ALPS VS APENNINES

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ABSTRACT: The comparison between Alps and Apennines shows they are orogens with distinct characters both in terms of geological and geophysical data. They have respectively 1) convergence rate faster than the slab retreat vs. convergence rate slower than the slab retreat; 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 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; 7) shallow vs. deep foredeep; 8) low vs. high dip of the foreland monocline; 9) thickened vs. thinned crust under the ridge; 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 present a new forming Moho; 11) thickened lithosphere vs. a shallow asthenosphere in the hangingwall; 12) no vs. well developed backarc basin and related alkaline-tholeiitic magmatism; 13) scarce vs. larger abundance of subduction-related volcanism; 14) smooth vs. high amplitude gravity and heath flow anomalies.

The two belts interfered since the southern prolongation of the Alps has been incorporated into the internal Apennines, and the Apennines slab retreat is subsiding much part of the Alps, partly counteracting their uplift.

These differences mimic worldwide asymmetries as the eastern vs. western Pacific (i.e., Andes vs. Marianas) or Himalayas vs. Barbados subduction zones, and favor a global scale explanation such as the "westward" drift of the lithosphere rather than regional slab-pull related variations in the tectonic style.

INTRODUCTION

The Alps and the Apennines are the two belts characterizing the Italian geology (Figs 1 and 2), which developed due to the closure of the Mediterranean Mesozoic Tethyan basins. Even the related foreland areas are in somehow deformed or tilted by the two orogens. Italy is one of the few countries in the world containing two belts, i.e., specifically two opposite subduction zones. The Alps are related to the subduction of Europe "eastward-southeastward" underneath the Adriatic plate, whereas the Apennines are generated by the "westward" subduction of the Adriatic plate.

The Alpine subduction and related orogen are inferred to have initiated during the Cretaceous with the subduction of the oceanic Pennidic lithosphere underneath the Adriatic plate to the south or east, evolving to collision with the arrival at the subduction hinge of the European lithosphere during the Eocene (e.g., DAL PIAZ *et alii*, 2003). The collisional stage seems to have slowed down since the late Pliocene, but it locally shows to be still active as evidenced by compressional seismicity in frontal areas and uplift of the belt. The Alps have a conjugate antithetic retrobelt, i.e., the Southern Alps, which started to develop since the early stages of the subduction, like it occurred in the Andes where the retrobelt is even wider than the frontal belt, synthetic to the subduction.

The history of the Apennines has been interpreted mainly in two different ways: 1) the Apennines are related to a steady northwestward directed subduction since the Cretaceous (e.g., TREVES (1984); FACCENNA *et alii*, 2001), or 2) they are rather developed along the retrobelt of the southwestward prolongation of the Alps, since the Oligocene, when the "east-ward" Alpine subduction was gradually replaced by the opposite westward-directed Apennines subduction (e.g., DOGLIONI *et alii*, 1998; 1999a). According to this second model, the Apennines developed rapidly and mostly after the late Oligocene.

LAUBSCHER (1988), as usually a pioneer in his interpretations, noted relevant differences between Alps and Apennines, defining them respectively as a push arc and a pull arc. The push arc is a classic collisional environment, where two continental plates converged. The pull arc in his paper is rather a belt associated to slab retreat and generation of a backarc basin such as the Tyrrhenian Sea.

