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Key Points:
- Along-strike segmentation of the northern Apennine lithosphere is recognized
- Multiple seismological and geological datasets show a left bend in the orogen
- Incipient tearing may separate contrasting styles of lithospheric deformation

Supporting Information:
- Readme
- Figures S1 and S2 and Text S1

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Crustal and upper mantle responses to lithospheric segmentation in the northern Apennines

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Abstract Lithospheric tear faults are expected to develop in response to along-strike variations in the rates of slab rollback. However, the exact geometry of such structures and their crustal and upper mantle expressions are still debated. We present an analysis of seismic, structural, and morphological features that possibly represent the expression of lithospheric segmentation in the northern Apennines. Geophysical observations show evidence for the existence of a discontinuity in the lithospheric structure beneath the northern Apennines, characterized by a change in the spatial distribution of intermediate-depth seismicity, along-strike variations in the pattern of crustal seismicity, and a bend in the Moho topography. The near-surface expression of this discontinuity is associated with an abrupt change in the morphology and exhumation history of the northern Apennines in the proximity of the Livorno-Sillaro Lineament. We interpret these features as evidence for incipient tearing of the lithospheric slab beneath the northern Apennines, marking the boundary between domains that underwent contrasting styles of lithospheric deformation, which are either associated with different rates of slab rollback or a transition from underplating to retreat. We suggest that similar types of structures may play a crucial role in the evolution of convergent plate boundaries, allowing segmentation of orogenic belts and facilitating the development of orogenic curvatures. Ultimately, further tearing along such structures could potentially lead to the occurrence of tear-related magmatism and the formation of slab windows.

1. Introduction

Subduction zones are mobile tectonic elements, which are commonly subjected to varying rates of slab rollback [*Jarrard*, 1986; *Schellart et al.*, 2007]. The primary control on this process is the negative buoyancy of the subducting oceanic lithospheric slab and its gravitational instability relative to the surrounding asthenosphere [*Elsasser*, 1971; *Garfunkel et al.*, 1986]. Subduction rollback, therefore, is strongly sensitive to changes in the buoyancy of the incoming plate [*Martinod et al.*, 2005; *Moresi et al.*, 2014], as well as to other parameters such as the slab width [*Dvorkin et al.*, 1993; *Schellart et al.*, 2007] and the convergence velocity [*Schellart*, 2005]. This means that in most subduction zones, the rates of slab rollback vary along strike, implying that many subducting slabs must be subjected to internal deformation accommodated by bending and/or tearing (Figure 1).

Lithospheric tear faults are expected to occur at the edges of retreating subduction segments (Figure 1a). This type of subvertical tearing, commonly referred to as Subduction-Transform Edge Propagator (STEP) faults [*Govers and Wortel*, 2005], has been documented, for example, at the edges of the retreating Lesser Antilles trench [*Clark et al.*, 2008], South Sandwich trench [*Barker*, 2001], and Tonga trench [*Millen and Hamburger*, 1998]. In addition, tear faults and/or slab bending are expected to develop in response to progressive curvature of subduction zones in cases where variations in slab rollback occur along the strike of the subduction segment (Figures 1b and 1c). In the Italian region, for example, progressive curvature of the subduction zone during slab rollback has led to subvertical tearing of the subducting slab, which gave rise to the strongly segmented 3-D slab structure observed in seismic tomography [*Lucente et al.*, 1999; *Benoit et al.*, 2011; *Giacomuzzi et al.*, 2012]. Furthermore, these lithospheric-scale discontinuities have possibly provided pathways for ascending magmas, thus controlling the spatial and temporal distribution of tear-related magmatism [*Gvirtzman and Nur*, 1999; *Rosenbaum et al.*, 2008; *Gasparon et al.*, 2009]. While the combination of seismic tomography and magmatism provides an insight into the deep lithospheric structure of slab tear faults, the upper crustal expression of these structures is still debated [*Scrocca*, 2006; *Gallais et al.*, 2013; *Argnani*, 2014].

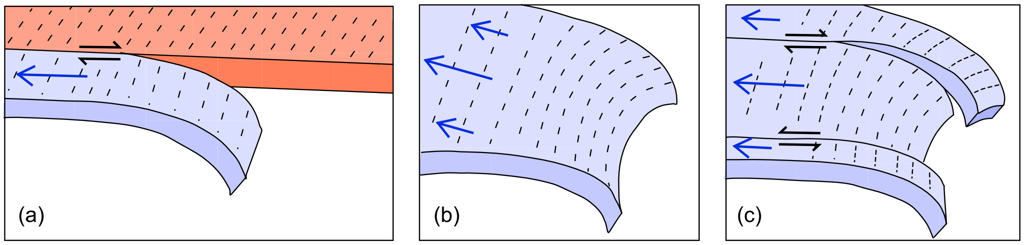

Figure 1. Schematic illustrations of tearing and bending of a subducting slab in response to along-strike variations in subduction rollback (blue arrows). (a) Subduction-Transform Edge Propagator (STEP) fault separating a retreating oceanic subducting slab from the continental lithosphere. (b) Bending of the subducting lithosphere due to along-strike variations in the rates of slab rollback. (c) Higher rates of rollback in a central slab segment relative to the other two segments, accommodated by the development of two opposite-sense slab tear faults.

The aim of this paper is to characterize the geometry and behavior of slab deformation in a retreating convergent boundary and to understand how this deformation is expressed within the overriding continental crust. We focus on an area in the northern Apennines (Figure 2), and we investigate seismic, structural, and morphological data that provide evidence for lithospheric segmentation. The geophysical and geological data used in our analysis have been published by earlier authors [*Chiarabba et al.*, 2005; *Di Stefano et al.*, 2009; *Thomson et al.*, 2010; *Piccinini et al.*, 2014], but whether or not these features correspond to lithospheric segmentation is not yet resolved. Here we systematically investigate the different data sets, highlighting their possible relationships to lithospheric segmentation and discussing the implications of these observations for understanding the evolution of slab tears in retreating subduction zones.

2. Tectonic Setting

The Neogene to Quaternary tectonic evolution of the western Mediterranean was controlled by southeastward subduction rollback, which was accompanied by widespread overriding-plate back arc extension [*Malinverno and Ryan*, 1986; *Royden*, 1993; *Faccenna et al.*, 2001; *Rosenbaum et al.*, 2002]. Within this system, the Tyrrhenian Sea is the youngest (<10 Ma) extensional basin, characterized by thinned continental crust in its northern part and incipient oceanic crust in the southern Tyrrhenian. The latter has developed in the last ~5 Ma, during a period of ultrafast subduction rollback (60–100 km/Ma) of the narrow (~500 km) Calabrian slab segment [*Faccenna et al.*, 2001; *Rosenbaum and Lister*, 2004a] (Figure 2a).

