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Alps vs. Apennines: The paradigm of a tectonically asymmetric Earth

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ABSTRACT

Alps and Apennines developed along opposite subductions, which inverted the tethyan passive continental margins located along the boundaries of Europe, Africa and the Adriatic plates. The Alps have higher morphological and structural elevation, two shallow, slow subsiding foreland basins. The Apennines have rather low morphological and structural elevation, one deep and fast subsiding foreland basin. While the Alps sandwiched the whole crust of both upper and lower plates, the Apennines rather developed by the accretion of the upper crust of the lower plate alone. Alpine relics are boudinated in the hangingwall of the Apennines, stretched by the Tyrrhenian backarc rifting. Relative to the upper plate, the subduction hinge moved toward it in the Alps from Cretaceous to Present, whereas it migrated away in the Apennines from late Eocene to Present, apart in Sicily where since Pleistocene(?) it reversed. The asymmetry appears primarily controlled by the slab polarity with respect to the westward drift of the lithosphere.

Contents

1. Introduction

The geology of the Alps and the Apennines (Fig. 1) is the result of the evolution from Paleozoic orogens (mostly Hercynian), the Permo-Mesozoic Tethyan rifting and related passive continental margins, and, eventually the Cretaceous-to-present Alpine-Betic subduction, and the Eocene to present Apennines-Maghrebides subduction (Beltrando et al., 2010a, and references therein). The two belts are associated with foreland areas somehow deformed or tilted by the orogen-related deformation, and they are very distinct belts (Fig. 2), which developed due to the closure of the Mediterranean Mesozoic Tethyan basins along two opposite subduction zones. The Alps are

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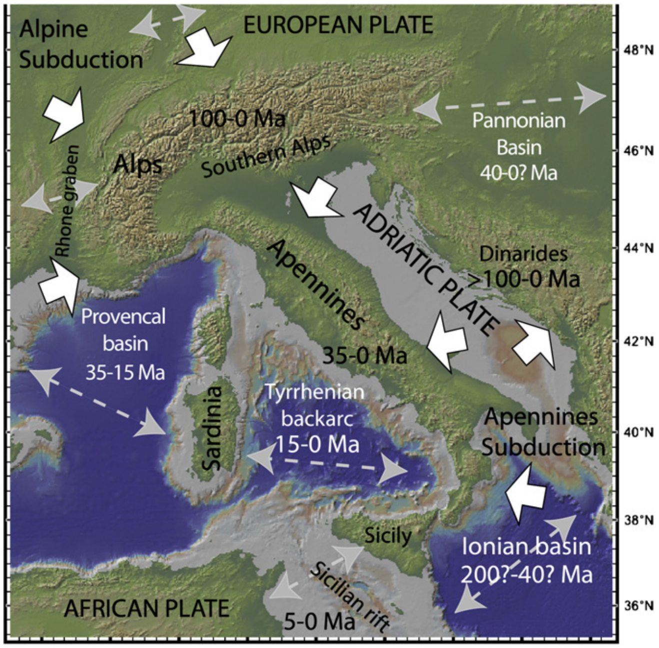

Fig. 1. The Alps and Apennines are the two belts in the hangingwall of two opposite subduction zones. In the Alps the European plate subducted beneath the Adriatic plate, whereas in the Apennines the Adriatic, Ionian, Sicily and African plates subducted "westerly", retreating from the European upper plate. White arrows: subduction directions. Ma: million years life of the tectonic feature. The gray arrows show the main rifting directions.

related to the subduction of Europe "eastward–southeastward" underneath the Adriatic plate (Panza and Mueller, 1978; Calcagnile and Panza, 1979; Dal Piaz et al., 2003), whereas the Apennines were generated by the "westward" subduction of the Adriatic plate (Calcagnile and Panza, 1980; Scandone, 1979; Malinverno and Ryan, 1986; Doglioni, 1991).

The motion of the subduction hinge toward or away relative to a fixed upper plate has been shown to be the simple kinematic control for the occurrence of two different subduction styles (Doglioni et al., 2007). When the subduction hinge converges toward the upper plate the upper plate is shortened and a double vergent belt, such as the Alps, forms. On the contrary when the slab and the related hinge retreat relative to the upper plate, the upper plate is stretched (a backarc basin opens) and a single vergent belt develops, such as the in the Apennines-Tyrrhenian Sea system.

This article will summarize the main achievements in understanding the post-Paleozoic Italian geology, showing how the differences between Alps and Apennines (Laubscher, 1988; Royden and Burchfiel, 1989; Doglioni, 1992) mark an asymmetry. This is similar to what can be followed in subduction zones worldwide, as a function of their subduction polarity (Doglioni et al., 1999a). Therefore the Italian geology (Fig. 2) may represent a case history of the asymmetric Earth, confirming the archetypes of the opposed subduction zones along the Pacific margins. In order to highlight the differences between the two subduction zones and related orogens, a number of parameters can be examined, such as the rates of convergence, subduction, uplift in the orogen, subsidence in the foredeep, the dip of the foreland regional monocline, the dip of the slab, the depth of the basal decollement, the PTt paths, the nature and thickness of the upper and lower plates, thermal state, seismicity, stress field, backarc basin development or not, etc. In this article only the most significative of these parameters will be discussed (Fig. 3).

2. Stratigraphic background

The stratigraphy of Italy records Permo-Mesozoic passive margin sequences lying onto the variegated Paleozoic high- to low-grade metamorphic basement. Cretaceous to Pleistocene flysch and molasse deposits of the Alps and Apennines active margins sequences were deposited above the passive margin series, recording the vitality of the related subduction zones.

2.1. Basement

The crust of the Adriatic plate is mainly Panafrican (Precambrian), although overprinted by Paleozoic and minor Mesozoic tectonometamorphic events (e.g., Vai et al., 1984; Vai, 2001 and references therein). The Italian basement recorded a possible Caledonian subduction of oceanic crust, with Ordovician granites (e.g., the 440 Ma granite found offshore Venice by the Agip Assunta well), later deformed in orthogneiss during the Hercynian orogeny. Detrital zircons from the Alps display pre-Cambrian ages (1500–2000 Ma). The Cambrian outcrops in the Iglesiente (SW-Sardinia) with sandstones and marls. It is deformed by the 'Sardic' phase (about 500 Ma), considered as an early Caledonian phase. The Hercynian orogeny in Italy (Devonian to Early Permian times) was characterized by oceanic subduction, crustal thickening, wrench tectonics (Carosi and Palmeri, 2002) and polyphase metamorphism (the metamorphic climax was dated about 340 Ma; Vai et al., 1984), as inferred in the Alps (Spalla et al., 1999), in Sardinia (Carmignani et al., 1994; Giacomini et al., 2005), in Calabria (Graessner and Schenk, 1999; Graessner et al., 2001; Langone et al., 2010), in NE-Sicily (Peloritani Mts., Appel et al., 2011) and in a few scattered outcrops in W-Tuscany (Bagnoli et al., 1980; Elter and Pandeli, 1990). External Hercynian units, anchimetamorphic to non-metamorphic and fossiliferous, were drilled in the Po Plain, Umbria and Puglia, and found as reworked clasts in Basilicata (Vai, 2001). Middle Ordovician Calcalkaline volcanic activity recorded in central Sardinia and HP-LT metabasites in northern Sardinia (e.g., Franceschelli et al., 1998), in the northern Adriatic Sea and in the Alps (e.g., Miller and Thoeni, 1995) suggest the onset of oceanic subduction and the development of an Andean-type margin (Carmignani et al., 1994). The oceanic subduction ended with the collision between Gondwana-Armorica in Early Carboniferous time and the Variscan Belt was later dissected by late Variscan low angle normal faults, which were accompanied by by LP/HT metamorphism and by the emplacement of calcalkaline batholiths (along the Western and Central Alps, Sardinia and Calabria) and ignimbrites (e.g., the "Piastrone Porfirico Atesino" in the Southern Alps) and the deposition of molasse sediments in Late Carboniferous-Early Permian times (Carmignani et al., 1994).

The Hercynian orogen was double vergent, as inferred from the vergence of contractional structures in Sardinia and Southern Alps. In Sardinia the Hercynian orogen was poorly affected by the Alpine or Apenninic tectonics, here represented by Oligocene–Aquitanian strike–slip faulting (also recognized in Corsica) that reactivated Hercynian structures (Carmignani et al., 1995; Oggiano et al., 2009). Restoring Sardinia to its original position, prior to the Oligocene–Miocene counterclockwise rotation of the Corsica–Sardinia block (Vigliotti and Kent, 1990), Devonian-Carboniferous thrust faulting (Carmignani et al., 1994) was south-west vergent in this region, with a metamorphic degree increasing toward northeastward (Conti et al., 2001). In the Southern Alps, the vergence was toward the east, being the Hercynian foredeep located in the Carnian Alps, and in the Adriatic Sea. In the eastern Southern Alps, unmetamorphosed, or low-grade metamorphosed pre-Permian sedimentary rocks crop out, possibly representing the retrobelt of the Hercynian orogen (Zanferrari and Poli, 1994). The metamorphic degree grows toward the west in the basement of the Southern Alps (e.g., Sassi et al., 2004; Marotta and Spalla, 2007; Fig. 4), with green-schist phyllites and gneisses in the Dolomites basement, amphibolitic facies rocks in the Orobic Alps and granulitic facies in the western Southern Alps (Ivrea–Verbano zone). Biotite-sillimanite gneisses (Dioritic–Kinzigitic unit) outcrop also in Calabria. The Hercynian orogen was dissected by extensional tectonics, the prelude to the Tethyan opening: a basal unconformity with

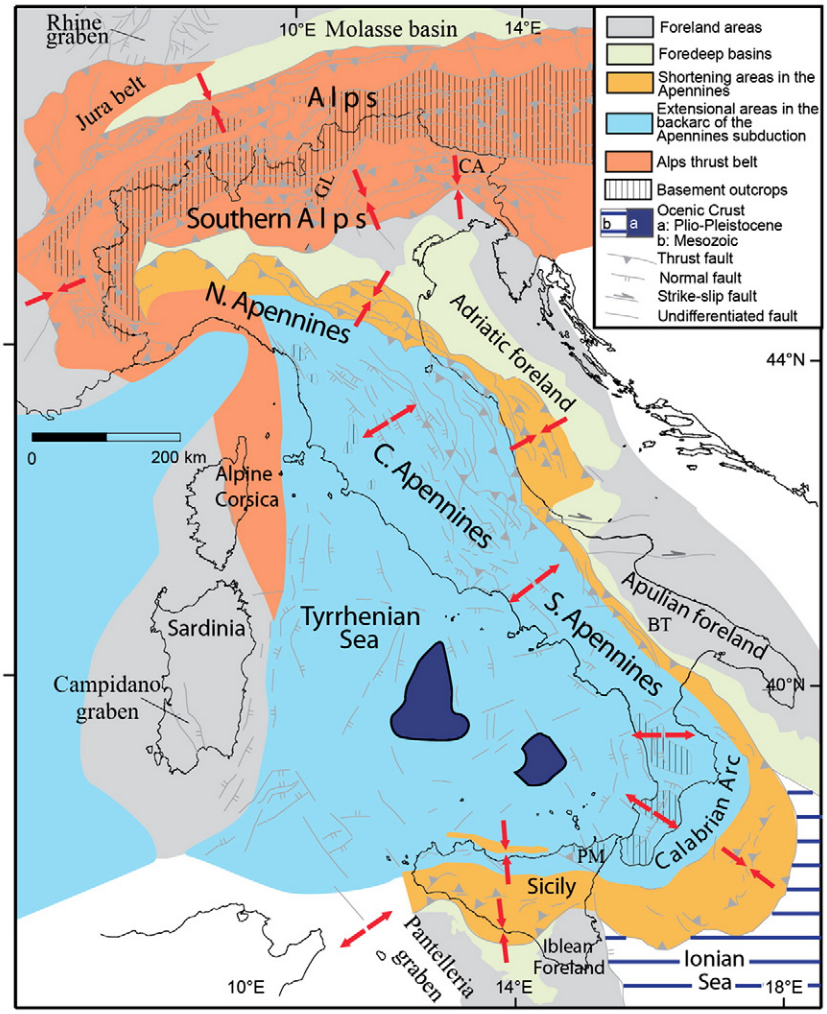

Fig. 2. Simplified tectonic map of Italy, showing the major tectonic and geodynamic settings in the region. The faults in this map as in the following figures are from the Structural map of Italy (Consiglio Nazionale delle Ricerche, 1992). BT, Bradanic trough; CA, Carnic Alps GL, Giudicarie Line; PM, Peloritani Mountains.

red beds of Late Permian–Triassic age gradually covered the subsiding orogen, suturing both Hercynian thrusts and following collapse-related normal faults.

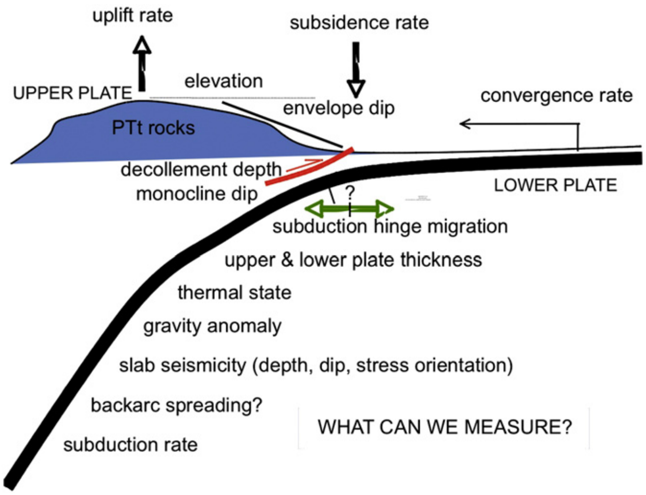

Fig. 3. Main parameters along subduction zones. Most of them are used here to compare Alps and Apennines.

In Italy two areas exhibit sections of lower continental crust uplifted during the Alpine orogeny: the Ivrea–Verbano zone in the western Alps (e.g., Quick et al., 2009), and the Serre area in the Alpine unit of Calabria (e.g., Caggianelli et al., 1991). The transition between the magmatically stratified lower crust and the mantle peridotites of Finero in the Ivrea–Verbano zone is considered a paleo-Moho (Mazzucchelli et al., 2010), uplifted also by the Mesozoic rifting.

2.2. Passive margin stratigraphy

The Late Permian to Cretaceous sequences recorded the rifting and the drifting history of the Tethys margins. Most of Italy was part of the passive margin of the western and northern Adriatic plate (Bernoulli, 1964; Colacicchi et al., 1970; Bernoulli et al., 1979; Farinacci et al., 1981; Bertotti et al., 1993; Carminati et al., 2010a; Santantonio and Carminati, 2011) during the Upper Jurassic–Lower Cretaceous opening of the western Tethys or Ligure-Piemontese oceanic basin. Tensional or transtensional tectonics during Late Permian–Triassic times controlled subsidence rates on horsts and grabens, and facies development. The typical basal succession with red beds, evaporites and mainly shallow-water carbonates gradually evolved through time all along these margins. During Early Jurassic times, diffuse normal faulting brought to foundering of vast areas of the previous platform areas and oolitic Bahamas-type carbonate platforms were interrupted by intervening

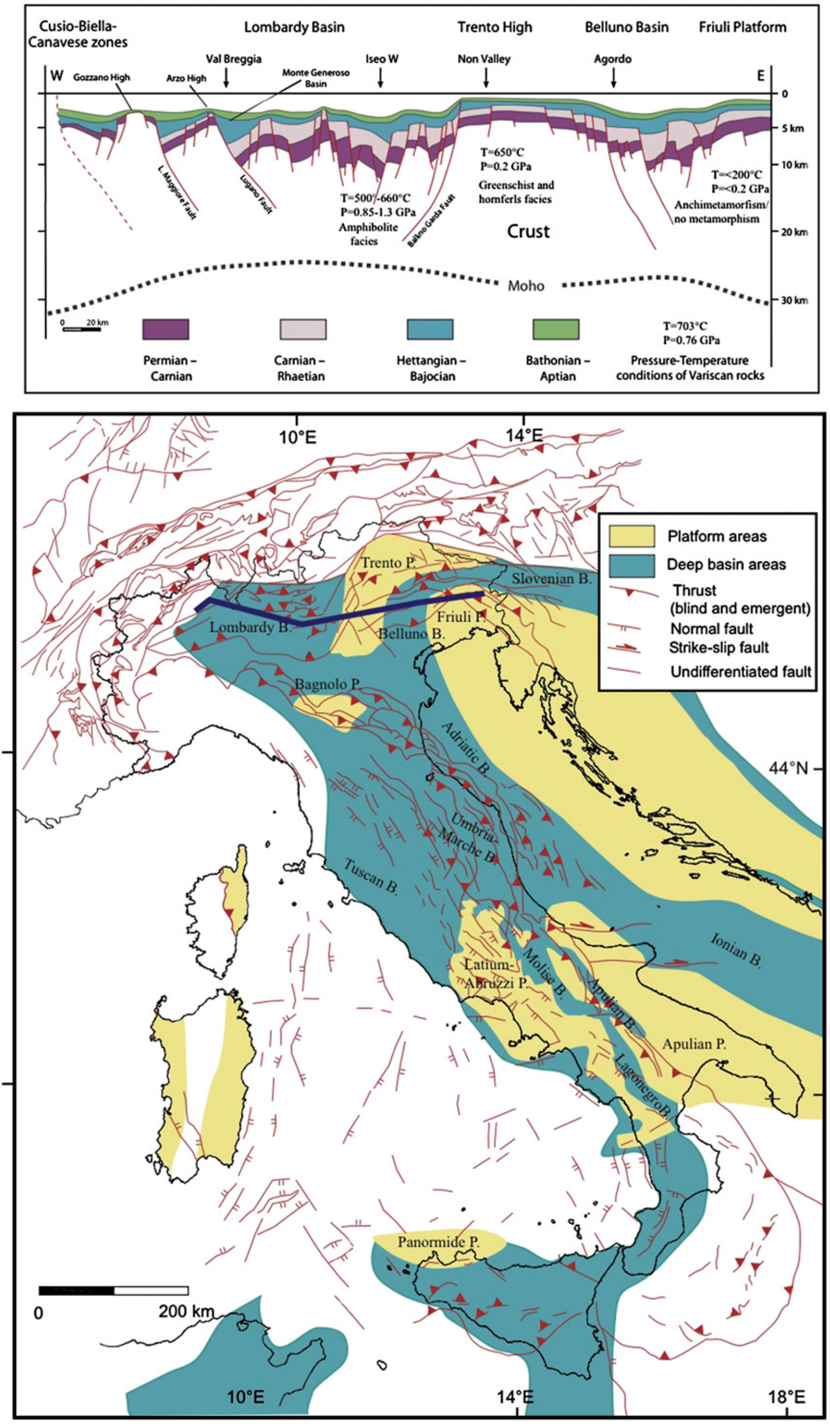

Fig. 4. Late Liassic–Neocomian paleogeographic map of the Italian area (redrawn from Zappaterra, 1994). The tethyan rifting affected the margins of the Adriatic plate. Horst and graben controlled the paleotectonic and paleogeographic evolution, particularly where and when the sedimentation rate was lower than the subsidence rate. The crust crosscut by the Permo-Mesozoic rifting was previosuly structured by the Hercynian orogeny. For a discussion on P–T data for Variscan rocks of the Southern Alps basement, refer to the additional text. The blue line in the map locates the cross section of the Southern Alps at the top of the figure. Modified from Bertotti et al. (1993) and Fantoni and Scotti (2003).

basins. The ratio between subsidence rate and sedimentation rate determined either thickness changes in the syntectonic sediments (ratio <1), or thickness and facies changes (ratio >1, Doglioni et al., 1998a). The occurrence of highs and lows also characterized later passive continental margins. At the end of Jurassic, three main paleogeographic environments were present: 1) An oceanic domain, where radiolarites and abissal limestones were deposited above ophiolites; 2) basinal domains onto thinned continental lithosphere, dominated by carbonate pelagic and hemipelagic sedimentation, where deeper areas alternated with horsts (e.g. the Trento swell in the Southern Alps, or the Trapanese, Saccense and Iblean zones in Sicily), characterized by condensed sedimentary sequences; 3) wide shelves, where deposition of shallow marine carbonates continued (Fig. 4). Some of the residual carbonate shelf areas persisted throughout the Cretaceous, like the

Apulia, Friuli, Latium-Abruzzi and Campano-Lucana carbonate platforms (Fourcade et al., 1993; Zappaterra, 1994). On these carbonate platforms, widespread Lithiotis facies developed during the Liassic and Rudistic facies during the Late Cretaceous. Typical pelagic and hemipelagic sedimentats are the Early Cretaceous Maiolica or Biancone (white marly limestone) and the Late Cretaceous Scaglia Rossa (reddish marls and marly limestone). Platform-to-basin transitions were characterized by debris flows and local megabreccias. Well preserved carbonate platform-to-basin transitions crop out at the western margin of the Friuli Platform, in the Maiella Massif (Central Italy), and in the eastern Gargano (Puglia), and were detected by oil exploration in the eastern offshore of Puglia. The thickness of the Permian-Mesozoic sedimentary cover ranges between 1 and 6 km. In Sardinia a few isolated patches of Triassic (Germanic facies) to Upper Cretaceous sediments consist mostly of shallow marine carbonates and they are about 1 km thick. They overlie a Lower Cambrian to Lower Carboniferous basement.

