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**SPECIAL ISSUE 1 : A showcase of the Italian research in petrology: magmatism in Italy**

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# Some remarks on the geodynamics of the Italian region

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ABSTRACT. — In this paper we present geological and geophysical data which constrain the Tertiary and Quaternary evolution of the Italian region, relevant to the interpretation of the genesis of magmatism in the frame of the geodynamic processes. GPS results show that, at the longitude of Sicily, the African approaches the Eurasian plate at a velocity of about 5 mm/yr in a NW direction. Furthermore, data show that the Adriatic foreland presently moves independently from the African plate. Geodetic and seismic data show that NW-SE oriented extension is the main active tectonic process in the Apennine chain.

Relative and absolute motions of the Africa and the Eurasia plates indicate several hundred kilometers of convergence since the early Tertiary, in the central Mediterranean. This convergence has been achieved by northwestward dipping subduction of the African plate. The main present-day geodynamic feature of the Italian region is represented by seismicity on a well defined Benioff zone, which reveals a still active process of subduction from the Ionian foreland below the Calabrian Arc and Tyrrhenian Sea. This slab is the result of a NW directed long running subduction process active since the Tertiary, which consumed the Ligure oceanic basin first, then a small fragment of the Apulian continental lithosphere, and finally most of the present-day Ionian lithosphere, whose subduction is still ongoing.

We also suggest that the lateral break-off of the Ionian subducting lithosphere could allow lateral astenospheric flow above the subducted plate either from the Apulian plate and from the Sicily Channel-western Sicily.

RIASSUNTO. — Nel presente lavoro viene ricostruita l'evoluzione tettonica dell'area italiana durante il Terziario ed il Quaternario. I dati presentati costituiscono vincoli di primo ordine per l'interpretazione geodinamica del magmatismo nell'area italiana. I dati GPS mostrano che, alla longitudine della Sicilia, la placca africana si muove verso NW ad una velocità di circa 5 mm/a rispetto a quella euro-asiatica. I dati mostrano anche che l'avampaese adriatico si muove attualmente in maniera indipendente dall'Africa. I dati geodetici e sismici dimostrano inoltre che nell'area appenninica il principale processo tettonico in atto è costituito da una estensione orientata NE-SW. Le ricostruzioni cinematiche di Africa ed Eurasia, basate sia sulla cinematica relativa tra le due placche, che sulla cinematica assoluta rispetto ai punti caldi, concordano nell'evidenziare nel Mediterraneo centrale una convergenza di alcune centinaia di chilometri durante il Terziario. Questa convergenza è stata accomodata da processi di subduzione, le cui evidenze sono ben riconoscibili dai dati di tomografia sismica.

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Il principale processo geodinamico attivo nell'area italiana è rappresentato dalla subduzione della litosfera ionica al di sotto dell'Arco Calabro e del Tirreno meridionale. L'estensione della placca subdotta, ben definita dall'andamento della sismicità profonda e dalle immagini di tomografia sismica, e i principali indicatori geologici (metamorfismo di HP/LT, e sviluppo dei bacini di avanfossa e di retroarco) suggeriscono che i processi di subduzione sono stati attivi in maniera continua durante il Terziario.

KEY WORDS: *Geodynamic, central Mediterranean, subduction, back-arc basin, present-day kinematics, volcanism.*

## INTRODUCTION

The present-day structure of the Italian region derives from the convergence of Africa and Eurasia. Over the Tertiary, Africa has been slowly converging toward stable Eurasia at about 1-2 cm/yr on average, and the total convergence can be estimated in 400-500 km in central Mediterranean (Dewey *et al.*, 1989). During that time the Ionian-Adriatic lithosphere continuously subducted toward northwest underneath the Eurasia plate. This process leads to the progressive closure of the intervening Mesozoic oceanic basins of Tethyan domain, with the formation of a complex arcuate orogenic belt (Apennine-Maghrebide belt) and extensional back-arc basins (Ligure-Provençal and Tyrrhenian basin) (Dewey *et al.*, 1989 and references therein) (Fig. 1). Apennine orogeny and back-arc extension were accompanied by the emplacement of plutonic bodies and by a long-standing volcanic activity which continues today. Magmatism represent one of the most impressive features of the Italian geodynamic evolution, and it is characterized by a large petrologic, geochemical and isotopic variability (e.g., Conticelli and Peccerillo, 1992; Conticelli *et al.*, 2002, 2004; Lustrino *et al.*, 2004).

To explain the magma genesis and the most important petrologic and isotopic variations of primary magmas, several different geodynamic models have been proposed. These models mainly consider the role of subduction processes, the possibility of a reversal from an Alpine to an Apenninic subduction during the late Mesozoic and Tertiary, the present-day geodynamic scenario (see the recent reviews by Savelli, 2000, 2002; Peccerillo, 2003).

In this paper we briefly summarize the main features of the Apennines-Tyrrhenian Sea tectonic evolution, starting from the present-day kinematics, as evidenced by GPS data and the geometry and evolution of subduction processes as derived by mantle tomography and deep seismicity. Then we describe the Africa-Eurasia past kinematics, using both relative and absolute motion. The subduction history of the Central Mediterranean is then described using first order geodynamic markers such as HP/LT metamorphism, foredeep migration and back-arc basins opening. These features can be used as proper constraints for the geodynamic interpretation of the Tertiary and Quaternary magmatism in the Italian region.

## THE PRESENT-DAY KINEMATICS OF THE ITALIAN REGION

The relative Eurasia-Africa angular velocities (as described by the Eulerian pole of rotation estimated using various geological and active tectonic features averaged over the last 3 My; DeMets *et al.*, 1994), show that, at the longitude of Sicily, the African approaches the Eurasian plate at a velocity of about 7 mm/yr in a N10°W direction. The advent of the Global Positioning System (GPS) as the major geodetic tool for geodynamic purposes, now allows to estimate a space-based geodetic Eulerian pole of rotation describing the relative motion between Eurasia and Africa. Fig. 2 shows the velocity vectors predicted by the Nuvel-1A model (e.g., plate motion averaged over the last 3 My; DeMets *et al.*, 1994) and the convergence vectors predicted by the GPS pole of rotation (Sella *et al.*, 2002). In Africa only sites located west of the East African Rift (i.e. that part of the African plate called Nubia;

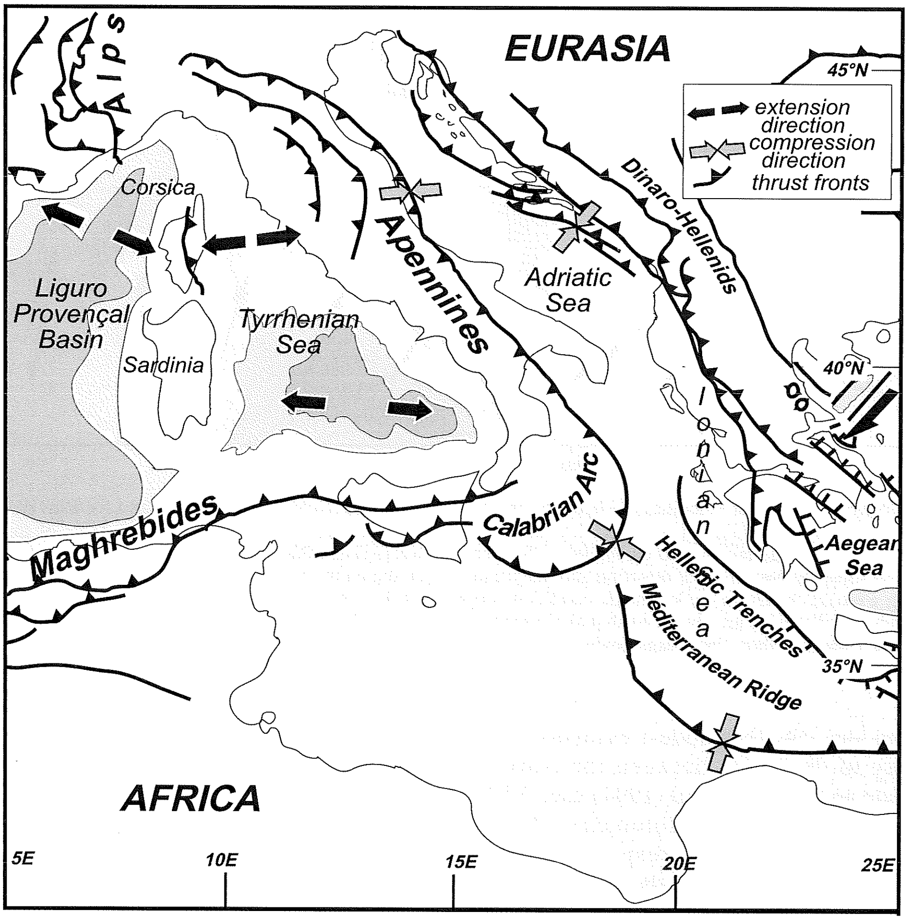

Fig. 1 – Schematic map of the Central Mediterranean area.