Along-strike variations in the rates of subduction rollback have played a major role in the formation of orogenic curvatures in the western Mediterranean [*Royden*, 1993; *Lonergan and White*, 1997; *Faccenna et al.*, 2004; *Rosenbaum and Lister*, 2004b], a process that has involved large vertical axis block rotations in the Italian peninsula and Sicily [*Speranza et al.*, 1999; *Cifelli et al.*, 2007]. At a lithospheric scale, this curvature was accommodated by tearing and segmentation of the subducting slab (Figure 1c), as inferred from seismic tomography [*Lucente et al.*, 1999; *Di Stefano et al.*, 2009; *Benoit et al.*, 2011; *Giacomuzzi et al.*, 2012] and the pattern of upper mantle anisotropy [*Lucente and Margheriti*, 2008]. The most pronounced expression of this process is the slab window beneath the central Apennines (Figure 2a), which represents a broad gap between fragmented slab segments.

The style of deformation in the Apennines is characterized by a partitioning between contractional strain in the external (Adriatic) part of the orogen and extension in the internal (Tyrrhenian) part (Figure 2a). During the evolution of the orogenic system, both thrust fronts and extensional fronts have migrated eastward as a result of subduction rollback [*Malinverno and Ryan*, 1986; *Patacca and Scandone*, 1989; *Faccenna et al.*, 2001; *Rosenbaum and Lister*, 2004a]. Along-strike segmentation is evident in the spatial distribution of foredeep basins [*Royden et al.*, 1987], variations in topography [*Thomson et al.*, 2010; *Faure Walker et al.*, 2012] and crustal thickness [*Piana Agostinetti and Amato*, 2009], and the pattern of GPS velocity fields [*Devoti et al.*, 2011]. In addition, crustal segmentation is recognized by a series of orogen-perpendicular transverse faults [*Fazzini and Gelmini*, 1982; *Pascucci et al.*, 2007], which seem to show a general correlation with the spatial and temporal distribution of "tear-related" magmatism [*Gvirtzman and Nur*, 1999; *De Astis et al.*, 2006; *Rosenbaum et al.*, 2008; *Gasparon et al.*, 2009]. However, the exact link between these faults and the deeper (lithospheric-scale) structures is unclear.

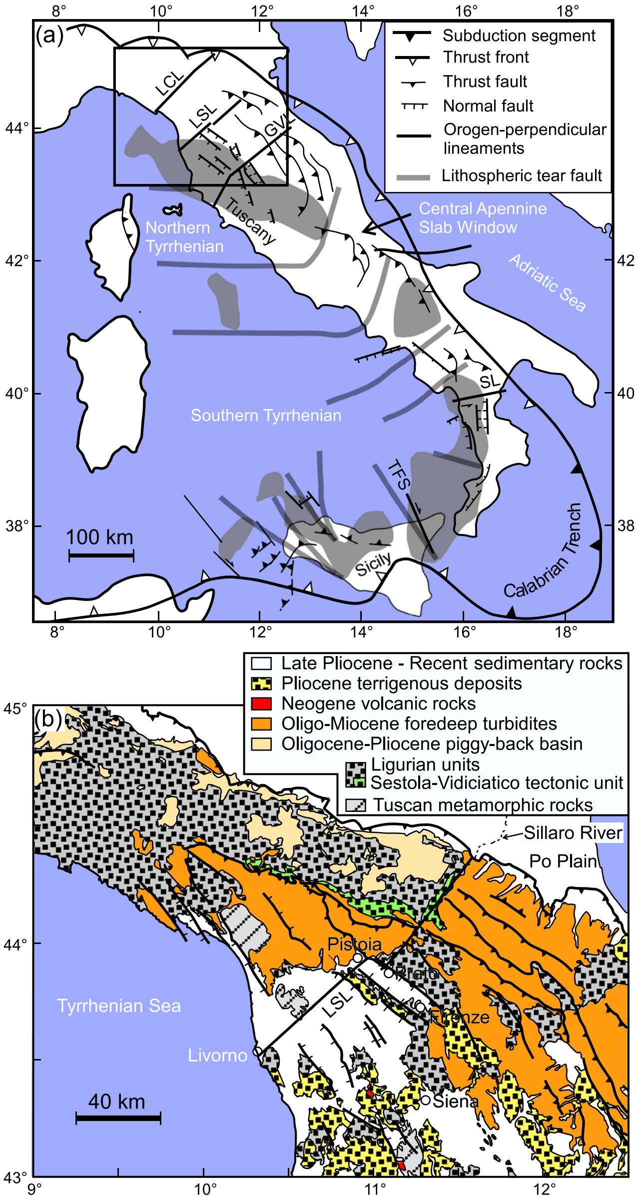

Figure 2. (a) Tectonic map of the Apennines and the Tyrrhenian Sea showing major crustal structures and inferred lithospheric tear faults [after *Rosenbaum et al.*, 2008]. Grey areas show the projection of slab segments at 100–170 km depth as inferred from positive *P* wave seismic velocities [*Lucente et al.*, 1999; *Rosenbaum et al.*, 2008]. LCL, La Spezia-Concordia Line; LSL, Livorno-Sillaro Line; GVL, Grosseto-Val Marecchia Line; SL, Sangineto Line; and TFS, Tindari Fault System. (b) Geological map of the northern Apennines (modified after *Remitti et al.* [2007] and *Thomson et al.* [2010]). The two segments of the Livorno-Sillaro Lineament (LSL) are also shown [after *Bortolotti*, 1966].

A number of orogen-perpendicular lineaments in Italy have been suggested as possible near-surface expressions of lithospheric-scale tear faults associated with slab segmentation. These include, for example, the Tindari Fault System in Sicily [*Billi et al.*, 2006], Sangineto Line in the southern Apennines [*Rosenbaum and Lister*, 2004a], and a number of inherited lineaments in the northern Apennines [*Fazzini and Gelmini*, 1982; *Nirta et al.*, 2007] (Figure 1a). The most prominent orogen-perpendicular structure in the northern Apennines is the Livorno-Sillaro Lineament (LSL, Figure 2b) [*Bortolotti*, 1966; *Bettelli and Panini*, 1992; *Nirta et al.*, 2007; *Bettelli et al.*, 2012]. It runs along two en echelon segments, Livorno-Pistoia and Prato-Sillaro, which are separated from each other by a distance of 10–20 km (Figure 2b). The Prato-Sillaro segment, which represents the easternmost outcropping area of the Ligurian units in the external northern Apennines [*Bettelli and Panini*, 1992], is most likely an inherited weakness zone that originated in the Late Cretaceous and was reactivated during the subsequent growth of the fold-thrust belt [*Nirta et al.*, 2007]. Reactivated deformation along the LSL since the Miocene has been described in association with sinistral strike-slip faulting [*Fazzini and Gelmini*, 1982; *Nirta et al.*, 2007; *Pascucci et al.*, 2007], although direct evidence for strike-slip kinematics is ambiguous [e.g., *Dellisanti et al.*, 2008; *Bettelli et al.*, 2012].

