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Subduction and back-arc extension in the Tyrrhenian Sea
Subduzione e distensione di retro-arco nel Mar Tirreno

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ABSTRACT - This paper is a synthesis of the work we have done in the Central Mediterranean subduction zone. Our effort is to tie together the geological signature of the subduction process and the plate kinematics with the deep images of the mantle to unravel a tectonic model at the scale of the Central Mediterranean mantle. This model is tested by means of laboratory experiments where we simulated the retreat of subducting slab sinking inside a stratified material. Geological data have been mainly collected in the Calabrian orogenic wedge where we can have preserved the trace of the oldest subduction event and in the back-arc region where we can infer the amount of retreat of the Calabrian trench. The amount of subduction in time has been reconstructed by estimating the amount of convergence from plate kinematics model with the amount of back-arc extension. These data have been used to propose a tectonic scenario and to backtrack the evolution of the Calabrian slab, starting from the present-day tomographic images. Finally the tectonic scenario is tested by means of laboratory experiments.
Our results give a dynamic picture of the evolution of the back-arc basins, suggesting that the kinematics and the dynamics of the central Mediterranean system is driven by the subduction of the land-locked oceanic lithosphere and that the episodic and intermittent phase of extension that produced the opening of the Liguro-Provençal first and of the Tyrrhenian basin, after, is the result of the interaction between the subducting slab and the 660-km discontinuity in a restricted convecting mantle.

KEY WORDS: central Mediterranean mantle, subduction kinematics, analogue modeling, episodic back-arc extension

RIASSUNTO - Questo lavoro rappresenta una sintesi del lavoro effettuato sull'evoluzione della zona di subduzione del Mediterraneo centrale. A tal fine sono stati integrati dati geologici, cinematici e sismologici. Il modello prodotto è stato testato utilizzando esperimenti di laboratorio a scala del mantello dove viene simulata l'evoluzione di un piano di subduzione all'interno di un mezzo viscoso stratificato.
I dati geologici analizzati riguardano le unità metamorfiche affioranti in Calabria, dove sono meglio preservate le testimonianze del cuneo orogenico, e nei bacini di retro-arco dove è possibile ricostruire la quantità di estensione e di arretramento della cerniera della placca in subduzione. Questi ultimi dati, sommati ai dati riguardanti la quantità di convergenza delle placche Africa-EurAsia hanno permesso di stimare la quantità di subduzione nel tempo. Questi valori sono stati confrontati con le immagini del modello tomografico al fine di produrre una paleoricostruzione terziaria del piano di subduzione. I risultati di questo esercizio, sono stati poi confrontati con quanto ottenuto in laboratorio.
Il modello proposto suggerisce che l'evoluzione del Mediterraneo Centrale è dinamicamente congruente con un modello di arretramento di una placca in subduzione. In particolare il discontinuo processo di arretramento della placca in subduzione, producendo l'apertura dei due bacini di retro-arco distinti (Liguro-Provenzale e Tirrenico) viene messo in relazione con l'interazione tra la placca in subduzione e la discontinuità posta a 660 km di profondità in un quadro convettivo ristretto al mantello superiore.

PAROLE CHIAVE: mantello Mediterraneo centrale, cinematica della subduzione, modelli analogici, estensione di retro-arco episodica

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1. - INTRODUCTION

The origin of backarc basins represents an important task in plate tectonics. Their formation is somehow problematic as extensional processes and creation of new oceanic crust develop just to the back of convergent margins where oceanic lithosphere is consumed and digested into the mantle. Exploration of backarc basins around the globe, especially along the Western Pacific margin, allow us to define their peculiarities and differences if compared to oceanic basins. One of the striking characteristic of backarc basins is represented by their ephemeral life, which is generally in the order of 1-3 108 years. In some cases, namely to the back of the Izu-Bonin, the Marianas and the Tonga trench, backarc extensional process occurred episodically and the locus of extension jumps trenchward after quiescent periods of stasis. This represents the most enigmatic aspect of backarc extension and give us a complicated image of what can be the driving mechanism for backarc extension. Apart for the classical, Western Pacific examples, other basins around the world have been interpreted in terms of backarc extension. The Aegean and the Tyrrhenian Sea (fig. 1), for example, have been interpreted in terms of backarc extension (MALINVERNO & RYAN, 1986; KASTEN *et alii*, 1988; PATACCA *et alii*, 1990; SARTORI, 1990; DOGLIONI, 1991; ROYDEN, 1993; FACCENNA *et alii*, 1996; GIUNCHI *et alii*, 1996; JOLIVET & FACCENNA, 2000).