McKenzie *et al.*, 1970) have been used for inversion of the pole of rotation. The comparison between the two vectors shows a significant difference in the convergence direction of the plate that may suggest a recent change in the kinematics conditions imposed in the deformation zone (Calais *et al.*, 2002).

Between the Africa and Eurasia converging plates we now observe a diffuse and spatially complex pattern of deformation shown by the scattered distribution of crustal seismicity and the coexistence of extensional and compressional regimes. The existence of areas with a relatively minor seismic activity within this wide boundary between two major plates (Fig. 2), has suggested the hypothesis of kinematically-indipendent microplates between Africa and Eurasia. In this sense the last twenty years have seen the scientific debate mostly concentrated on the existence of an independent microplate in the Adriatic region. Using the direction of slip vectors of large earthquakes around the Adriatic Sea, Anderson and Jackson (1987) proposed an Eulerian pole of rotation in north Italy, predicting extensional deformation along the Apennines and contraction along the Dinarides and the eastern Alps. The major still unresolved issue implied

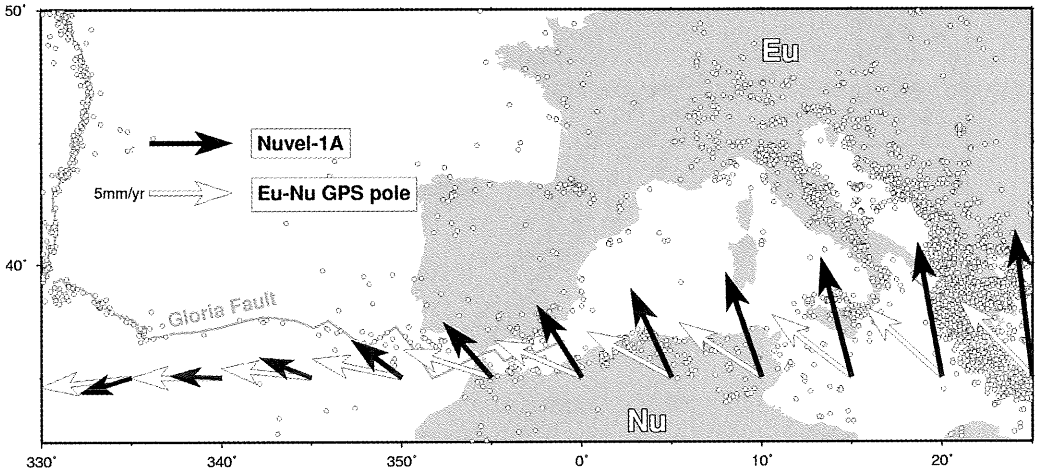

Fig. 2 – Convergence vector velocities predicted by the Nuvel-1A model (*DeMets et al., 1994*) and the REVEL GPS pole of rotation (*Sella et al., 2002).* The Nuvel-1A model is based on various types of observation (rates of mid-oceanic spreading, transform azimuths and earthquake slip vectors) averaging relative plate motion over the last 3 My. A significantly different convergence direction and magnitude are predicted by the two models in the Central Meditterranean suggesting a recent change in the kinematic conditions imposed at the boundary of the deformation zone between the two major plates. Small circles are crustal earthquakes (depth < 50km) with M > 4 occurred in the interval 1980-2003 from the USGS/NEIC catalogue (http://neic.usgs.gov/neis).

in this model was the modest evidence for a boundary to the South between the Adriatic microplate and Africa. Ward (1994) used VLBI (Very-Long Baseline Interferometry) data to estimate velocities with respect to stable Eurasia for various sites in the Italian region. The Matera (MATE) and Medicina (MEDI) sites, located along the Adriatic side of the Apennines, showed 2-6 mm/yr N to NE oriented velocity vectors in agreement with a counterclockwise (CCW) rigid-rotation of the Adriatic region around a pole in northern Italy, close to the one estimated by Anderson and Jackson (1987). The VLBI station in Noto in Sicily also showed a remarkable agreement with the Nuvel-1A Eu-Af convergence direction, suggesting the affinity of southern Sicily with the Africa plate. This study provided one of the first spaced-based geodetic evidence for a Eurasia-Africa independent motion of the sites located in the deformation zone.

Starting from the early '90s, several continuous GPS stations have been installed in the Italian territory. These GPS stations have now extensive and reliable position time-series from which it is possible to rigorously evaluate site velocities in the appropriate reference frame. Fig. 3 shows the GPS velocities of geodetic sites in a reference frame attached to the stable Eurasian plate. This GPS velocity field confirms the Eurasia-fixed N to NE directed motion of the geodetic sites located along the Adriatic side of the Apennines (MATE, MEDI, CAME) and the NW to NNW directed motion of the LAMP (Lampedusa) and NOTO (Sicily). This velocity field also shows very small residual velocities of CAGL (Cagliari, Sardinia) and AJAC (Ajaccio, Corsica), implying their affinity with the Eurasian plate. Because of the coarse geographical distribution of the geodetic sites, this velocity field allows only a preliminary definition of the kinematics of this region and do not provide a precise estimate of strain accumulation across active faults. Preliminary estimates of the strain accumulation across the seismogenic belt running along the Apennines,