The Southern Alps have an inherited Mesozoic background (Fig. 4; Bernoulli, 1964; Bertotti et al., 1993; Berra and Carminati, 2009), consisting, from west to east of: the Canavese zone (transition with the ocean Tethys or Ligure-Piemontese to the west), the Lugano horst, the Lombard basin, the Trento horst, the Belluno basin, the Friuli platform and the Tolmino basin. Toward the east the Vardar Ocean was also bordering the Adriatic plate. These schematic subdivisions are sometimes a misleading mixture of paleogeographic and paleostructural features. In fact the term platform indicates shallow water carbonate platform environment, which may or may not have drowned during the Middle Jurassic (e.g. the Trento Platform, where the Liassic carbonate platform is covered by the pelagic Ammonitico Rosso).

The main Mesozoic paleogeographic and structural subdivisions in the Apennines (D'argenio et al., 1975; Farinacci et al., 1981; Casero et al., 1988; Menardi Noguera and Rea, 2000; Santantonio and Carminati, 2011) are: in the northern part, from west to east, the Ligurian basin (partly oceanic, Bracco Nappe; Decandia and Elter, 1972; Elter, 1975), the Tuscan zone with platform facies until the Liassic, then pelagic sedimentation like in the adjacent Umbro-Marchigiano (or Umbria-Marche) basin. To the south-east is the Latium-Abruzzi platform. In the southern Apennines, from west to east the main paleogeographic zones are the Campano-Lucana platform, the Lagonegro-Molise basins (located to the north of the Ionian oceanic basin) and the Apulian platform (Fig. 4). To the east of the Apulian platform another basin developed during the Mesozoic (e.g., the East Gargano basinal sediments), and this was coeval with the opening of the southern Adriatic basin. The forward propagation of thrusts piled up the paleogeographic domains, having in the thrust hangingwall the units originally located westward relative to the footwall. In Sicily similar Mesozoic subdivisions are indicated by the Panormide platform, Imerese basin, Trapanese platform, Sicanian basin, Saccense and Iblean platforms (Channell et al., 1990; Roure et al., 1990a; Catalano et al., 1996; Giunta et al., 2000). The Trapanese, Saccense and Iblean carbonate platforms drowned to pelagic facies during the Middle Jurassic.

Mantle peridotites, serpentinites, gabbros, prasinites, and pillow lavas of ophiolitic suites recording the Jurassic–Early Cretaceous spreading in the Tethys are entirely or partially preserved in northern Calabria, in the northern Apennines (Tuscany and Liguria), in the western Alps (Piemonte, Val d'Aosta), in Liguria (Gruppo di Voltri), and in the Engadine, Tauern and Rechnitz tectonic windows, in the Alps of Switzerland and Austria. Ophiolites in the Alps are largely metamorphosed (HP-LT) by subduction processes (with the exception of the Arosa, Platta and Chenaillet in the Alps and the Balagne nappe in Corsica; Oberhänsli, 1994; Molli, 2008), whereas Apenninic ophiolites are not. Alpine ophiolites are large slices of oceanic crust accreted during the subduction process. Northern Apennines ophiolites are rather often olistoliths or small size resedimented blocks included in flyschoid units.

2.3. Active margin stratigraphy

The inversion of relative motion (from divergence to convergence) between Europe and Adriatic plates began during Cretaceous time and generated compression at the western margin and dextral transpression at the northern margin of the Adriatic plate. The spatial and temporal evolution of the Alps and later of the Apennines during Cretaceous and Cenozoic is recorded by the clastic sediments, flysch and molasse, which overlaid diachronously the earlier passive margin sequences, whose geometry and thickness variations greatly influenced the following foredeep flexure and contractional tectonics (e.g., Lenci et al., 2004).

Molasse and foredeep deposits accumulated both at the front of the Alps and the Southern Alps. In the Southern Alps, Upper Cretaceous flysches, related to syn-subduction shortening, were deposited in the Lombard basin (Bergamo Flysch; Bersezio and Fornaciari, 1987). Eocene flysch related to the Dinaric orogen and its interference with the eastern Alps deposited in NE Italy (Friuli and east Veneto foothills and plains). In areas not yet affected by shortening and uplift, shallow water carbonate platforms and associated shaly basins persisted during Paleogene times. Messinian conglomerates also formed during the Mediterranean sea-level drop in the Southern Alps foredeep, while evaporitic facies deposited all around the Apennines (the Gessoso-Solfifera Formation).

Cretaceous-Eocene flysch deposits accumulated along the Apenninic foredeeps during the Alpine phase and the Early Apenninic evolution. The Apenninic foredeeps migrated “eastward” particularly since the Oligocene as indicated by the forward propagation both of thrusts and of piggy-back basins (Ricci Lucchi, 1986; Boccaletti et al., 1990a,b; Patacca et al., 1990; Patacca and Scandone, 2001).

3. Geodynamic background

The subduction zones in the central Mediterranean were controlled by the pre-existing tethyan plate heterogeneities. The inherited Mesozoic paleogeography and lithospheric structure of the Adriatic plate (Fig. 4) deeply controlled the regional stress and strain distribution in the Alps, Apennines and Dinarides. Both oceanic and continental lithosphere has been consumed along the active margins of the Mediterranean. The occurrence and dimension of a subduction zone can be inferred from several pieces of evidence, such as seismicity whenever present, amount of shortening in the orogeny, geochemistry of the magmatism, tomography, etc.

The Alps are morphologically more elevated (average 1500 m) than the Apennines (about 500 m; Fig. 5). Moreover, the Alps were affected by a much larger erosion (few tens of km) than the Apennines (few km), because uplift in the Alps was much longer, and exhumation more efficient than in the Apennines (Fig. 6). Consequently, the structural elevation is much higher in the Alps with respect to the Apennines. This is linked to the more deeply rooted thrusting in the Alps with respect to the shallower thrusting in the Apennines. The structural and morphological evolution of the two belts is also very distinct. In fact the Alps grew by lateral expansion along both sides of the wedge, and by vertical upraise. Moreover, in the Alps the highest peaks tend to coincide with the water divide (Fig. 7). On the contrary, the Apennines developed growing mostly laterally, “easterly” propagating toward the foreland. Tectonics is faster than erosion, and this may explain why the highest peaks of the Apennines tend to be located to the east of the water divide, suggesting a delay of the erosion in trying to catch the tectonic wave moving toward the east (Fig. 7). Moreover the Alps uplifted while the entire belt was undergoing contraction. In the Apennines, rather paradoxically, the active portion of the accretionary prism is located in the area of largest subsidence, whereas the area of the belt that is uplifting is characterized by extension (Fig. 8). Moreover the extension continues into the Tyrrhenian backarc basin (no backarc basin occurs in the Alps), where stretching is normally associated with

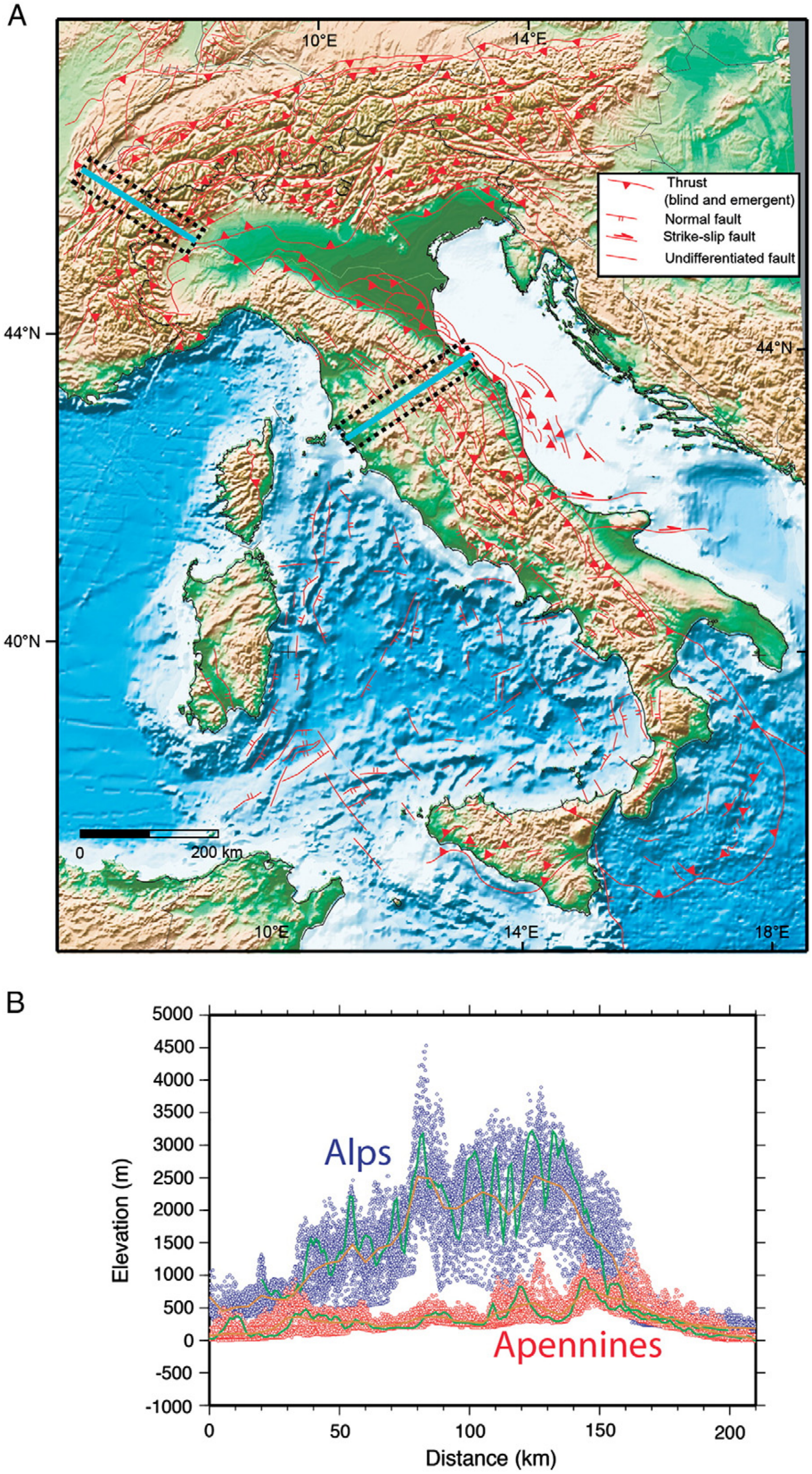

Fig. 5. (A) Shaded relief and bathymetry map of Italy and surrounding seas. The topography data are from the USGS-NASA GTOPO30 data base (http://edcdaac.usgs.gov/gtopo30/gtopo30.asp), whereas the bathymetry data are from the NGDC ETOPO2 data base (http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html). The traces of the sections of panel b (black thin lines and dashed boxes) are shown. (B) The topography data (from the GTOPO30 data base; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) falling in the dashed boxes were projected onto the section traces as points. The solid lines represent the exact topographic profile along the lines of cross sections, whereas the dashed lines show the average topography.

subsidence and not anymore with uplift as in the Apennines (Fig. 8). All this may be interpreted as the coexistence of several different mechanisms controlling the vertical movements in the belts, such as: i) the thickening of the lithosphere controls uplift in the Alps; ii) subsidence in the two foredeeps of the Alps is due to the load provided by the orogeny itself; iii) subsidence in the Apennines foredeep is controlled by the

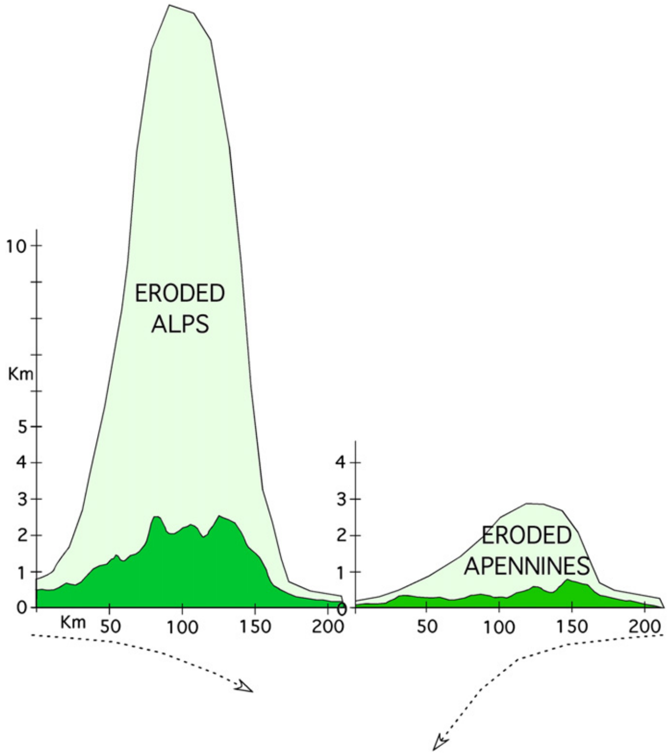

Fig. 6. The Alps have a mean topography more than twice higher than the Apennines. However, the structural elevation of the Alps (i.e., the hypothetical elevation without erosion) is even more pronounced than in the Apennines, by 5 times. These are the two end members of the subduction style, i.e., the elevation is similar to the structural elevation in the Apennines, whereas it is much smaller than structural elevation in the Alps. Moreover, in the internal part of the Apennines there may be the inherited relic of the pre-existing Alps, with a pre-Apennines topographic and structural elevation characteristic of the alpine system, stretched and collapsed within the Tyrrhenian backarc basin.

retreat of the Adriatic-Ionian slab and by the associated downflexure; iv) long-wavelength uplift in the Apennines is related either to the mantle wedging at the subduction hinge or the thickening at depth of the accretionary wedge; v) long-wavelength subsidence/uplift in the Apennines backarc is related to tectonic stretching, thermal subsidence; vi) long wavelength vertical motions are overprinted by local features associated with normal faulting activity (downslip of hangingwall and footwall uplift); vii) in crustal swells, such as in Sardinia, uplift could possibly due to the underlying transit of depleted asthenosphere (Carminati et al., 2010b).

The Italian crust is continental, apart in the Tyrrhenian abyssal plain where 10 km thick Late Miocene–Pliocene oceanic crust is present, and the Ionian Sea, where a possibly Mesozoic-Cenozoic(?) oceanic crust is buried underneath a thick pile of sediments (Catalano et al., 2001). The Alps present thickened continental crust (>50 km, Fig. 9) and lithosphere (>130 km, Fig. 10), due to the duplication of the Adriatic plate overriding the European plate (e.g., Boriani et al., 1989; Dal Piaz et al., 2003; Brandmayr et al., 2010). The Apennines have rather a strong asymmetry, with a Moho and lithosphere base becoming deeper moving from the Adriatic Sea toward the belt (Mele and Sandvol, 2003), being the slab steeper and deeper underneath the Apennines. In the hangingwall of the Apennines subduction both shallow, lower velocity "Tyrrhenian" Moho (20–25 km) and asthenosphere (30–40 km) were detected (Calcagnile and Panza, 1979, 1980; Panza and Calcagnile, 1980; Mele and Sandvol, 2003), compatible with the kinematics of W-directed subduction zones (Doglioni, 1991). In stable areas (Sardinia, Adriatic sea and Puglia), the Moho occurs at about 30–35 km depth. In foreland areas the lithosphere thins in the northern Adriatic sea at about 70 km, while is about 110 km thick to the southeast in Puglia (Fig. 10). The arrival of such a thick continental lithosphere at the subduction hinge has been interpreted as the reason for the buckling of the Puglia lithosphere, which is an about 100 km wide anticline (Doglioni et al., 1994). In the Tyrrhenian Sea the lithosphere thins to 20–30 km (e.g., Panza and Calcagnile, 1980). The

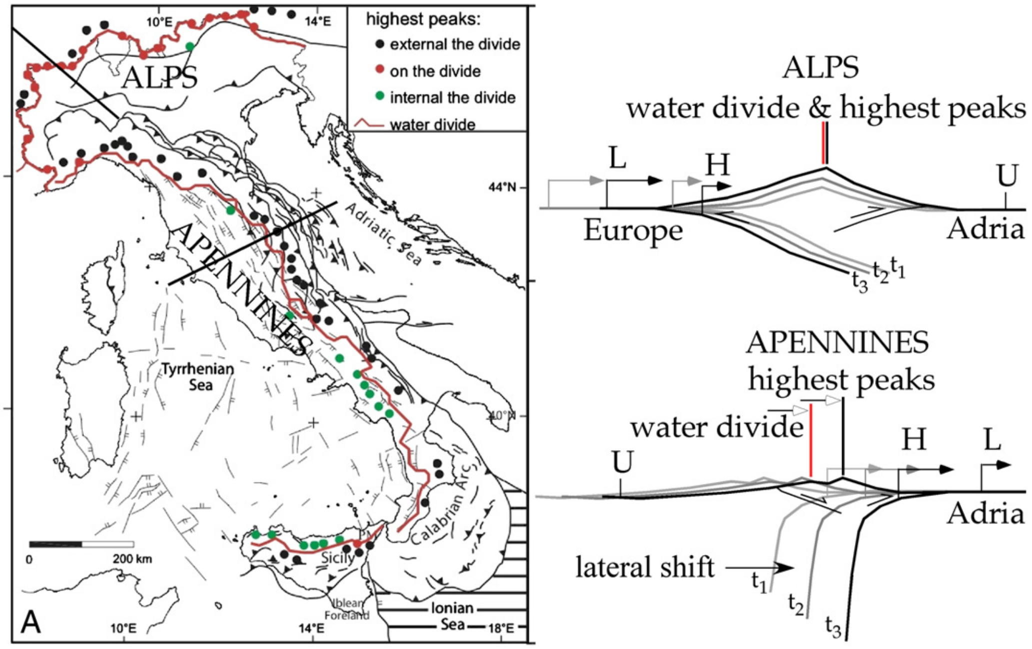

Fig. 7. Alps and Apennines have a different relationship in the location and evolution of the water divide. In the Alps, the water divide is almost everywhere coincident with the highest peaks of the orogen. In the Apennines, the water divide and the highest peaks are frequently shifted apart. The highest peaks often located to the east of the water divide, apart for those zones where the subduction retreat is practically stopped and/or where the lithological contrast dominates the erosion rate (e.g., the Southern Apennines). The offset between the highest peaks and the water divide is inferred as related to the faster eastward migration of the subduction hinge and all the related tectonic settings with respect to the erosion rate. The Alps grew up both laterally and vertically, whereas the Apennines developed mostly laterally.