If this is the case, they represent rare examples of active back-arc basins developed on continental lithosphere. The Tyrrhenian basin, in particular, has been deeply explored and studied during several geophysical and geological surveys. The huge amount of data available at present on the Tyrrhenian basin structure and on its evolution makes it a unique candidate to analyse plate tectonic processes such as the ones that cause the internal dynamics of a back-arc system.

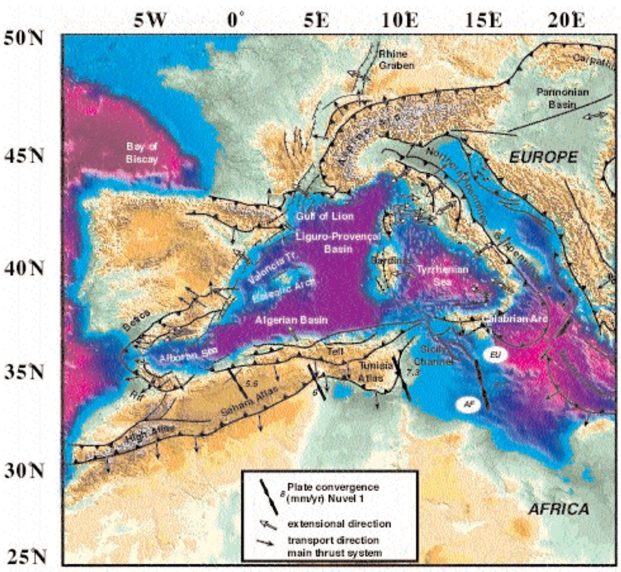

Fig. 1 - *Tectonic map of the western Mediterranean region. Sense of transport along main thrusts fronts (black arrows) and along the main extensional detachments (white arrows) are shown (see text for references).*

Here, we address the problem concerning the origin of the Tyrrhenian Sea, testing the hypothesis that its formation is related to the retreat of the Calabrian subducting slab. In this hypothesis, in fact, some questions still need to be answered. For example, it is not clear why did extensional processes take place in an overall convergence regime produced by the Africa-EurAsia relative motion or why did back-arc extension in the central Mediterranean create two different basins which intermittently opened reaching high rates of extension (up to 5-6 cm/y).

Our contribution to the problem is based on a multidisciplinary approach where the internal dynamics of the subduction-back-arc system is analysed using surface geological data in the back-arc region and subduction-accretionary wedge, tomography images at the scale of the mantle below the central Mediterranean, and tectonic reconstructions. The result of this different data set is integrated to set up laboratory experiments at the scale of the mantle with the aim to physically test the different models and hypothesis.
Our results give a dynamic picture of the evolution of the back-arc basins, suggesting that the kinematics and the dynamics of the central Mediterranean system is driven by the subduction of the land-locked oceanic lithosphere and that the episodic and intermittent phase of extension that produced the opening of the Liguro-Provençal first and of the Tyrrhenian basin, later, is the result of the interaction between the subducting slab and the 660-km discontinuity.

In this paper we synthesise the work we have done during the last years, first introducing the geological data, then the tomographic images at upper mantle level. Afterwards, on the base of a revised tectonic reconstruction, we will unravel the kinematics of the subducting system that will be tested using laboratory experiments.