The possibility that post-Miocene deformation along the LSL was linked to deeper deformation processes associated with the segmentation of the Adriatic lithosphere has been discussed by *Nirta et al.* [2007]. The lineament coincides with a transitional zone in the pattern of active seismicity [*Eva et al.*, 2005; *Elter et al.*, 2011] and with an abrupt orogen-parallel change in the level of erosion [*Thomson et al.*, 2010]. In addition, the Livorno-Pistoia lineament seems to separate two orogenic segments that have been subjected to different tectonic processes during the Neogene and Quaternary, with the southeast segment showing evidence for magmatism and widespread sedimentary basins [*Boccaletti et al.*, 1990; *Boccaletti and Sani*, 1998]. In contrast, Neogene to Quaternary magmatic rocks are not exposed in the northwestern segment, and the extent of sedimentary basins is considerably reduced.

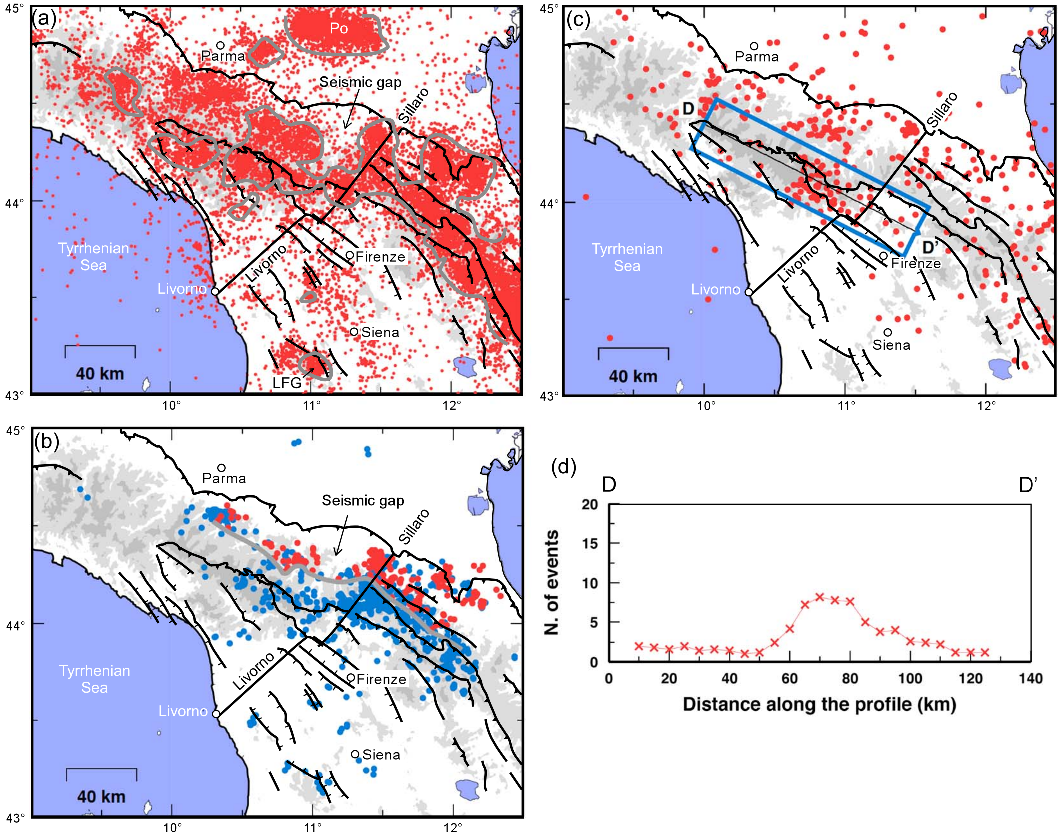

Figure 3. (a) Crustal earthquakes in the northern Apennines based on the CSI [*Chiarabba et al.*, 2005] and ISIDE (http://iside.rm.ingv.it) catalogs. The thick grey line is a density contour that bounds areas with >20 seismic events per 5 × 5 km grid. LGF, Larderello Geothermal Field. (b) Distribution of shallow (<20 km; blue) and deep (20–35 km; red) earthquakes [*Piccinini et al.*, 2014]. The thick grey line highlights the southwestern extent of deep crustal earthquakes. (c) Map showing the distribution of intermediate seismicity (>35 km) based on the CSI [*Chiarabba et al.*, 2005] and ISIDE (http://iside.rm.ingv.it) catalogs. The blue rectangle shows the area used for the data integration along cross-section DD'. (d) Diagram showing the total number of seismic events for 10 km wide boxes within the blue rectangle and parallel to DD'. Note that each two adjacent boxes have a 50% overlap.

3. Seismic Evidence for Lithospheric Segmentation

3.1. Seismicity

The spatial distribution of crustal earthquakes in the northern Apennines is presented in Figure 3a. Data plotted were taken from the catalog of Italian seismicity (CSI) [*Chiarabba et al.*, 2005] for the period 1981–2001 and from the online catalog ISIDE (Italian Seismological Instrumental and parametric DatabasE, http://iside.rm.ingv.it) for the period from 2002 to 2013. The two catalogs were compiled using data from the permanent Italian seismic network, which guarantees a robust horizontal location of the events. The events plotted are only those that were located by more than 10 seismic phases. Figure 3a shows high-density seismicity along the Apennines and diffused seismicity in the Tyrrhenian and Adriatic margins. Two other notable clusters of seismic activity are recognized in the Po Plain and in the area of the Larderello geothermal field. Most importantly is the substantial decrease in the density of seismic activity in a ~20 km wide zone northwest of the Prato-Sillaro lineament (Figure 3a), separating two major seismic segments along the Apennine chain [see also *Eva et al.*, 2005].

