular geometry. Intriguingly, the front is broadly parallel to the present day convergence between the Africa and Eurasia plates and spaced only some tens of kilometres from the extensional region.

Since the late 80's, different models described the Apennines as formed by the subduction and retreat of a mostly continental lithosphere (Malinverno and Ryan, 1986; Dewey *et al.*, 1989; Doglioni, 1991), developed after the Tethys ocean closure and plate collision, the former Alpine history. Geological and geophysical data accumulated in the 90's were used to support geodynamic models whose common base is the W-dipping subduction of Adria (Patacca and Scandone, 1989; Serri et al., 1993; Gueguen et al., 1998; Faccenna et al., 2001; 2003; Peccerillo and Lustrino, 2005; Scrocca et al., 2007; Avanzinelli et al., 2009). The fast slab rollback and retreat is indicated as the cause for the eastward migration of the paired compression-extension pair (Faccenna et al., 2003) and opening of the Tyrrhenian back arc. Such evolution occurred at the back of the former developed Alpine belt, after the Eurasia and Africa collision, which remnants are visible in the Tyrrhenian side and, further south, in the Calabrian arc.

Evidence for the deflection of the Adria lithosphere beneath the belt are numerous and from independent sets of data. Flexural model of subsidence data supported a model of fore-deep formation controlled by deep subsurface load, like a sinking slab (Royden and Karner, 1984; Royden *et al.*, 1987; Royden, 1993, Doglioni, 1994). Modelling is coherent with the deflection of the regional monocline, i.e., the Mesozoic sedimentary sequence of Adria (Mariotti and Doglioni, 2000). Intermediate-depth seismicity occurring along the Apennines (Selvaggi and Amato, 1992; Chiarabba *et al.*, 2005; Chiarabba *et al.*, 2009a) consistently defines the west-dipping Adria lithosphere down to a depth of about 70 km. On the contrary, only tomographic models suggest that the slab is sinking in the upper mantle, revealing the positive velocity anomalies that plunge into the mantle (Lucente *et al.*, 1999; Wortel and Spakman, 2000; Piromallo and Morelli, 2003). Very recently, seismic anisotropy showed that the mantle flow, indicated by the SKS splitting, is not that expected by the retreat of Adria (Salimbeni *et al.*, 2007).

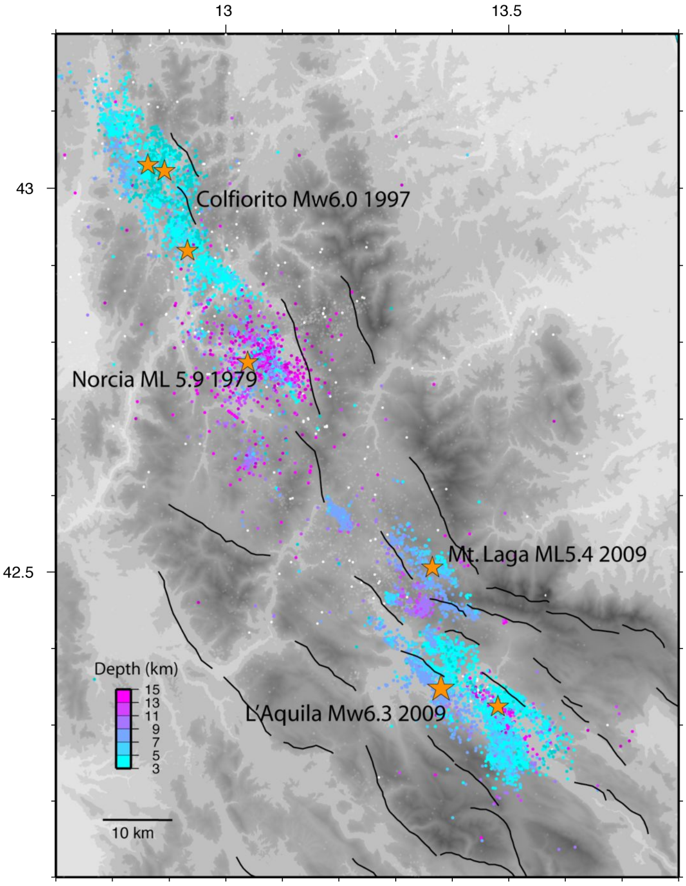
The linked formation of Alps and Apennines is addressed by rotation of individual blocks of the belts revealed by paleomagnetic studies (Mattei *et al.*, 1995; Speranza *et al.* 1997; 1998; Maffione *et al.*, 2008 and references therein). Those data suggest a common dynamic that drives the Alpine and the Apennine slabs evolution, with the last process being a rollback of the Apenninic slab and related back-arc spreading of the Liguro-Provencal Basin and drift of the Corsica-Sardinia block.

In this scenario, extensional tectonics spread along the Apennines range previously formed by compression. Normal faulting earthquakes, with magnitude up to 6.9, develop on a set of adjacent and fragmented NW-trending faults. For the most recent large earthquakes (Chiaraluce *et al.*, 2004; 2005; Chiarabba *et al.*, 2009b), instrumental data indicate that the dip of the normal fault is of about 40-50 degree, smaller than that expected for Anderson-like faults. Since extension replaced the Mio-Pliocene compression sharing an almost parallel strike of the faults, the re-activation of pre-existing thrusts at depth is a likely scenario. In this paper, we show that a recently developed crustal tomographic model along with a complete catalogue of seismicity yield insights on seismotectonics and strongly support the hypothesis that, in the Apennines, normal faulting earthquakes often re-activate pre-existing thrusts.

Seismicity

The huge collection of P- and S-waves arrival times recorded by permanent seismic networks operating in Italy yields a very complete seismic catalogue (CSI1.1, Castello *et al.*, 2006). The distribution of thousands of earthquakes that have occurred in the past 30 years give a consistent picture of seismicity in northern-central Apennines (Figure 1). Seismicity follows the Apennines range and its lateral geometrical offsets and rotations. The seismic belt consists of a western stripe of shallow seismicity with hypocenters mostly located above 8-12 km depth and an eastern belt with deeper crustal earthquakes (hypocentral depth of about 18-20 km). The northern portion of the Apennines has a more intense and diffuse seismicity (Chiarabba *et al.*, 2005), with respect to the central Apennines that was mostly silent in the past 20 years before the 2009 L'Aquila earthquake, with a few and sparse earthquakes (Bagh *et al.*, 2007).

Figure 2. Focus on the normal fault system.