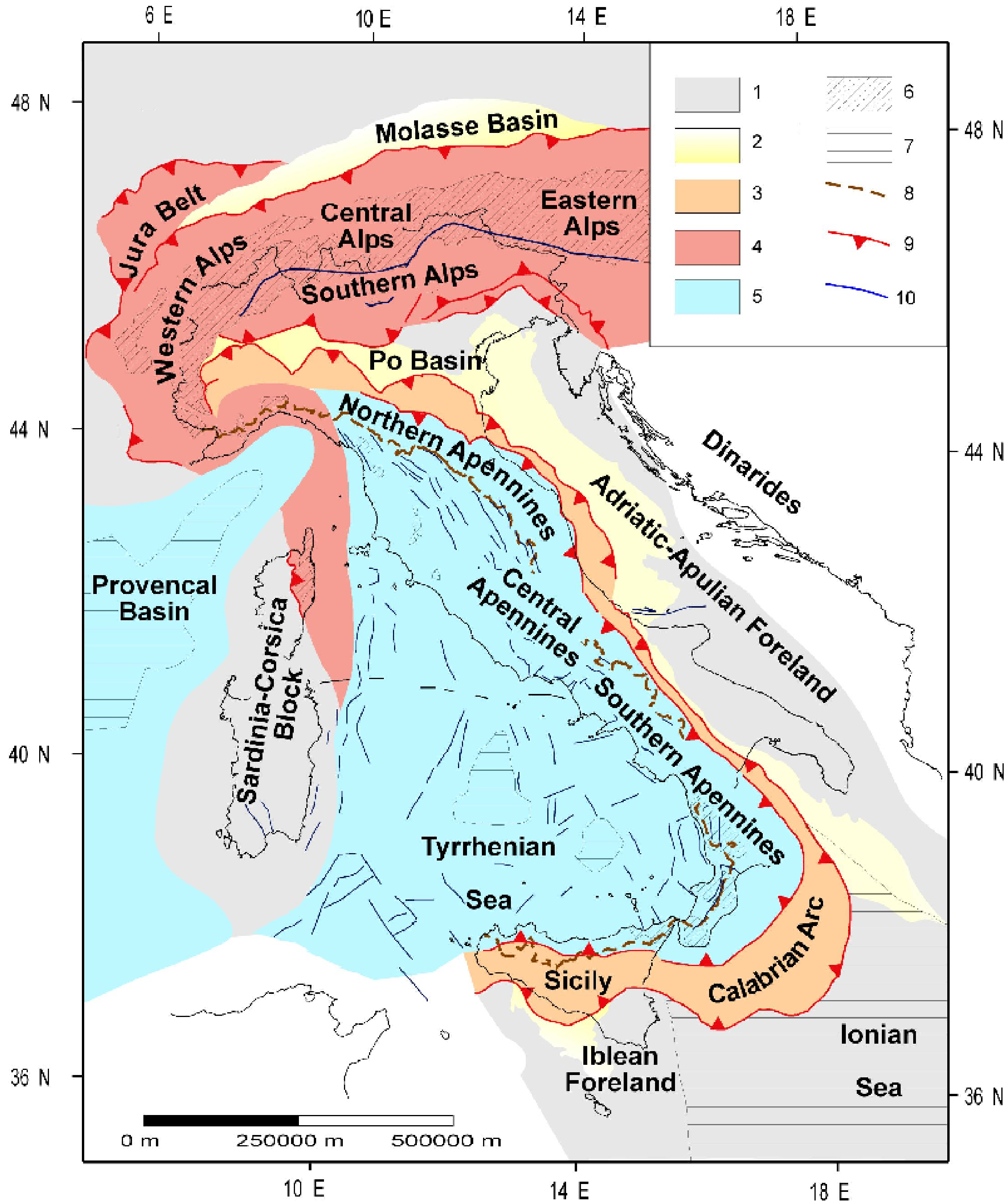

Fig. 1 – Synthetic tectonic map of Italy and surrounding regions after SCROCCA *et alii* (2003). 1) foreland areas; 2) foredeep deposits (delimited by the –1000 m isobath); 3) domains characterised by a compressional tectonic regime in the Apennines; 4) thrust belt units accreted during the Alpine orogenesis in the Alps and in Corsica; 5) areas affected by extensional tectonics: these areas can be considered as a back-arc basin system developed in response to the eastward roll-back of the west-directed Apenninic subduction; 6) outcrops of crystalline basement (including metamorphic alpine units); 7) regions characterised by oceanic crust: an oceanic crust of new formation has been recognised in the Provençal Basin (Miocene in age) and in the Tyrrhenian Sea (Plio-Pleistocene in age) while an old Mesozoic oceanic crust can been inferred for the Ionian Basin; 8) Apennines water divide; 9) thrusts; 10) faults.

Similar differences were also highlighted by ROYDEN & BURCHFIEL (1989) and DOGLIONI (1990; 1992). WASCHBUSCH & BEAUMONT (1996) modeled these differences in terms of the ratio between the slab retreat and the convergence rate. When the slab retreats slower than the convergence rate, then a double vergent belt such as the Alps forms. On the contrary when the slab retreats faster than the convergence rate, there forms a single vergent belt with related backarc basin such as the Apennines-Tyrrhenian Sea system. The presence of two subduction zones end-members and related orogens is very evident when comparing the western and eastern Pacific subduction zones (e.g., DICKINSON, 1978). This asymmetry has been ascribed either to the more efficient slab pull in the western Pacific (FORSYTH & UYEDA, 1975) or to the westward drift of the lithosphere relative to the underlying mantle (DOGLIONI *et alii*, 1999b). The same different interpretations have been used for differentiating the Alps and the Apennines as related to different slab pull effect (ROYDEN & BURCHFIEL, 1989; ROYDEN, 1993), or as related to the "eastward" relative mantle flow (DOGLIONI *et alii*, 1999a & b). Recent analysis shows how the dip of the slabs does not simply correlate with the age of the downgoing lithosphere (CRUCIANI, 2004).

These two orogens are so different that they can represent two end members of a global classification. In this paper, we compare Apennines and Alps in order to describe their gross features and differences and to provide a model for interpreting such variations.

GEOLOGICAL DIFFERENCES

The Alps (Figs 2 and 3) have widespread outcrops of basement rocks (e.g., BIGI *et alii*, 1989), whereas the Apennines are mainly composed of sedimentary rocks, apart internal relicts of Variscan basement slices likely emplaced during the earlier alpine phase (Fig. 4). The difference between Alps and Apennines is even stronger when the structural elevation is considered. Indeed the core of the Alps has been eroded several tens of km as indicated by the occurrence of ultrahigh-pressure rocks, whereas along the main ridge, the Apennines have been overburden only by a few km, providing evidence for much lower structural elevation and consequently lower erosion. Alpine ophiolites have usually higher metamorphic grade with respect to those of the Apennines.

The Alps (DAL PIAZ, 1997) show a double vergent propagation of the orogen (Figs 1 and 3) while the Apennines (Figs 1 and 4) have a single-vergent migration (BALLY *et alii*, 1986; SELLA *et alii*, 1988; CALAMITA *et alii*, 1994; BARCHI *et alii*, 1998; DOGLIONI *et alii*, 1999c; MERLINI & CIPPITELLI, 2001) and the accretionary wedge is coupled to an extensional and more elevated area to the "west" (e.g., DOGLIONI, 1991; LAVECCHIA *et alii*, 1994). In the Apennines it has been suggested an "eastward" retreat of the slab (SCANDONE, 1979; ROYDEN *et alii*, 1987) and a consequent "eastward" migration of the Neogene to present paleogeographic domains (BOCCALETTI *et alii*, 1990).

The Alps grew laterally and vertically expanding first the retrobelt and then the forebelt during the subduction stage, eventually involving the footwall continental lithosphere during collision, and amplifying the elevation and the lateral expansion of both sides (Figs 2 and 5). Therefore the Alps gradually grew to the present high structural and morphologic elevation (highest peak, Monte Bianco, 4810 m). The Apennines rather migrated only laterally, and they never reached high structural and morphological elevation. The Apennines recorded an eastward propagating wave (Figs 2 and 5). The elevation of the Apennines is higher (central Apennines, Gran Sasso, 2914 m) 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 a larger subduction underneath Calabria with respect to the central Apennines (BIGI *et alii*, 2003; LENCI *et alii*, 2004).