Figure 3b shows the distribution of crustal earthquakes, for which robust determinations of hypocentral depths have been conducted using data compilation from both the Italian seismic network and a local network [*Piccinini et al.*, 2014]. Figure 3b highlights the relocated seismic events at two different depth ranges of 0–20 km (blue dots) and 20–35 km (red dots). Similar to Figure 3a, this data set also shows a seismic gap northwest of the Prato-Sillaro lineament, but in addition, the spatial distribution of deep earthquakes highlights a left step over in the pattern of seismicity (thick grey line in Figure 3b), thus providing further

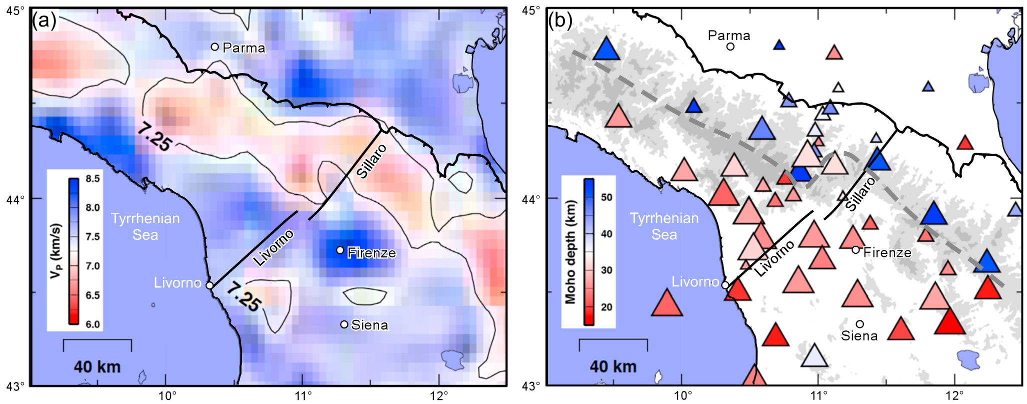

Figure 4. (a) Regional shallow V_P tomography at 38 km depth [after *Di Stefano et al.*, 2009]. Thin black lines are contours of $V_P = 7.25$ km/s. (b) Map showing the depth of the Moho based on receiver function analysis [*Piccinini and Piana Agostinetti*, 2010]. Each triangle indicates a seismic section, with larger symbol sizes indicating better quality data. Dashed grey line highlights the approximate location of the 35 km Moho depth contour.

support for the segmentation of the Apennine chain in the proximity of the seismic gap [see also *Piccinini et al.*, 2014, Figure 5].

The spatial distribution of intermediate-depth earthquakes (Figure 3c) provides first-order information on the existence of along-strike segmentation beneath the northern Apennines. Figure 3c shows the distribution of upper mantle earthquakes (>35 km focal depths) based on the CSI and ISIDE catalogs. Earthquakes plotted in Figure 3c are only those that were located by using more than 25 seismic phases. The cross-section DD′ (Figure 3d) shows the number of events over a 30 km wide area along the profile, using a 10 km wide, 50% overlapping moving window. The data show that intermediate earthquakes are concentrated mainly in the external Apennines (Adriatic side), where the lower continental crust is supposedly delaminated from the upper plate [*Piana Agostinetti et al.*, 2011]. A noticeable exception is recognized at distance 65–80 km along profile DD′ (Figure 3d), where intermediate-depth earthquakes (focal depth between 35 and 65 km) also occur beneath the inner part of the orogen (i.e., Tyrrhenian side). This uneven distribution of intermediate-depth earthquakes along the strike of the orogen indicates that a change in the lithospheric structure occurs in the proximity of the seismic cluster. *Chiarabba et al.* [2014] have recently interpreted this observation as an indication for deep underplating of crustal material.

3.2. Regional Tomography

Seismic tomography based on the model by *Di Stefano et al.* [2009] is presented in Figure 4a, showing the seismic *P* wave velocity at depth of 38 km. The regional tomography was constrained by 166,000 Pg and Pn data recorded by the Italian national seismic network during the period 1981–2002. The model is composed of 615 × 15 km horizontal layers, irregularly spaced at 8, 22, 38, 52, 66, and 80 km depth. Due to the grid vertical spacing, the *P* wave velocity at depth of 38 km represents an average of lower crust and upper mantle velocities. Thus, the exact source of the relatively low *P* velocity (7.0 km/s) beneath the Apennines cannot be unambiguously interpreted (e.g., as the mountain root or hydrated upper mantle).

The seismic tomography image (Figure 4a) shows lower V_P velocities beneath the Apennines and higher velocities in the Adriatic and Tyrrhenian sides. The lower velocities beneath the Apennines likely represent the existence of a thickened (>38 km) crust, whereas higher velocities may correspond to the existence of the mantle lithosphere at 38 km depth. A noticeable feature is the slight left bend in the low-velocity zone (red area bounded by the 7.25 km/s contour in Figure 4a), which occurs northwest of the Prato-Sillaro lineament and possibly indicates along-strike segmentation of the Apennine chain.

3.3. Geometry of the Moho

The depth of the Moho was calculated using receiver function from teleseismic records computed from 24 stations [*Piccinini and Piana Agostinetti*, 2010]. This method can constrain the Moho depth by utilizing *P*-to-*S* converted waves generated by teleseismic events at the Moho discontinuity. Due to the frequency content of