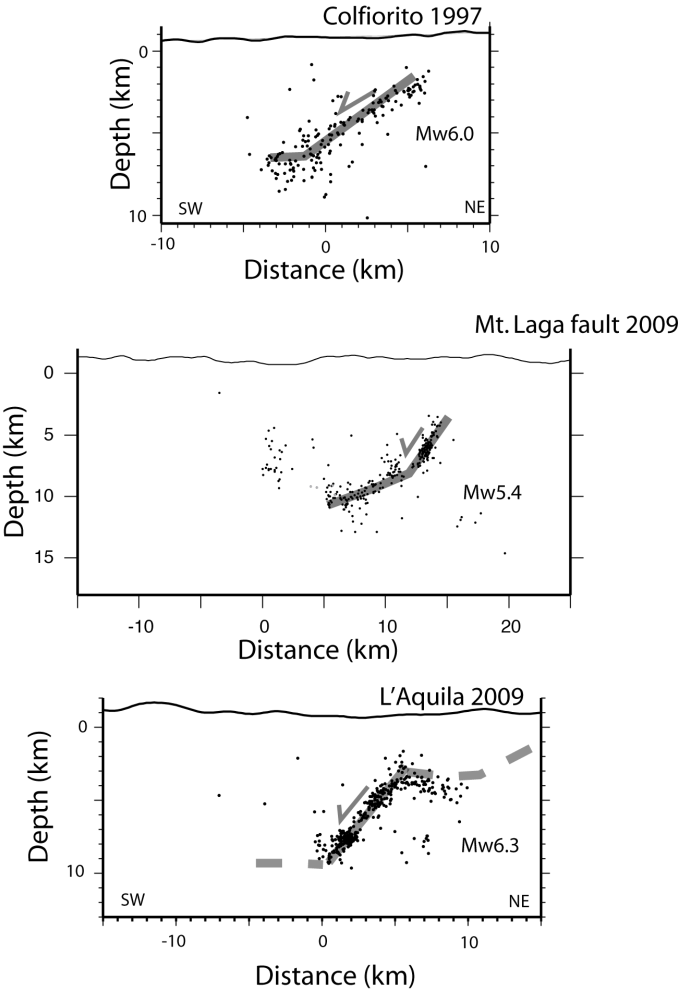


Details of seismicity in the region struck by the recent normal faulting earthquakes. White dots are epicenters form the CSI catalog. The mainshocks and aftershocks of the 1979 Norcia, 1997 Colfiorito, 2009 L'Aquila seismic sequences are shown with a colour scale relative to hypocentral depths. Fault segments from .. are shown. Not the striking continuity of the NNW-striking normal faulting system.

There are two main regions with intermediate-depth earthquakes (35 > z >70 km): one located in the northeastern part and one in the central region (Umbria-Marche), separated by an area where this type of seismicity is poor (Figure 1). None of the intermediate-depth earthquakes occur further west, where a high velocity anomaly is found in the shallow mantle by teleseismic tomography (white dashed line, modified after Giacomuzzi et al, 2010). Numerous studies on subduction zones document that earthquakes in the Benioff zone, sometimes delineating a double seismic layer (Brudzinski *et al.*, 2007), occur for metamorphism and dehydration of slabs (Hacker *et al.*, 2003). In our case, deep focus earthquakes are likely generated by the dehydration of the lower crust in the flexed Adria lithosphere, down to the depth after which the eclogitization is probably complete. The positive velocity anomaly at 70 km depth defines the top of the eclogitized Adria lithosphere.

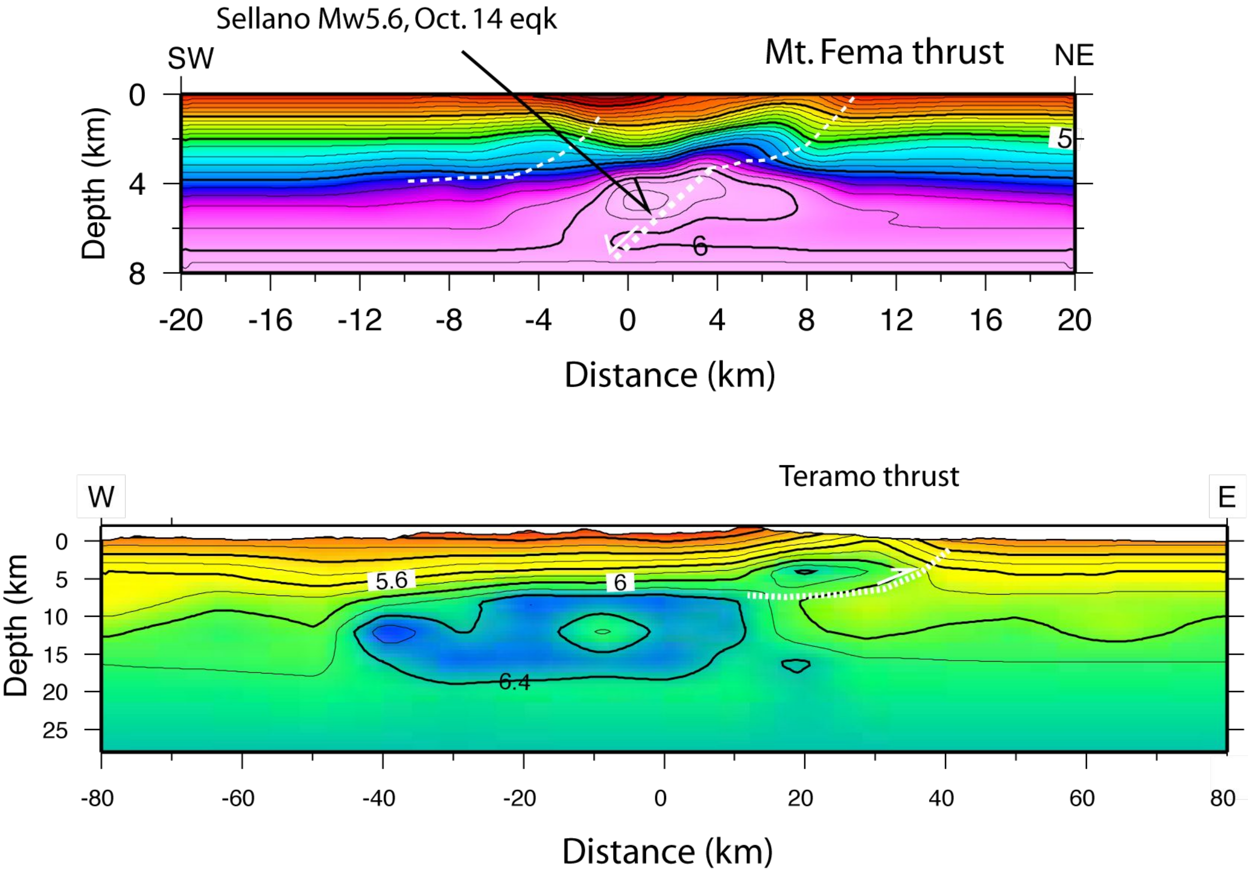
The external belt of deep crustal earthquakes is characterized by reverse faulting mechanisms (Frepoli and Amato, 1997; Piccinini *et al.*, 2006; Chiarabba *et al.* 2009a) with compression at mid – low crustal depths. Generally, this deep seismicity has moderate magnitude. Historical earthquakes such as the 1741, 1799, 1873 and the 1943, Imax<9, are those characteristic for this region.

Figure 3. Fault geometry by aftershocks.