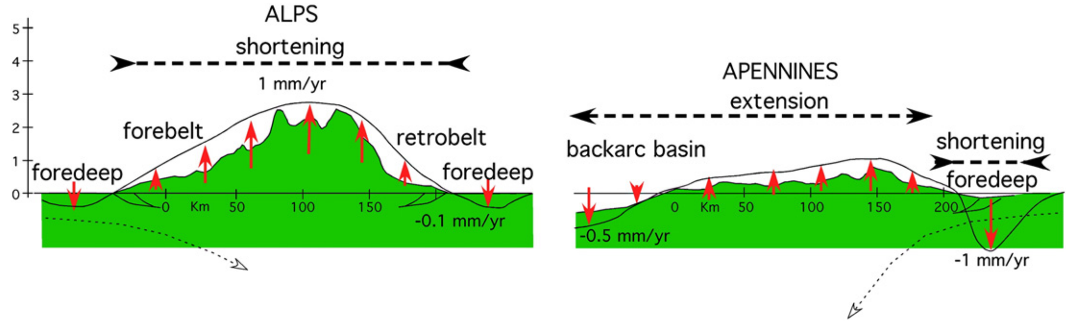

Fig. 8. The Alps are characterized by diffuse contraction and the belt is entirely uplifting, apart in the two adjacent foredeeps (in the foreland of the forebelt and of the retrobelt). In the Apennines accretionary prism, shortening is paradoxically located in the area of largest subsidence, close or beneath the foredeep. The remaining portions of the belt (to the west) are rather uplifting while stretching. Along the western margin of the Apennines, uplift decreases and switches to subsidence in the Tyrrhenian backarc basin.

Adriatic continental lithosphere and the Ionian oceanic lithosphere are subducting westward almost vertically underneath the Apennines. In the Alps two pre-subduction, possibly Mesozoic in age, Mohos are justaposed (Figs. 9 and 11). The hangingwall Moho of the Adriatic plate is shallower (25–30 km depth, Kummerow et al., 2004), whereas the European lower subducting plate Moho is deeper and steeper. In the Apennines there are rather three Mohos: 1) the Adriatic Moho, pre-subduction, Mesozoic in age, which is deepening and steepening beneath the accretionary prism (e.g., Di Stefano et al., 2009), mimicking the foreland monocline of the basement top (Mariotti and Doglioni, 2000) and the lithosphere base (Panza et al., 2003, 2007a,b); 2) a new Moho formed with the opening of the Tyrrhenian backarc basin, due to the replacement of the retreating slab by the asthenospheric mantle (Doglioni, 1991); this Moho is interpreted as easterly rejuvenating as the basin progressively propagated in the same direction; 3) the pre-subduction Moho, Mesozoic in age, of the hangingwall European plate,

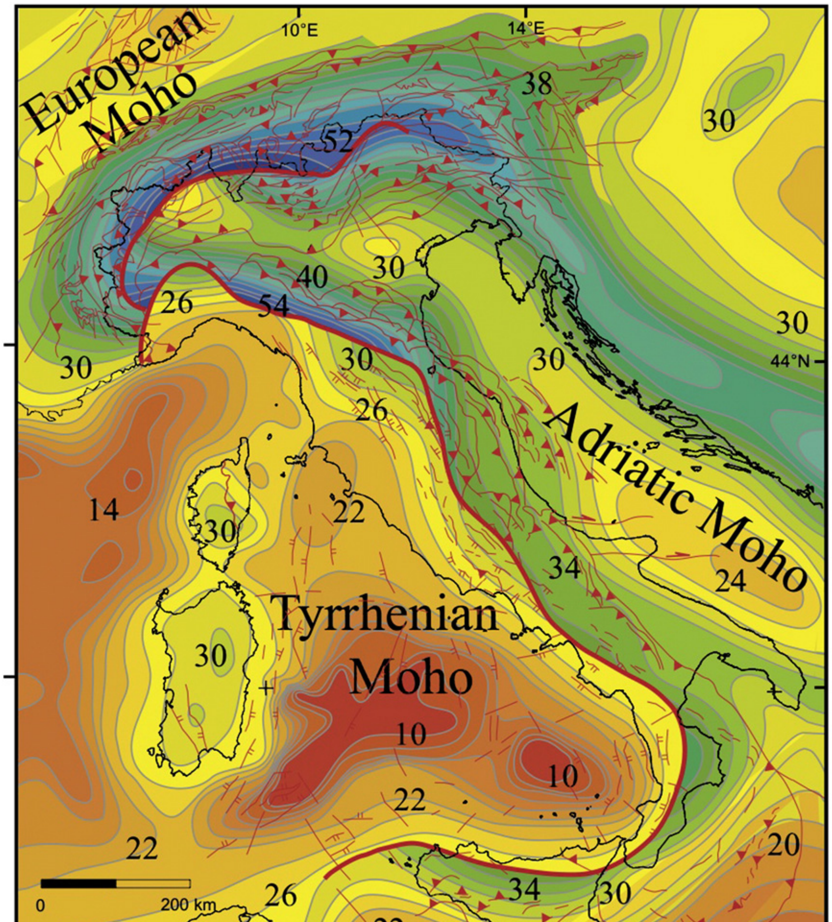

Fig. 9. Moho thickness (km) in the Italian area and surroundings (modified after Dezes and Ziegler, 2002). The thick red line separates the European Moho from the Adriatic and African Moho (all pre-subduction Mohos in the Alps), and the Tyrrhenian shallower new-formed Moho in the hangingwall of the Apennines subduction.

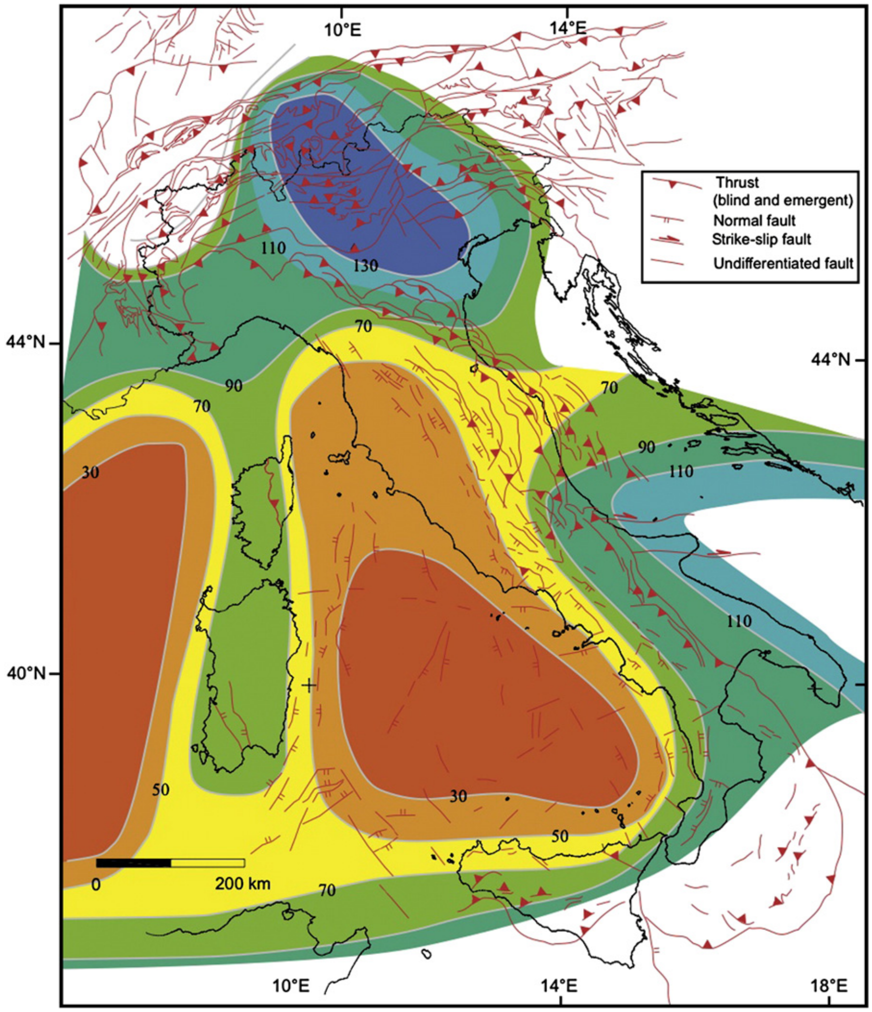

Fig. 10. Thickness of the lithosphere (km) in the Italian area (after Panza et al., 1992).

that is now stretched and abandoned westward underneath Sardinia (Nicolich, 2001).

Mantle tomography has been used extensively in order to delineate the geometry of slabs. Moreover, a number of tomographic studies have been proposed to delineate the geometry of the Mediterranean slabs (e.g., Piromallo and Morelli, 2003). Mantle tomography studies can be subdivided into two classes: absolute tomography and relative tomography. Absolute tomography shows the absolute velocities of seismic waves, whereas relative tomography describes seismic velocity variations relative to a 1D reference velocity profile. The continuous lateral variations in the lithosphere compositions, such as those occurring in the Mediterranean (e.g., Calcagnile and Panza, 1980), asks for caution in interpreting relative mantle tomography. In fact, continental lithosphere has lower velocity than oceanic lithosphere. When transported into subduction, such a continental slab, even if present, it will not be imaged in relative mantle tomography. During the last years a vast literature considered relative mantle tomography cross-sections as sort of geological sections, which may be quite critical (e.g., Anderson, 2006). Mantle tomography usually considers homogeneous mantle geochemistry, which has been shown false for the Mediterranean area by the highly variable chemistry and mineralogy in the Mediterranean magmatism (see Peccerillo, 2005). The isochemical assumption is used to interpret velocity variations as evidence for differences in mantle temperature. In fact the relation “red = hot = lighter” or “blue = cold = denser” has been questioned when chemical variations are introduced (Trampert et al., 2004). Compositional variations can determine variations in seismic velocity. Moreover, it is often forgotten that the seismic velocity is inversely proportional to density. Therefore, higher velocity should correspond to lighter material, which is usually exactly the contrary of common interpretations, i.e., faster velocity is considered as evidence of higher density. What obviously matters is the rigidity/density ratio, which is proportional to seismic velocity. With this premise, in this article we show only absolute tomographic sections (Fig. 11) because they do not depend on the 1D reference velocity profile of relative tomographic models, which cannot satisfactorily apply especially in an heterogeneous area as is the Mediterranean. The Alpine and Apenninic subduction zones are suggested by the faster velocities in Fig. 11. However, the inversion of gravity measurements allowed Brandmayr et al. (2011) to infer that the subduction zones, even if seismically faster, may be lighter than the hosting mantle, pointing out that the slab pull cannot be efficient. For example, the downwarping of the 3.3 g/cm^3 isodensity lines beneath Calabria in the Tyrrhenian–Apennines section, suggests a positive buoyancy of the slab, and the lower velocity in the hangingwall of the subduction (i.e., the backarc basin), which is instead missing in the Alps. In the tomographic sections through the Alps, the subduction of the European continental lithosphere (Mueller and Panza, 1986) is evident. In contrast to the Apennines subduction, no intermediate depth seismicity is observed in the western Alps. The subducting lid beneath the Alps is also characterized by negative density anomaly.

The gravity Bouguer anomaly (Fig. 12) reaches values lower than −160 mGal along the Alpine axis, increasing to −40 mGal in more stable lateral areas. A positive gravimetric Bouger anomaly and a magnetic anomaly occur in Piemonte along the Ivrea–Verbano zone, along the internal side of the western Alps. In the Apennines there is a shift between

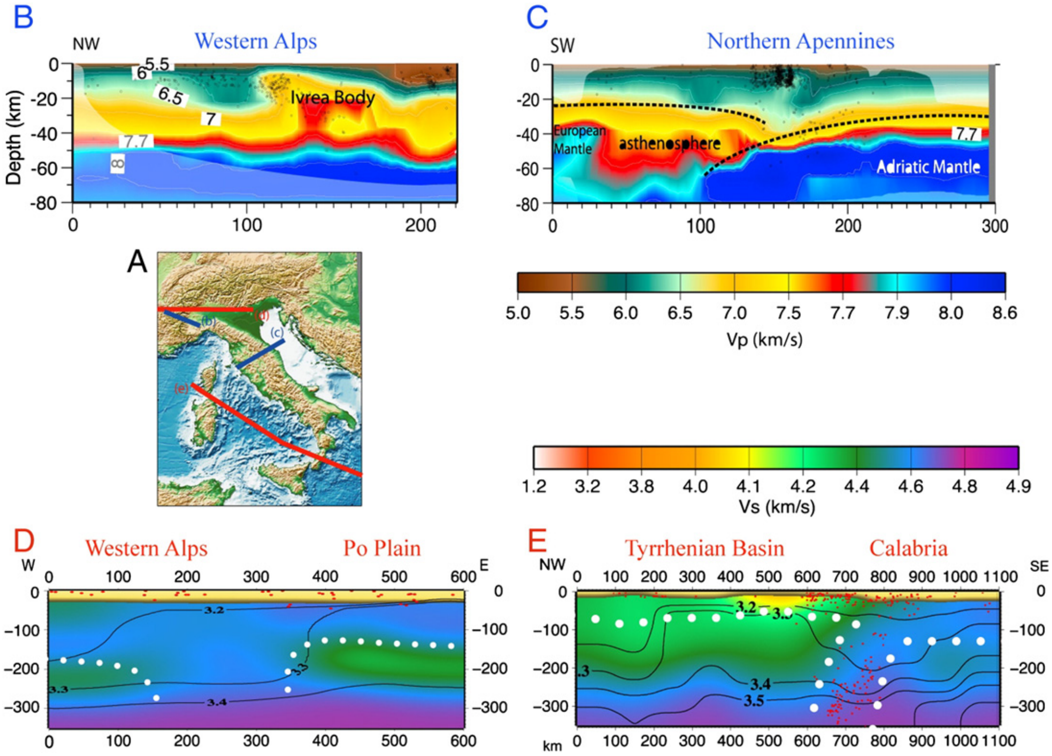

Fig. 11. A) Traces of the tomographic cross sections. P waves absolute tomographic sections for the Alps (B) and the Apennines (C) are modified after Di Stefano et al. (2009). Vs absolute tomographic sections for the Alps (D) and the Apennines (E) and the related density models are modified from Brandmayr et al. (2011). Note that in the Vs sections (D and E) the density of the slab is lower than the hosting mantle, disproving the negative buoyancy (or slab pull) as the main mechanism for the subduction.

the highest topographic relief and gravity, being the lowest values located toward the foredeep areas (Po Basin, Adriatic coast) and ranging between −120 and 0 mGal. The anomaly gradually increases to positive values moving westward toward the belt and in the Tyrrhenian Sea, up to 240 mGal. Along the belt, the 0 mGal isogal is approximately located where, at depth, the shallow asthenosphere and new Moho of the hangingwall meet the hinge of the subducting foreland. The geoid map of Italy confirms the asymmetry between the Alps and the Apennines, plus the variations in the forelands (Fig. 13). The highest geoid elevations occur along the Western Alps, whereas the lowest are in Ionian Sea and along the foredeep of the Apennines. Positive magnetic anomalies occur in correspondence of magmatic spots.

Heat flow values are smoother in the Alps (Fig. 14) and generally not very high, ranging between 50 and 90 mW/m^2. In the Apennines, the heat flow densities are more extreme since their values are very low in the foredeep (30 mW/m^2) and very high in the western side of the belt and in the Tyrrhenian Sea (even higher than 200 mW/m^2, Mongelli et al., 1991).

The seismicity in the Alps is chiefly concentrated at the margins of the orogen, in areas of low elevation, although some relevant earthquakes are reported also within the belt itself (Fig. 15). The main focal mechanisms are compressive, apart some either strike–slip or extensional events. The Apennines are rather dominated by extensional seismicity along the main ridge of the belt, at 10–15 km depth (Guidarelli and Panza, 2006). Compressive mechanisms (thrust ramps or decollements) were recorded in the frontal Apennines to the "east" in the external, low-relief or marine areas of the accretionary prism. Local transfer zones are accommodated by strike–slip faults in all areas.

Low magnitude deep seismicity in the Tyrrhenian Sea is the evidence for a W-directed Benioff zone as deep as 550 km. Sardinia is quite a stable area, apart for Neogene–Quaternary stretching in the Campidano graben, that represents the NW-prolongation of the Sicily channel–Sirte Basin–Red Sea rift zones alignment (Corti et al., 2006).

The stress map of Italy confirms the pattern shown by the seismicity (Fig. 16): compression all around the Alps, compression at the submersed front of the Apennines, and extension along this belt, plus some strike–slip transfer zones, mainly located in areas where the velocity of advancement of the thrust front changes abruptly. One of these transfer zones occur in the Gargano area. The stress pattern is also consistent with space geodesy data (Fig. 17). GPS show intersites data with velocities up to about 5 mm/yr, whereas strain rates are in the order of 10–40 nanostrains/year. Extension can be observed along the Apennines axis and in the Tyrrhenian Sea. Compression occurs at the front of the Apennines accretionary prism, and along the front of the Alps, consistently with seismicity. Contraction is also visible between Sicily and Sardinia (Fig. 17).

4. Magmatism of the Alpine cycle

4.1. Rifting and drifting related magmatism

Several Triassic to Present magmatic episodes with different geodynamic significance occurred in Italy (e.g., Serri et al., 1993; Peccerillo, 2005; Carminati et al., 2010b). Calcalkaline-shoshonitic magmatism (both intrusive and effusive) of Middle Triassic age is widepread in the Southern Alps. Triassic magmatism is also reported in the Po Plain subsurface, in western Trentino region, in Lombardia (the Carnian volcaniclastic Val Sabbia Sandstone), in the northern Apennines, in the Lagonegro Basin (southern Apennines) and in Sicily.

Mantle peridotites, serpentinites, gabbros, prasinites, and pillow lavas of ophiolitic suites recording the Jurassic–Early Cretaceous spreading in the Tethys are preserved as ophiolitic bodies in northern Calabria, in the northern Apennines (Tuscany and Liguria), and in the Alps. Syn-drifting magmatism also occurred on the passive margins, as recorded in the Iblean Plateau (Middle Jurassic magmatism of the Ragusa basin, Middle-Late Cretaceous and Pliocene in the Siracusa area) and in the Trapanese basin (Late Jurassic volcanism) of Sicily.