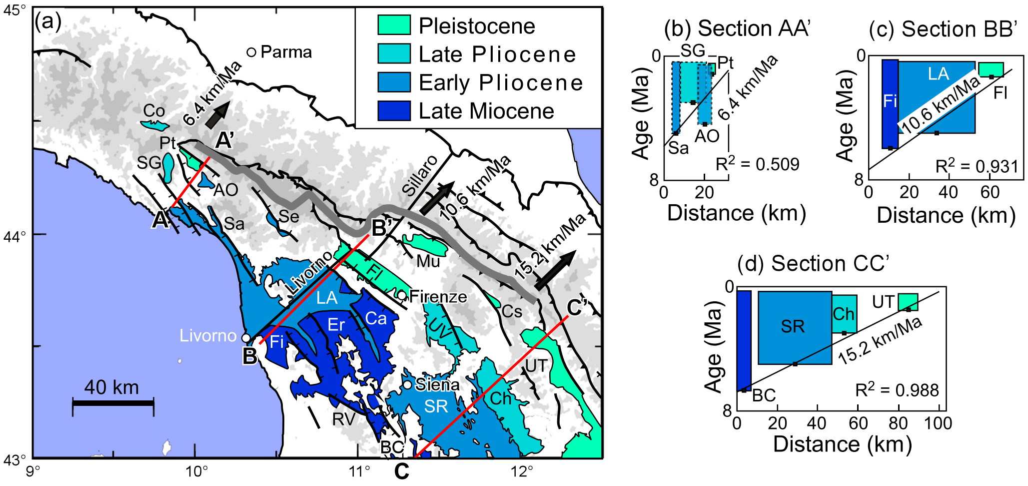

Figure 5. (a) Map showing the distribution of sedimentary basins in the Tyrrhenian margin of the northern Apennines [after *Boccaletti and Sani*, 1998]. Thick arrows show estimated rates of rollback based on the northeastward younging of basin formation highlighted in three sections perpendicular to the orogen (red lines AA′, BB′, and CC′). Also shown is the position of the drainage divide (thick grey line). Sedimentation ages are after *Boccaletti and Sani* [1998]. AO, Aulla-Olivola Basin; BC, Baccinello-Cinigiano Basin; Ca, Casino Basin; Ch, Chiana Basin; Co, Compiano Basin; Cs, Casentino Basin; Er, Era Basin; Fi, Fine Basin; Fl, Florence Basin; LA, Lucca-Altopascio Basin; Mu, Mugello Basin; Pt, Pontremoli Basin; RV, Radicondoli-Volterra Basin; Sa, Saranza Basin; Se, Serchio Basin; SG, Sesta-Godano Basin; SR, Siena-Radicofani Basin; UT, Upper Tiber Basin; and UV, Upper Valdarno Basin. (b) AA′ section; (c) BB′ section; and (d) CC′ section.

teleseismic *P* wave, the method has been widely used to map the Moho topography on a regional scale [e.g., *Piana Agostinetti and Amato*, 2009].

The results show a general crustal thinning from the Apennines (50 km) toward the Tyrrhenian coast (20 km) (Figure 4b). In addition, we recognize along-strike variations in the depth of the Moho, highlighted by a left bend in the approximate location of the ~35 km Moho depth contour (grey dashed line in Figure 4b). We emphasize, however, that the data around the bend are ambiguous, so we cannot determine whether the change is sharp or gradual.

3.4. Additional Data Sets

Additional geophysical data sets that seem to support lithospheric segmentation are presented in Text S1 in the supporting information. Figure S1 shows data from synthetic and observed reflected surface waves [*Stich et al.*, 2009], which allow recognition of lateral heterogeneities (irregular stripes). These heterogeneities roughly correspond to the position of vertical density and seismic structure boundaries (see Text S1 for more information). The importance of this data set is the striking difference between the synthetic and observed data, with the former showing continuous stripes along the Apennine chain and the latter indicating along-strike segmentation in the crustal structure.

Figure S2 shows a map of focal plane solutions for crustal earthquakes using data from *Pondrelli et al.* [2011]. The results show that the southeastern sector of the northern Apennines is dominated by normal faulting in the internal part of the orogen and reverse faulting in the external part, as expected in a retreating orogen [*Malinverno and Ryan*, 1986]. However, in the northwestern sector, a more ambiguous pattern of focal plane solutions is recognized. The transition from a relatively simple pattern of focal plane solutions in the southeastern sector to a more complex pattern in the northwest may correspond to a change in the deformation style along the strike of the Apennine chain.

4. Near-Surface Expression of Slab Tearing

4.1. Surface Geology and the Spatiotemporal Distribution of Sedimentary Basins

The surface geology and the morphology of the Apennine chain provide additional evidence for along-strike segmentation. Figure 5a shows the position of the drainage divide (grey line), which is characterized by an abrupt left bend. In addition, the recognition of a series of transfer faults, most prominently the LSL

(Figure 2b), have been recognized and discussed in previous geological literature [*Bortolotti*, 1966; *Bettelli and Panini*, 1992; *Bettelli et al.*, 2012]. In the external Apennines, older rocks of the Ligurian units [*Elter*, 1975; *Marroni et al.*, 2001] are juxtaposed adjacent to Oligocene and Miocene foredeep turbidites (Figure 2b). The NE striking contact between these units is the Prato-Sillaro segment of the LSL [*Bettelli and Panini*, 1992; *Landuzzi*, 2006; *Bettelli et al.*, 2012]. This lineament records a prolonged geological history, showing evidence that it may have originated as a seafloor morphological feature that influenced the distribution of Late Cretaceous to Eocene turbidite sedimentation [*Abbate and Sagri*, 1982; *Boccaletti et al.*, 1984; *Nirta et al.*, 2007]. The occurrence of a tectonic mélange (Sestola-Vidiciatico tectonic unit, Figure 2b) parallel to the Prato-Sillaro Lineament has been interpreted to represent an erosive subduction channel emplaced at the early Miocene transition from oceanic subduction to collision [*Remitti et al.*, 2007; *Vannucchi et al.*, 2008, 2012]. Based on lithological contrasts and thickness variations, *Bettelli et al.* [2012] have suggested that late Miocene deformation within this unit has involved northeastward differential translations of the rocks aligned parallel to the Prato-Sillaro Lineament relative to those situated southeast of it (see stippled green areas in Figure 2b). The sense of kinematics associated with such differential translations is inconsistent with the suggestion that post-Miocene deformation along the LSL involved sinistral strike-slip faulting [*Fazzini and Gelmini*, 1982; *Nirta et al.*, 2007; *Pascucci et al.*, 2007], leaving the question on the possible kinematics along this segment unresolved. Alternatively, it is possible that the lithological and thickness contrasts at both sides of the LSL do not reflect any displacements along a tectonic contact, but rather represent a boundary between two domains that experienced different exhumation histories. As discussed in the next section, such an interpretation is also supported by thermochronological data [*Cerrina Feroni et al.*, 2001; *Zattin et al.*, 2002; *Thomson et al.*, 2010].

In the area of the Livorno-Pistoia segment of the LSL (Figure 2b), the surface geology is dominated by late Miocene to Pleistocene sedimentary basins (Figure 5a) deposited in an extensional setting [*Martini and Sagri*, 1993; *Bartole*, 1995]. The spatial and temporal distribution of these basins was likely affected by the eastward retreat of the extensional front [*Jolivet et al.*, 1998; *Rosenbaum and Lister*, 2004a]. Two pronounced features recognized in Figure 5a are the younging of sedimentary basins from southwest to northeast and the along-strike variations in the depositional ages, with the occurrence of late Miocene basins in the southeast (Fine, Era, and Casino) and the late Pliocene Lucca-Altopascio Basin in the northwest. Closer to the core of the orogen, Pleistocene basins (Florence and Mugello) are found exclusively southeast of the LSL [*Pascucci et al.*, 2007]. In general, the sedimentary basins southeast of the LSL are considerably larger and record a longer period of deposition (Figure 5a).