Vertical sections of aftershocks across the 1997 Colfiorito, 2009 L'Aquila and 2009 Laga Mt faults (locations from Chiarabba *et al.*, 2009c and Chiarabba *et al.*, 2009b). The seismicity delineates gently dipping faults that flatten at depth.

Figure 4. Normal faults vs. thrusts from tomography.



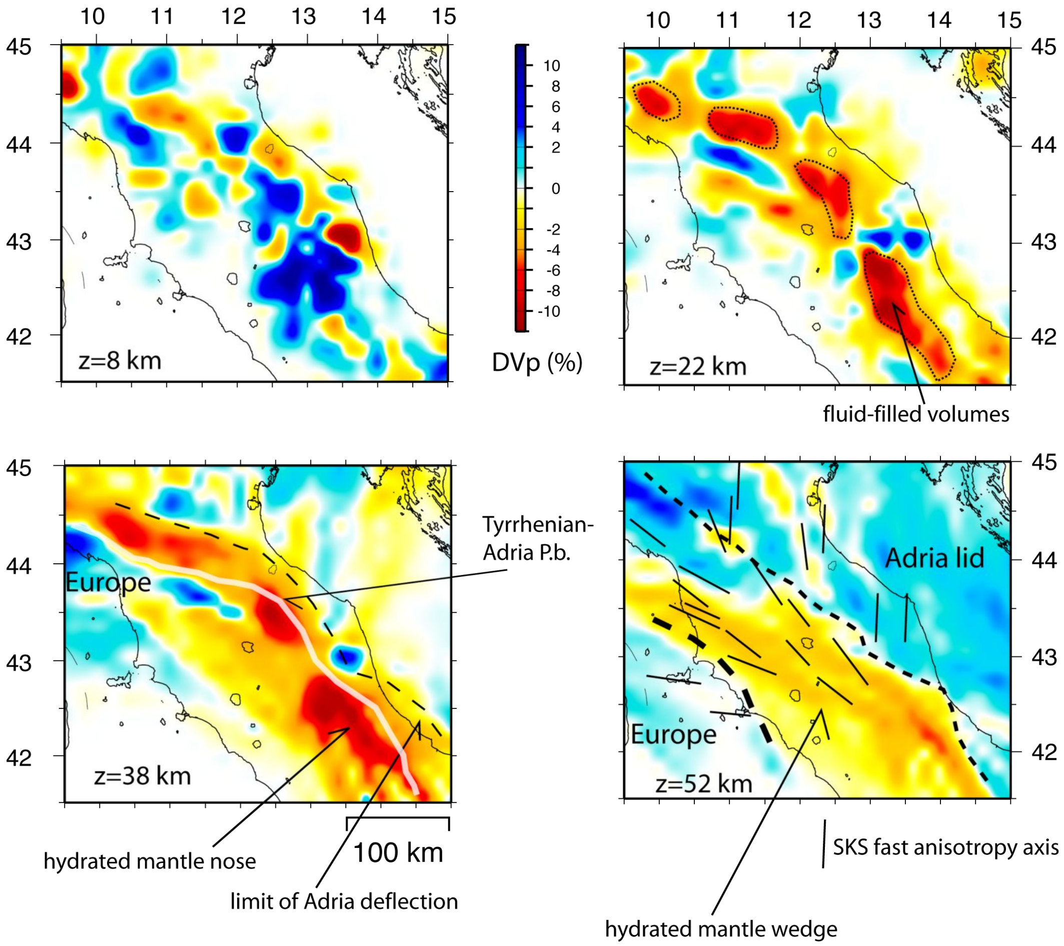
Details of the upper crust structure across two main thrusts of the central-northern Apennines (Fema-Cavallo Mts., and Teramo thrust) from the seismic tomography by Chiarabba *et al.* (2009c) and Chiarabba *et al.* (2010). In the first case, the Mw5.4 October 14 1997 earthquakes originated on a deep steep ramp of the Fema thrust (bold. dashed white line), while the upper portion is more propagated eastward on a flat located at 2-3 km depth (white dashed line).

The western belt of seismicity underneath the mountain range accommodates the extension of the Apennines wedge revealed by geodetic data (Hunstad *et al.*, 2003; Serpelloni *et al.*, 2005; D'Agostino *et al.*, 2008; Devoti *et al.*, 2008). The recent large magnitude normal faulting earthquakes occured on southeastward gently dipping (40-50°) normal faults (Chiaraluce *et al.*, 2004; Chiarabba *et al.*, 2009b). Figure 2 shows the past year's seismicity of the normal faulting belt in the central area from Umbria-Marche to Abruzzi. It is strikingly evident the NNW-elongated fault system, along which moderate and large magnitude earthquakes develop, spanning from the 1979 Norcia to the 2009 L'Aquila events (Figure 2). The normal fault system is almost continuous, but fragmented into segments with length in the order of tens of kilometres. The distribution of aftershocks in vertical sections of aftershocks, across the portions of the fault system for which high resolution seismological data are available (Figure 3), reveal that the normal faults have dip less than 40-50° and present flattening both on decollements at depth (between 6 and 9 km) and in some cases upward (see section 2). The strictly linear stripe of normal faulting earthquakes does not mirror the surface trend of pre-existing faults, except in a few cases. Although such an argument has been used to contrast the possibility that normal faults re-activate old thrusts (see Chiarabba *et al.*, 2009c and references therein for a discussion), the striking linearity of the fault system and the gentle dip of the ruptured faults are strong support to this concept. One explanation for this inconsistency could be a de-coupling of deformation between upper, sometimes rootless, nappes and the deep units occurring along shallow decollements, mostly developed within the Mesozoic cover, (2-4 km depth). Recently developed local earthquake tomographic studies of the Umbria-Marche 1997 and Abruzzi regions (Chiarabba *et al.*, 2009; Chiarabba *et al.*, 2010) shows that the upper sedimentary cover is deformed by compressional tectonics differently from the deeper portion of the upper crust and the main thrusts seems to be decolled at shallow levels (figure 4). The shallow portion of the stack units has average displacements of a ten of kilometers, in agreement with geologic data (Mazzoli *et al.*, 2005), while at depth the thrusts have high angle ramps within the basement.

The crustal-mantle structure: bottom to top

Today's active extension takes place underneath the Apennines range replacing the Mio-Pliocene compression. Since the extension is relatively young, graben-like structures are still not over-printed on the former compressional features. This conclusion comes from several tomographic studies of the upper crust (Chiarabba and Amato, 2003 and references therein), computed in past years for isolated spot-like portions of the Apennines fault system. All these studies give valuable information on the structure of the uppermost crust, but fail in illuminating the middle and lower crust. Thus, the overall geometry of the Apennines is better imaged by regional tomographic studies, whose lateral definition of structures is smaller than in small-scale studies, but resolution is even for the whole lithosphere - asthenosphere system (Chiarabba *et al.*, 2009a; Di Stefano *et al.*, 2009).

Figure 5. P-wave velocity in the crust and uppermost mantle.