The highest peaks of the Alps mainly coincide with the water divide (KÜHNI & PFIFFNER, 2001). In the Apennines they are instead often located eastward relative to the water divide (SALUSTRI GALLI *et alii*, 2002). This offset of the highest peaks 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 alii*, 1996). Therefore the slower divide cannot maintain the position of the high peaks, which are generated by the faster eastward migrating tectonics.

The foreland monocline (MARIOTTI & DOGLIONI, 2000) at the front of the Alps is less steep (2-5°) than in the Apennines (4-10°). In spite of the higher elevation, the Alps have two small foredeeps with slow subsidence rates (<0.3 mm/yr). The Apennines have one deep foredeep with fast subsidence rates (>1 mm/yr). In cross-section, the area of the Alps above sea level is larger than the foredeep, whereas the opposite occurs in the Apennines. This is a paradox because a wider and thicker orogen should have a thicker and deeper foredeep. Nevertheless the Alps and the Apennines show the opposite signal, similarly to the other foredeeps on Earth (DOGLIONI, 1994).

Magmatic suites in the Alps and Apennines show also significant differences (e.g., SERRI *et alii*, 2001; SAVELLI, 2002). In the Alps the scarce occurrence of subduction-related magmatism suggests low rates of convergence (<20 mm/yr). The Apennines have a well developed magmatic arc whose geochemistry reflects the composition of the downgoing lithosphere (e.g., Serri et al., 2001).

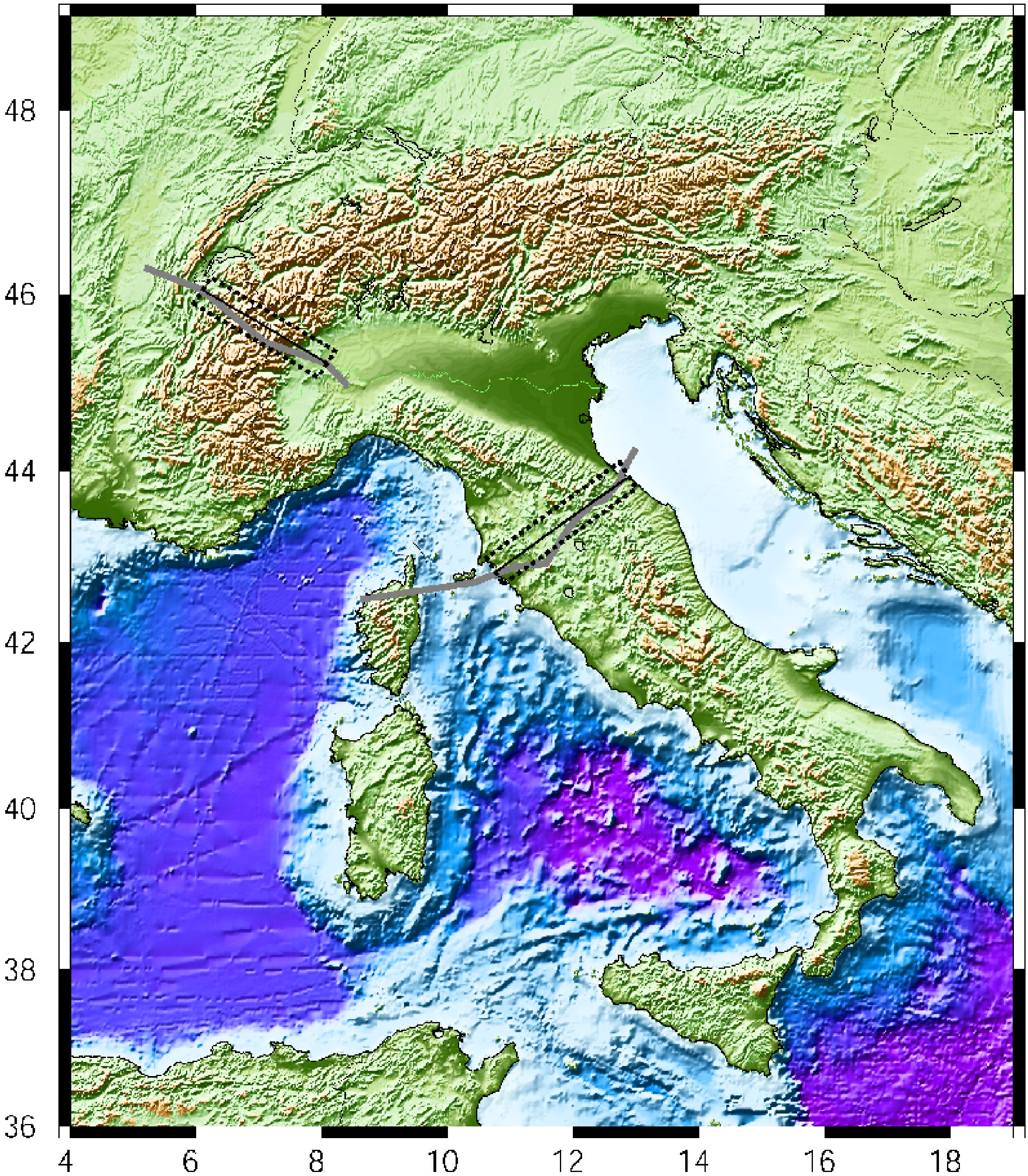

Fig. 2 – Shaded relief and bathymetry map of Italy and surrounding seas. The topography data are from the USGS-NASA GTOPO30 data base (http://edcdaac.usgs.gov/gtopo30/gtopo30.asp), whereas the bathymetry data are from the NGDC ETOPO2 data base (http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html). The traces of the sections of Figs 3 and 4 (thick grey lines) and Fig. 5 (black lines and dashed boxes) are shown.

GEOPHYSICAL DIFFERENCES

The Alps present a thickened continental lithosphere (150-200km, e.g., BABUSKA *et alii*, 1985) with respect to the adjacent undeformed continental areas, and the asthenosphere is then deeper (Fig. 3). The Apennines have rather a strong asymmetry, with a shallow asthenosphere (30-40 km) beneath their western side (DOGLIONI, 1991; MELE *et alii*, 1997), steep and deep lithospheric roots underneath the belt (Fig. 4).