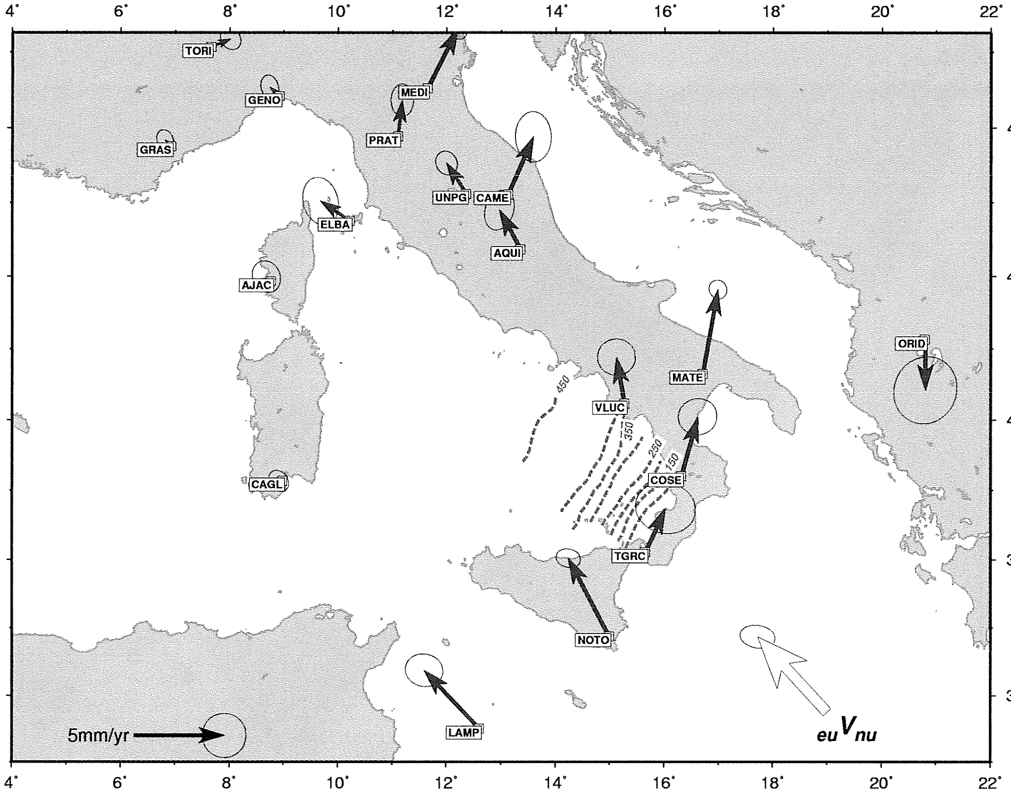

Fig. 3 – GPS velocities relative to Eurasia of continuous stations in Italy and surrounding regions. The velocity estimates are based on linear inversion of position time series for interval longer than 2.5 years. Error ellipse represent the 95% confidence interval. The $_{EU}V_{NU}$ arrow at 19E, 36N is the convergence vector predicted by the GPS pole of rotation inferred from geodetic sites lying on the stable part of the Eurasia (*Noquet et al., 2001*) and Nubia (the African plate West of the East Africa Rift) plates. Dashed lines represent seismicity contours (labelled in km) of the Calabrian-Ionian Wadati-Benioff zone.

where most of the instrumental seismicity is recorded and where the large part of the destructive large-magnitude historical earthquakes occurred, is given by survey-mode GPS studies, characterized by a denser geographical coverage but a larger uncertainty in site velocities. Those studies provided estimates of extension in the Apennines of about 3-6 mm/yr, localized in the area of maximum release of instrumental and historical seismicity (Anzidei *et al.*, 2001; D'Agostino *et al.*, 2001).

The application of the GPS technique has also allowed to map the distribution of 100-yrs time interval crustal strain in the Italian peninsula, through the re-measurements of the national first-order triangulation network (Hunstad *et al.*, 2003) and the calculation of the shear strains in the polygonal regions formed by the vertices of the network (Fig. 4). This work showed a continuous 30-50 km wide belt of active extension along the Apennines crest, where the rate of extension can be evaluated in 3-5 mm/yr in agreement with GPS to GPS comparison on a much shorter time interval. The orientation of the principal axes of the strain tensor showed a good consistency with the direction of crustal extension from

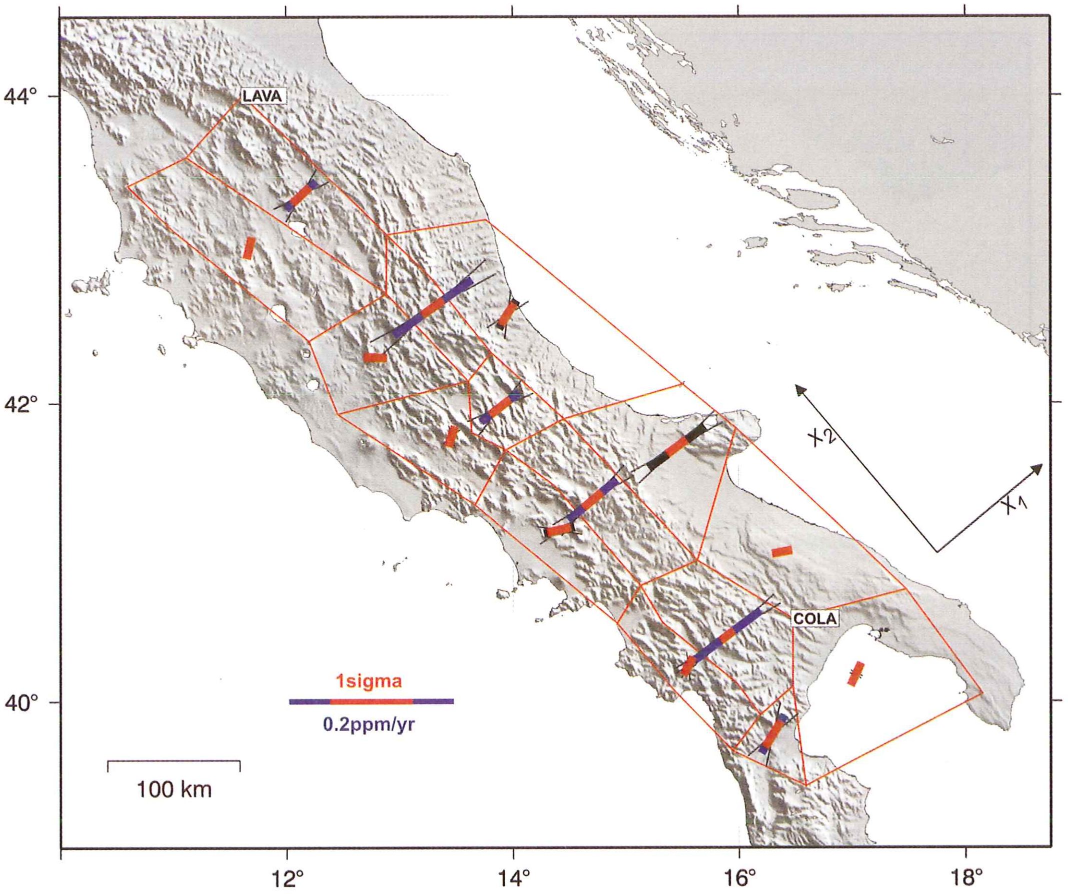

Fig. 4 – Positive (blue bars) and negative (black) shear strain rates for polygonal regions plotted in the direction of maximum and minimum extension respectively (from *Hunstad et al., 2003*). The shear strains have been derived by the GPS reoccupation of the vertices of the first-order Italian triangulation network established by IGM (Istituto Geografico Militare) between 1869 and 1881. The red part of the bars represents 1sigma error. Thin lines define the uncertainty in the azimuth of the principal strain rate axes. The positive shear strains along the Apennines are in agreement with a continuous belt of 3- 5 mm/yr active extensional deformation.

geological and seismological information although the magnitudes of the seismic strain release (evaluated by the summation of the seismic moment of large historical earthquakes with Mw > 6.0) was about 25% of the geodetic rate. This discrepancy comes as no surprise as the amount of seismically-released tectonic strain by large earthquakes (M > 6) is usually only a fraction of the geodetic-measured strain (Jackson and McKenzie, 1988).

## AFRICA-EURASIA KINEMATICS IN THE PAST

Various kinematic reconstructions were proposed for the Mediterranean region to illustrate how Africa converges towards Eurasia. Classical tectonic reconstructions are based on magnetic anomalies in the Atlantic fixing Eurasia as a reference frame (e.g., Ricou, 1994 and references therein). In Figure 5a we plot the displacement of a point carried by the