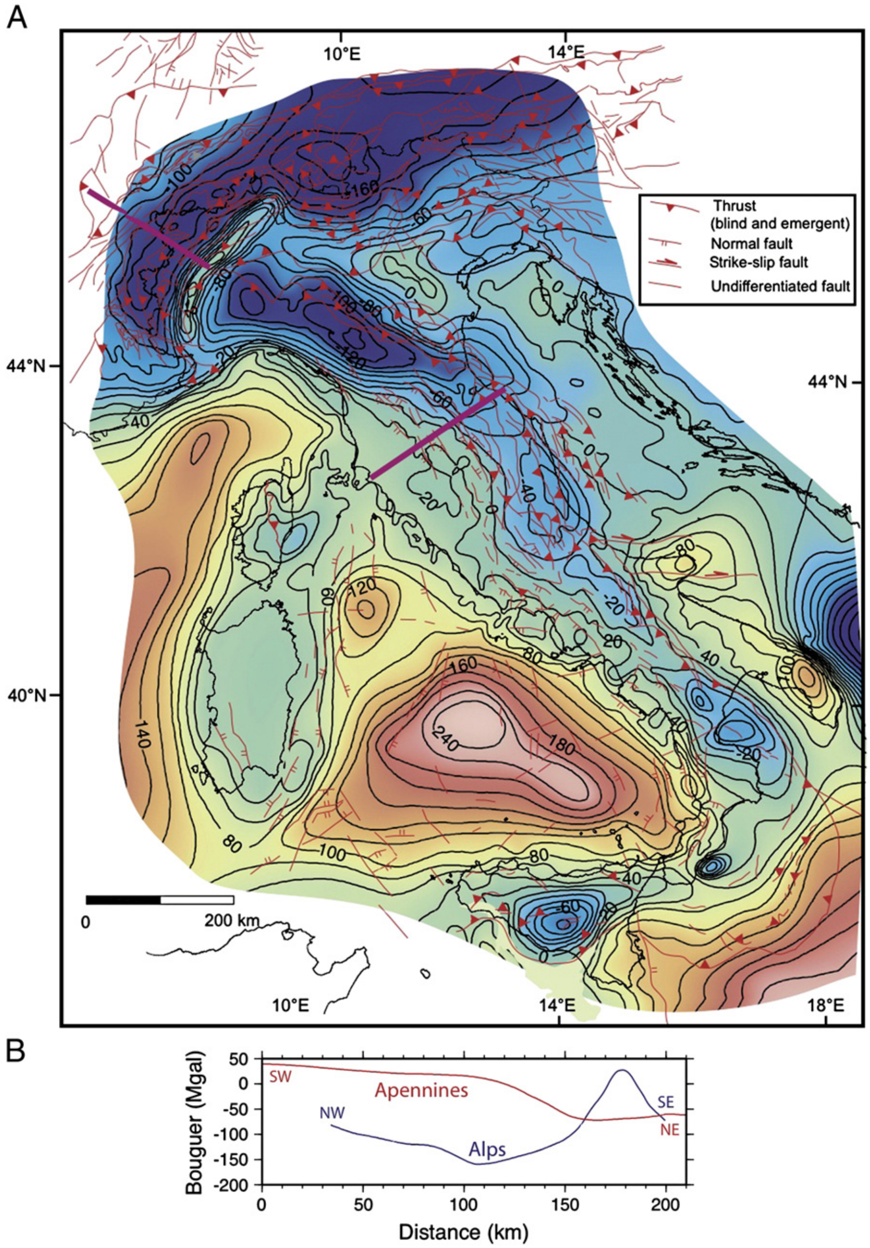

Fig. 12. A: Bouguer gravity map of Italy (data after Mongelli et al., 1975). B: Low gravity anomaly characterizes the Alps, apart the Ivrea zone where a relict of mantle outcrops. The Apennines rather show lower values in the foredeep and accretionary prism, whereas the internal part and the backarc basin shows higher values to the west, supporting the long wavelength of the mantle uplift.

4.2. Subduction related magmatism

No syn-oceanic-subduction calcalcaline magmatism was recorded in the Alps (Fig. 18), apart in resedimented Cenozoic sandstones (Lustrino et al., 2011). In the Lessini Mountains and Colli Euganei in west Veneto, alkaline magmatism (basalts, trachitic laccolites and sills and volcaniclastics) took place during Paleogene in synsedimentary N–S trending grabens in the foreland of the Southern Alps. 60 Ma old alkaline basaltic dikes have been reported in the Dolomites. Tertiary alkaline sienites crop out also at the Punta delle Pietre Nere (Northern Puglia).

Along the axis of the Alps, close to the Insubric Line, several plutons or batholiths of granodiorites, tonalites, sienites-monzonites mainly Late Eocene–Oligocene in age (42–29 Ma; i.e., syn-collisional; e.g., Del Moro et al., 1983) and calcalkaline in chemistry record an acid, late Alpine, magmatic event (e.g., Adamello and Bergell). Several minor dikes of basaltic andesites occur close to the intrusions. The Adamello batholith (the largest outcropping Tertiary intrusion of Italy) cross-cuts pre-existing folds and thrusts of the central Southern Alps, indicating pre-Late Eocene shortening, that was likely active since Late Cretaceous time as suggested by coeval flysch deposits and other structural indicators (Doglioni and Bosellini, 1987; Bernoulli and Winkler, 1990; Carminati and Siletto, 1997; Carminati et al., 1997). The elongated shape of the Bregaglia batholith has been related to Oligocene syn-emplacement dextral shear along the Insubric Line (Schmid et al., 1989; Rosenberg, 2004).

In west Sardinia during Eocene–Middle Miocene (38–13 Ma, with acme between 22 and 18 Ma) calcalkaline lavas emplaced, whereas alkaline to subalkaline lavas formed from Late Miocene to Late Pleistocene (7–0.1 Ma). During Miocene (Burdigalian-Serravallian) calcalkaline riodacitic volcaniclastic tuffites deposited along the external Apennines (both northern and southern: Emilia, Romagna, Irpinia and Sicily). During Pliocene and Pleistocene times, several volcanoes were operating in Italy (Fig. 18). These volcanoes mainly developed along grabens with an Apenninic trend (NNW-SSE). Both in Tuscany and in the Tyrrhenian

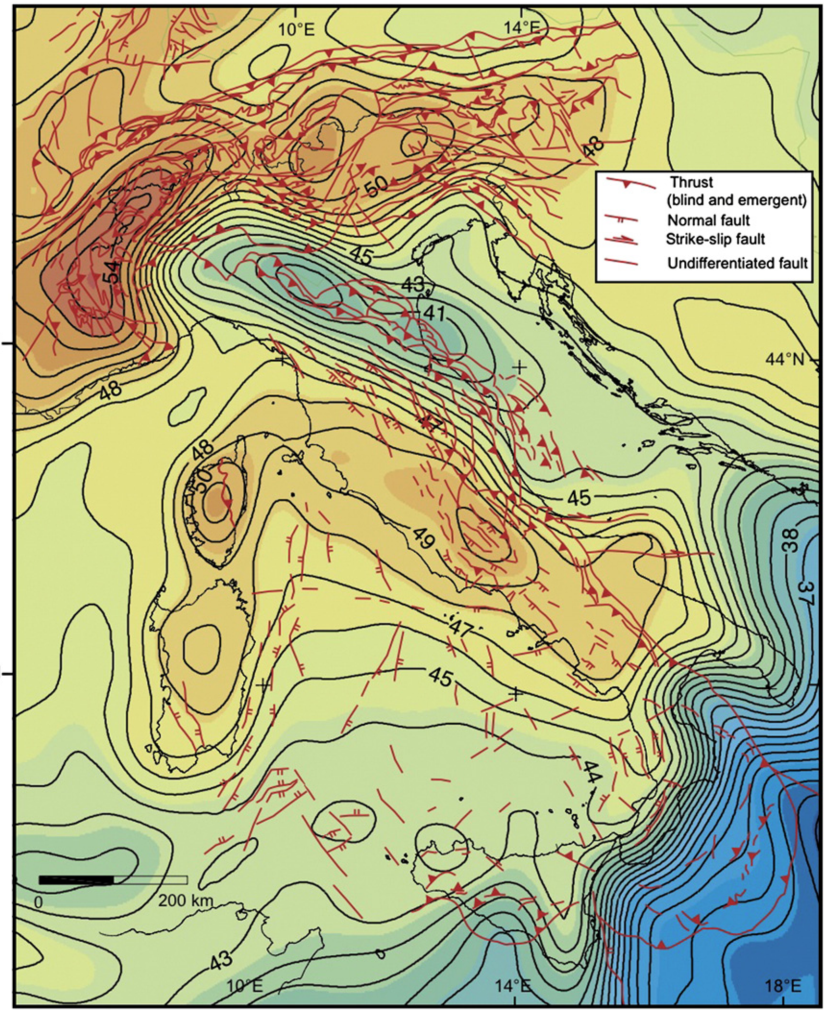

Fig. 13. Geoid height (m) in the Italian area (data after the EGM96 model, http://cddis.nasa.gov/926/egm96/egm96.html).

Sea, plutonism (Capraia, Elba, Montecristo and Giglio islands, and Gavorrano) and volcanism (Mt. Amiata, Radicofani, Mt. Cimino, etc.) rejuvenated eastward, ranging in age from 9 to 0.18 Ma. Some volcanoes are active in Southern Italy: the most important cones are the Vesuvio, Etna, Stromboli, Vulcano and a few scattered centers in the Sicily channel.

The geochemistry of the Tertiary magmatic activity along the Tyrrhenian–Apennines system covers a wide spectrum (e.g., Carminati et al., 2010b and references therein): alkaline–tholeiitic magmas of the Tyrrhenian basin, where oceanic crust is interpreted to have formed in the Vavilov and Marsili seamounts; calcalkaline shoshonitic rocks of the Eolian Islands are interpreted as subduction related; the Roman Province (Vulsini, Cimini and Albani mountains) shows higher K-contents, but still with subduction related signature, more contaminated by continental crust. These geochemical variations have been related to the different composition of the Adriatic and Ionian subducting lithospheres (Serri et al., 2001; Peccerillo, 2005). The Tuscany plutons and volcanoes are related to rifting due to the opening of the Tyrrhenian backarc basin. The Etna and the Vulture volcanoes, that lay at the forefront of the Apennines prism, at the hinge of the Adriatic-Ionian subduction, show alkaline characters. They have been interpreted as related to transtensional tears generated by differential slab retreat (e.g., the righ-lateral reactivation of the Malta Escarpment, allowing mantle uprise beneath the Etna, Doglioni et al., 2001). The magmatism in the Sicily channell (Pantelleria) is instead related to the Plio-Pleistocene extension, which is separating the Pelagian shelf (Africa) from Sicily. Similarly, the Late Tertiary alkaline volcanism in Sardinia was associated with extensional tectonics (Campidano graben). Variable CO_2 degassing throughout the whole western Mediterranean (Frezzotti et al., 2009) indicates significant mantle heterogeneities and metasomatism.

5. Tectonics

Very limited areas in Italy have not been or were poorly involved by the two Alpine and Apenninic orogenic waves, i.e. the Puglia region, part of the Iblean Plateau (SE-Sicily), a few areas in the Po and Venetian plains, and the Sardinia island. But these foreland areas, even if not shortened, underwent subsidence or uplift connected to the migration of the Alpine or Apenninic fronts.

Alps and Apennines show typical thrust belt geometries, with fault-propagation folds, fault-bend folds, triangle zones, imbricate fans, etc. The Apennines thrust belt is dissected by several younger (Pliocene–Quaternary) normal faults. In the external portions of the Alps and in the Apennines, most of the structures formed in brittle conditions. Ductile deformation affected the Austroalpine and Penninic units in Piemonte and Val d'Aosta, the metamorphic rocks of Calabria and the Apuane window (Fig. 19), and the largest part of the Hercynian basement.

Alps and Apennines deformed the northern and western Mesozoic passive continental margin of the Adriatic plate (Figs. 4, 20), whose connection with Africa has been generally proposed on the basis of the paleomagnetic data showing a similar apparent polar wander

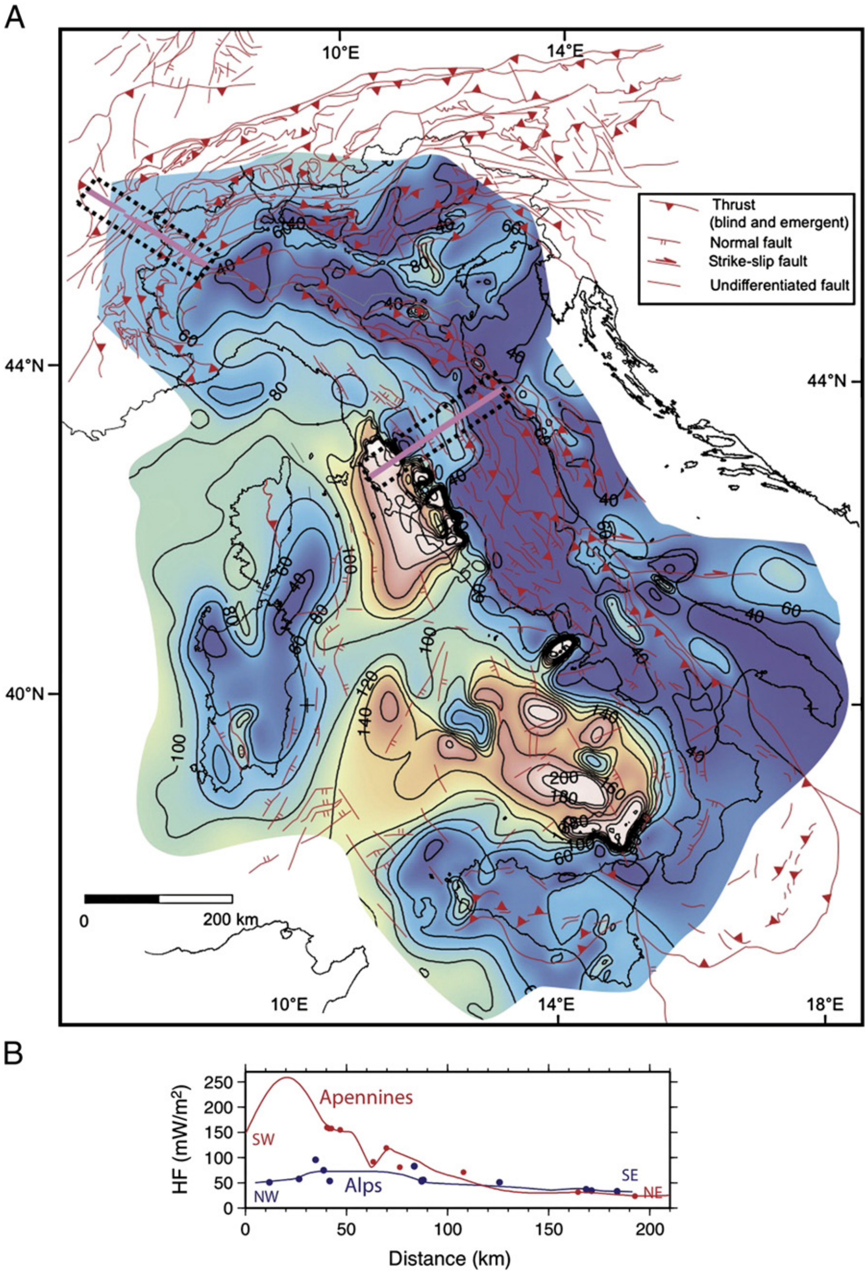

Fig. 14. A: Heat flow distribution (mW/m^2) in the Italian area. The heat flow data (after Pollack et al., 1993) were interpolated using the GMT software (http://www.soest.hawaii.edu/gmt/). B: Note the larger extreme values in the Apennines, with a "cold" foredeep and prism, and a "warm" backarc basin.

path of the Adriatic Mesozoic values with those interpreted for Africa. However the opening of the Ionian Sea during the Meso-Cenozoic(?) could have generated an independent Adriatic plate with respect to Africa at least during the growth of the Ionian oceanic basin.

The Ionian Sea is floored by 8–11 km of oceanic crust and 7–8 km of sedimentary cover of Mesozoic and Tertiary age. Low heat flow values (<40 mW/m2) and a thick lithospheric mantle (70–90 km) suggest an old age for this oceanic embayment. The Malta escarpment offshore east Sicily and the Salento offshore southwest Puglia appear to be two conjugate passive continental margins of Triassic–Jurassic age. A consequence of this is that the Ionian Sea in a section between Sicily and Puglia should be a complete oceanic section containing an aborted oceanic ridge of Mesozoic age whose relief is lost by thermal cooling and hidden by thick pelagic deposits ranging in age from Jurassic to Tertiary, and by the overlapping Apenninic thrust sheets. In this view the Ionian sea might be the oldest oceanic trapped crust of the world (Late Triassic?, Catalano et al., 2001), but a number of uncertainties still exist in terms of age of spreading and nature of the crust. A transitional or continental nature for the Ionian basin has been proposed by Calcagnile and Panza (1979), Calcagnile et al. (1982) and Panza et al. (2007a). Moreover the Permo-Mesozoic rifting could have evolved much later into the possible oceanization, i.e., in the Paleogene(?), as it happened in the North Atlantic, where the continental rifting initiated during the Permian times, but it evolved into oceanic spreading only 200 Ma later. The deep upper Triassic–Lower Jurassic sequences of the Lagonegro units in the Southern Apennines may have been the sediments accumulated on the passive continental margin adjacent to the Ionian basin. However it may remain the doubt of a later age of the basin, being the Timpa delle Murge unmetamorphosed ophiolites (Basilicata, Southern Apennines) late Jurassic–early Cretaceous(?) in age and involved in the accretionary prism (Knott, 1987).

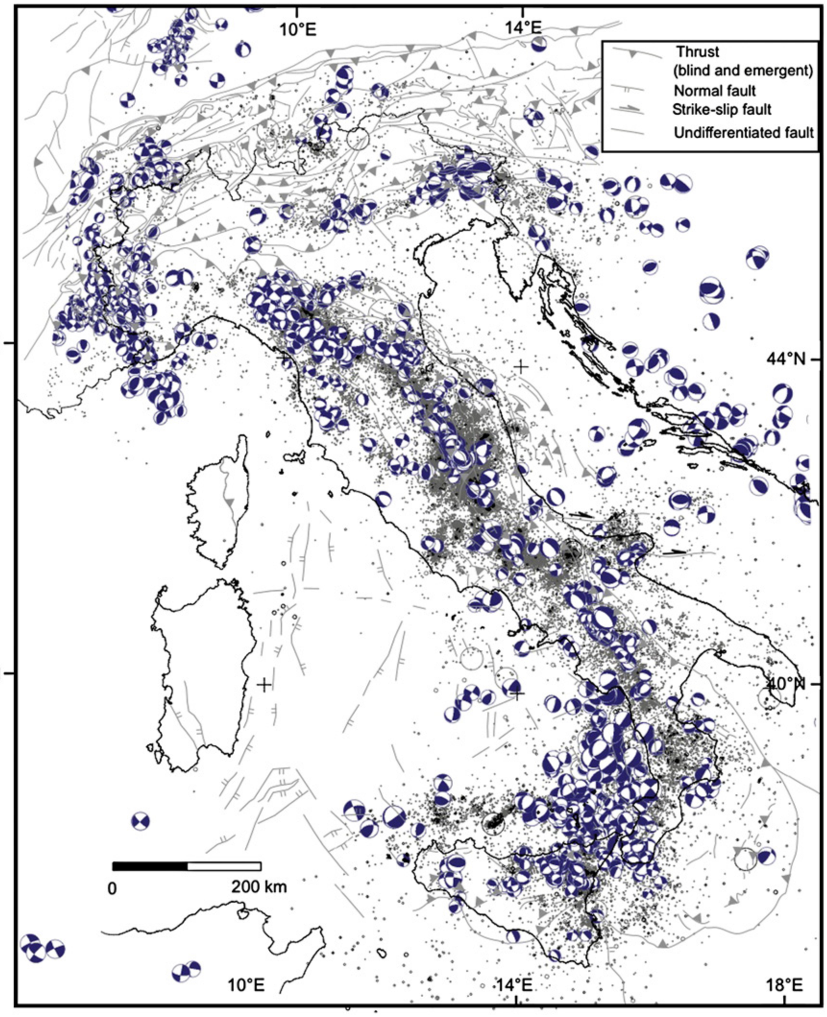

Fig. 15. The map shows the earthquakes distribution (instrumental data between 1981 and 2001 from Catalogo della Sismicità Italiana CSI 1.1, http://csi.rm.ingv.it/ and between 2002 and 2010 from Bollettino Sismico Italiano and http://bollettinosismico.rm.ingv.it and http://iside.rm.ingv.it/) and the CMT solutions (Pondrelli et al., 2006 and references therein) available for the Italian area. The earthquakes with hypocentral depths at fixed depths (e.g., 5, 10, 15 km) were filtered out and are not shown in the figure. Alps and Apennines show opposite seismic settings (i.e., shortening in the Alps and extension in the Apennines).