P-wave velocity perturbations of the crust and uppermost mantle in the central – northern Apennines (tomography by Di Stefano *et al.*, 2009). SKS simplified from Salimbene *et al.* (2007) are mapped on the upper mantle layer. The main features discussed in the text are shown with solid and dashed lines and labelled.

Figure 5 shows maps of velocity perturbations in the crust and uppermost mantle from Di Stefano *et al.* (2009) model, zoomed in the northern central Apennines. Velocity anomalies in the uppermost mantle are intriguing and give a first clue in understanding the structure and evolution of the Apennines. Beneath the northern Apennines, we find two positive P-wave velocity anomalies corresponding to the mantle lid of Europe (to the west) and Adria (to the east). In between them, a broad negative velocity extends in the Tyrrhenian inland region (Dv_p=-4-6 %). SKS anisotropy is mirroring this separation (Salimbene *et al.*, 2007). Fast anisotropy axes are mostly E-W trending in the European lithosphere, consistent with a long-route eastward flow of the mantle (see Lucente *et al.*, 2006), trench parallel in the Tyrrhenian inland region and broadly N-trending in the Adria lithosphere.

In the uppermost mantle, the Europe and Adria lithospheres have positive velocity anomalies and are separated by a very pronounced belt of low v_p anomalies (Dv_p= -10 %) that follows the curved Apennines range. As discussed by Di Stefano *et al.* (2009), this anomaly might be explained by down-dragging of crustal material. Intermediate-depth earthquakes occur at the border of this anomalous body.

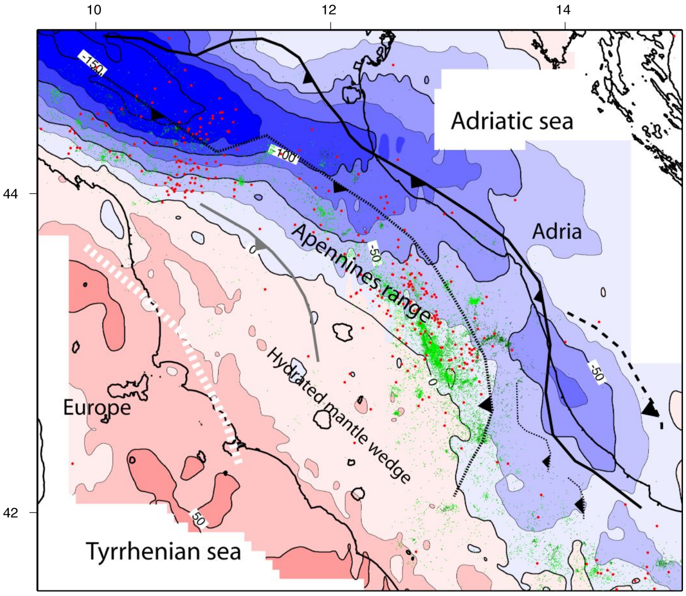
The lower crust layer shows the existence of several low v_p anomalies underneath the Apennines range (v_p less than 5.6-5.8 km/s). These anomalies may coincide with the Mesozoic limestones and basinal rocks, underplated during the formation of the accretional wedge. Regardless, the computed velocity values are much smaller than those attributable to the same rock types at pressure and temperature conditions of the shallow crust. These low velocities are hardly compatible with sedimentary rocks at pressure conditions of the lower crust, and suggest the existence of deep fluid-filled rock volumes.

The upper crust underneath the Apennines range is dominated by very high v_p anomalies (perturbation as high as 12 %) with a velocity of up to 6.7-7.0 km/s, values much higher than those measured for the sedimentary cover. Such strong high velocity bodies concentrate beneath the Apennines range and broadly spread in the Abruzzi region (see figure 5).

Seismicity and gravity Bouguer anomalies

The Bouguer anomaly map (Figure 6, from the gravity data of the National Geological Survey, M.G. Ciaccio, written communication) reveals strong variations in the northern central Apennines. Some main features can be recognized:

Figure 6. Bouguer anomalies and seismicity.



Bouguer anomaly map (data from the Geological Survey and elaborated by M.G. Ciaccio) and seismicity in the study area (CSI catalogue). Light to dark green dots are crustal earthquakes, with progressive greater depth; red dots are the intermediate-depth earthquakes. The main tectonic lines are shown, the dashed line is the outer fron from Scrocca (2006).

i) Lightly positive anomalies underneath the Tyrrhenian domain (20-40 mgal) consistent with the crustal thinning at the back of the Apennines wedge (see also Makris *et al.*, 1988; Caratori Tontini *et al.*, 2007). In the northern Tyrrhenian region, the gravity high is relatively small, suggesting that continental thinning did not lead to the break of the continental plate and oceanic opening, opposite to the southern Tyrrhenian region, where the ocean opening was triggered by the fast retreat of the Ionian slab (see Kastens *et al.*, 1986; Chiarabba *et al.*, 2008 and references therein).

ii) A diffuse area of relatively null anomalies from the belt axis to the Tyrrhenian margin (inland area). Since receiver function studies do not indicate a significant variation of crustal thickness between the Tyrrhenian Sea and the inland area (Piana *et al.*, 2002; Mele *et al.*, 2003; Di Bona *et al.*, 2008; Piana and Amato, 2009), we argue that the minor gravity anomaly observed in the inland, thinned lithosphere might result from a low density in the uppermost mantle.

iii) Negative anomalies along the north-eastern part of the Apennines, consistent with a broad deflection of Adria beneath the Apennines (Royden *et al.*, 1987). In the northern area, deep focus earthquakes occur within the strongly negative anomaly area (-150 mgal, see figure 3) suggesting the existence of a very thickened crust - a consequence of the continental collision. In the Umbria-Marche section of the Apennines, deep focus earthquakes occur in regions with null gravity anomaly, while the strongest negative values are observed more to the east, along the Adriatic coast and coincide with thick foredeep basins. In the Abruzzi area, a diffuse negative anomaly is present (see also Tiberti *et al.*, 2005). Since extremely high v_p anomalies are observed in the shallow crust (figure 3, layer 8 km), we argue that the main cause of this negative Bouguer anomaly is a deep low-density body.

Seismotectonics of northern-central Apennines

Seismicity, tomographic results, gravimetric anomalies and geophysical data outline four main deep features that are significant in understanding the evolution of the Apennines:

a) The broad low $\mathrm{v_p}$*, low-density anomaly in the Tyrrhenian inland uppermost mantle.* In this inland area, local earthquake tomography (figure 2), Pn-wave modelling (Mele *et al.* 1996) and Bouguer anomalies revealed the existence of low P-wave velocity and low-density anomalies in the uppermost mantle. Recently, Piccinini *et al.* (2010) found a high attenuation of P and S waves for teleseismic events sampling this mantle volume, and interpreted this anomaly as due to a strong hydration of the Tyrrhenian mantle at temperature lower the near-solidus condition. All this evidence, along with the concomitant presence of trench parallel fast axes, point to the existence of a serpentinized mantle wedge. In the case of B-type olivine, i.e., fluid enriched mantle, the fast axes of anisotropy align perpendicular to the plate motion (Jung and Karato, 2001; Long and Van der Hilst, 2006; Kneller *et al.*, 2008), as observed in subduction zones worldwide (Russo and Silver, 1994). The amount of splitting is consistent with a ten of kilometres thick serpentine layer and does not require a thicker anisotropic mantle, as in the case of A-type olivine. The lower temperature near the solidus condition indicates the mantle wedge is cold and not significantly melted, but warm enough to prevent significant magnetic anomalies typical of serpentinized mantle.