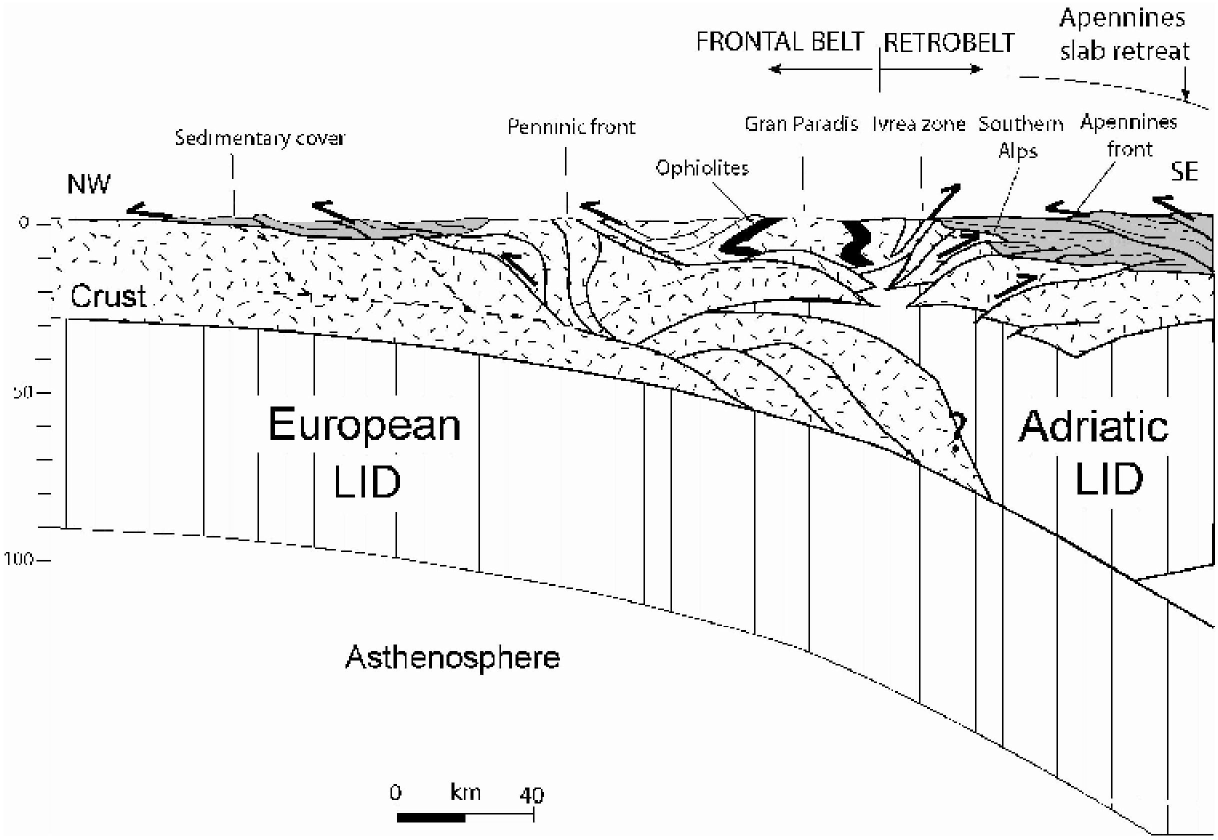

Fig. 3 - Schematic geological section through the Western Alps mainly after ROURE *et alii* (1990). The section trace is shown in Fig. 2. The following features are noticeable: 1) double vergence of the belt; 2) deep basement involved, as testified by the involvement of crystalline crustal rocks in thrusting; 3) shallow foredeeps; 4) low dip of the foreland monocline; 5) thickened crust and lithosphere under the belt; 7) no opening of backarc basin; 8) the basal décollement involves the whole crusts and the lithospheric mantle of the upper plate. Note also the tilting of the eastern side due to the Apennines slab retreat.

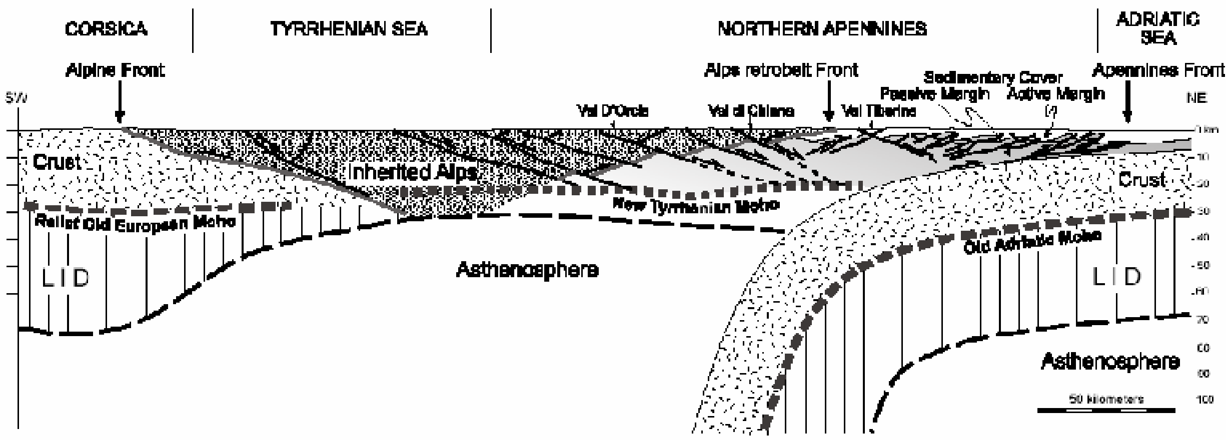

Fig. 4 - Schematic geological section through the Apennines-Tyrrhenian Sea system. The section trace is shown in Fig. 2. The shallow structure of the Apennines is largely based on the results of the CROP-03 Seismic Profile (BARCHI *et alii*, 1998) while the Moho geometry has been reconstructed considering the new results obtained by MELE & SANDVOL (2003). It is noticeable the Moho doubling below the Val Tiberina with a shallower new Tyrrhenian Moho, at about 20 km, above a deeper pre-subduction in age Adriatic Moho, at about 52 km. According to these new constraints, which support the geodynamic setting proposed by DOGLIONI *et alii* (1998), most of the Adriatic crust should be subducted below the northern Apennines accretionary wedge that, in turn, is mainly made up of stacked units of sedimentary cover off-scraped from the subducting plate. Note also the double vergent Alpine orogen (dotted) stretched by the back-arc extension related to the Apennine subduction.