The more widespread basin development southeast of the LSL indicates that this area was subjected to faster rates of subduction rollback. This can be quantified by calculating the rates of northeastward migration along three sections (Figures 5b–5d), using the ages of basin formation outlined by *Boccaletti and Sani* [1998] and assuming that these ages correspond to the eastward migration of the boundary. The two sections south of the LSL show consistent younging northeastward, which translate to rollback rates of 15.2 km/Ma and 10.6 km/Ma. North of the LSL the younging is not so consistent (note poor R^2 value) and the inferred rate of rollback is considerably lower.

4.2. Low-Temperature Thermochronology

Constraints on the exhumation history of the northern Apennines are available from low-temperature thermochronology [e.g., *Zattin et al.*, 2002; *Balestrieri et al.*, 2003; *Fellin et al.*, 2007; *Thomson et al.*, 2010; *Remitti et al.*, 2013]. *Thomson et al.* [2010] have shown that the spatial distribution of apatite fission track (AFT) and apatite U-Th/He (AHe) ages in the northern Apennines is characterized by a rapid decrease in ages close to the core of the orogen. The authors attributed this behavior to a total resetting of detrital ages. *Thomson et al.* [2010] have defined the “reset fronts” for AHe and AFT as the boundary between mixed ages and total resetting ages; the locations of these reset fronts are shown in Figures 6a and 6b.

Focusing on the shape of the AFT and AHe reset fronts (thick grey lines in Figures 6a and 6b), we can see that both boundaries are segmented. This is expressed in the curved shape of the thermochronological boundaries, highlighted in Figure 6c, which shows the distance between profile DD′ and the two reset fronts. The diagram shows that the AFT reset front (blue) is situated ~15 km away from profile DD′ in the northwestern segment, but this distance progressively increases southeastward until reaching an average distance of ~25 km (relative to profile DD′). The transition zone is situated at distance 100–110 km along the profile. Similarly, the AHe reset front (red) gradually changes its distance from profile DD′, from 15–20 km in the northwest to 35–40 km in the southeast. The largest change occurs at distance 105–115 km along the profile.

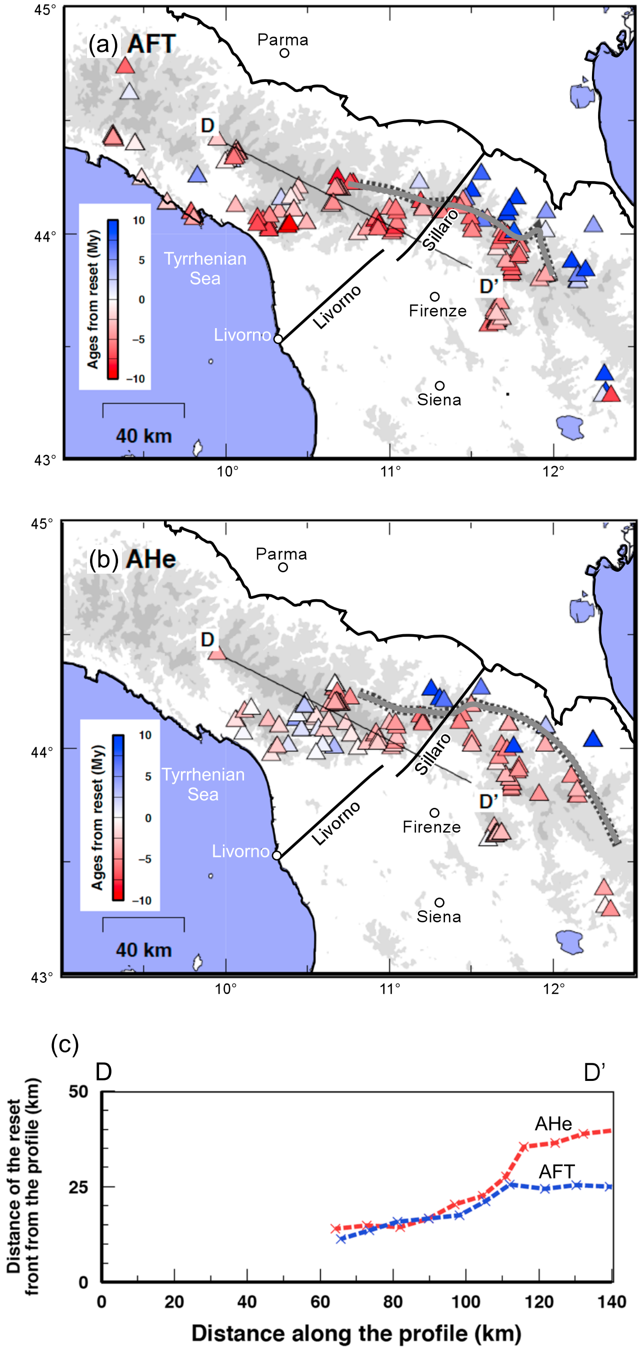

Figure 6. (a) Map showing the deviations of apatite fission track (AFT) ages from the reset age of 10 Ma [after *Thomson et al.*, 2010]. The thick grey line shows the reset front for AFT in the northern Apennines. (b) Deviations of apatite U-Th/He (AHe) ages from the reset age of 6 Ma, with the thick grey line showing the reset front for AHe [after *Thomson et al.*, 2010]. (c) Diagram showing the distance of the AFT (blue) and AHe (red) reset fronts relative to the reference line DD′.

5. Discussion

5.1. Along-Strike Segmentation in the Northern Apennines

The collective observations show evidence for lithospheric-scale discontinuities beneath the northern Apennines in the area that roughly corresponds to the LSL (Figure 7). In the upper mantle, a pronounced cluster of intermediate-depth seismicity (65–80 km along profile DD′; Figure 7h) may correspond to underplating, [*Chiarabba et al.*, 2014]. Together with a bend in the low V_P seismic velocity (95–110 km along profile DD′; Figure 7g), these data sets are indicative of lithospheric segmentation at 80–110 km along the profile. The segmentation is also detected in the depth of the Moho, which shows a left bend of the Moho structural contour at distance of ~75–90 km along profile DD′ (Figure 7f).

At crustal levels, segmentation is recognized within a diffused ~35 km wide zone situated at distance of 75–110 km along profile DD′ (Figures 7d and 7e). The pattern of crustal seismicity shows a slight bend and a seismic gap at a distance of ~90–100 km along profile DD′ (Figure 7d). In addition, a bend in the spatial distribution of deep crustal earthquakes is recognized at a distance of 75–110 km along profile DD′ (Figure 7e).

At the surface, the most pronounced evidence for segmentation is the LSL, which intersects profile DD′ at a distance of ~110 km (Figure 7a). It marks an abrupt change in the crustal architecture that has been inherited and reactivated since the Late Cretaceous [*Nirta et al.*, 2007]. The spatial and temporal distribution of sedimentary basins indicates that the area southeast of the LSL was subjected to higher rates of subduction rollback in comparison to the northwestern segment.