5.1. Alps

The main tectonic units of the Alps are from northwest to southeast: Helvetides, Pennides, Austroalpine and Southern Alps (e.g., Polino et al., 1990; Schmid et al., 2004). The Helvetides derive from the European continental margin. They were involved in the orogen during the collision and do not outcrop in Italy. The Pennides are constituted by ophiolites of the Tethys (Piemontese and Valais oceanic basins or a single basin in different paleogeographic reconstructions; see Polino et al., 1990 for a discussion), the Briançonnais thinned continental crust, and subduction related flysches. The Austroalpine and the Southern Alps derive from the Adriatic continental margin, and are respectively located to the north and south of the Insubric Line, a composite (transpressional) feature active at least since the Oligocene (Schmid et al., 1989). The convergence began with the subduction toward the east or southeast of the Tethys ocean under the Austroalpine and Southern Alps (Adriatic) continental lithosphere during Early Cretaceous (e.g., Panza and Mueller, 1978; Dal Piaz et al., 2003; Dal Piaz, 2010). Blueschists and eclogites facies recorded this eo-Alpine HP/LT event in the Penninic and Austroalpine units of the western Alps at 70–65 Ma (Berger and Bousquet, 2008; Beltrando et al., 2010b and references therein), although older ages, 130–90 Ma, were reported in Spalla et al. (1996). This is considered the prograde part of the alpine metamorphic P–T–t path (Ernst, 1971; Dal Piaz et al., 1972; Bousquet et al., 2008).

The collision with the overthrusting of the Adriatic plate over the European plate was likely diachronous and occurred mainly during Eocene?–Oligocene time (Beltrando et al., 2010b; Handy et al., 2010), after the complete subduction of the Ligurian-Piedmont-Penninic Ocean beneath the Adriatic continental lithosphere. The convergence continued with fast rates during the Neogene, and it is still active as indicated by the deformation of Pliocene–Pleistocene sequences and the present seismicity. The E–W striking central-eastern Alps and Southern Alps are considered the right lateral transpressive arm of the Alpine orogen. The collision brought to a phase of regional Barrovian metamorphism, characterized by high grade in the axial parts of the belt (e.g., Lepontine Dome and Tauern Window) and by decreasing grade moving toward the outer parts of the fold-and-thrust belt (Bousquet et al., 2008).

The Southern Alps show a general south–southeast vergence toward the Adriatic plate. The other Alpine units of the forebelt synthetic to the subduction are vergent toward the European plate, westward and northwestward. The Southern Alps have an inherited Mesozoic rifting-related background (Fig. 4), consisting, from west to east of: the Canavese zone (transition with the ocean Tethys or Ligure-Piemontese to the west), the Lugano horst, the Lombard

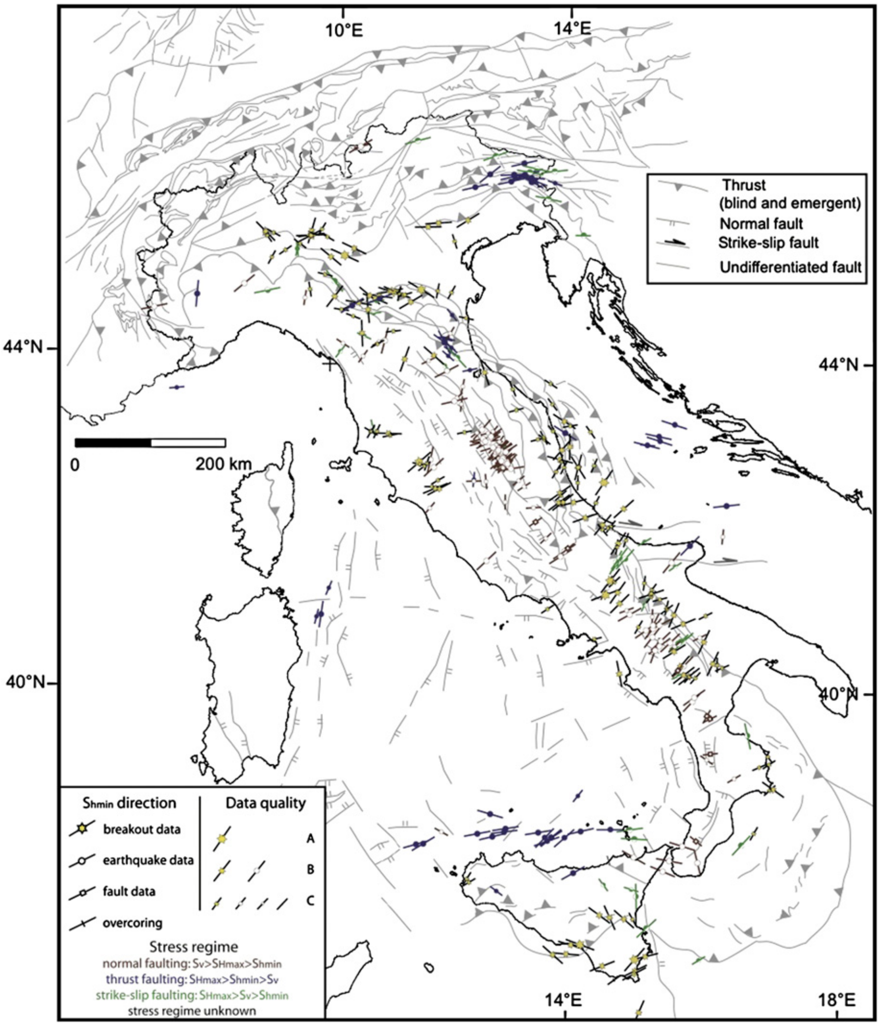

Fig. 16. Orientation of Shmin from well breakouts and seismological data (after Montone et al., 2004). A is the best data quality. Note the contraction at the front of the Apennines and and the Alps, whereas the Apennines are dominated by extension.

basin, the Trento horst, the Belluno basin, the Friuli platform and the Tolmino basin (Bertotti et al., 1993; Berra and Carminati, 2009). Similar paleogeographic domains are preserved also in the Australpine Domain (Manatschal and Bernoulli, 1999). Toward the east the Vardar ocean was also bordering the Adriatic plate (Schmid et al., 2008). Thickness variations of the sedimentary cover controlled the contractional tectonics. For example, the Milano belt (i.e., the portion of the central Southern Alps buried under the sediments of the Po Plain) is the salient and the left-lateral transpression of the Giudicarie belt in the central Southern Alps is the recess formed at the hinge zone between the Lombard basin to the west and Mesozoic Trento horst to the east. Since the onset of the inversion, from passive to active continental margin, the inversion occurred at high angle with respect to the pre-inversion paleogeographic zones and therefore the foredeep developed with a E–W trend overprinting the former mainly N–S trending Mesozoic features. The Southern Alps show in the internal portions ductile folding overprinted by brittle thrust faulting and, in the external parts, more brittle deformation, with thrust planes arranged with classic imbricate fan geometries (e.g., Schönborn, 1992; Carminati et al., 1997). A shortening of about 50–80 km can be estimated in the present retrobelt of the Alps, while the forebelt shortening is more difficult to quantify, but is certainly larger than few hundreds km.

Austroalpine units crop out in northern Italy, to the north of the Insubric (Pusteria) Line under the form of metamorphosed (blueschist/eclogitic and greenschist facies) thrust bodies and klippen. A thick slice of subducted continental crust crops out in the Sesia-Lanzo Zone. The Penninic units are thrust-sheets arranged in antiformal stack duplexes, with pervasive ductile internal deformation and HP/LT metamorphism generally overprinted by Barrowian metamorphism (Bousquet et al., 2008; Handy et al., 2010). Stretching lineations show mainly E–W component of the slip vectors since Cretaceous times (Malavieille et al., 1984; Choukroune et al., 1986; Handy et al., 2010 and references therein). Thrust planes and ductile milonitic zones are generally folded.

In the eastern Southern Alps, during Late Cretaceous and Paleogene, the Alps interfered with the Dinarides, an orogen related to the underthrusting of the Adriatic plate under the eastern European Iplate, after the consumption of the interposed Vardar ocean (an arm of the “Tethys” ocean). Eocene thrusts and foredeep of the NNW-trending and roughly WSW-vergent Dinarides are preserved in NE-Italy. North and west of the Alps, Eocene–Oligocene to present extension occurred in the Rhine and Rhone grabens, to the west and northwest of the Alps. In the eastern side of the Alps the Pannonian Basin in the hangingwall of the Capathians subduction interfered and collapsed with the Alps.

The Insubric Lineament is a composite structure, running from west to east, from the Canavese Line, to the Centovalli and Tonale fault system, merging into the northern Giudicarie Fault, then into the Pusteria-Gail fault system. Each segment has a peculiar

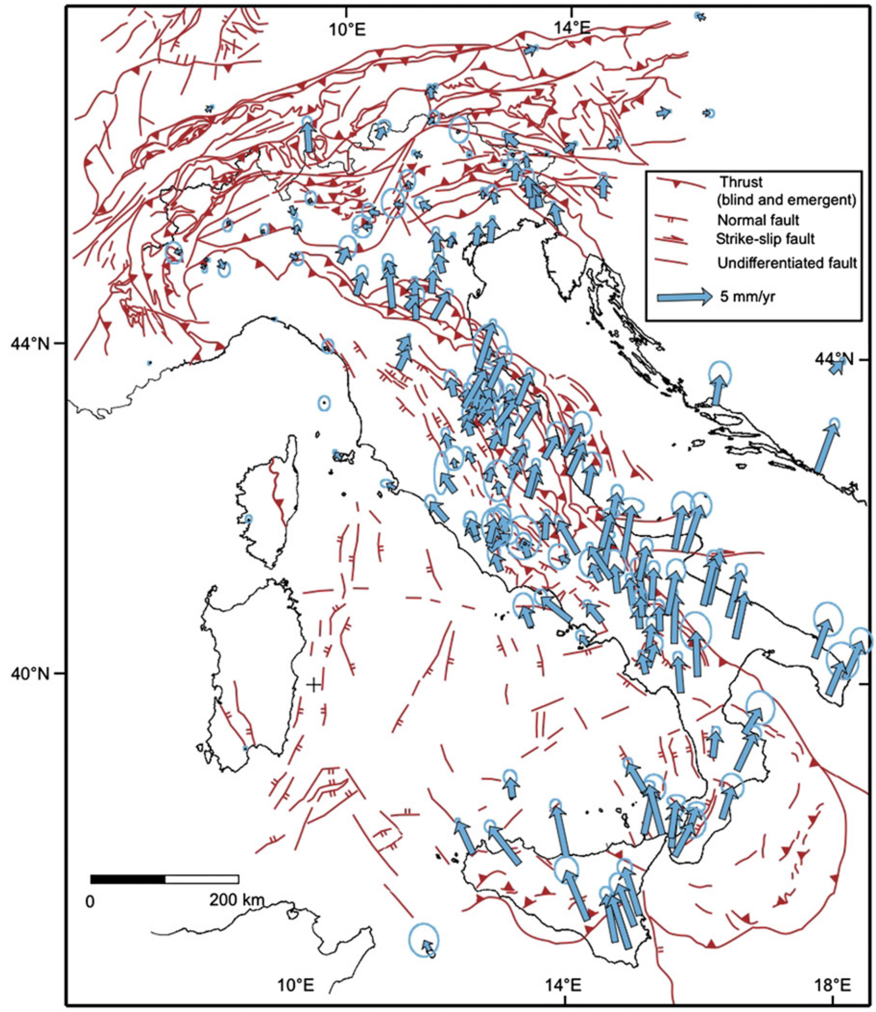

Fig. 17. GPS Velocities referred to stable Europe. Data after Devoti et al. (2008) and Caporali et al. (2011). Note how the Adriatic plate moves as an independent block.

kinematics as a function of its orientation. E–W segments show evidence of right-lateral transpression, whereas the NE-trending segments are rather ESE-verging backthrusts, such as the Canavese and Giudicarie faults. The Alps can be inferred as continuing southward, buried beneath the Tertiary Piemontese Basin. Therefore, the Canavese fault system should also be expected to continue to the south. Along its southern prolongation there is the N–S-trending Sestri-Voltaggio Line in Liguria (marking the contact between the the Voltri Group with ophiolites and sheared peridotites to the west, and, to the east, a flyschoid complex belonging to the Ligurian and Subligurian Units, formerly known in the literature as Argille Scagliose). This fault is conventionally interpreted to separate Alps and Apennines (e.g., Laubscher, 1971), but it is a backthrust, as the Canavese (Insubric) fault. Miletto and Polino (1992) for example considered the Sestri/Voltaggio zone as a major backthrust of Alpine above Apenninic units. Therefore this lineament may represent the southward prolongation of the Insubric Line. In the northern alpine part the Insubric lineament persisted to be active during most of the whole subduction history, whereas where it was incorporated into the Apennines system to the south it may have been deactivated. This is in agreement with the sealing of the Sestri-Voltaggio fault by Late Eocene sediments as described by Molli et al. (2010) and references therein.

5.2. Apennines

The Italian peninsula and Sicily are mainly formed by an asymmetric disrupted thrust belt, the Apennines, surrounding the asymmetric back-arc Tyrrhenian basin (Vai and Martini, 2001). Shortening is larger in the Calabrian arc, in correspondance with maximum back-arc extension in the southern Tyrrhenian sea. The Ionian Sea hosts the frontal part of the Apennines-Calabrian accretionary prism, mostly decoupled into the Messinian evaporites (Bigi et al., 2003; Polonia et al., 2011), and shows a frontal anticline deforming the sea-floor (Gutscher et al., 2006). A conservative value of present-day shortening rates of about 5 mm/yr in the Ionian accretionary prism has been proposed (Devoti et al., 2008). Since Pleistocene(?), the front of the Southern Apennines seems to have stopped and the slab to have buckled generating the lithospheric scale anticline of Puglia (Doglioni et al., 1994). Moving along strike of the Apennines, the total shortening decreases from more than 280 km in the Southern Apennines (Scrocca et al., 2005), to 170 km in the Central and 35 km in the Northern Apennines (Bally et al., 1986). The extension in the Tyrrhenian Sea is linearly decreasing northward as well, confirming that extension and compression are genetically linked. Counterclockwise rotations (20°–60°, up to 90°) have been pointed out in the thrust sheets of the central-northern Apennines, and stronger clockwise rotations ranging between 90° and 140° have been described in the Sicilian thrust belt which represents the southern Apenninic arm (Channell et al., 1990).

The main transition is between parallels 40° and 41°, that also separate two major magmatic provinces (Carminati et al., 2010b). This asymmetry resulted from an irregular subduction. The Adriatic lithosphere is continental in origin while the Ionian lithosphere is oceanic, although, as discussed, some debate persists for the nature of the

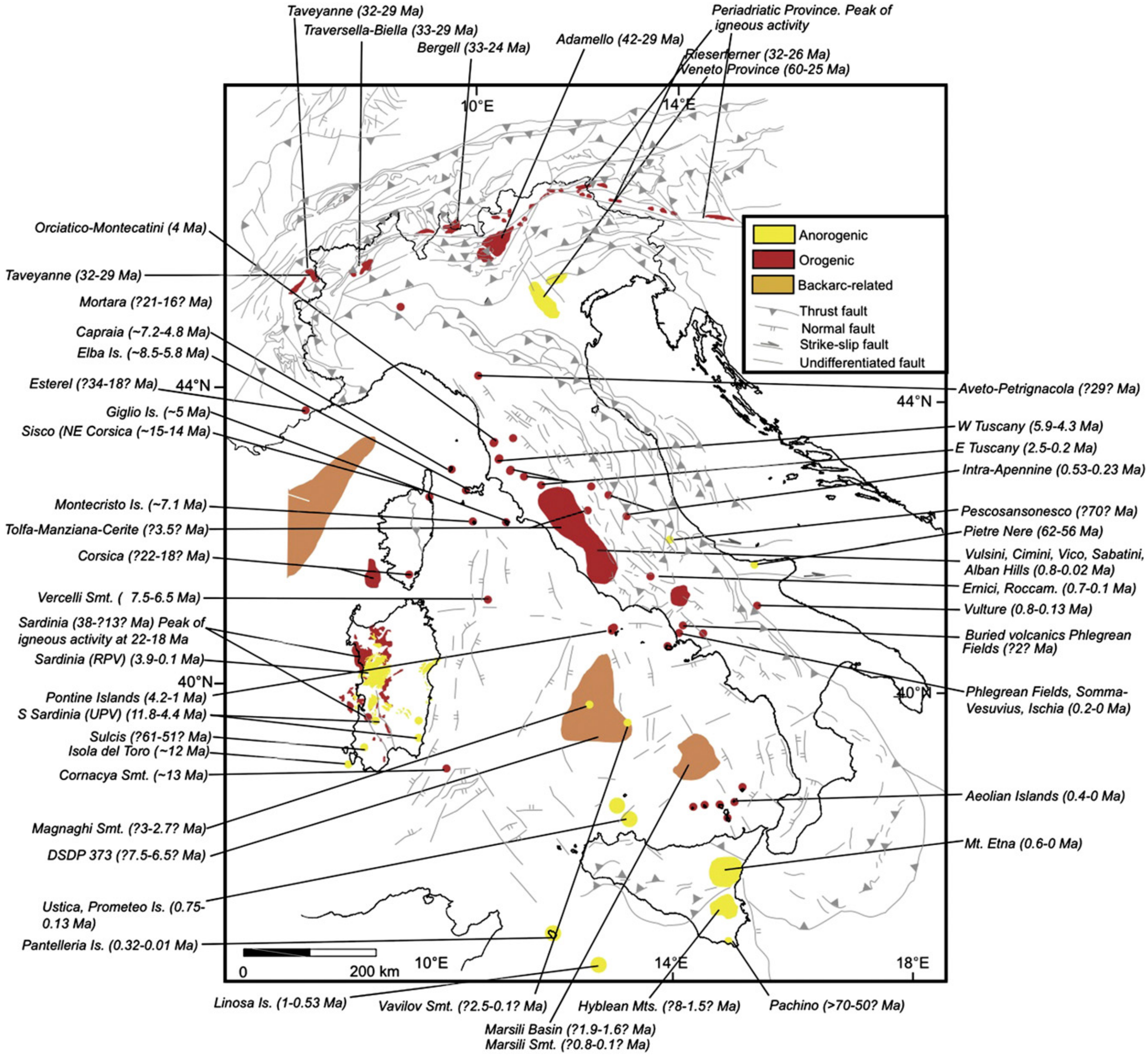

Fig. 18. Distribution, type (orogenic, i.e. subduction related, or anorogenic) and age of the post-Tethyan magmatism in the Italian area (after Carminati et al., 2010b).

Ionian segment (Calcagnile and Panza, 1979). The northward decreasing extension of the Tyrrhenian basin is interpreted as a function of the northward decreasing capability to subduct of the northern Adriatic continental lithosphere. The differences in composition and thickness of the Apenninic subducting slab are in fact also recorded by the present seismicity. The W-directed Caribbean–Barbados subduction and related backarc basin (Gonzales et al., 2011) shows tomographic characters similar to the Apennines (Panza et al., 2007a, 2007b).

In the Apennines, extension (presently affecting the most elevated ridges) was and is coeval with compression in adjacent thrust-fold belts to the east, normally located below the sea level. The extension-compression couple migrated radially, northeastward in the northern Apennines, eastward in the central-southern Apennines, and southeastward in Calabria and Sicily with velocities of 1 to 3 cm/yr and was induced by the eastward retreat of the hinge of the Adriatic subducting slab. There is a clear eastward migration of rifting in the Tyrrhenian itself, from Tortonian in the western part to Plio-Pleistocene in the east. Similarly, continental rifting and related magmatism in Tuscany show an eastward migration. Smaller arcs (salients and recesses) due to inherited Mesozoic horsts and grabens or facies changes produce several fans with dispersion of the maximum stress trajectories. The major undulations occur in the northern and southern parts of the arc, at the intersection with inherited N–S trending features, i.e. the big salient in the Ionian Sea and the recess at the Iblean Plateau–Malta escarpment intersection, or the Adventure Bank, etc. Similar undulations controlled by inherited paleogeographic features, occur in the portion of the northern Apenninic chain buried under the Po Plain sediments, where three main salients and related recesses occur.