In the Alps (e.g., KISSLING, 1993) a pre-subduction, possibly Mesozoic in age, European Moho can be distinguished from an Adriatic plate Moho. The European Moho reaches depths deeper than 55 km accompanying the lithospheric subduction. The hangingwall Moho of the Adriatic plate is shallower (25-30 km). In the Apennines there are rather three Moho: the Adriatic plate, pre-subduction Mesozoic age Moho which is deepening and steepening beneath the accretionary prism (SCARASCIA *et alii*, 1994; MELE & SANDVOL, 2003), mimicking the foreland monocline of the basement top (MARIOTTI & DOGLIONI, 2000) and the lithosphere base (PANZA *et alii*, 2003). Then there is a new Moho, forming with the opening of the Tyrrhenian backarc basin, due to the replacement of the mantle associated to the slab retreat (DOGLIONI, 1991). This new Moho should rejuvenate eastward as the basin progressively propagated. The third is the pre-subduction, Mesozoic in age, Moho inherited in the hangingwall European plate (Fig. 4), that is now stretched and abandoned westward underneath Sardinia (LOCARDI & NICOLICH, 1988; NICOLICH, 2001).

The gravity Bouguer anomaly reaches values lower than –160 mGal along the Alpine axis, increasing to –40 mGal in more stable lateral areas. In the Apennines there is a shift between the highest topographic relief and gravity (MONGELLI *et alii*, 1975), being the lowest values located toward the foredeep areas and ranging between –120-0 mGal (Fig. 5). The anomaly gradually increases to positive values moving westward toward the belt and in the Tyrrhenian Sea, up to 240 mGal. The 0 mGal isogal is approximately located along the belt where, at depth, the shallow asthenosphere and new Moho of the hangingwall meet the hinge of the subducting foreland.

Heat flow values are smoother in the Alps (Fig. 5) 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 alii*, 1991; DELLA VEDOVA *et alii*, 2001).

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. 6). The main focal mechanisms are compressive (Fig. 7), apart some of those located in the belt which can be either strike-slip or extensional. The Apennines are rather dominated by extensional seismicity elongated parallel to the main ridge of the belt, and compressional seismicity to the "east" in the external, low-relief or marine areas of the accretionary prism (Fig. 7). Local transfer zones are accommodated by strike-slip faults.

ALPS –APENNINES INTERACTIONS

The thrust sheets in northeast Corsica are usually attributed to the Alps (Figs 1 and 4), due to their similarity to the Schists Lustrés with meta -ophiolites. The main emplacement of those rocks occurred during the Eocene, well before the opening of the Provençal Basin. Therefore, once restored the Early Miocene counterclockwise rotation of the Corsica -Sardinia microplate, which accompanied the Provençal basin, the Corsica thrust -sheets match the Maritime Alps. In oth er words, the tectonics of Alpine Corsica has to be related to the subduction of the European plate to the east, as for the Western Alps, and it is a natural element of the alpine orogen.

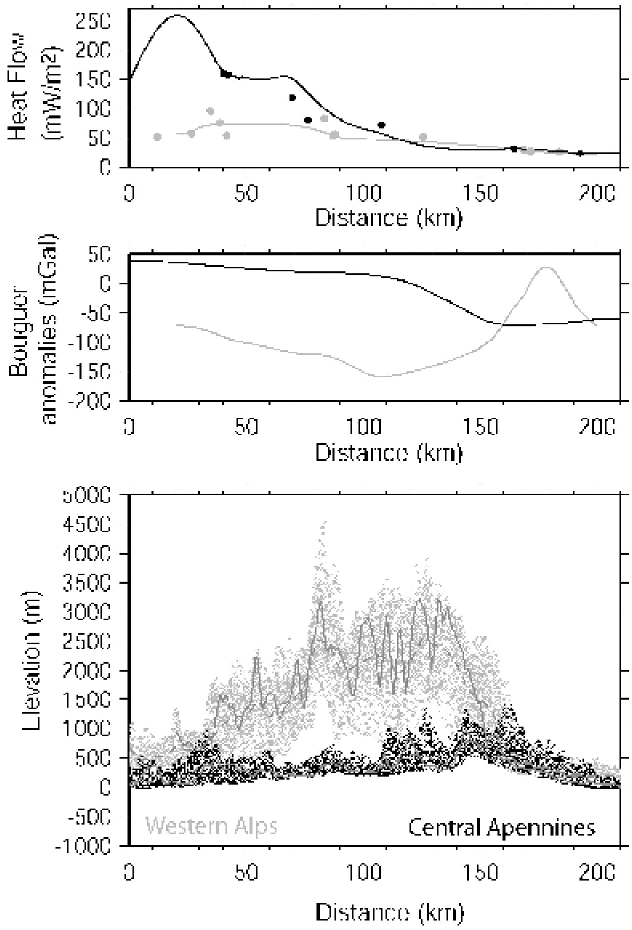

Fig. 5 - The heat flow (a), Bouguer gravimetric anomalies (b), and topography (c) of Alps and Apennines are compared. The data are referred to the traces shown in Fig. 2. In all panels the grey lines and circles are referred to the Western Alps, whereas the black lines and circles to the Central Apennines. (a) The heat flow data (after Pollack et alii, 1993) falling in the dashed boxes of Fig. 1 were projected onto the section traces (black lines of Fig. 1) as solid circles. The lines represent the interpolation of the data. (b) The Bouguer anomalies are drawn from the map of Mongelli et alii (1975). (c) The topography data (from the GTOPO30 data base; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) falling in the dashed boxes of Fig. 2 were projected onto the section traces (black lines of Fig. 2) as circles. The solid lines represent the exact topographic profile along the black lines of Fig. 2, whereas the dashed lines show the average topography within the dashed boxes.