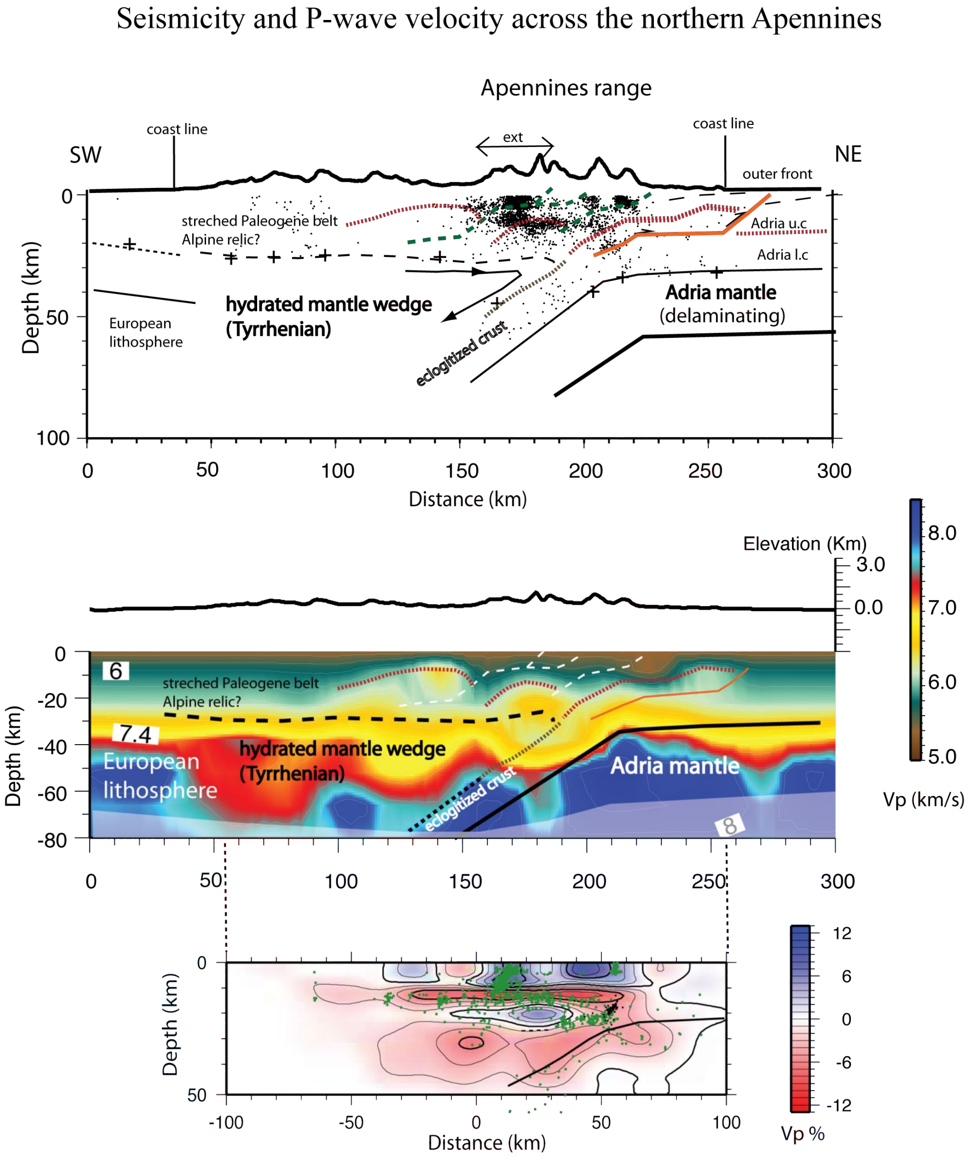
b) The outer ring of low $\mathrm{v_p}$ *anomalies.* Di Stefano *et al.* (2009) interpreted this feature as crustal material down-dragged in the subduction of Adria beneath the Apennines. Intermediate-depth earthquakes indicate that the thickness of this crustal layer is of about 10 km (figure 7), much thinner than the extent of the low velocity anomaly. A high-resolution velocity model recently obtained for the area (Chiarabba *et al.*, 2009a) shows low velocity anomalies located above the west-dipping seismic plane (see section in the lower panel of figure 7) and supports the explanation of part of this anomaly as a "bob-up" wedge nose, i.e. the easternmost advanced portion of the Tyrrhenian hydrated mantle, a seismic signature of the asthenospheric nose described by Cavinato and De Celles (1999).

c) Low $\mathrm{v_p}$ *spots in the Apennines lower crust.* These anomalies are distributed widely beneath the Apennines range, just underneath the extensional seismic belt. We hypothesize that the major contribution to the lowering of P-wave velocity is given by super-critical CO_2 filled volumes stocked in the middle-lower crust. In support of this hypothesis, Chiodini *et al.* (2000; 2004) showed a close relationship between seismicity and the very high CO_2 flux observed in the Apennines. Velocity reductions in the middle-lower crust are also interpreted as CO_2 filled volumes underneath the thrust stack units (Chiarabba *et al.*, 2009a). The location of these fluid-filled volumes just underneath the normal faulting belt suggests an active role of fluids in promoting seismicity in the Apennines. We hypothesize that the fluids temporarily stocked in the crust are those coming from the strongly hydrated Tyrrhenian mantle.

d) Extensive high $\mathrm{v_p}$ *bodies in the crust.* Underneath the Apennines belt, several high v_p bodies are evident in the crust, especially in the Abruzzi region (figure 5). Although the origin of such bodies is highly debated (see Chiarabba and Amato, 1997; Chiarabba *et al.*, 2010), they might define basement rocks ripped by the compressional tectonics and stack in the belt. The extremely high P-wave velocities, of about 6.7-7.0 km/s, are more compatible with a mafic basement.