Morphologically, a pronounced change in the topography of the Apennines occurs at a distance of ~100 km along profile DD′, indicated by a sharp left bend in the position of the drainage divide (Figure 7b). A similar

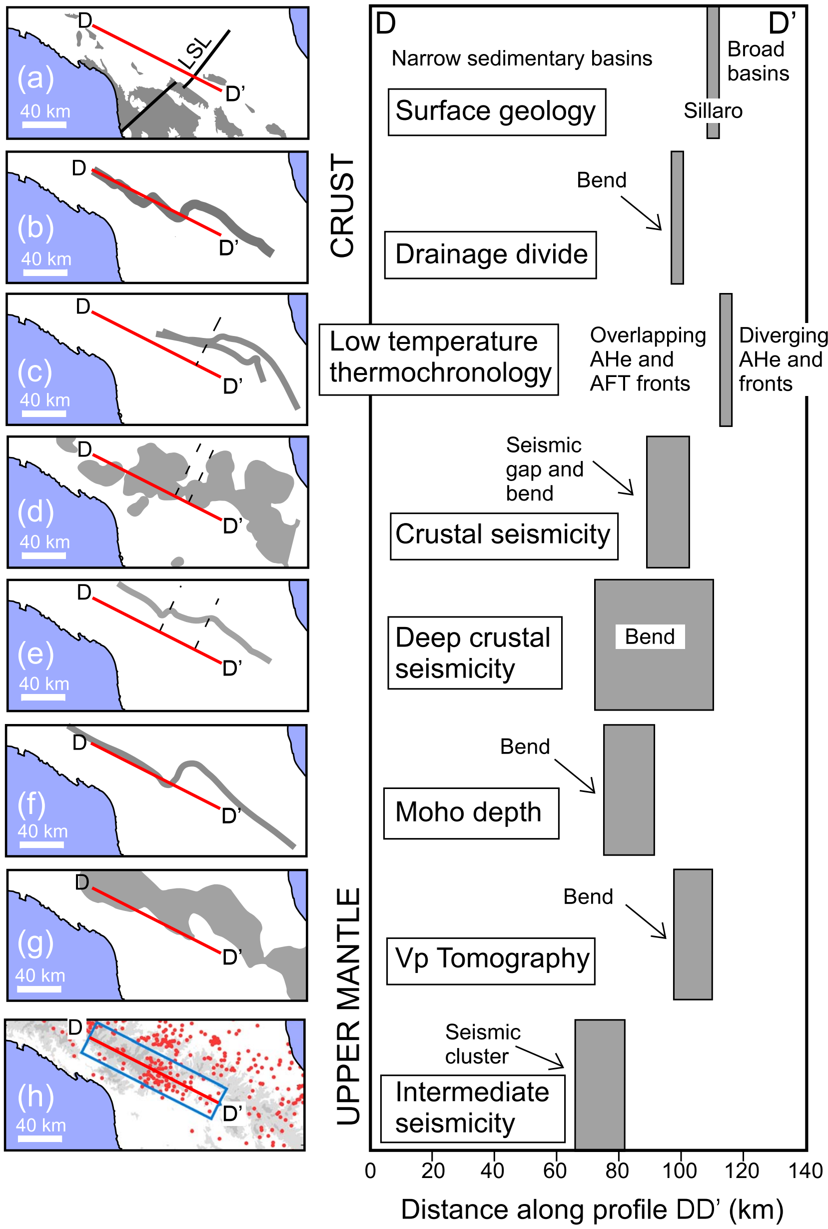

Figure 7. Indicators for along-strike segmentations in the northern Apennines based on the collective geological and geophysical evidence. (a) Surface geology. Shaded area shows the spatial distribution of sedimentary basins. (b) Drainage divide (grey line). (c) Low-temperature thermochronology. Grey lines indicate reset fronts for AHe and AFT. (d) Crustal seismicity. Shaded area indicates >20 seismic events per 5×5 km grid. (e) Deep crustal seismicity. Grey line indicates the southwestern extent of deep crustal earthquakes. (f) Moho depth. Grey line indicates the 35 km structural contour. (g) V_P tomography. Shaded area indicates lower ($V_P < 7.25$ km/s) seismic velocities. (h) Intermediate seismicity.

behavior is also expressed in the spatial distribution of low-temperature thermochronological ages, which are indicative of higher extent of exhumation in the southeast [*Thomson et al.*, 2010]. Focusing on the reset fronts for AHe and AFT ages, we can see that this change occurs at 105–115 km (for AHe) and 100–110 km (for AFT) along profile DD′ (Figures 6c and 7c). As discussed by *Thomson et al*. [2010], the thermochronological data are consistent with the suggestion that the two domains separated by the LSL have experienced different modes of wedge kinematics, with the southeastern segment dominated by frontal accretion [e.g., *Batt and Brandon*, 2002] that gave rise to a ~20 km offset between the AFT front and the AHe front (see diverging diagrams in Figure 6c). Northwest of the LSL, the two fronts overlap (Figure 6c), indicating that at least until the middle Miocene (~15 Ma), frontal accretion was not the primary mode of wedge kinematics in this segment of the orogenic belt, which was more likely dominated by underplating [*Vannucchi et al*., 2008; *Remitti et al*., 2013].

The combined geophysical and geological observations support the idea that the lithosphere in the northern Apennines is segmented [*Royden et al*., 1987]. The upper mantle and crustal expressions of this geometry is recognized at a distance of 65–115 km along profile DD′ (Figure 7). This behavior may represent the expression of two contrasting kinematic processes that operated in the northern Apennines during the Neogene and Quaternary, with the southeastern segment undergoing faster rates of subduction rollback. Contrasting rates of slab rollback could account for slab deformation along an incipient tear, accompanied by a rather diffused zone of crustal segmentation. The fact that we do not recognize a single discontinuity across the orogen is not surprising, because deformation has been transferred from the downgoing (Adriatic) plate to the overriding orogenic wedge. Moreover, during this process, Adria has moved northward with respect to Europe [*Channell et al*., 1979; *Rosenbaum et al*., 2004], further modifying the plate boundary. The overriding-plate expression of tearing, therefore, has not necessarily been localized along specific shear zones, although it is possible that preexisting crustal heterogeneities, such as the (Cretaceous) Prato-Sillaro lineament, may have been reactivated in response to tearing. We emphasize, however, that given the lack of significant evidence for faulting along these orogen-perpendicular structures, it remains questionable whether the effect of tearing is indeed expressed in upper crustal structures.