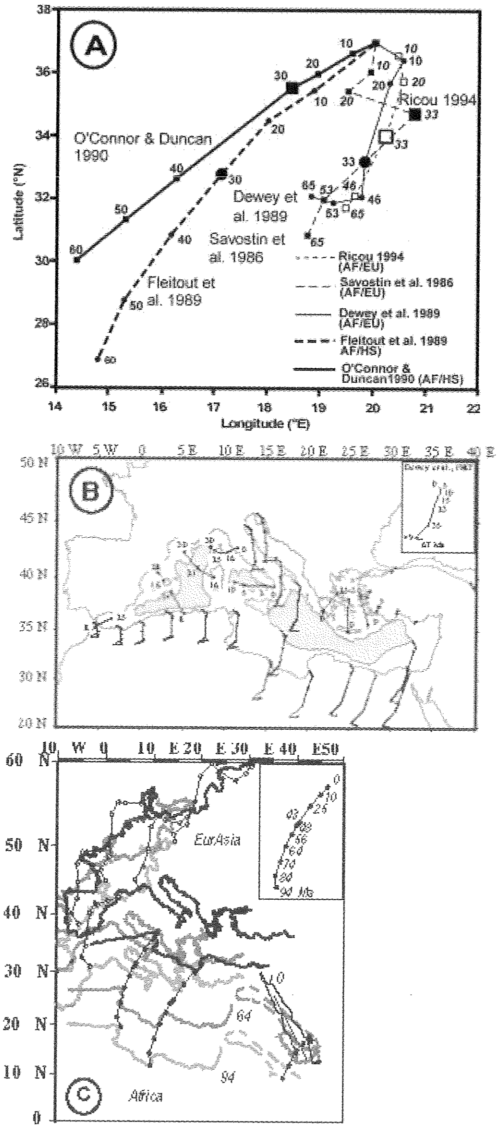

Fig. 5 - A) Trajectories of relative motion according to the models of Ricou (1986); Savostin (1986); Dewey *et al.* (1989). Also shown the absolute motion of a point presently located in the Peloponnese. B) Path of relative convergence over the Mediterranean (including Adria) in the Dewey *et al.* (1989) model over the Tertiary. C) Absolute motion over the last 94 My of Eurasia and African plate calculated using the Gordon and Jurdy (1986) model for the Tertiary and Lithgow-Bertelloni and Richards (1998) model for the oldest time lapses (back to 94 My) (modified after Faccenna *et al.*, 2003).

African Plate now located west of the Peloponnese with respect to Eurasia in different reconstructions during the Tertiary (e.g., Savostin, 1986; Dewey *et al.*, 1989; Ricou, 1994). The direction of convergence is close to N-S during the whole Cenozoic except during the last 10 My because the position of the rotation pole imposes a change from NNW-SSE in the east to WNW-ESE in the west. Despite slight differences in the paleopositions, the different models all lead to a curved path from the start of the Cenozoic to the Present with a slower motion in the Neogene. A decrease in the convergence rate occurs either 35 My ago (Savostin, 1986) or later at 20 My (Dewey *et al.*, 1989; Ricou, 1994) from about 1.5 cm/y to about 0.5 cm/y (Fig. 5a). Figure 5b shows the path and change in the relative motion along the north-African coast of the Mediterranean in the Dewey *et al.* (1989) model and including also the motion that Adria would have if linked to Africa: one may appreciate the increasing rate moving eastward and northward.

The absolute motion of the African Plate has been recently reconsidered based on an earlier study of the Walvis Ridge - Rio Grande Rise hot spot in the South Atlantic (O'Connor and Duncan, 1990). The motion of the same point carried by the African Plate in the Mediterranean region (Fig. 5a) shows a northeastward path and a significant decrease after 30 My from an average velocity of 2.5 cm/yr to less than 1 cm/yr. A more recent paper (O'Connor and le Roex, 1992) revised this interpretation and proposed a smoother curve. A significant decrease of the absolute velocity occurs after 30 My. However this data set is based upon ages of hotspot volcanism on the African plate only and little data constrain the displacement between 30 My and the present. An independent analysis of the African plate absolute motion shows the same velocity decrease after 35 My (Fleitout *et al.*, 1989). A more recent study uses data from hotspots on the African plate as well as from other neighbouring plates (Müller *et al.*, 1993). This study shows the same path but a decrease of the absolute velocity of Africa after 45 My. Burke (1996) has interpreted the increase of African hot spot volcanic activity by 30 My as due to a slower motion proposing that Africa was almost stationary with respect to the underlying asthenosphere after 30-35 My. This interpretation is at variance with the more recent proposition that a single plume has touched the base of the African lithosphere in east Africa and that the partial melting domain was controlled by the topography of the base of the lithosphere creating several distant volcanic regions (Ebinger and Sleep, 1998). To illustrate the way Africa and Eurasia move in a hot-spot reference frame we plot the absolute motion of Africa and Eurasia based on pole of rotation of Gordon and Jurdy (1986) for the Tertiary and Lithgow-Bertelloni and Richards (1998) for the oldest time lapses (back to 94 My); (Figure 5c). Result of this analysis shows that Africa and Eurasia moved to the northeast but the first of about 2300 km and the latter of 1200 km in the last 94 My.

## DEEP STRUCTURE OF THE ITALIAN REGION

The Apennine-Calabrian system is segmented in three arcs characterized by a different pattern of seismicity: subcrustal earthquakes occur down to 90 km depth below the northern Apennines (Selvaggi and Amato, 1992), no subcrustal seismicity is recorded in the southern Apennines (Amato *et al.*, 1993) and deep seismicity is detected only in the Calabrian Arc, along a wide (roughly 200 km) and steep (70°) Benioff plane down to about 500 km (e.g., Anderson and Jackson, 1987; Selvaggi and Chiarabba, 1995). The presence of seismicity on a well defined Benioff zone reveals a direct trace of a still active process of lithospheric subduction from the Ionian foreland below the Calabrian Arc and Tyrrhenian Sea. Further information can be supplied by indirect seismological studies, such as seismic tomography, which are able to give insights into the three-dimensional deep structure of the region, providing images of deviation from an average reference velocity profile. This allows to determine the spatial distribution and lateral dimensions of the fast seismic velocity anomalies, in order to assess the extent of subducted lithosphere, if any, of the aseismic slab and to detect the presence of low seismic velocity areas.

All regional-scale tomographic models detect high seismic velocity features at depth under the Apenninic arc, unanimously interpreted as the signature of subducted lithosphere, and a low velocity anomaly below the Tyrrhenian extensional domain (e.g., Amato *et al.*, 1993; Spakman *et al.*, 1993; Piromallo and Morelli, 2003; Lucente *et al.*, 1999). In Figure 6 we show some images of the recent model PM0.5 of Piromallo and Morelli (2003) to better illustrate some outstanding features. The low velocity anomaly below the Tyrrhenian basin, the Apennines and the Sicily Channel well correlates with the extensional domain.

In the Apennines two major units are recognized: the northern part, in which the signal of westward subducted lithosphere (high seismic velocity anomaly) is particularly clear in the layers between 100-200 km depth (Figure 6a,b,d), and the southern part in which a slow anomaly is instead found at these depths, as a well resolved interruption in the subducted slab, corresponding to the area where no subcrustal seismicity is recorded (Figure 6a,b,e).

The Calabrian slab is characterized by a narrow high velocity tongue (Figure 6a,b) dipping to the NW at a steep angle, lining up with the Benioff plane, widening (Figure 6f) as depth increases, and bending almost to horizontal in the transition zone. At 250 km and deeper, northern and southern Apennines join into a single, wide fast anomaly belt which, through the Calabrian slab, connects with continuity to the north African subducted lithosphere (Spakman *et al.*, 1993; Lucente *et al.*, 1999; Piromallo and Morelli, 2003). The map at 500 km depth of Figure 4c, in the middle of the transition zone, shows that the Apenninic and Calabrian slabs feed, together with the Alpine-Carpathians, Betic-Alboran