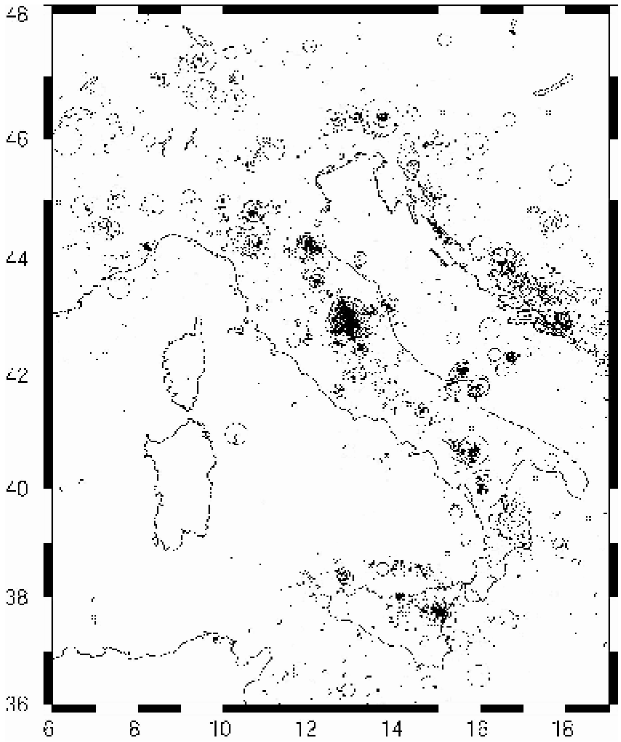

Fig. 6 - Earthquake hypocentres recorded by the Italian telemetered seismic network (ITSN) in the years 1989-1998 whose magnitudes are greater than 2.4. Data from INGV (http://www.ingv.it).

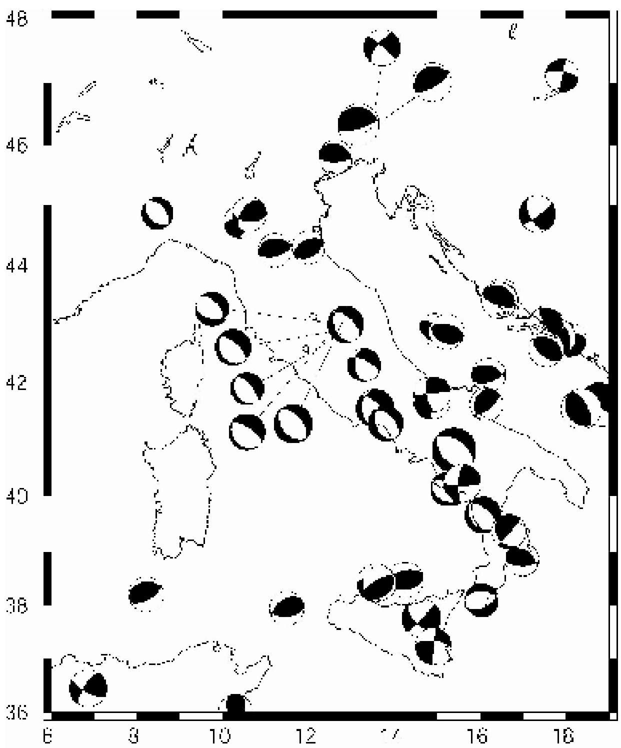

Fig. 7 - Centroid moment tensor solutions available for the Italian area. Only earthquakes shallower than 40 km were selected. Data from the Harvard CMT Catalog (http://www.seismology.harvard.edu/CMTsearch.html).

The Alps and similar contractional belts are double vergent (Fig. 1), with a conjugate retrobelt (i.e., the Southern Alps). The present Alps, from the front of the forebelt to the front of the retrobelt are usually 200-250 km wide. According to this constraint, the front of the alpine retrobelt of the Corsica front should have been at least 200 km more to the east. The alpine thrust sheets outcropping in Corsica can be followed in the western Tyrrhenian Sea both in seismic lines and dredging. Again, restoring Corsica-Sardinia rotation, the Alps front can be connected to the Betics front from the Balearic promontory to the Guadalquivir basin. Similarly to the Alps, the Betics show low dip foreland monocline, high elevation, widespread outcrops of basement rocks, high-pressure metamorphism, etc.. For these reasons they can be reasonably considered to be part of the same belt.

Analyzing the Atlantic examples of west-directed subduction zones such as the Barbados and the Sandwich arcs, DOGLIONI *et alii*, (1998; 1999a) proposed that the initiation of a west-directed subduction 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 foreland. 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 was present to the “east” (Fig. 8). The candidate for the central-western Mediterranean would be the northwestern prolongation of the Ionian Mesozoic basin (CATALANO *et alii*, 2001). In this view, the Alps-Betics orogen has been stretched, boudinated and incorporated into the internal part of the Apennines-Maghrebides orogen (Fig. 4). The metamorphic basement slices outcropping in Tuscany, Calabria, northeast Sicily and Algeria could be interpreted as relicts of that inherited orogen (e.g., BONARDI *et alii*, 1994). Alpine relicts, stretched and collapsed by the backarc extension can be recognized in the Tyrrhenian basin (see sections by MAUFFRET *et alii*, 1999; and PASCUCCI *et alii*, 1999). Even the magmatism is supporting the occurrence of an alpine metasomatized mantle within the Apennines (PECCERILLO, 1999). Along their southern prolongation, the Alps were probably still active (late Oligocene-early Miocene) while the Apennines subduction initiated. This could explain the co-existence of early Miocene HP/LT metamorphism (Alpine type) in the Tuscan archipelago while western Sardinia calcalkaline magmatism and foredeep subsidence provide evidence of active Apennines subduction at the same time.