The elevation of the Apennines is higher (central Apennines) where the basal décollement of the accretionary wedge is deeper (e.g., about 10 km in the western Adriatic basin) with respect to areas where the décollement is shallower (e.g., about 3 km in the Ionian Basin), in spite of the larger subduction underneath Calabria with respect to the central Apennines (Bigi et al., 2003; Lenci et al., 2004).

The Apenninic history follows the 'Alpine' evolution until the Late Eocene: a common Mesozoic paleogeography and the later inversion. However, during the late Eocene–Oligocene a W-directed subduction started along the retrobelt of the southwestward prolongation of the Alps, a belt that should have been located to the east of the Sardinia–

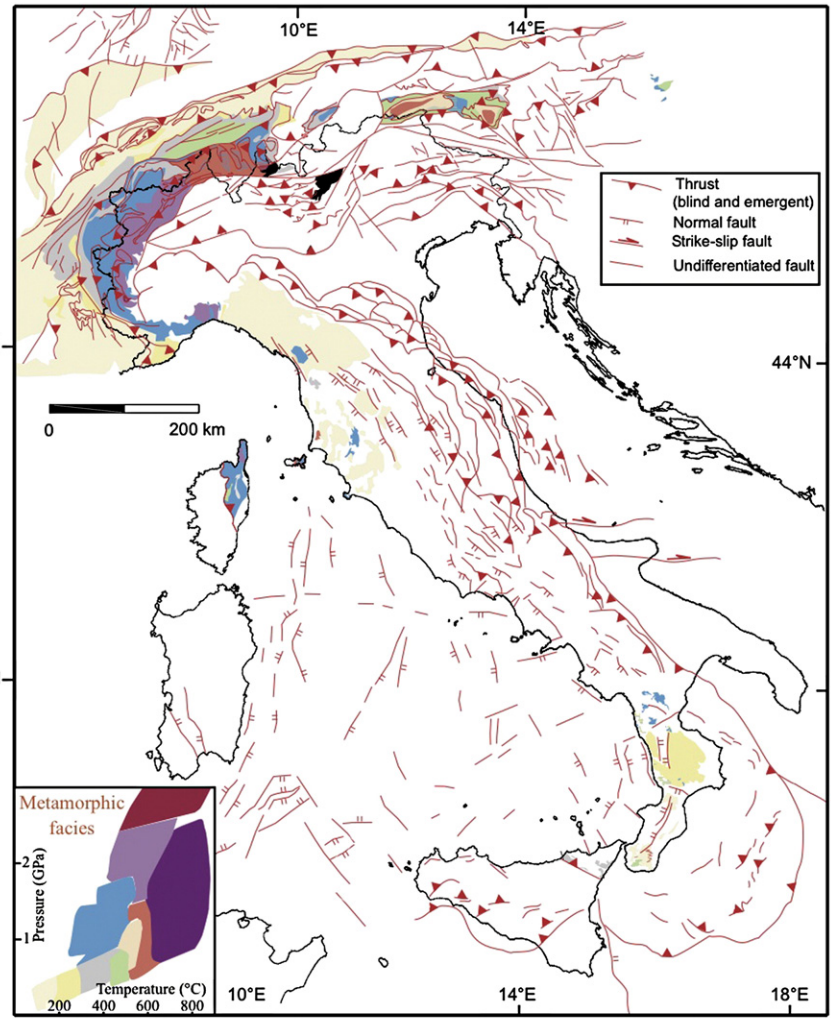

Fig. 19. Map of the climax facies of post-variscan metamorphism in the Allps and Apennines. The data are from Bousquet et al. (2008) for the Alps, Corsica and Tuscany-Liguria regions, Vignaroli et al. (2008) for the Peloritani Mountains; Rossetti (2004) and Iannace et al. (2007) for northern Calabria; Heymes et al. (2010) for southern Calabria.

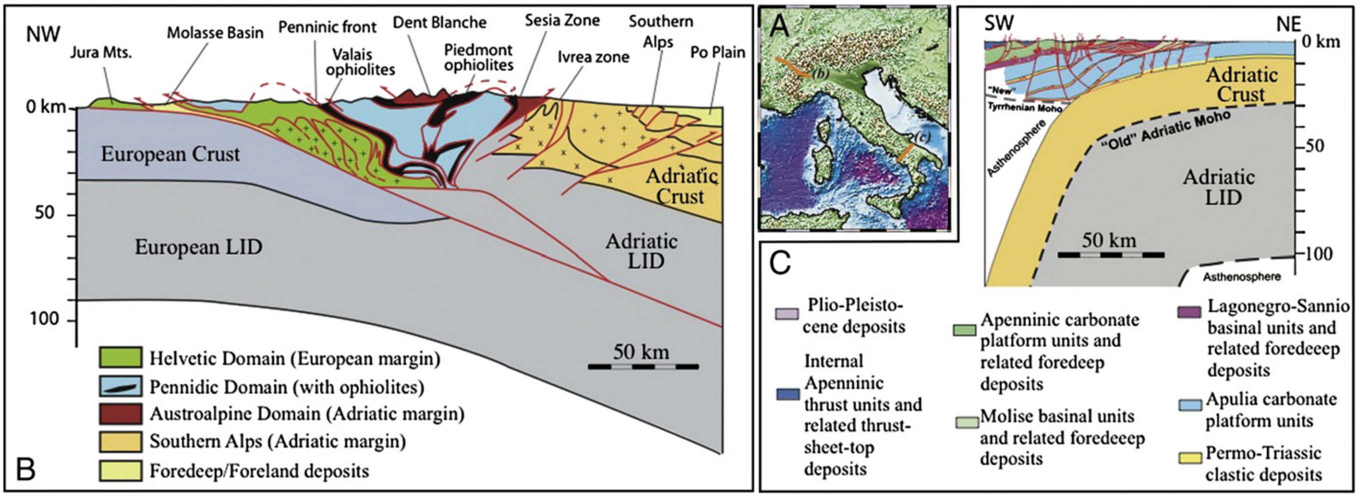

Fig. 20. (a) Map locating the geological cross sections. b) Schematic geological section through the Western Alps (redrawn and modified after Roure et al., 1990b; Dal Piaz et al., 2003). Notice the following features: 1) double vergence of the belt; 2) deep rocks involved, as testified by the occurrence of crystalline crustal rocks in thrusting; 3) shallow foredeep; 4) low dip of the foreland monocline; 5) thickened crust under the belt; 7) no backarc basin; 8) thickened lithosphere 9) the basal decollement involves the whole crusts and the lithospheric mantle of the upper plate. c) Geological cross section through the Southern Apennines (after Scrocca et al., 2005). Notice the following features: 1) single vergence of the belt; 2) thin-skinned (i.e., only sedimentary cover or top basement involved) tectonics; 3) deep foredeep; 4) steep foreland monocline; 5) thinned crust in the western part of the belt belt; 7) opening of backarc basin; 8) shallow asthenosphere in the western side; 9) a new forming Tyrrhenian Moho in the western side.

Corsica block, before and during its post-Eocene 37° counterclockwise rotation (Vigliotti and Kent, 1990). During the Neogene, the Apennines (Fig. 20) accreted the sediments of the Adriatic plate Mesozoic passive continental margin, and of the Ionian oceanic basin.

The "easterly"-directed Alpine subduction was gradually replaced by the opposite "westerly"-directed Apennines subduction (e.g., Doglioni et al., 1999b; Carminati et al., 2010b). An alternative view is discussed in Molli and Malavieille (2011), taking the example of Taiwan. However, as suggested by Doglioni et al. (2007), the E-directed subduction zones should actually move "out" relative to the mantle, i.e., in this model the subduction occurs because the upper plate is faster than the lower plate. Moreover, the slab releases fluids which lubricate the base of the upper plate, self-perpetuating its faster velocity relative to the lower plate. Carminati et al. (2012) tried to reconcile these views in proposing a gradual, transitional model of flip. In this reconstruction, the Apennines backarc basin (Ligure-Provencal Basin) could start to develop even if the Alpine subduction was still operating. According to this model, the Alpine subduction continued until at least the Middle Miocene, whereas the Apennines developed rapidly and mostly after the Late Eocene–Oligocene. Therefore there must have been a long period (Late Eocene–Mid Miocene), in which two subduction zones coexisted, well before the stop of the alpine thrusting. The Hercynian structural grain of the basement cropping out in Sardinia, Calabria, and Tuscany (e.g., Vai, 2001), allows us to constrain their position prior to the rotation of the Corsica–Sardinia block (Vigliotti and Kent, 1990) and of the dismembering of the Alpine belt positioned to the SE of this block (Carminati et al., 2012). The Hercynian basement of Corsica and Sardinia represents the direct continuation of the Hercynian belt preserved in Central and Southern Europe (e.g., Ziegler et al., 2004) The Hercynian basement outcrops stretched and scattered in the internal parts of the Apennines (Tuscany and Calabria) are clearly different from the rest of the Panafrican Precambrian basement of the Adriatic plate (Vai, 2001) and are more similar to the basement cropping out in the Alps (Spalla et al., 1999). This supports their origin as exotic blocks previously belonging to the Alpine edifice. The Alpine units of Calabria and NE Sicily are bounded by the Sangineto Line to the north in Calabria, and by the Taormina Line in NE Sicily (Peloritani).

Like in the Alps, the inversion associated with the Apennines subduction generated new paleogeographic zones (foredeep basins) superimposing with different angles the earlier subdivisions. However foredeep depocenters and steeper foreland regional monoclines are regularly located along pre-existing Mesozoic grabens or paleogeographic basinal facies (Mariotti and Doglioni, 2000). The main steps of the Apennines evolution may be considered the Eo-Alpine phase (Cretaceous?) and Liguride phase (Paleocene–Eocene) with Alpine W-vergence and structural style (e.g., recumbent folds in the Ligurides Units), and the Sub-Ligure phase (Oligocene). During the Tuscan phase (Tortonian) the main nappes emplaced (Liguridi, Tuscan nappe, Cervarola nappe). The Apuane unit underwent metamorphism starting from 27 Ma (Kligfield et al., 1986; Fellin et al., 2007). During the Tortonian the Apuane were already exhumed at temperature cooler than 250 °C. So the Apuane unit was under active extensional thinning during the Tuscan phase (Carmignani and Kligfield, 1990; Molli and Vaselli, 2006: Fellin et al., 2007; Molli, 2008). Recent data support a late Eocene onset of the exhumation in the northern Apennines (geographic term), (Balestrieri et al., 2011). In fact the uplift can be related either to the late Alpine evolution or to the Apennines history.

The history of the Apennines has been interpreted in two different ways: 1) the Apennines are related to a steady northwestward or westward directed subduction since the Cretaceous (e.g., Faccenna et al., 2001; Balestrieri et al., 2011), or 2) they are rather developed along the retrobelt of the southwestward prolongation of the Alps, since the Eocene–Oligocene, when the "east-ward" Alpine subduction was first accompanied and then replaced by the opposite westward-directed Apennines subduction (e.g., Doglioni et al., 1999b; Molli, 2008; Carminati et al., 2010b; Molli and Malavieille, 2011). According to this second model, adopted in this paper, the Apennines developed rapidly and mostly after the late Eocene. In this scenario, the subduction flip was triggered by the existence of oceanic lithosphere at the front of the Alpine retrobelt. However, the subduction of continental lithosphere has been widely proven (Mueller and Panza, 1986), such as in the Alps or Apennines (e.g., the Adriatic plate). Therefore, the W-directed slab may have been initiated and active even if in some segments in the foreland of the retrobelt there was thinned continental lithosphere and not necessarily oceanic lithosphere.

The reason for preferring the second model (subduction flip) is twofolds: 1) The HP rocks in the core of the Apennines need deep rooted decollements which, at present-day, do not form in a context of W-directed subduction zones, where the accretionary prism is mainly formed by the peeling-off of the shallow layers of the lower plate alone and very minor re-exhumation occurs (Doglioni et al., 1999b); 2) The western vergence in NE-Corsica ophiolites (which are physically connected to the Alps after restoring the Corsica–Sardinia Miocene rotation) is associated with the alpine subduction, and supports a double verging orogen which is typical of E- or NE-directed subduction zones, characterized by high topography, deep thrusts and wide involvement of metamorphic rocks which may have had a prograde and retrograde PTt path (Doglioni et al., 1999a).

The transition from the Alpine subduction to the definitive onset of the Apennines subduction may have had a long time of overlap of the mechanisms, such as those occurring in areas of the Pacific or central America, where the two opposite subductions still coexist. In the model where the W-directed Apennines slab evolved after the Alpine evolution as proposed above, the age of their onset is still debated. Lustrino et al. (2009) proposed an Eocene age based on syn-subduction magmatism in west Sardinia. However, the start of the subduction could have been diachronous along strike, between Paleocene–Early Eocene to Late Eocene (Molli, 2008; Molli and Malavieille, 2011; Molli et al., 2010). The Apennines slab retreat and accretion in the outer eastern side certainly continued during the Oligocene and persisted until today along most of its strike.

The Apennines slab retreat (550–600 km in 35–45 Ma?) has been few times faster than the Africa-Europe relative convergence (about 150 km in 30 Ma). Therefore, regardless if the driving force is the slab negative buoyancy or the eastward mantle flow (or both together) the Apennines subduction is an independent process with respect to the Africa indenter. However, the few mm/yr Africa convergence contemporaneous to the slab retreat supports the coexistence of two independent geodynamic processes. The contraction in the southern Tyrrhenian Sea (inversion of the northern offshore Sicilian margin; Pepe et al., 2005) can be ascribed to the Africa convergence, which is responsible for the deformation of the southern, E–W trending margin of the Apennines, from Sicily to the Maghrebides.

The Tyrrhenian Neogene back-arc basin hosts several smaller basins developed on the continental shelf, slope, and bathyal plain and can be as deep as 3000–3600 m. Horsts and grabens are mainly N–S trending, with several transfer zones. Several kilometers thick peri-Tyrrhenian Neogene basins are located off-shore Sardinia (Sardinia basin), Calabria and Sicily. The Tyrrhenian Sea floor consists of Hercynian basement, abyssal oceanic tholeiites, and sedimentary basins filled with Miocene clastics, Messinian evaporites and Pliocene–Quaternary clastics.

The Sicily channell is due to the Plio-Pleistocene extension between Sicily and Tunisia (Africa plate). This is responsible for the Pantelleria, Malta and Linosa basins, NW–SE trending grabens parallel to similar features outcropping in Tunisia and the offshore Pelagian shelf.

6. Why do we distinguish Alps and Apennines?

Alps and Apennines are different in many respects (Table 1). Laubscher (1988) defined the Alps as a push-arc, whereas the

Table 1
The parameters illustrated in Fig. 3 may help to analyze subduction zones. They can be used to differentiate the Alps from the Apennines. This is a summary of these first order differences. At the bottom are two further parameters of the eastern and western Pacific subduction zones, area that show most of the same characters of the Alps (even if a collision is absent around the Pacific) and Apennines archetypes (apart deep seismicity and magmatism). For a recent review of the slab dip and seismic distribution see Riguzzi et al. (2010).

Parameter	Alps	Apennines
Average topography	≈1.5 km	≈0.5 km
Axial structural elevation	>20 km	<5 km
Basement outcrop	>40%	<5% (alpine)
Foreland monocline dip β	2–3°	7–10°
Prism fold-envelope dip α	≈5–7°	≈-3–0°
Foredeep subsidence	<0.2 km/Ma	>1 km/Ma
Prism uplift	>1 km/Ma	<1 km/Ma
Water divide	Static	Migrating east
Highest peaks vs. Water divide	Coincident	West offset
Orogen/foredeep section area	>1	<1
Basal décollement depth	>30 km	<20 km
Convergence/subduction rate	>1	<1
Convergence/shortening rate	>1	<1
Frontal ramp slab dip	<40°	>60°
Vergence & growth	double	single
Foredeep or foreland basin #	2	1
UHP rocks–PTt	yes-CCW	no-
Arc effusive magmatism	scarce	abundant
Backarc basin	no	yes
Slab hinge wrt upper plate	toward	away
Lifespan	100 Ma(?)	38 Ma(?)
Deepest seismicity	30 km(?)	550 km
Analogies with the parameters below	Andes-Himalaya	Marianas-Barbados
Down-dip in-slab seismicity	Extension	Compression
Seismic coupling	High	Low

Apennines as a pull-arc. This interpretation is consistent with the observed characters of the two belts, which, as plate kinematics is concerned, may be synthetized into a subduction where the subduction hinge converges relative to the upper plate (Alps), or diverges from it (Apennines), as described in Doglioni et al. (2007). Blue schists and coesite occurrences and the large outcrops of Barrowian-type metamorphic assemblages in the Alps (Bousquet et al., 2008) indicate that now at the surface are rocks previously metamorphosed at depths of several tens of kilometers. On the other hand the Apennines exhibit predominant outcrops of unmetamorphosed sediments, and only a few scattered occurrences of metamorphic rocks.

The Alps (Dal Piaz, 2010) show a double vergent propagation of the orogen while the Apennines display a single-vergent migration (Figs. 20, 21; Bally et al., 1986; Sella et al., 1988; Calamita et al., 1994; Barchi et al., 1998; Doglioni et al., 1999c; Merlini and Cippitelli, 2001) and the accretionary wedge is coupled to a tensional and more elevated area to the "west" (e.g., Doglioni, 1991; Lavecchia et al., 1994). In the Apennines it has been suggested an "eastward" retreat of the slab (e.g., Scandone, 1979) and a consequent "eastward" migration of the Neogene to present paleogeographic domains (Boccaletti et al., 1990a,b).

The diffuse Neogene extension in the Apennines has a different character from the localized extension in the Alps. The geodynamic context is different, timing, and uplift rates strongly differ. The extension in the Apenninic ridge cannot be considered as the collapse of the orogen, but rather the uplift of the accretionary wedge that formed in the external parts of the arc at lower morphological and structural conditions. In fact the prism forms even deeper than the foreland (Figs. 8 and 21). The Alps have a different structural evolution. First they thickened and uplifted, and then they may have collapsed, or simply had some extension accommodating axial culminations (e.g., the margins of the Tauern Window), or extension related to the northward prolongation into the Western Alps of the Provencal and Tyrrhenian rifting.

The foreland monocline (Mariotti and Doglioni, 2000) at the front of the Alps is less steep (2°–5°) than in the Apennines (4°–10°). The foredeep of the Southern Alps (Fig. 22) had subsidence rates that rarely exceeded the 200 m/Myr (1-4 km of sediments deposited in 15–40 or more Ma). In contrast, the Apennines have a very pronounced foredeep, with the Pliocene base down to 8.5 km depth (Bigi et al., 1989), indicating subsidence rates ranging between 1000 and 1600 m/Ma. The >200 km far field effect of the Apennines slab flexure and related subsidence affected most of the central western Alps. The long-term (tectonic) subsidence of Venice, even if far away from the Apennines, is related to the Apennines slab retreat (Carminati et al., 2003). Much part of the Apenninic foredeep is located on top of the accretionary wedge (wedge top or piggy-back basins), and not only at its front. Minor clastic supply in the Apenninic foredeep was provided by the Apenninic accretionary wedge, whereas the majority of the sediments were originated by erosion of Alps and Dinarides (e.g. Elter and Pertusati, 1973; Garzanti et al., 2007; Garzanti and Malusà, 2008). In the eastern Southern Alps, the foredeep interfered with the Dinaric foredeep since at least the Paleocene up to the Early Miocene.

In cross-section, the area of the Alps above sea level is larger than that of the two foredeeps, whereas the opposite occurs in the Apennines, where the area of the belt above sea-level is smaller than the area of the single foreland basin. Therefore the ratio between the area of the belt and the area of foredeep in cross section is >1 in the Alps, and <1 in the Apennines (Table 1). This is a paradox because a wider and thicker orogen should have a thicker and deeper foredeep. However this appears as a rule at global scale (Doglioni, 1994). This contrasting style generated rapid filling (flysch to molasse transition) and bypassing of the alpine foredeeps, while the Apennines foredeep was initially underfilled until it was fed by alpine clastics.