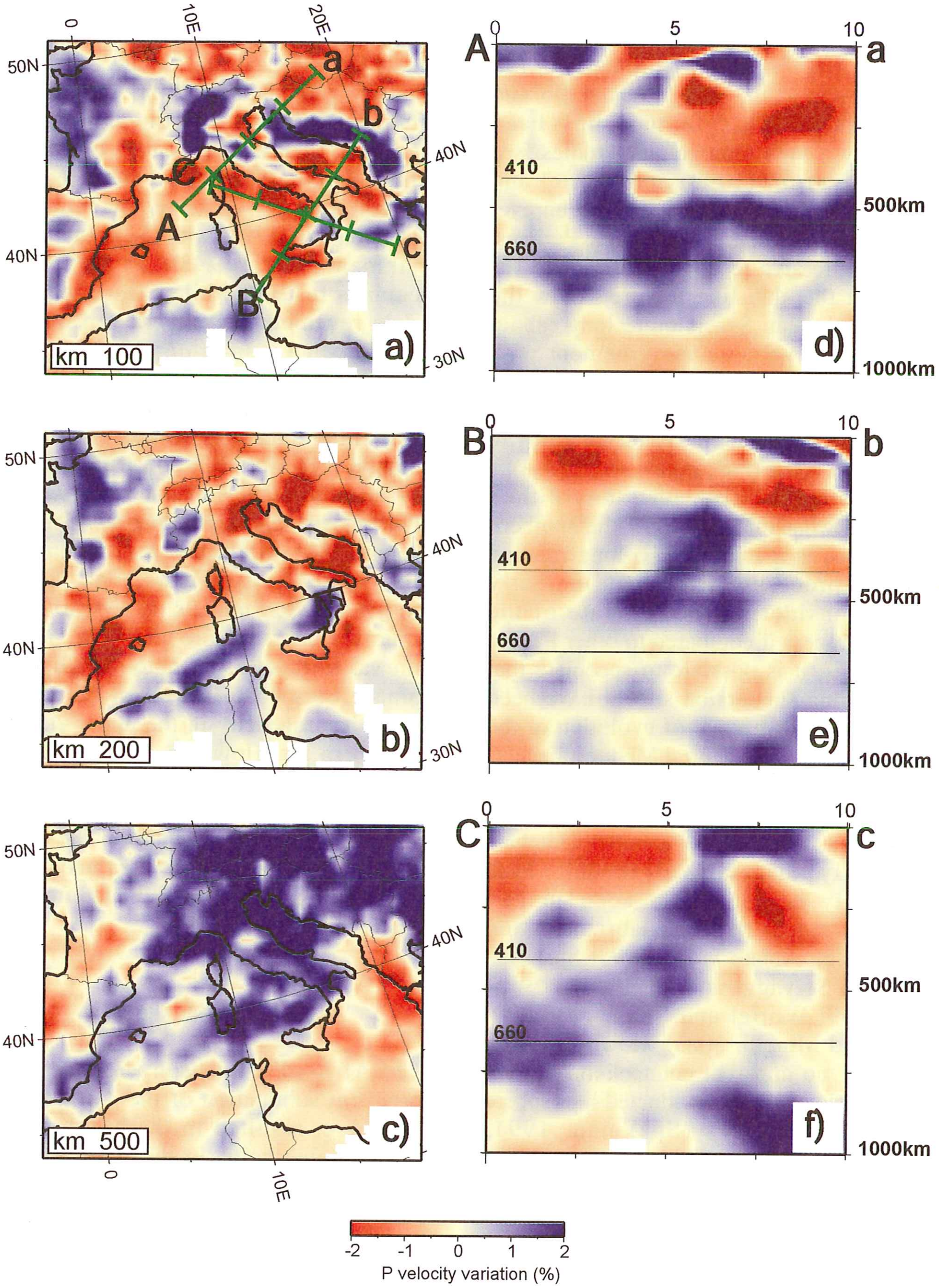

Fig. 6 - a), b), c) Map views of tomographic results at 100, 200 and 500 km and d), e), f) cross-sections from model PM0.5 of Piromallo and Morelli (2003). Velocity anomalies are displayed in percentages with respect to the reference model sp6 (Morelli and Dziewonski, 1993).

and Algerian subductions, a broad positive anomaly, spreading all over central Europe and the western Mediterranean (Piromallo *et al.*, 2001; Faccenna *et al.*, 2003; Piromallo and Morelli, 2003). This feature has been confirmed by all the tomographic studies [see also Lucente *et al.* (1999) and Wortel and Spakman (2000)], and can be used to unravel the gross tectonic structure of the area. Perhaps, the rather impressive result of these images is the fact that the slab-like feature below the southern Tyrrhenian Sea is quite long (about 1200 km). This value is in agreement with tectonic prediction on the amount of subduction for example in Calabria, estimated summing the back-arc extension and the convergence process (Faccenna *et al.*, 2001a).

If this model is valid, one should then consider that what imaged below the southern Tyrrhenian sea is the result of a long running subduction process active since the early Tertiary. Considering the low rate of the subduction process if compared to other Pacific Ocean settings, it is possible to speculate that the NW dipping subduction should have been active since the early stage of evolution of the orogenic process in the central Mediterranean.

Another intriguing aspect is represented by the vertical continuity of the slab below the Apenninic belt, which is still a matter of debate as not clearly imaged by all models. Slab discontinuity is not really seen in any tomographic model in the Calabrian section (Figure 6f; e.g., Amato *et al.*, 1993; Spakman *et al.*, 1993; Selvaggi and Chiarabba, 1995; Cimini, 1999; Wortel and Spakman, 2000; Piromallo and Morelli, 2003). However, some models show no apparent connection between the Adriatic plate and the subducted lithosphere under the Appennines (Spakman, 1991; Spakman *et al.*, 1993). This led Wortel and Spakman (2000) to propose a model of slab detachment: the lateral progression from NW to SE of a tear in the subducting slab, initiated in the vicinity of the Alps. The slab break-off view is not shared by all tomographic studies. The uppermost mantle below the northern Apennines indeed exhibits a continuous high seismic velocity anomaly (interpreted as subducted lithosphere) in most tomographic models (see Figure 6d; Amato *et al.*, 1993; Piromallo and Morelli, 2003; Lucente *et al.*, 1999), considering that the same northern Apenninic cross section (cf. Figure 7c in Carminati *et al.*, 1998) shows enhanced vertical continuity in the more recent model BSE (Bijwaard *et al.*, 1998) with respect to EUR89B (Spakman *et al.*, 1993). In the southern Apennines instead, while earlier teleseismic models revealed the presence of an almost unperturbed (Amato *et al.*, 1993) or slightly positive (Lucente *et al.*, 1999) uppermost mantle, models based on both regional and teleseismic data (Spakman *et al.*, 1993; Piromallo and Morelli, 2003; Bijwaard *et al.*, 1998) and a recent teleseismic study with direct and secondary teleseismic phases (Cimini and De Gori, 2001) all detect a pronounced low velocity anomaly (see Figure 6b-c). Therefore, from most recent models, it appears that the seismic velocity structure along the Apenninic chain varies from a continuous high velocity anomaly below the northern arc to a low velocity heterogeneity in the upper 200 km in the southern arc. However, we should keep in mind that, at present, vertical gaps in the slab as large as 80-50 km or less, cannot be quantitatively resolved by any of the available tomographic models in the area and therefore the slab break-off issue is still far from being solved.

## THE APENNINIC OROGENY

The Africa-Eurasia convergence and the consequent subduction of the Adriatic-Ionian lithosphere, resulted in the building of the Alps-Apennine belts. In the Apennine chain, the main geological signatures of such process are the deposition of thick siliciclastic deposits in the foredeep basins and the HP/LT metamorphism in the internal part of the orogenic wedge (Faccenna *et al.*, 2001a and reference therein). Such features represent useful geological markers to reconstruct the dynamics of the orogenic wedge and of the subduction processes in the Italian region.

In the Apennines, the migration of the orogenic front is marked by the onset of siliciclastic deposits which get progressively younger toward the Adriatic-Ionian foreland. Foredeep basins formed in response to loading of the adjacent thrust belt and by subduction-related processes, and their evolution in time was mainly controlled by the flexural retreat of the subducting lithosphere (Royden *et al.*, 1987). Such process was particularly severe during Plio-Pleistocene times as evidenced by the presence, in the external part of the Apenninic chain, of a foredeep-basin system which contains up to 8 km of Pliocene-Quaternary sedimentary rocks (Royden *et al.*, 1987) (Fig. 7). Thrusting and nappe emplacement were also accompanied by complex rotations of the nappe fronts (e.g., Mattei *et al.*, 1995; Speranza *et al.*, 1999; Gattaceca and Speranza, 2002; and references thereins) forming major arcs convex towards the Adriatic and Ionian foreland, whose geometry mainly refletcs the Mesozoic paleogeographic complexity and the subducting plate configuration.