While the Alps did not stop in Liguria (LAUBSCHER *et alii*, 1992) but were rather forming an elongated belt toward the southwest (DOGLIONI *et alii*, 1999a), later stretched by the Apennines backarc extension, the Apennines end in southern Piemonte, where their subduction disappears and the related accretionary prism vanishes. The slab retreat of the Apennines generated a bending of the downgoing lithosphere, determining subsidence, particularly evident in the Po basin.

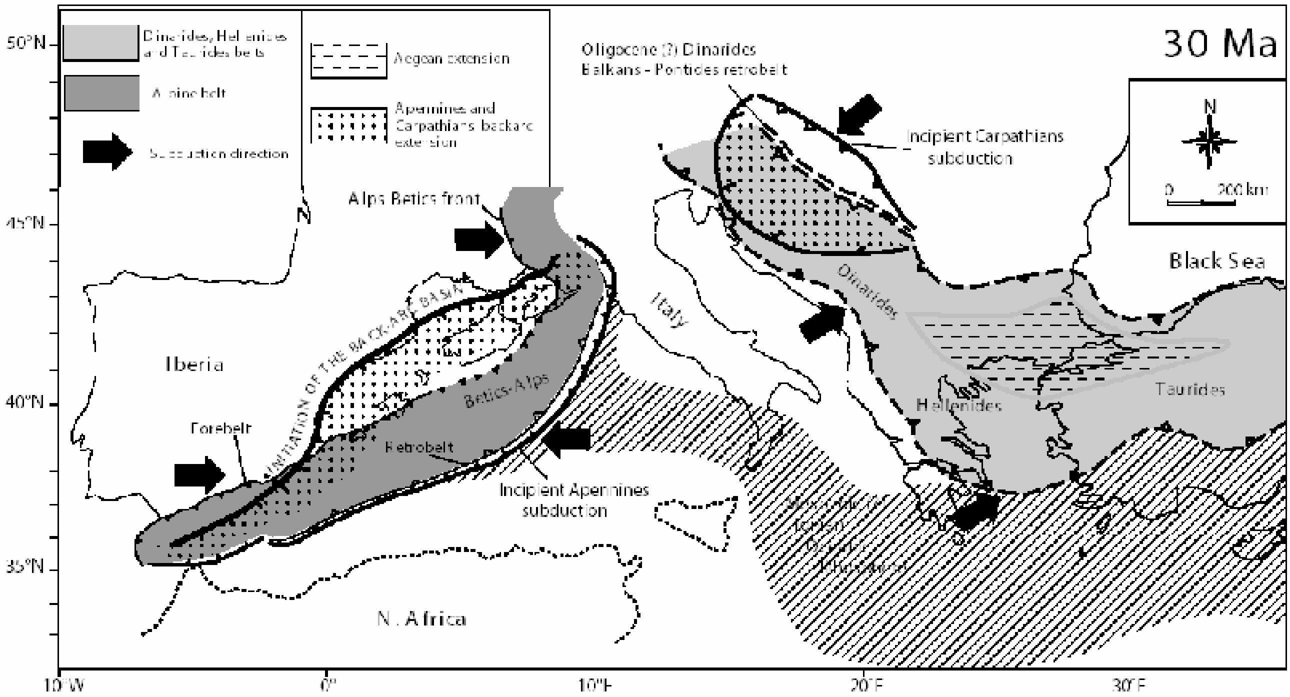

Fig. 8 - Paleogeodynamics at about 30 Ma. The location of the subduction zones is controlled by the Mesozoic paleogeography. The Alps-Betics formed along the eastward directed (SE-dipping) subduction of Europe and Iberia underneath the Adriatic and Mesomediterranean plates. The Apennines developed along the Alps-Betics retrobelt, where oceanic or thinned pre-existing continental lithosphere was present to the east. Similarly, the Carpathians started to develop along the Dinarides retrobelt (i.e., the Balkans). The fronts of the Alps-Betics orogen are crosscut by the Apennines-related subduction backarc extension (after CARMINATI & DOGLIONI, 2004).

Following the foreland regional monocline of the northern Apennines, the bending can be traced at least 240 km away from the Apennines ridge, for example from Bologna to Friuli in northeast Italy. The long-term natural subsidence of Venice can be ascribed to this process (CARMINATI *et alii*, 2003). The Apennines subduction-related Adriatic plate flexure produces a subsidence component in the Central and Southern Alps, which counteracts the generalized uplift of the orogen related to the alpine tectonics. This is testified by the burial of the Alpine front in the western Southern Alps, beneath the Po basin. Moving eastward where the Apennines bending is lower and the Alps strike more oblique to the Apennines, the Southern Alps front is outcropping and the first foothills correspond to the structural Alpine front (DOGLIONI, 1993). This observation shows how in the same area more than one geodynamic field can interact. 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 sub-aerially eroded due to the Dinarides uplift, and later subsided and partially onlapped by the Apennines foreland evolution.

CONCLUSIONS

Alps and Apennines represent two end members of orogens and related subduction zones. The most relevant variation in the two belts is the location of the basal décollement. In the Alps, the basal decollement is very deep, involving the whole basement both in the hangingwall and footwall plates and the lithospheric mantle of the Adriatic upper plate. On the contrary, in the Apennines the Adriatic -Ionian-African lower plate is involved by the décollement only in the upper crust, i.e., sedimentary cover and locally the very top of the crystalline basement, and most of the foreland lithosphere is subducted. In the Apennines, there is not an upper converging plate (as a consequence the term collision should be abandoned), and the accretionary prism is mainly composed of rocks scraped off from the top of the downgoing plate.