5.2. Geodynamic Implications

We proposed in the previous section that slab segmentation has likely been driven by along-strike variations in the rates of subduction rollback, with the southeastern segment retreating faster than the northwestern segment (Figure 5). Alternatively, it is possible that segmentation was primarily controlled by a change in the mode of lithospheric deformation along the strike of the orogen, from underplating in the northwestern sector to delamination and retreat in the southeastern sector [*Chiarabba et al*., 2014]. The absence of ubiquitous geological observations supporting strike-slip faulting and the fact that seismicity is not localized along specific crustal structures suggest that segmentation has not been driven by crustal processes but was likely controlled by deeper deformation of the lithospheric slab. The crustal response to this segmentation is recognized in a diffused zone associated with along-strike variations in the style of crustal deformation, as indicated by the seismic, geological, and morphological data (Figure 7).

The observed left bend associated with segmentation in the northern Apennines is consistent with the larger-scale geodynamics of the Italian Peninsula, which is generally characterized by increasing rates of subduction rollback from north to south [*Faccenna et al*., 2001; *Rosenbaum and Lister*, 2004a], and the progressive development of lithospheric tear faults [*Cinque et al*., 1993; *Scrocca*, 2006; *Rosenbaum et al*., 2008]. These tear faults are more mature in the central and southern Apennines, where their lithospheric expressions can be recognized in seismic tomography models as segmented slab remnants [*Rosenbaum et al*., 2008; *Benoit et al*., 2011; *Giacomuzzi et al*., 2012]. The upper crustal expression of these tear faults is somewhat diffused but may be represented by orogen-perpendicular lineaments, such as the Tindari Fault System and its offshore continuation [*Billi et al*., 2006; *Gallais et al*., 2013] or the Sangineto Line in the southern Apennines [*Rosenbaum and Lister*, 2004a] (Figure 1a). Ultimately, the process of lithospheric segmentation was responsible for the development of lithospheric gaps, with the most extreme expression recognized in the Central Apennine slab window (Figure 2a).

It appears therefore that changes in the style of tearing along the Apennines provide a snapshot to the evolution of slab segmentation, from incipient tearing to the formation of slab windows (Figure 8). In this context, the style of segmentation discussed in this paper may represent the earliest stage of tearing (Figure 8a). Farther south, in the island of Capraia and in Tuscany, a cluster of tear-related magmatic centers occurs, propagating from west to east [*Gasparon et al*., 2009] (Figure 8b). In this area, a discontinuity in the slab structure (as imaged by seismic tomography [*Benoit et al*., 2011]) has been interpreted to represent a lithospheric-scale tear fault that runs from Capraia to Tuscany [*Gasparon et al*., 2009] or the delamination of a formerly thick continental lithosphere [*Benoit et al*., 2011; *Chiarabba and Chiodini*, 2013]. Magmatism in this area does not seem to be associated with asthenospheric upwelling and was more likely derived from lithospheric melting and magma ascent along the tear [see also *Pérez-Valera et al*., 2013]. We attribute these observations to an intermediate stage in the evolution of slab tearing.

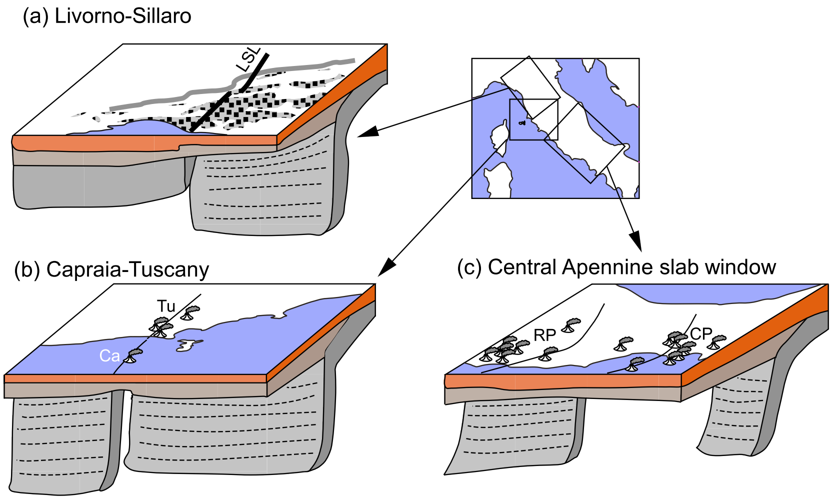

Figure 8. Schematic 3-D block diagrams showing the evolution of tearing as expressed in three segments in the Apennines. (a) Segmentation in the proximity of the LSL accommodating a change from slab rollback (southeastern segment) to underplating (northwestern segment). Thick grey line indicates the map view shape of the drainage divide, and stippled pattern shows the spatial distribution of late Miocene to Pleistocene sedimentary basins (Figure 5a). (b) Tearing and magmatism along the Capraia (Ca) - Tuscany (Tu) discontinuity [after *Gasparon et al*., 2009]. (c) Central Apennine slab window and associated magmatism [after *Rosenbaum et al*., 2008]. RP, Roman Province and CP, Campanian Province.

The most mature stage in the evolution of a slab tear is represented in the central Apennine slab window (Figure 8c), as well as in the tear faults that bound the fast-retreating Calabrian slab. These tears seem to propagate from the base of the lithosphere all the way to the surface, thus providing pathways for asthenospheric-derived melt and associated volcanism [*Gvirtzman and Nur*, 1999; *Rosenbaum et al*., 2008].

6. Conclusions

Geophysical and geological observations support the suggestion that the slab beneath the northern Apennines is segmented. Slab segmentation is recognized at different lithospheric levels, affecting the Moho topography, the style of seismicity, and the landscape evolution of the mountain chain. The fact that crustal deformation is diffused and is not focused on specific tear faults is consistent with the suggestion that segmentation is controlled by deeper processes.

Incipient tearing is attributed to a change in the geodynamic mechanism along the strike of the Apennine chain. In the southeastern segment, orogenic processes have been dominated by subduction rollback, giving rise to widespread overriding-plate extension and the development of Late Miocene to Pleistocene sedimentary basins. In contrast, the northwestern segment has experienced lower rates of subduction rollback, and has possibly been dominated by underplating [*Vannucchi et al*., 2008]. Farther south along the Apennines, the Capraia-Tuscany tear fault [*Gasparon et al*., 2009] and the central Apennine slab window [*Rosenbaum et al*., 2008] are the expressions of more advanced stages in the evolution of tearing. Collectively, these observations provide an insight into the fundamental process of plate boundary segmentation.

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