The onset of siliciclastic deposition occurred in northern Apennines during Late Cretaceous in the oceanic Ligurian domain. The Ligurian oceanic domain was deformed during Late Cretaceous to Early Eocene time, and formed a double vergent accretionary wedge, now outcropping from Corsica to Italian peninsula (Treves, 1984; Carmignani *et al.*, 1994). Starting from the Oligocene onwards, foredeep basins migrated eastward and formed on the top of continental sequences, pertaining to the passive margin of Apulia. Their incorporation into the Apenninic orogenic wedge marked the subduction of Adriatic continental lithosphere underneath Europe. Afterwards, during the Neogene, the foredeep basin further migrated toward the Apulia foreland in front of the migrating thrust nappes. In central and northern Apennines such process is well documented by stratigraphic and seismic studies which precisely constrain the Neogene evolution of the foredeep basins in the front of the Apenninic chain. Foredeep basin formed on the top of progressively more external units, with an eastward migration to reach the site of the Quaternary deposition in the Adriatic foreland, where the foredeep deposition is no more active (Cipollari and Cosentino, 1995, and references therein). During the Quaternary the southeastward rollback of the subducting Ionian plate was expressed in the southern Apennines by the progressive shifting toward southeast (that is parallel to the longitudinal axis of the chain) of the Bradanic foredeep basin (Tropeano *et al.*, 2002, and references therein) and of the Apenninic outer thrust front, which is presently located off-shore, in the Ionian Sea (Doglioni *et al.*, 1999 and references therein).

In the interior of the Apenninic chain, the metamorphic signature associated to the orogenic process and subduction is characterised by a high pressure-temperature ratio (HP/LT) during the metamorphic climax, mostly equilibrated under low-grade blueschist facies metamorphic conditions. The HP/LT metamorphism is widespread in the northern Tyrrhenian region, moving from Alpine Corsica to Tuscany (Jolivet *et al.*, 1998a and references therein), whereas in the southern Tyrrhenian region it is found only in northern Calabria and at the Calabria-Lucania border (e.g., Knott 1987; Monaco and Tortorici, 1995; Rossetti *et al.*, 2001a; 2004 and references therein) (Fig. 7).

The most common blueschist index minerals in the Tyrrhenian region are (Fe, Mg)-carpholite, chloritoid and lawsonite in metasediments, as well as jadeitic-rich pyroxene, Na-amphibole and lawsonite in metabasites. In the northern Tyrrhenian region the P-T estimates were based on the measured (Fe,Mg)-carpholite, chlorite, and chloritoid activities in schist and calcschists from the oceanic-derived Scistes Lustrées Nappe of Alpine Corsica (Fournier *et al.*, 1991; Jolivet *et al.*, 1998a) and Gorgona island (Rossetti *et al.*, 2001b), and the Tuscan continental-derived (Verrucano Group) metamorphic rocks of the

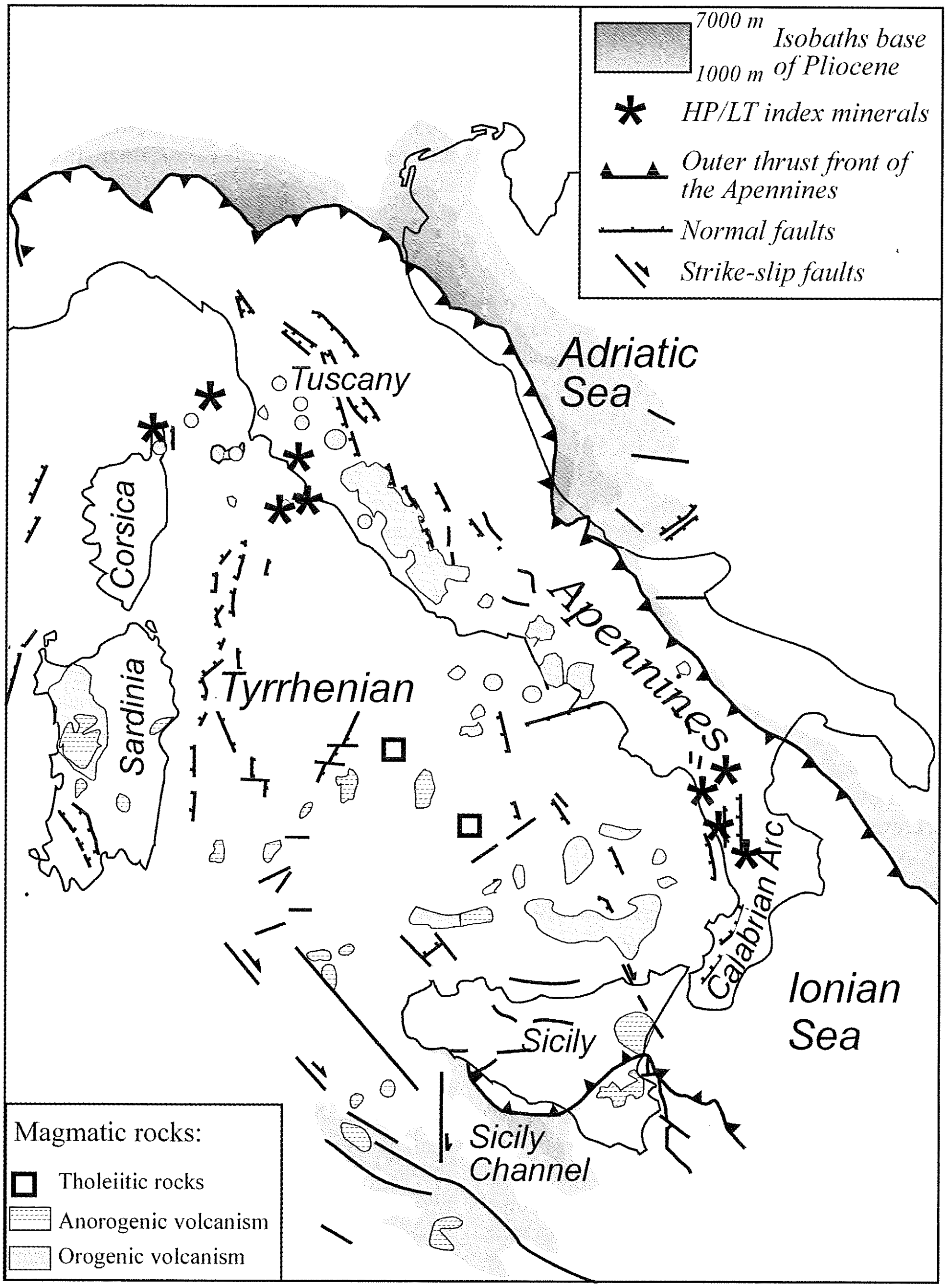

Fig. 7 – Structural sketch of the Tyrrhenian Sea and Apennines (Royden *et al.*, 1987). Cenozoic magmatic rocks according to their inferred dominant magma sources (data from Savelli, 2000, 2002; Conticelli *et al.*, 2002, 2004; Peccerillo, 2003) are also reported.

Argentario (Theye *et al.*, 1997), Giglio Island (Rossetti *et al.*, 1999) and Monticiano-Roccastrada Ridge (Giorgetti *et al.*, 1998). Peak pressure conditions decrease towards the east, from 1.8 GPa (Alpine Corsica) to 0.8 GPa (Monticiano-Roccastrada Ridge), for temperatures between 250 and 450°C. Similarly, ages of this metamorphic event appear to progressively decrease eastwards, from Paleocene-Eocene in Alpine Corsica to the Early Miocene in the Tuscan region ($^{40}Ar/^{39}Ar$ method on syn-metamorphic phengites: Brunet *et al.*, 2000 and references therein).