The highest peaks of the Alps mainly coincide with the water divide (Kuhni and Pfiffner, 2001). In the Apennines they are instead often located eastward relative to the water divide (Salustri Galli et al., 2002). This can be explained by considering that the topography generated by the fast "eastward" migration of the tectonic wave (e.g., 10–20 mm/yr) grows faster than the erosion rate (<1 mm/yr; Bartolini et al., 1996). Therefore the slower divide cannot maintain the position of the high peaks, which are generated by the faster eastward migrating tectonics.

Magmatic suites in the Alps and Apennines show also significant differences (e.g., Serri et al., 2001). In the Alps there is scarce occurrence of subduction-related magmatism. The Apennines have a well developed magmatic arc, whose geochemistry reflects the composition of the downgoing lithosphere (e.g., Serri et al., 2001). Referring to the parameters of Fig. 3, Table 1 lists the main differences between Alps and Apennines. In summary, the characters of the two belts recall the asymmetry existing between E- or NE-directed and W-directed subduction zones worldwide (Fig. 25; e.g., Doglioni et al., 2007). The complex present-day geodynamics of the Italian area is sketched in Fig. 23.

7. Alps–Apennines interaction

The most important interaction between Alps and Apennines consists in the fact that some portions of the Alps became part of the Apennines fold-and-thrust belt. The thrust sheets in northeast Corsica are usually attributed to the Alps (Fig. 2), due to their similarity with the Schists Lustrés with meta-ophiolites cropping out in the Alps. The main emplacement of those rocks occurred during the Eocene, well before the Oligo-Miocene opening of the backarc Provençal Basin. Therefore, once restored the Early Miocene counterclockwise rotation of the Corsica–Sardinia microplate, the Corsica thrust-sheets match the Maritime Alps. In addition, the Alps front can be connected to the Betics front (southern Spain) through the Balearic promontory. For these reasons Alps, Alpine Corsica and the Betics

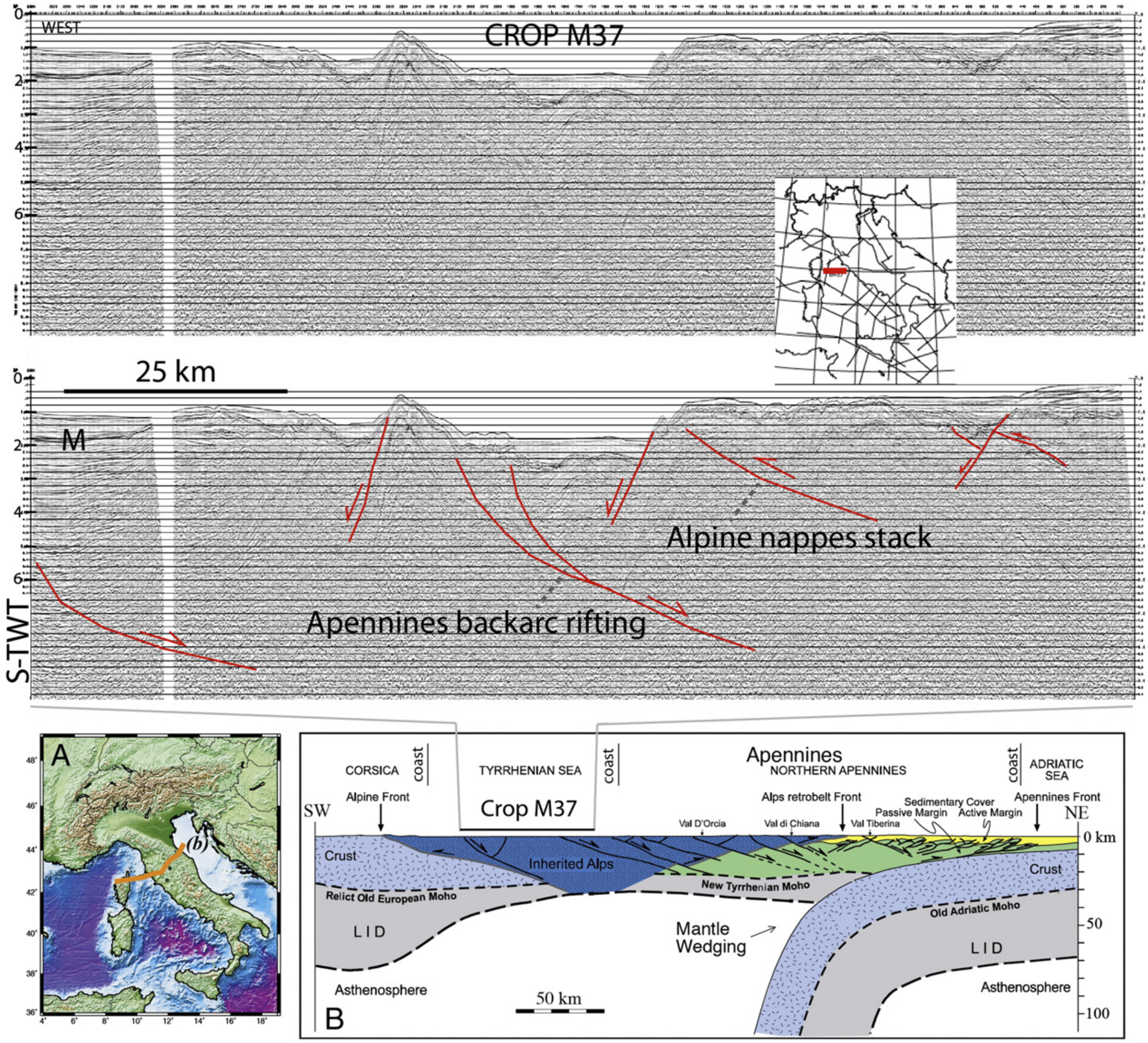

Fig. 21. Uninterpreted and interpreted seismic reflection profile Crop M37 (modified from Scrocca et al., 2003) between Corsica and Tuscany; Note the diffuse normal faulting, cross-cutting the previous thrusts, here interpreted as alpine related features. M, Messinian evaporites. Lower panel, geological cross-section through the Northern Apennines (modified after Doglioni et al., 1998b). In blue are the doubly-verging Alps, stretched and boudinated in the Tyrrhenian backarc rift, associated to the Apennines subduction. The "true" Apennines accretionary prism in green involved only the upper layers of the lower plate.

can be reasonably considered to be part of the same belt (e.g., Argand, 1924; Doglioni et al., 1997, 1998b; Carminati et al., 2010b).

The alpine thrust sheets outcropping in Corsica can be followed in the western Tyrrhenian Sea both in seismic lines and dredging. Analyzing the Atlantic examples of west-directed subduction zones such as the Barbados and the Sandwich arcs, Doglioni et al. (1998b, 1999b) proposed that the initiation of a west-directed subduction generally occurs along the retrobelt of a pre-existing orogen related to an eastward directed subduction zone, when oceanic or thinned continental lithosphere is present in the retroforeland. The application of this model to the Alps-Betics would predict the onset of the Apennines-Maghrebides along the retrobelt of the orogen, where a relic branch of the Mediterranean Tethys (the Ionian lithosphere) was present to the "east" (Figs. 4 and 26). In this view, the Alps–Betics orogen has been stretched, boudinated and incorporated into the internal part of the Apennines–Maghrebides orogen. The metamorphic basement slices outcropping in Tuscany, Calabria, and northeast Sicily could be interpreted as relicts of that inherited orogen (e.g., Bonardi et al., 1994). Alpine relicts, stretched and collapsed by the backarc extension can be recognized in the Tyrrhenian basin (see sections by Mauffret et al., 1999; and Pascucci et al., 1999; Sartori, 2005). Also magmatism supports the occurrence of an alpine metasomatized mantle within the Apennines (Peccerillo, 2005; Frezzotti et al., 2009). Along their southern prolongation, the Alps were probably still active (late Oligocene–early Miocene) while the Apennines subduction had already initiated possibly during the Eocene (Lustrino et al., 2009). A similar coexistence can be observed in central America-Barbados (Bigi et al., 2003).

The occurrence of early Miocene HP/LT metamorphism (Alpine type) in the Tuscan archipelago and in western Tuscany (Rossetti et al., 1999, 2001), deserves a longer discussion. The age of the HP stage has been constrained to ~31–27 Ma (Brunet et al., 2000), i.e., it is synchronous with western Sardinia calcalkaline magmatism and foredeep subsidence associated with the activity of the Apennines subduction. A similar age was proposed for the metamorphism of the Apuane Unit (Kligfield et al., 1986; Fellin et al., 2007).

Two not necessarily alternative solutions are here proposed. The first one considers the Miocene HP/LT metamorphism of the Tuscan archipelago and western Tuscany as developed within the Alpine subduction system. This metamorphism implies a thickened crust (>50 km). This means crustal thrusts and thickened lithosphere, a tectonic setting, which may (at least theoretically) occur only along

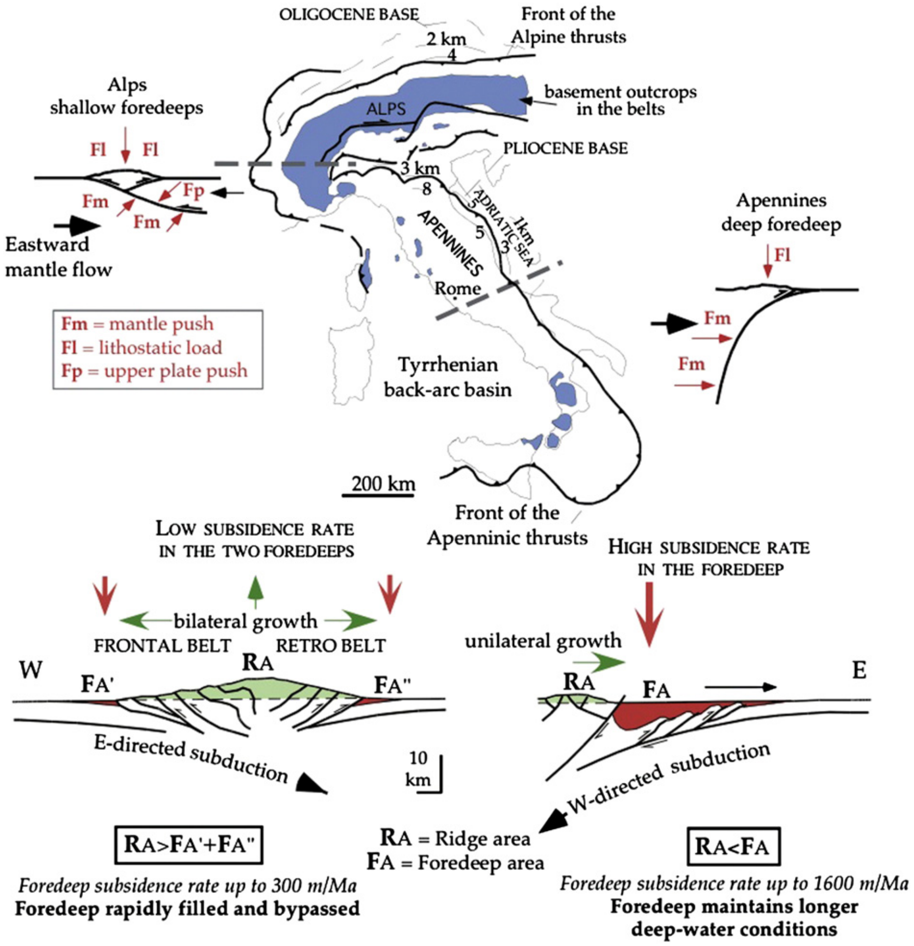

Fig. 22. The asymmetry between Alps and Apennines is well marked by their respective foredeeps. In spite of the much higher elevation, the Alps have two shallow and low-subsiding foreland basins. The Apennines have one deep, fast subsiding, foreland basin. In cross-section, the area of the Alps is larger than the area of the foreland basins. This explains why those basins have rapidly been filled and bypassed. In the Apennines the area of the belt is rather smaller than the foredeep, where deep-water conditions have been maintained for longer period. Most of the filling of the Apennines foreland basin is supplied by the Alps. The Apennines have a steeper foreland regional monocline and a few scattered outcrops of basement rocks, which are interpreted as relics of the earlier alpine belt to the west. The Alps evolved growing both vertical and bilaterally. The Apennines rather developed mainly laterally and "eastward", with minor uplift related to the shallower depth of the basal decollement of the accretionary prism. The interpretation of this asymmetry is ascribed to the "eastward" mantle flow, implicit in the net rotation of the lithosphere or "westward drift". The origin of the foredeeps in the Alps is favoured by the load of the belt, but contrasted by the sustaining mantle flow. In the Apennines, where the load of the belt is insufficient to explain the subsidence, the mantle flow determines the retreat of the slab, and the consequent subsidence at its hinge.

subduction zones where the subduction hinge converges relative to the upper plate (i.e., the Alps; Doglioni et al., 2007). Such subductions produce double verging orogens involving the whole lithospheric section, where the distance from the forebelt to the retrobelt front cannot be shorter than 100 km. This distance is expected to grow as subduction continues, and the orogen expands. The present width

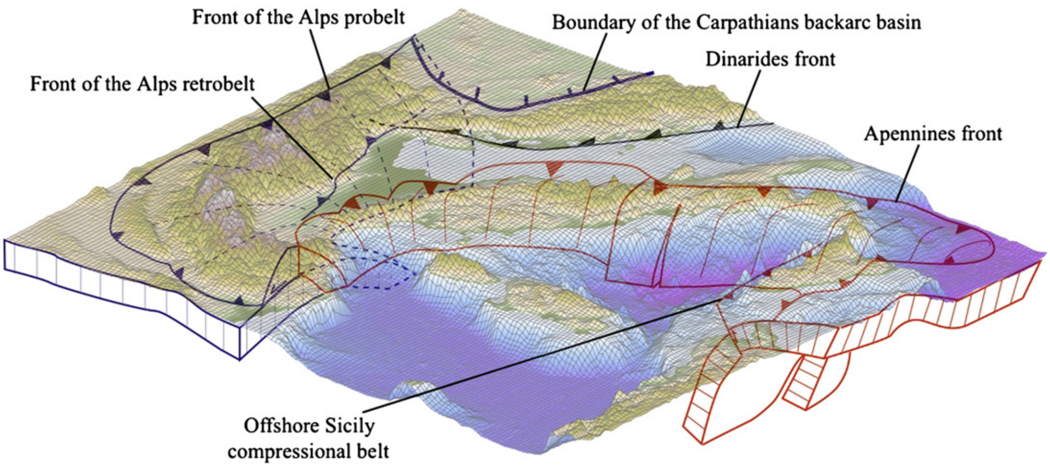

Fig. 23. Block diagram showing the Apenninic and Alpine subductions zones from a northern Africa perspective. The Alps have a shallower and less steep slab with respect to the Apennines. Moreover they have higher elevation and no backarc basin. The Apennines arc is subdivided into smaller subarcs, possibly associated to variable slab retreat, lengthening of the slab, and generation of vertical slab windows, which may have triggered magmatic upraise (e.g., Etna and Vulture).

of the Alps is around 200–250 km, which means a gradual lateral growth of about 100–150 km. Therefore, being the thrust sheets in NE Corsica the alpine forebelt, the related retrobelt must have had its leading edge not closer than 100–150 km to the east, i.e., in present-day Tuscany. And this figure does not consider the later stretching associated with the opening of the Tyrrhenian backarc basin, that increased the distance between the Alpine Corsica front and the retrobelt front. Therefore the scattered outcrops of basement in that region could be interpeted as relics of alpine thrust bodies, emplaced before the boudinage and collapse of the belt into the Apennines-related backarc setting (Fig. 19). In this scenario, the emplacement should have occurred along the retrobelt of the Alps, since the protoliths of the metamorphic rocks also belong to the Tuscan Domain (Rossetti et al., 2001), located to the east of the Neotethys branch (Fig. 27) that triggered the Apennines subduction. Furthermore, the emplacement should have happened in a regime of depressed isotherms, necessary to produce HP-LT metamorphism. The origin of a thermal state typical of subduction zones in the backarc of the Alps could tentatively be explained by the synchronous occurrence of the Apennines subduction. If this view is correct, the “alpine” type subduction (and the retaled contractional tectonics in the retrobelt) should have been active during the Miocene, a period for which a wealth of evidence supports the activity of the W-directed Apennines subduction.

In a second hypothesis, the HP-LT metamorphism in Tuscany could effectively be associated with the Apennines subduction. As already discussed, in “west”-directed subduction zones the coupling between upper and lower plate is generally low and no exhumation of subducted (and consequently metamorphosed) rocks occurs. However, Carminati et al. (2012) pointed out that the full efficiency of the rollback of the Apennines slab was achieved much later than its onset, as testified by the fact that extension in the backarc region (Sardinia, Gulf of Lions, Valencia trough) postdated by some 10–15 Ma the onset of subduction since about 30 Ma ago, the subducting slab started to retreat effectively. The age of the metamorphic peak in Tuscany is strikingly synchronous to this change of dynamics of the Apennines slab, and no younger HP-LT metamorphic rocks have been reported in this region. In the first stages of the Apennines subduction, the sluggish retreat of the slab and the related higher coupling between upper and lower plates could have enhanced the exhumation of such HP-LT metamorphic rocks. The material subducted at later stages was, on the contrary, never exhumed. This second solution could easily explain the metagabbros in blue schist facies cropping out in Tuscany and in its archipelago (Rossetti et al., 2001). In this scenario, such rocks could be ophiolites deriving from the Neotethys branch, that enhanced the Apennines subduction.

The Apennines end northwestward in southern Piemonte, where their subduction disappears and the related accretionary prism vanishes. The slab retreat of the Apennines generated flexural subsidence in the downgoing lithosphere, particularly evident in the Po basin. Following the foreland regional monocline of the northern Apennines, the bending can be traced at least 240 km northward and northeastward of the Apennines ridge (Fig. 24), thus producing a subsidence component in the Alps, which counteracts the generalized uplift of the orogen related to the alpine tectonics (Carminati et al., 2003). This is testified by the burial of the Alpine front in the western and central Southern Alps, beneath the Po basin (Fig. 24). In fact, moving eastward and far away where the Apennines bending is less effective, the Southern Alps front outcrops and the first foothills correspond to the structural Alpine front (Doglioni, 1994; Doglioni and Carminati, 2008). The Apennines subduction-related bending of the lithosphere can be recorded also in the Dinarides front in the eastern side of the Adriatic where the external anticlines have been subaerially eroded due to the Dinarides uplift, and later subsided and partially onlapped due to the downbending of the Apennines foreland (Cuffaro et al., 2010). Therefore, the Po basin and the western Adriatic depression are the foreland basin of the Apennines, being highly asymmetric, with the deepest depocenter and the larger subsidence close to the Apennines, above the steeper regional foreland monocline. This steep dip illustrates the bending of the downgoing Adriatic lithosphere subducting “westward” beneath the Apennines. Variations in dip of the Miocene to Present monocline are associated with the inherited Mesozoic horst and graben generated by the tethyan rift, being the monocline in correspondence of the grabens generally more inclined than in the horsts (Mariotti and Doglioni, 2000). The downflexure of the Apennines subduction tilted and subsided the earlier Southern Alps (Fig. 24) and the Dinarides fronts.

8. The origin of the differences

Since the early development of plate tectonics, the geological characteristics of the Alps were interpreted as the result of an oceanic subduction, followed by continental collision (e.g., Laubscher, 1969; Dewey and Bird, 1970; Dal Piaz et al., 1972). Also the Apennines were soon related to subduction processes (e.g., Boccaletti and Guazzone, 1974; Malinverno and Ryan, 1986), with some variations, such as the delamination of the lower part of the lithosphere (e.g., Channel and Mareschal, 1989). However, it was immediately clear that the characteristics of the Apenninic chain were different from those of the Alps, and soon a number of models were proposed to explain such differences. The differences between the two belts were interpreted as the result of differential slab pull (Royden and Burchfiel, 1989). However, beneath the Apennines, the slab of the Adriatic lithosphere is continental (Panza and Mueller, 1978), possibly apart beneath Calabria, and nevertheless is very steep (Chiarabba et al., 2005). Moreover, the slabs around Italy were suggested to be less dense than the hosting mantle (Brandmayr et al., 2011), as visible in the Vs sections of Fig. 11.