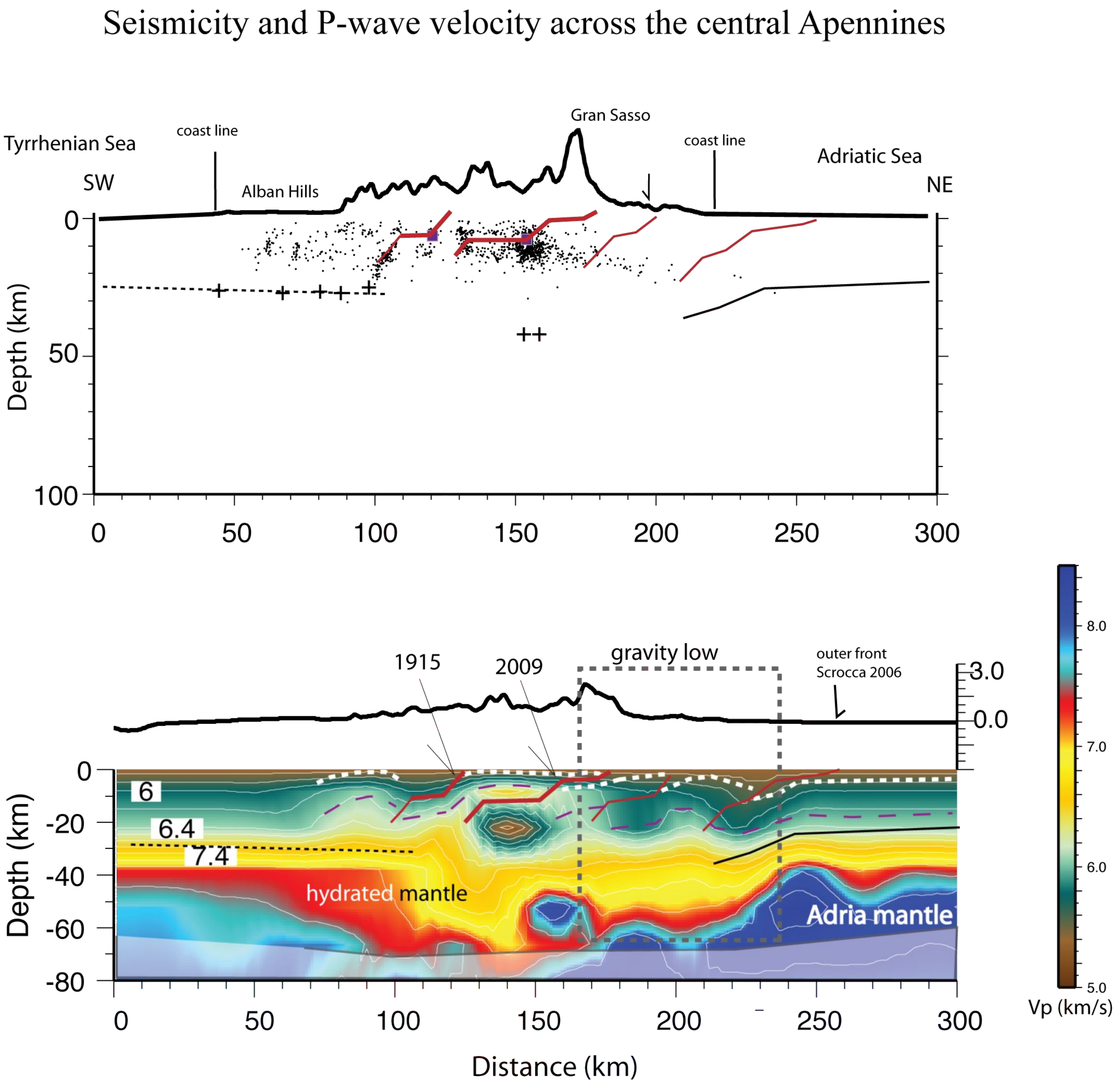
To better visualize the structure of the Apennines, we show vertical sections of seismicity and P-wave velocity across the belt (Figures 7 and 8 for the Umbria-Marche and Latium-Abruzzi regions, respectively). The general feature emerging from tomograms is that the compressive features developed during the wedge accretion dominate the deep structure. At a broad scale, the architecture of the belt consists of deep thrusts that stack composite piles of sedimentary and, probably, basement rocks. The warping and trend of the 7.0 km/s iso-velocity line describe the geometry of the deep crust material stack in the Apennines wedge. If we accept the interpretation of the high velocity anomalies as basement rocks, this isoline maps the top of the basement involved in thrust tectonics.

Figure 7. Seismicity and P-wave velocity across the northern Apennines.



Vertical sections of seismicity (top panel), P-wave velocity from Di Stefano *et al.* (2009, middle panel) and P-wave perturbations from Chiarabba *et al.* (2009a, lower panel) across the northern Apennines (see the track in Figure 1). The dashed area in the tomographic model is poorly resolved. The crosses are the Moho depth from Piana and Amato (2009). The bold and dashed black lines are the Adria and Tyrrhenian Moho discontinuities, respectively. The geometry of the deep units, drawn in the tomographic panel, are reported in the upper panel on the seismicity and interpreted. In the lower panel, the green dots are the 3D located seismicity (from Chiarabba *et al.*, 2009a), while the black dots are the earthquakes during the January 2010 sequence, delineating a steep SW-dipping ramp.

Figure 8. Seismicity and P-wave velocity across the central Apennines.



Vertical sections of seismicity (top panel) and P-wave velocity from Di Stefano *et al.* (2009, middle panel) across the central Apennines (see the track in figure1). The dashed area in the tomographic model is poorly resolved. The crosses are the Moho depth from Piana and Amato (2009). The geometry of the deep units, drawn in the tomographic panel, are reported in the upper panel on the seismicity and interpreted. The dashed white line is the top of the Adria limestone, the violet dashed line is the top of the high v_p bodies, reasonably the metamorphic basement. The bold and dashed black lines are the Adria and Tyrrhenian Moho discontinuities, respectively.

Northern area

In this area, a paired couple of extension and compression is documented by geologic data and recent seismicity (Calamita and Deiana, 1988; Frepoli and Amato, 1997; Chiaraluce *et al.*, 2004; Chiarabba *et al.*, 2005; Carminati *et al.*, 2010). Barchi *et al.* (1898a,b) Barchi *et al.* (2006), and Collettini *et al.* (2006) proposed a model of progressive eastward migration of paired crustal stretching, at the back and in the upper cover, and frontal shortening, from the Tyrrhenian to the Adriatic areas. Seismicity distribution (figure 7) shows that the eastward thrust, whose emersion fit the location of the compression front at the surface, is rooted down to 20-30 km depth and still active. Deep crustal seismicity (see also figure 1) originates on flat and ramp of this thrust accommodating, with steep angle inverse faults, a low-rate compression in the wedge. Historical earthquakes with M<6.0 are documented in this region probably originating on the ramps of the system. The compression is paired with the extension of about a few mm/yr revealed by GPS data and localized at the contact between the Adria lithosphere and Tyrrhenian mantle wedge. In this narrow belt, the normal fault system is fragmented into small segments, which have a lateral extent less than 10 km and rupture during M6.0 earthquakes (Chiaraluce *et al.*, 2004).

Central area

Differently from the northern area, stress indicators do not indubitably reveal active compression (Montone *et al.*, 2004). Instrumental data show the absence of deep crustal seismicity and intermediate depth earthquakes (see figure 1). These features document a first order variation in active tectonic process along the northern-central Apennines.