Exhumation of the HP/LT metamorphic cores resulted in the transposition of the blueschist fabric while the lithostatic pressure was decreasing, with a final re-equilibration in the low-grade, greenschist facies conditions (Jolivet *et al.*, 1998a). The ages of this retrogressive stage are between the Late Oligocene in the Alpine Corsica (Jolivet *et al.*, 1998a) and Middle Miocene in the Tuscan region ($^{40}Ar/^{39}Ar$ method on phengites Kligfield *et al.*, 1986 and references therein) (Fig. 7). In western Tuscany the retrogressive evolution was accompanied by the late emplacement of Pliocene and Quaternary granitoid intrusives within the previously exhumed metamorphic piles.

In northern Calabria, the Alpine orogenic metamorphic signature shows a great variability within the tectonic slices constituting the nappe edifice. Where recorded, the Alpine metamorphism is poliphased, starting from an early high-to-moderate P-T ratio, with a final re-equilibration under low-grade greenschist-facies conditions. In the pre-Alpine continental-derived basement rocks of the Calabrian Complex, the Alpine orogenic overprint occurred in the lowermost levels and under low-grade greenschist to lawsonite-blueschist metamorphic conditions (Rossetti et *al.*, 2001b, and references therein). Peak pressure metamorphic conditions are 0.4-0.6 GPa for temperatures in the order of 300 °C.

The oceanic-derived units reveal a poliphased and heterogeneous metamorphic history (Cello *et al.*, 1991 and references therein). Mafic HP rocks were found either as tectonic blocks embedded within an ophiolitic mélange flyschoid sequence or constituting coherent tracts of an exhumed metamorphic pile, where (Fe,Mg)-carpholite-bearing metamorphic cover is also preserved (Rossetti *et al.*, 2001b). Peak pressure metamorphic conditions are equilibrated under the blueschist-greenschist facies transition or within the blueschist facies of Evans (1990), with P in the range of 0.6-1.2 GPa and T lower than 400 °C.

Orogenic metamorphism is also recorded in the continental-derived Apenninic units, consisting of phyllites and carbonatic rocks and calcareous-dolomitic alternances, of the Triassic to Lower Miocenic San Donato unit. The metamorphic climax was equilibrated under low-grade greenschist up to blueschist facies metamorphic conditions, with pressure ranging from 0.3-0.4 to 1.2 GPa over temperature less than 400°C (Rossetti *et al.*, 2004 and references therein).

There are a small number of studies defining the timing of Alpine deformation and metamorphism using geochronology of metamorphic phases in Calabria. Nevertheless, Tertiary (Eocene to Oligo-Miocene) ages, derived by using different methods on different rock types, have been commonly provided for the Alpine orogenic metamorphism in Calabria (e.g., Schenk, 1980; Rossetti *et al.*, 2001b, and references therein). Fission track (zircon and apatite) data on the Calabrian basement rocks indicate a rapid unroofing of these units from 30 to 18 Ma, confirming the Tertiary age of the main contacts within the nappe pile (Thomson, 1994; 1998). In the San Donato unit, $^{40}Ar/^{39}Ar$ geochronology on syn-kinematic phengites provides ages of 35-38 Ma and 15-20 Ma for the metamorphic peak and the retrogressive stage, respectively (Rossetti *et al.*, 2004).

Based on this scenario, the metamorphic signature of the exhumed HP/LT metamorphic pile exposed in the Apennine chain and Calabria testify for a high P/T ratio during the Tertiary metamorphic climax associated with crustal thickening. The low geothermal gradient (< 15 °C/km) is typical of subduction-related metamorphism, and is similar to those associated to the Alpine-type metamorphic gradients associated to the Thetyan subduction (Jolivet *et al.*, 1998b).

The occurrence of the highly temperature-sensitive (Fe, Mg)-carpholite-bearing parageneses in metapelites provides a major constraint to the thermal conditions during the HP/LT stage, as it is indicative of low-grade metamorphic conditions (temperature not in excess of 450 °C) and its preservation requires cooling or nearly isothermal retrograde paths (Jolivet *et al.*, 1998b). We can therefore infer that low temperature conditions persisted through time within the exhumed metamorphic pile, at least until the deep-seated rock reached mid crustal conditions.

## BACK-ARC EXTENSION

The Miocene-to-Present evolution of the Mediterranean region is characterized by the fast opening of the Liguro-Provençal and Tyrrhenian back-arc basins. Basin spreading was related to the south-eastward retreat of a NW-W dipping Ionian/Adriatic slab, and was progressively accompanied by drifting and rotation of the Corsica–Sardinia and Calabria blocks and formation of new oceanic crust (e.g., Malinverno and Ryan, 1986; Lonergan and White, 1997; Faccenna *et al.*, 2001a; 2004, and references therein).

The Liguro-Provençal basin is a triangular sea located between the Provençal-Catalan coasts and the Corsica-Sardinia block, which opened during Oligo-Miocene times (Burrus, 1984; Seranne, 1999). The Liguro-Provencal spreading took place simultaneously with the eastward drift of the Corsica-Sardinia block, which rotated counterclockwise about a pole located north of Corsica (e.g., Van der Voo, 1993 and references therein). The rifting stage, however, is rather well documented on both Provençal and Sardinia shoulders, where a thick sedimentary pile accumulated between 30 and 21 My (e.g., Seranne, 1999, and references therein). The timing of the Liguro-Provençal basin spreading has been mainly extrapolated by analysis of paleomagnetic data from Corsica and Sardinia. Since the late '60s and during the '70s, several paleomagnetic studies were carried out on the Sardinian rocks (De Jong *et al.*, 1973; Coulon *et al.*, 1974; Edel, 1979; Horner and Lowrie, 1981, and references therein). The data showed two 30° counterclockwise rotation events with respect to Europe occurring during late Mesozoic-early Tertiary and early-middle Miocene times (e.g., Van der Voo, 1993). Recently, new paleomagnetic data (Vigliotti and Langenheim, 1995) seemed to indicate that at 15°-18° Ma, the rotation was not yet completed, whereas Deino *et al.* (2001) confirm that Sardinia started rotating at 21 My, and indicate that the overall rotation was as high as 50°. Rifting and drifting processes in the Corsica-Sardinia were related to the southeastward retreat of the subducting Ionian slab, and were accompanied by arc-related volcanism, which appeared first in Sardinia (~32My) and in Provençe and continued until ~14 My in southwestern Sardinia (i.e., Beccaluva *et al.*, 1985; Lustrino *et al.*, 2004).

After the end of the Corsica-Sardinia drifting, back-arc extension continued in the southern Tyrrhenian Sea (Fig. 1). In this basin oceanic crust formed diachronously in two sub-basins: ~4.3-2.6 Ma in the Vavilov basin and <2 Ma in the Marsili basin (Trua *et al.*, 2002). Seismic, structural and stratigraphic data on the on-shore western Calabria-Peloritani terrane (Kastens *et al.*, 1988; Sartori, 1990; Mattei *et al.*, 2002) suggest that rifting started along the western margin of the southern Tyrrhenian Sea (Sardinian margin) during Serravallian, and progressively migrated south-eastward in the Vavilov (late Messinian-Early Pliocene) and Marsili (Late Pliocene) basins. The overall back-arc opening of the southern Tyrrhenian basin was accompanied by southeastward drifting and clockwise rotation of the Calabria-Peloritani terrane, where the conjugate Serravallian extensional basin outcrops (Mattei *et al.*, 2002).