Other models were proposed to explain the peculiar features of the Apennines. The widespread and chemically highly variable magmatism and the thinning in the Tyrrhenian and Provençal basins were explained by an upwelling of the mantle, impinging the south-eastern European lithosphere around Late Oligocene (e.g., Wezel, 1982; Bell et al., 2006; Lavecchia and Creati, 2006), eventually migrating from the Alboran to the Aegean basin from Oligocene to the Present (Morelli, 1998). As fully discussed in Carminati et al. (2012), there is no need to relate the widespread and chemically various igneous activity in these Italian region to the existence of active or fossil upraise of solid mantle from the deep mantle. The geochemical characters of magmatism (commonly considered the strongest evidence for the existence of such type of processes) can be explained in terms of a very fertile and strongly heterogeneous mantle (Lustrino and Wilson, 2007; Lustrino and Carminati, 2007, and references therein).

The lateral migration of the compression and extension couple in the Apennines were explained with the lateral expulsion of crustal wedges (e.g., Mantovani et al., 2002), determined by the convergence between Africa and Europe. We believe that such a process cannot be the driving mechanism for the geodynamics of the Central Mediterranean, because the eastward migration of the compressive and extensional fronts was more than 5 times faster than the plate convergence.

In this work, the asymmetry between Alps and Apennines can be interpreted as related to the geographic polarity of the subduction rather than to the effectiveness of the slab pull (Figs. 11 and 25). The combination of the “eastward” mantle flow with the mantle density heterogeneities (Doglioni et al., 2007; Panza et al., 2007a, 2007b) could explain such differences. At the base of the two end members is the different behaviour of the decollement at the base of the plates, which is polarized due to the net rotation of the lithosphere (Crespi et al., 2007). In fact the contrasting characters among the two orogens recall the differences reported at the Earth's scale between subduction zones following or opposing the “eastward” undulated mantle flow, determining the subduction hinge to either to approach or to move away from the upper plate (Doglioni et al., 2007). An eastward

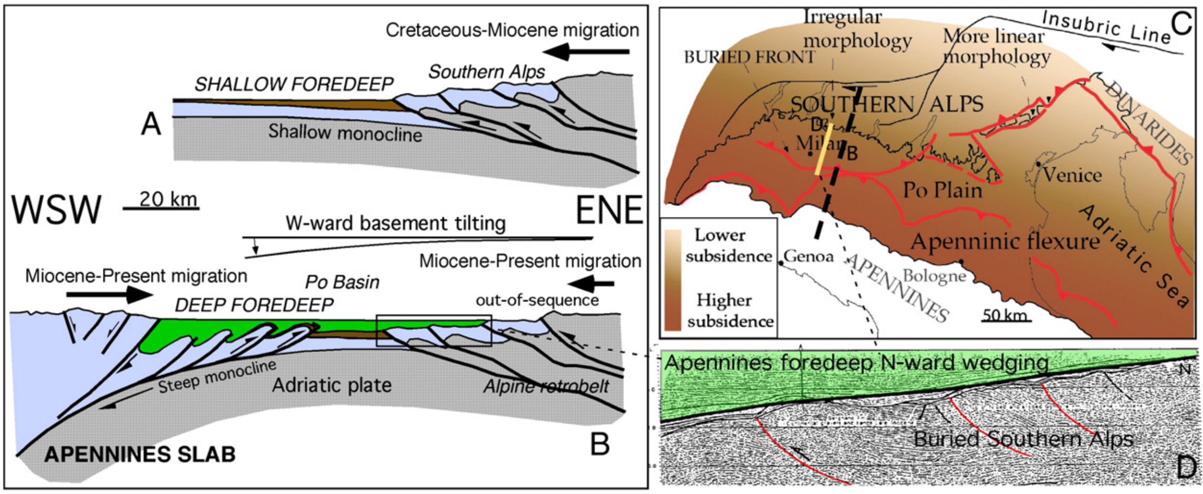

Fig. 24. The Po basin is the area of maximum interference between Alps, bounding the basin to the north, and Apennines, bounding it to the south. The Southern Alps, i.e., the retrobelt of the Alps, developed since the early stages of the belt (Zanchetta et al., in press), as shown in the sketch A. The northeastward propagation of the Apennines accretionary prism developed since Miocene in the hangingwall of the retreat of the SW-dipping Adriatic slab (section B). The downbending of the lithosphere generated the ultradeep asymmetric foredeep-foreland basin of the Po basin, being the base of the Pliocene close to the Apennines somewhere deeper than 8 km, and often above the accretionary prism. The bending and subsidence of the Adriatic plate tilted southward the Alps, partly counteracting their uplift (panel C). In fact, in the western Southern Alps, closer to the Apennines, the alpine front is buried beneath the Po basin foredeep sediments (section D). The foredeep subsidence was generated by the Apennines subduction, but most of the sediments filling (in green) was supplied by the Alps (modified after Doglioni, 1994; Carminati et al., 2003).

mantle flow in the Tyrrhenian Sea encroaching the Apennines slab can be inferred also by the alignement of the elongated axes of olivine parallel to the Apennines trench revealed by shear wave splitting (Margheriti et al., 2003).

9. Conclusions

Alps and Apennines are the two belts that shaped Italy since Cretaceous (Alps) and Eocene–Oligocene (Apennines) to Present. They are associated to two opposite subductions, which inverted the Permo-Mesozoic tethyan passive continental margins bordering segments of southern Europe, the Adriaric plate, northern Africa and possibly an intevening microplate. In spite of a similar background, Alps and Apennines have very different geologic signatures and represent two end members of orogens related to subduction zones. In synthesis, the following characters can be recognised in Alps and Apennines respectively: 1) Subduction hinge converging and diverging relative to the upper plate; 2) Double vs. single vergence; 3) High vs. low morphological and structural elevation; 4) Deep vs. shallow rocks involved; 5) The occurrence of higher metamorphic degree vs. lower

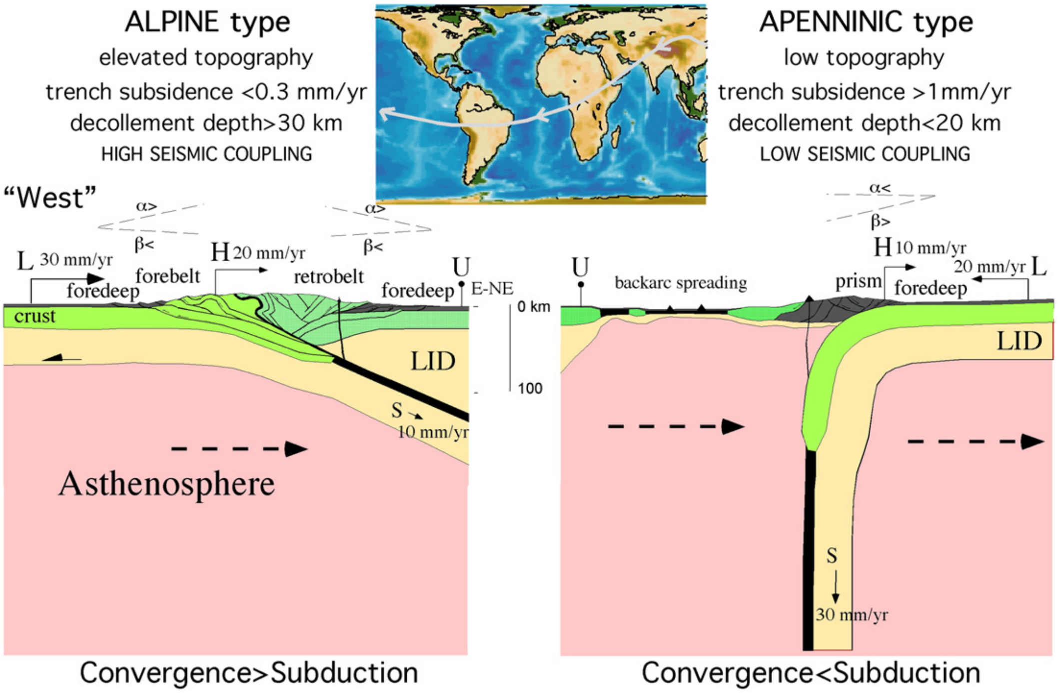

Fig. 25. Main differences between Alps and Apennines. In the Alps the subduction hinge H is converging relative to the Adriatic upper plate U (velocities are only for example). The subduction S is slower than the convergence and the belt is composed by slices of the whole crustal sections of both upper and lower plates L. In the Apennines, the subduction hinge is rather moving away with respect to the upper plate (apart the recent inversion in Sicily). The subduction is faster than the convergence rate, and the prism is composed by the peeling off of the top layers of the lower plate alone, plus inherited boudinated relics of the earlier alpine orogen scattered in the backarc basin. The difference between the two subduction zones mimics those at the margins of the Pacific ocean, and it is here interpreted as related to the "westward drift" of the lithosphere relative to the underlying mantle.

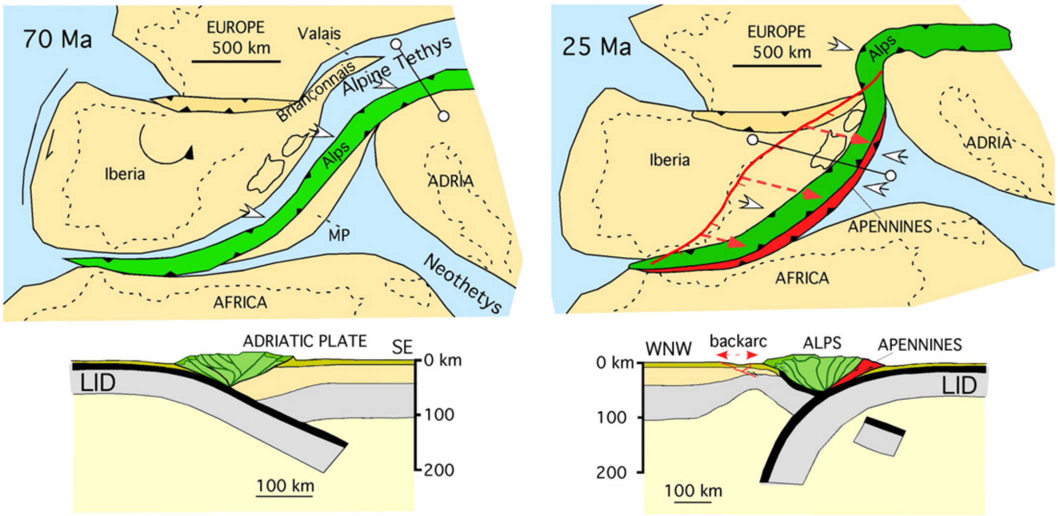

Fig. 26. Cartoons of the hypothetic paleogeography of the western Mediterranean area at at 70 Ma and 25 Ma. Since the Cretaceous, the Alpine-Betic belt was generated by an "easterly" directed subduction and the related orogen was doubly verging since the early stages (see text for discussion). MP is the Mesomediterranean microplate, sensu Doglioni (1992) and Guerrera et al. (1993), required in order to generate the subduction flip. The initiation of the Apennines subduction (at about 45–40 Ma?) and the associated backarc basin in the foreland of the Alps, developed along the retrobelt of the Alps where oceanic or thinned continental lithosphere was present (Doglioni et al., 1999b; Carminati et al., 2012). The paleogeographic distribution of the lithospheric anisotropies controlled the evolution of the subduction zones. The largest retreat of the Apennines subduction occurred along the corridor of the pre-existing Ionian lithosphere. For the interpretation of the Ionian basin geometry, see Catalano et al. (2001). Alternative paleogeographic reconstructions do not consider the occurrence, at 70 Ma, of the Valais trough and of the intervening Briançonnais swell (e.g., Polino et al., 1990).

metamorphic degree; 6) The basal décollement involves the crust and the LID of both upper and lower plates whereas only the shallow crust of the lower plate contributes to the accretionary prism; in the Apennines, the upper plate was not structured as a contractional retrobelt (as a consequence the term collision should be abandoned), but it was stretched and dismemberd to form the backarc basin; 7) Alpine shallow vs. apenninic deep foredeep; 8) Low vs. high dip of the foreland monocline; 9) Thickened crust all over the alpine belt, whereas it is thinner in the western side of the Apennines; 10) The Alps have both in the upper and in the lower plate a pre-subduction Moho, whereas the Apennines have in the footwall plate a pre-subduction Moho, but in the hangingwall they have a new forming Moho; 11) Thickened lithosphere vs. a shallow asthenosphere in the hangingwall; 12) No vs. well developed backarc basin and related

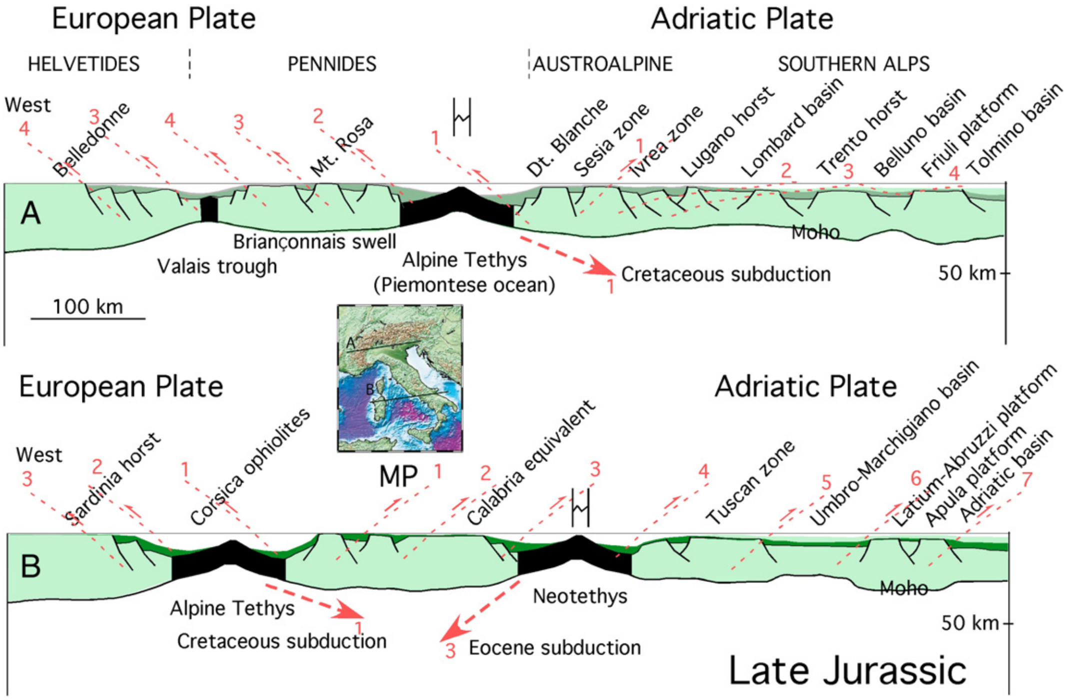

Fig. 27. Two interpretative Jurassic paleogeographic cross-sections at the latitude of the Western Alps (above) and the central Apennines (below). The alpine subduction initiated along the eastern margin of the Alpine Tethys in both sections. The Apennines subduction rather developed along the western margin section the western margin of the Neothetys, along the retrobelt of the Alpine orogen. The dashed red lines and numbers indicate the location of the main thrusts and their kinematic progression. The alpine section is modified after Pfiffner, in Blundell et al. (1992), and Doglioni and Flores (1997). Alternative paleogeographic reconstructions do not consider the occurrence, at 70 Ma, of the Valais trough and of the intervening Briançonnais swell (e.g., Polino et al., 1990).

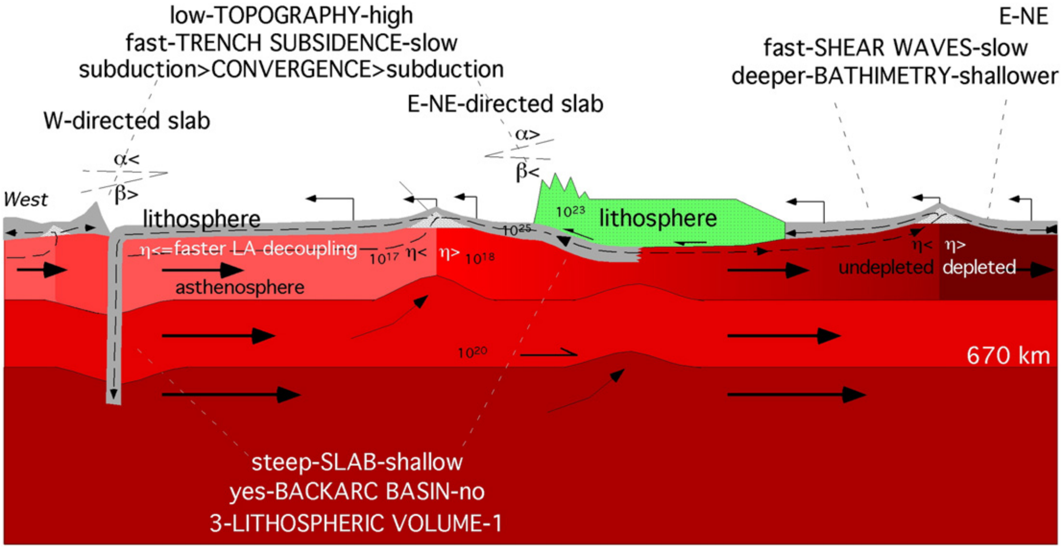

Fig. 28. W-directed subduction zones such as the western Pacific slabs and the Apennines are faster, steeper and deeper than the opposite E- or NE-directed slabs such as the Cordillera and Alpine–Himalaya subduction zones. Along oceanic ridges, the western side is in average few hundreds meters deeper and the underlying mantle is less depleted. In this interpretation mantle convection is also asymmetric, but strongly controlled by the "westerly" polarized flow of plates.

alkaline-tholeiitic magmatism; 13) Scarce vs. larger abundance of subduction-related volcanism; 14) Smooth vs. high amplitude gravity and heath flow anomalies.

The differences between the two belts seem to be more sensitive to the geographic polarity of the subduction rather than to the effectiveness of the slab pull. In the Alps the subduction hinge moved toward the upper plate (Fig. 25), whereas it moved away from it in the Apennines (apart Sicily since early Pleistocene?). Alps and Apennines interfered and still overlap in distinct ways. In the hangingwall of the Apennines subduction there occurs the boudinated and stretched relict of the former double verging Alps, and only more externally in the central-eastern side the real Apennines accretionary prism was developed. The Apennines slab retreat affected most of the present central-western Alps, generating a subsidence partly counteracting the alpine uplift. The Africa convergence appears as a secondary effect in shaping the geodynamics of the Apennines. The Apennines nucleated along the retrobelt of the Alps, where there was oceanic or thinned continental lithosphere to be consumed (Fig. 26). The polarity of any subduction appears controlled primarily by the lateral distribution of the pre-existing anisotropies of the lithosphere, i.e., an E-directed subdction may develop only if to the west of a plate boundary it occurs a thinner and heavier lithosphere, and the opposite for W-directed subduction zones. A simplified pre-subductions Jurassic tethyan tectonic setting across two alpine and apenninic and alpine subductions is presented as Fig. 27. The main paleotectonic and paleogeographic discontinuities controlled the polarity of the subduction and the propagation of the alpine and apenninic main thrusts (Fig. 27).

The differences between Alps and Apennines mimic the asymmetry that can be recognized along the subduction zones worldwide (Fig. 28). This observation, combined with the asymmetry of rift zones (Panza et al., 2010), may support an asymmetric pattern of the mantle convection, strongly driven by the "westerly" polarized flow of plates, which makes an angle of about 30° with respect to the equator (Crespi et al., 2007).

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