The velocity structure shows the existence of several strongly positive anomalies (v_p around 7.0 km/s) describing the incorporation of deep crust units in the wedge, even at very shallow depth. We observe two main deep high-velocity antiforms, located in the western and eastern sides of the mountain range, the former is also seen by sharp reflections in the CROP11 seismic profile and interpreted as a deep compressional feature (Billi *et al.*, 2006; Billi and Tiberti, 2009). The main feature is a central uplifted high velocity body (basement and overlaying sedimentary cover?). As already said, the nature of these high v_p, high v_s bodies is speculative. Based on the extremely high velocity, Chiarabba *et al.* (2010) proposed that mafic, strongly exhumed, rocks compose the basement upon which the Mesozoic sedimentary cover was deposed. This exhumation probably occurred during the Mesozoic rifting episodes of the Tethys Ocean and thinning of the continental margin. The accretion of this thin continental lithosphere to the Apennines wedge during the Mio-Pliocenic compression is probably a cause of the structural complexity revealed by tomography (Figure 8).

The external high v_p deep antiform (X=200, in the section) might represent an uplifted block on the hanging wall of an inverted normal fault. Its upward extent, that follows the warping of anomalies at shallow depths, matches the thrust front proposed by Scrocca (2006). In this recent reconstruction, the front, which incorporates the Mid Adriatic Ridge, is located in the Adriatic offshore tens of kilometres eastward of that commonly accepted (Figure 1). Our velocity model agrees with this model and favours the eastward location of the thrust front. The overall resulting geometry is a progressive eastward retreated flexure of Adria from northern Apennines moving southward, until the Gargano region.

Today, the active extension concentrates in the central part of the Apennines range (Galadini and Galli, 2001). The normal faults responsible for the two most relevant earthquakes of the region (the Mw6.7 1915 Avezzano earthquake and the Mw6.3 2009 L'Aquila earthquake) follow the location and geometry of the central uplifted unit.

Apennines tectonics as caused by lithosphere delamination

The deep structure of the crust and uppermost mantle, along with the intermediate-depth earthquakes, are consistent with a progressive delamination and foundering of the Adria lithosphere beneath the Apennines. Such a process was proposed in mid-1990 on the basis of broad low velocity and high attenuation in the Apennines mantle revealed by the propagation of Pn waves (Mele *et al.*, 1996; 1998). It was competing with a model of Adria subduction, which was anchored on the positive velocity bodies diving in the mantle recognized by teleseismic tomography (Lucente *et al.*, 1999, Piromallo and Morelli, 2003) and the presence of "sub-crustal" earthquakes (Selvaggi and Amato, 1992). The recent improvement of the seismological observational networks and the availability of a huge set of earthquake data (Castello *et al.*, 2005) yielded high-resolution velocity and attenuation models of the uppermost mantle (Di Stefano *et al.*, 2009; Chiarabba *et al.*, 2009a; Piccinini *et al.*, 2010). These studies localize the negative velocity and high attenuation zones in the mantle above a narrow stripe of deflected and dehydrating Adria crust. Furthermore, new teleseismic model (Giacomuzzi et al., 2010) shows pronounced low velocities in the Adria uppermost mantle. Thus, can such weak continental lithosphere subduct? On the other hand, intermediate-depth earthquakes only testify for down-dragging, and dehydration, of crustal material, compatible with both delamination and subduction processes. All these evidences may be explained by delamination and foundering of the Adria continental edge, with complexity and lateral irregularities that follows those of the original Tethys margin (figure 9).

The existence of a negative buoyancy between a continental lithosphere and a warm, hydrated and mobilized asthenosphere is required for delamination (Meissner and Mooney, 1998; Leech, 2001). In the Apennines, this condition is generated by a weakening of the Adria mantle, as a consequence of the Paleogene subduction. The negative velocity anomalies recently found by teleseismic tomography beneath Adria is evidence of such weakening (see Giacomuzzi *et al.*, 2010).

The difference in the deep structure between the northern and central portion of the Apennines (figures 7 and 8) implies that the length of delaminated lithosphere is variable along the belt, also at short distances (hundred of kilometers). This is mirrored by the irregular front of compression and change in dip of the regional monocline (see Mariotti and Doglioni, 2000). We hypothesize that pre-existing variation of rheological properties along the Adria continental margin and a different timing, or velocity, of delamination causes these lateral irregularities. The delamination seems to be at a progressively younger stage moving from south to north, suggesting that the recent fast subduction and retreat of the Ionian slab in the southern Tyrrhenian region have favoured and accelerated the process. The Apennines delamination can be seen as a terminal process of evolution in the continental lithosphere at the margin of the subduction of the Ionian ocean.

In the northern Apennines (figures 7 and 9a) the delamination is ongoing in a restricted portion encompassing the Mt. Conero, promoting compression in the external area, deep rooted in the basement, and extension in the belt. The active foundering is testified by the intermediate depth seismicity well defining the narrow strip of dehydrating crust.

In central Apennines (Abruzzi, figures 8 and 9b), the foundering of the Adria lithosphere seems to be absent or ceased since the lack of intermediate-depth earthquakes and the marked negative velocity anomaly in the mantle (see also Chiarabba et al., 2009a). This evidence, along with the external position of the thrust front recently proposed by Scrocca (2006), might be consistent with a southward increase of delamination in the continental edge, i.e., greater toward the still subducting Ionian oceanic slab. The asthenosphere mobilization on top of the delaminated crust may be the cause of strong uplift and sustained topography invoked by D’Agostino and Mckenzie (2000) based on free air gravimetric anomalies, and consistent with a mature delamination (England and Houseman, 1989).

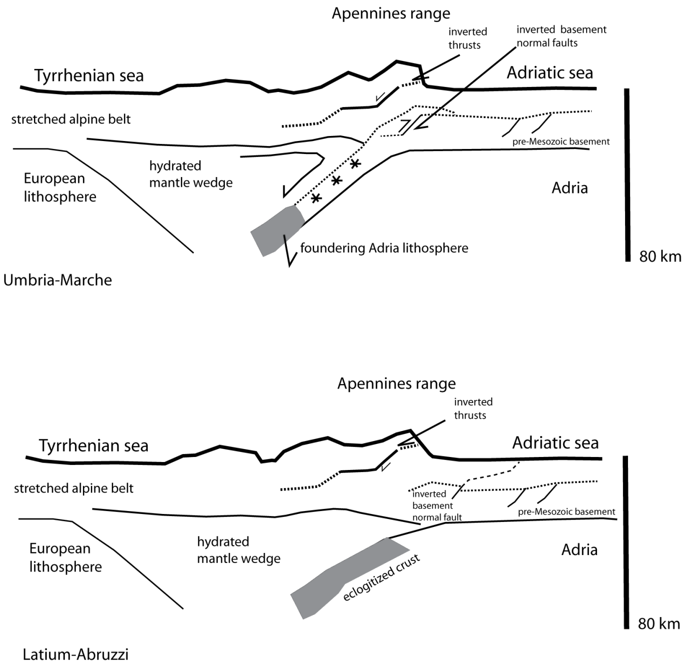
Tectonic inversion

The tectonic model that best applies to the formation of the Apennines is widely debated (see for this topic Bally *et al.*, 1986; Doglioni, 1991; Bigi *et al.*, 2002; Speranza and Chiappini, 2002; Tozer *et al.*, 2002, Scrocca *et al.*, 2005, Mazzoli et al, 2005, among many others). We add some evidence from seismologic data: i) extension is accommodated on gently dipping normal faults interpretable as pre-existing thrusts (figure 3); ii) in the eastern side of the belt, compression is taking place in the Adria basement, the seismicity occurs on flat and ramps, the latter have dip higher than 60° and are likely pre-existing normal faults (figure 7); iii) the thrust system defined by geologic data at the surface appears to be rooted at depth, with uplifted high v_p body in the hanging wall of steep thrust faults (figures 7 and 8). These onservations offer an intriguing scenario in which shallow decollements ripping the Mesozoic cover, deep steep ramps that likely invert basement normal faults and extension in the sedimentary cover exist for the gravitational readjustment within the wedge, as also proposed based on geologic data (Ghisetti and Vezzani, 1999; Mazzoli et al, 2008).