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 (Fig. 9). In fact, beneath the Apennines, the slab of the Adriatic lithosphere is continental and nevertheless is very steep (PIROMALLO & MORELLI, 2003). The contrasting characters among the two orogens recall the differences reported at the Earth scale between subduction zones following or opposing the “eastward” undulated mantle flow (DOGLIONI *et alii*, 1999b) inferred from the hotspot reference frame (e.g., the net rotation of the lithosphere of GRIPP & GORDON, 2002). An eastward mantle flow in the Tyrrhenian Sea encroaching the

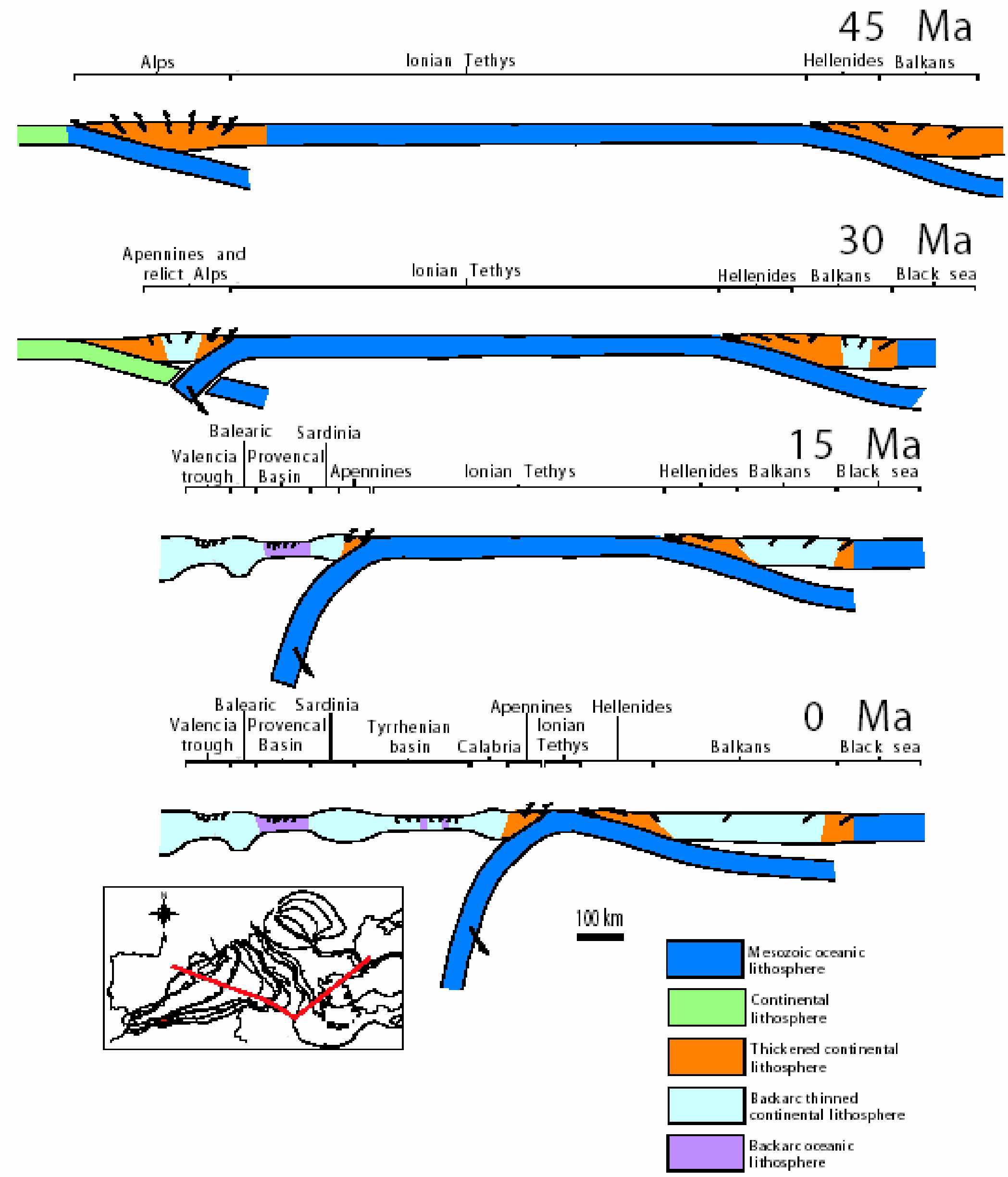

Fig. 9 - During the last 45 Ma, the evolution of the Mediterranean along the trace shown in the map is the result of three main subduction zones: i.e., the early E -directed Alpine subduction; the Apennines subduction switch along the Alps retrobelt; the Dinarides-Hellenides subduction. The last two slabs retreated at the expenses of the inherited Tethyan Mesozoic oceanic or thinned continental lithosphere. In their respective hangingwalls, a few rifts formed as backarc basins, progressively younger toward the subduction hinges. The slab is steeper underneath the Apennines, possibly due to the W -ward drift of the lithosphere relative to the mantle (after CARMINATI & DOGLIONI, 2004).

Apennines slab can be inferred by shear wave splitting (MARGHERITI *et alii*, 2003).

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 there is the real Apennines accretionary prism. The Apennines slab retreat affected most of the central-western Alps generating a subsidence partly counteracting the alpine uplift.

ACKNOWLEDGMENTS

We dedicate this paper to Enzo Locardi, who spent his life trying to understand the Italian geology. We are grateful to Uberto Crescenti, Rosalino Sacchi and Massimo Santantonio for inviting us to contribute to this volume on the geology of Italy. Discussions with Sabina Bigi, Fabrizio Innocenti, Federica Lenci, Giuliano Panza and Angelo Peccerillo and the lost friend Giampaolo Pialli were very much appreciated. Some figures were drawn using the GMT software (WESSEL & SMITH, 1995). Research supported by ASI 2002.

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