In the northern Tyrrhenian Sea lithospheric extension caused the formation of Neogene sedimentary basins. N-S to NW-SE oriented extensional basins developed on the previously thickened Alpine crust in the hinterland, contemporary with flexural basins in the foreland (e.g., Kastens *et al.*, 1988) which get younger eastward as well documented by the age of the infilling sedimentary sequences. In the westernmost Tyrrhenian sea these sedimentary sequences are Lower Miocene in age and are characterized by N-S trending east-dipping normal faults (Bartole, 1995) while they are Pleistocene in age in the Umbrian region where extensional tectonics is presently active and most of the normal faults strike NW-SE and dip towards the west (Jolivet *et al.*, 1998a). The N-S/NW-SE oriented Messinian-Pleistocene extensional basins of the northern Tyrrhenian margin did not undergo any vertical axis rotation (Sagnotti *et al.*, 1994; Mattei *et al.*, 1996). These data, together with the progressive migration of the age of the extensional processes toward the Apenninic chain, suggests that extension in northern Tyrrenian Sea was not driven by a rigid counterclockwise rotation of the Italian peninsula about a pole located to the north.

## GEODYNAMIC CONSTRAINTS FOR THE MAGMATISM GENESIS AND EVOLUTION

Magmatism in the Tyrrhenian-Apennine systems begun during Miocene lasting to present time with an eastward migration with time, following the eastward migration of the Apennine Chain (Savelli, 2000, 2002, and references therein). During this time elapse calc-alkaline, shoshonitic, alkaline potassic and ultrapotassic magmas with orogenic signatures have been outpoured (Conticelli and Peccerillo, 1992; Conticelli *et al.*, 2002, 2004, and references therein). Coevally on the Sardinia-Corsica block Oligicene to Miocene calc-alkaline magmatism was exausting, but withinplate anorogenic, tholeiitic to Na-alkaline magmas were outpoured (e.g., Lustrino *et al.*, 2004, and references therein).

Nowdays there is a general agreement on the orogenic nature of the magmatism found along the eastern border of the Tyrrhenian basin (e.g., Peccerillo, 1985, 1993; Conticelli *et al.*, 2002, 2004). Open debate is mainly focus the oceanic/continental nature of the subducted plate, the age, the extent and the polarity of subduction processes (see the recent reviews by Peccerillo, 1999; 2003; Savelli, 2000, 2003). In addition, an isotopic geographic polarity is found starting from Southern Latium to Vulture and Aeolian Arc, due to an increasing withinplate component Southward (e.g., Conticelli *et al.*, 2002, 2004, and references thereins). This characteristic is interpreted as the results of either i) lateral inflow of foreland mantle material into the mantle wedge due to subduction rollback (Peccerillo, 2001; Trua *et al.*, 2002), or ii) with an hot mantle plume piercing the subducted slab in the center of the Tyrrhenian basin (e.g., Gasperini *et al.*, 2002; Bell *et al.*, 2003).

Africa-Eurasia plate motions, both in relative and absolute reference frames, indicate several hundreds kilometers of convergence in the central Mediterranean since about 90 My. The slab geometry, as evidenced by seismic tomography, together with subduction-related metamorphism and foredeep migration suggest a long running subduction process active since the early Tertiary. This process is still ongoing below the Calabrian Arc and Tyrrhenian Sea and has been responsible for the Tertiary and Quaternary orogenic magmatism in the Italian region (e.g., Peccerillo, 2003) (Fig.7).

Since the early '70 several Authors hypothesized a possible consumption of the Ligurian oceanic basin during an E-dipping subduction process, with an inversion of the subduction polarity during the Tertiary (Boccaletti and Guazzone, 1970; Boccaletti *et al.*, 1971). This hypothesis, which considers the Northern Apennines as the Southern continuation of the Western Alps, is mainly based on the westward vergence of the Ligurian nappes (Abbate and Bortolotti, 1984 for a review), or on global plate-tectonics models (Doglioni, 1991). On the other hand, contrarily of what has been observed in the Western Alps, no evidences of eastward dipping subduction are imaged by seismic tomography in the Central Mediterranean region (Fig. 6), and the progressive eastward migration of the HP/LT metamorphism and foredeep basins are fully consistent with a long-running westward dipping subduction, (Faccenna *et al.*, 2001b and references therein).

Concerning the oceanic\continental character of the subducted plate, some differences can be observed from the northern Apennines to the Calabrian arc, which reflect the complex geometry of the Mesozoic paleogeographic domains of the northern African margin. In the Calabrian arc the tectonic evolution of HP/LT metamorphic units suggests that subduction consumed the Ligurian oceanic basin first, then a small fragment of the Apulian continental lithosphere, and finally most of the present-day Ionian lithosphere (Cello and Mazzoli, 1999; Rossetti *et al.*, 2001a).

In northern Apennines subduction first caused the closure of a small Jurassic oceanic basin (Ligurian ocean), which intervened between the Africa and the European continents (i.e., Dercourt *et al.*, 1986). This process is testified by the formation of foredeep basins and HP/LT metamorphism in the Ligurian nappes, widely recognised in Corsica, in the Tyrrhenian Sea, and in Tuscany (Jolivet *et al.*, 1998a and reference therein). In the northern Apennines the nature of the subducting plate changed during the Oligocene, when the continental Adriatic lithosphere entered the trench, and started to subduct below Europe. Subduction of the Adriatic lithosphere caused the progressive incorporation of continental rocks into the Apenninic orogenic wedge. This process is probably still active in the outer northern Apennines, as suggested by subcrustal seismicity and compressional focal mechanism.

In Fig. 3 the seismicity contours of the Calabrian-Ionian slab are reported as evidence of the small lateral extent of this active slab. This narrow slab is bounded to northeast and southwest by two regions characterized by well defined low velocity zones, which correspond to the southern Apennines and the Sicily Channel -western Sicily. These low velocity zones suggest the presence of lateral discontinuities in the upper portion (<250 km) of African-Adriatic slab, which correspond to the lateral boundaries of the oceanic Ionian lithosphere, which passes to the African and Adriatic continental ones toward southwest and northeast, respectively (Fig. 6a,b). These breaches could allow the lateral inflow of astenospheric mantle channelized into the wedge above the subducting Ionian Sea lithosphere (Gvirtzman and Nur, 1999; Faccenna *et al.*, 2004), giving rise to mantle sources formed by a mixture of intraplate and slab-derived components (Peccerillo, 2001).

## SUMMARY

In this paper we report geological and geophysical constraints on the Tertiary and Quaternary geodynamic evolution of the Italian region. The long-term kinematic history of the Africa and the Eurasia plates indicates several hundred kilometers of convergence since 94 My, in the Central Mediterranean, which trapped an assemblage of small undeformable continental blocks. Convergence has been absorbed by westward to northwestward dipping subduction of the African plate, which is still ongoing under the Calabrian arc, as testified by deep seismicity and seismic tomography data, and by collision zones.

The present-day kinematics in the Italian region is well described by GPS data. Results show that, at the longitude of Sicily, the African approaches the Eurasian plate at a velocity of about 5 mm/yr in a NW direction. Furthermore, data show that the Adriatic foreland presently moves independently from the African plate, from which it separated, and that, as suggested by seismicity, NW-SE oriented extension is the main active tectonic process in the Apenninic chain.

The westward dipping subduction polarity during the Tertiary is suggested by first order geodynamic markers, such as the progressive eastward migration of the foredeep basins and of the HP/LT metamorphism in Corsica, Calabria and in the northern Tyrrhenian sea. Conversely, in the Apenninic chain no evidences of a southward continuation of the western Alps eastward dipping subduction can be recognized on the base of first order geological data and seismic tomography. Therefore, a possible reversal from an eastward to a westward dipping subduction in the Apennines during the Tertiary has to be considered unlikely at the present state of knowledge.

According to seismicity and seismic tomography data, the Calabrian slab is characterized by a continuous, narrow high velocity tongue dipping to the NW at a steep angle. On the other hands, seismic tomography models suggest the presence of lateral discontinuities in the upper portion (<250 km) of the African- Adriatic subducted slab. These discontinuities could allow lateral inflow of astenospheric mantle from the foreland channeled into the mantle wedge above the subducting Ionian Sea lithosphere, either from the Apulian plate and from the Sicily Channel and Sicily.

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