There are several studies that investigate how the pre-existing structure of the basement controls the style of thrusting (Dewey *et al.*, 1989; Coward, 1994; Ziegler *et al.*, 1995) favouring tectonic inversions (Tavarnelli *et al.*, 2004; Scisciani, 2009). During the Apennines evolution, the subsequent repetition of extension and compression led to a complicated structure where pre-existing faults can be re-activated, although not optimally oriented with the active stress. Since only the sedimentary cover outcrops in the area (sometimes stacked in rootless nappes), we do not have direct observations of the basement structure, although it can be inferred by the subdivision of sedimentary facies in the Meso-Cenozoic realms. Only tomographic models and seismic profiles scan mid- to lower-crust depths. Since geophysical models are obviously not unique for both imaging and interpretation, we cannot definitely assess to which extent the pre-existing structure of the basement influenced the Apennines build up. So, our results are consistent with inverted normal faults in the basement (see figure 8), but the generalization of this evidence to a fully thick-tectonic model is still speculative.

Figure 9 shows a tentative scheme for the tectonics of the Apennines, explained through the reactivation of pre-existing structures. In this short section, we add some outlines from our seismological results

Figure 9. Geologic sketch of the Apennines.



Geologic sketch of the northern (top) and central (bottom) Apennines.

Inversion of normal faults during compression

There are examples worldwide that large thrust earthquakes invert pre-existing normal faults (El Asnam 1980, Chiarabba *et al.*, 1997; Mid-Niigata 2004, Kato *et al.*, 2005; Miyagi 2003, Okada *et al.*, 2007). The northeast Japan case is exemplary - the transition from basin to island arc is accomplished by a general and complete positive inversion of the steep Miocenic normal faults (Kato *et al.*, 2004).

In the Apennines, normal faults developed during two main and separate phases: i) the syn-rift evolution of the Tethys continental margin; ii) a diffuse Miocene extension, documented by geologic data, in the Adria region (Carminati et al., 2004; Bigi and Pisani, 2005). The two sets of normal faults are differently rooted in the Apennines structure, the former affecting the sedimentary cover, the latter prevalently the pre-Mesozoic basement. So, they were differently used during the formation of the thrust and fold belt (see Tavarnelli, 1999; Scisciani *et al.*, 2001; Scisciani, 2009). An example of inversion of normal faults in the basement is given by both the high velocity antiforms present in the Apennines deep structure (figures 7 and 8) and the deep crustal seismicity developing along the Adriatic margin of the Apennines. The recent seismic sequence occurred during January 2010, with the greatest event of ML=4.2, is a good example of a compressional event that develops on an about 60° SW-dipping fault, as constrained by aftershock data (see figure 7 and focal mechanisms available at *earthquake.rm.ingv.it*).

Inversion of thrust faults during extension

The Apennines is one of the best-documented examples worldwide of active extension developing on a compressional wedge. Sometimes the term "negative inversion" has been used to describe the reactivation of thrust as normal fault (Carmignani and Kliegfield, 1990; Jolivet *et al.*, 1998b; Thurner and Williams, 2004). Such a process is documented in active extension regions (Basin and Range, Wernicke, 1981; and Aegean sea, Gautier and Brun, 1994), and in the Apennines (Ghisetti *et al.*, 1993; Bosi *et al.* 1994; Ghisetti and Vezzani, 1997; D'Agostino *et al.* 1998; Bigi, 2006). Analog modelling shows that the reactivation is common when the dip of the pre-existing thrust exceeds 40°, while normal faults can splay on the deep decollement or develop independently for progressive smaller dip angles of the pre-existing thrust (Faccenna *et al.*, 1995). The high quality seismological data available for recent earthquakes indicate that extension is accommodated on gently dipping faults (around 40°-50°, see figure 3), with dip angles that are compatible with the inversion of thrust, as indicated by the analog modeling.

Since the angle and lateral continuity of the pre-existing thrust control the tectonic inversion, we expect that fault segments, which can rupture in normal faulting earthquakes, are controlled by the geometry of the old thrust system. The extreme fragmentation of the normal fault system, with individual en-echelon segments not longer than tens of kilometers, is directly reflecting the architecture of the thrust system at depths.

Reactivation of not-optimally oriented faults needs high fluid pressure (Sibson 1985; 1990; 2004). There are several examples that high pore pressure is conditioning seismicity in the Apennines. First, high pore pressure is observed to be a relevant factor modulating seismicity migration and multiple mainshocks sequences (Miller *et al.*, 2004; Chiarabba *et al.*, 2009b; 2009d). Second, a tight relation between Apennines seismicity and CO_2 flux is documented (Chiodini *et al.* 2004). Third, it is remarkable that past centuries large normal faulting earthquakes in northern-central Apennines occurred in regions where intermediate-depth seismicity indicate the foundering and dehydration of the Adria lower crust. Just on top of this sinking material, low v_p anomalies are found in the lower crust that might represent fluid-filled volumes.

Conclusions

We have proposed some new ideas on the tectonic evolution of the northern –central Apennines, based on high-resolution tomographic images of the lithosphere/asthenosphere system and seismicity. The remarkable difference in the deep structure and seismicity in the Apennines can be harmonized in a general process of delamination and foundering of the Adria continental edge lithosphere after the Africa-Europe plate collision. The complexity of this process, frozen in the deep lithosphere structure, is conditioned by lateral variations of the Adria continental margin following the subduction of the Ionian oceanic plate during the past 30 Ma. Thus, delamination can be a gravitational response of a continental margin developing in the far field of an oceanic subduction (the Ionian slab, in our case) and sustained by a mantle that was pervasively weakened by previous geodynamic processes.

This gravitation re-adjustment generates the paired compression and extension, and the collapse of the accreted wedge; re-mobilizing faults that, during times, experienced iterated tectonic inversions. This, along with the decoupling of deformation between the upper nappe, sometimes rootless, and the deeper basement, makes the individuation of active faults responsible for M>6 earthquakes in the Apennines difficult. Fluids released and mobilized during the delamination process favour the activation of pre-existing, not-optimally oriented faults, and tectonic inversion.

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