2. - THE CENTRAL MEDITERRANEAN SUBDUCTION ZONE: GEOLOGICAL STRUCTURE

Three distinct domains can be distinguished in the Central Mediterranean subduction zone. The inner orogenic domain, outcropping in northern Apennines and Calabria, which is constituted by polymetamorphic units and represents the oldest trace of a subduction process. It separates the extensional back-arc domain (Tyrrhenian, Liguro-Provençal) from the external domain, where slices of the sedimentary cover derived from the paleomargins are piled up (Apennines, Magrebides). Over the whole subduction zone, the extensional back-arc domain deforms contemporaneously with the external domain. Information concerning the evolution and the kinematics of the subduction system of the Tyrrhenian region can be found in the back-arc domain, which gives indications on the kinematics of subduction (amount and rate of trench retreat) and on the inner orogenic wedge that can give us information about the age of the oldest event and of its geothermal gradient. The external portion also furnishes a lot of information concerning the way the subducting plate is flexed, but often the oldest trace of subduction are digested inside the subduction zone.

2.1. - The backarc system

Figure 2 shows a cross section at the scale of the lithosphere running from the Gulf of Lyon to Calabria. The cross section cuts across the two basins parallel to the direction of extension. In the upper panel of the figure 2 the ages of the syn-rift deposits of the sedimentary basin and of the main magmatic event is projected.

In the Provençal region, an older Late Eocene phase of extension related to the central european rift system is recorded (Seranne, 1999). Extension related to the opening of the Liguro-Provençal basin initiated probably during the Late Oligocene (Cherchi & Montadert, 1982; Gorini *et alii*, 1994; Seranne, 1999) within a Hercynian continental crust, except in the Gulf of Lions, which was previously affected by external Pyrenean thrusting. Extension developed at the back of a NW dipping subducting oceanic lithosphere, as attested by the presence of a volcanic arc (basaltic-andesitic suites, 32-34 Ma to 13 Ma) erupting along the Sardinian and Provençal margins (Beccaluva *et alii*, 1989, and references therein) (fig. 2).

The age of the syn-rift deposits, located along the western Sardinian and Provençal margins, ranges from the Oligocene to the Aquitanian (Cherchi & Montadert, 1982; Gorini *et alii*, 1994). From the late Aquitanian, post-rift deposits unconformably overlie the syn-rift sequence (Gorini *et alii*, 1994; Seranne, 1999), and oceanic crust (probably Burdigalian in age;) was emplaced during the 25°-30° counterclockwise drifting of the Sardinia-Corsica block (Van der Voo, 1993). In southern Sardinia the rate of drifting, according to paleogeographic reconstruction (Burrus, 1984) and to the age of rotation proposed by , can be estimated in the order of 4-5 cm yr^{-1}. As a result, the basin is characterized by oceanic crust within the central abyssal plain surrounded by narrow (except for the Gulf of Lions) older sedimentary basins (fig. 2). Based on this geometry and the pattern of magnetic anomalies the existence of a mid-oceanic ridge has been proposed (Burrus, 1984) even if the characteristics of a spreading ridge relief has not been observed on deep seismic profiles (de Voogd *et alii*, 1990).

In the Tyrrhenian basin, syn-rift deposits are progressively younger (10-12 Ma to 5 Ma) from Sardinia margin towards the Vavilov basin (Kasten *et alii*, 1988; Sartori, 1990). The age of first syn-rift deposition in the Sardinia margin, however is still uncertain, as a Tortonian-Serravallian unit (B3.2 seismic unit, Sartori *et alii*, 1990), has been interpreted as a pre- or syn-rift unit (Mattei *et alii*, 2002). The conjugate, drifted margin of Sardinia is the Calabrian block, where the syn-rift deposits of the Amantea basin are composed by Serravallian coarse-grained conglomerates and sandstone (Mattei *et alii*, 2002). On the western side, the initial rifting phase is followed by an E/ESE migration of the locus of extension and magmatism (fig. 2). The average velocity of extension is in the order of 5-6 cm yr^{-1} (Patacca *et alii*, 1990; Spadini *et alii*, 1995). Formation of oceanic crust occurred since 5 Ma in two separate and rather small basins (Bigi *et alii*, 1990) during the drifting of the Calabria block (figs. 2 c-d). It started first in the Magnaghi-Vavilov (4-5 Ma) and then in the Marsili (2 Ma) basin, getting younger towards the ESE (fig. 2).

The precise timing of formation of the arcuate structure of the Calabria-Sicily region is not precisely

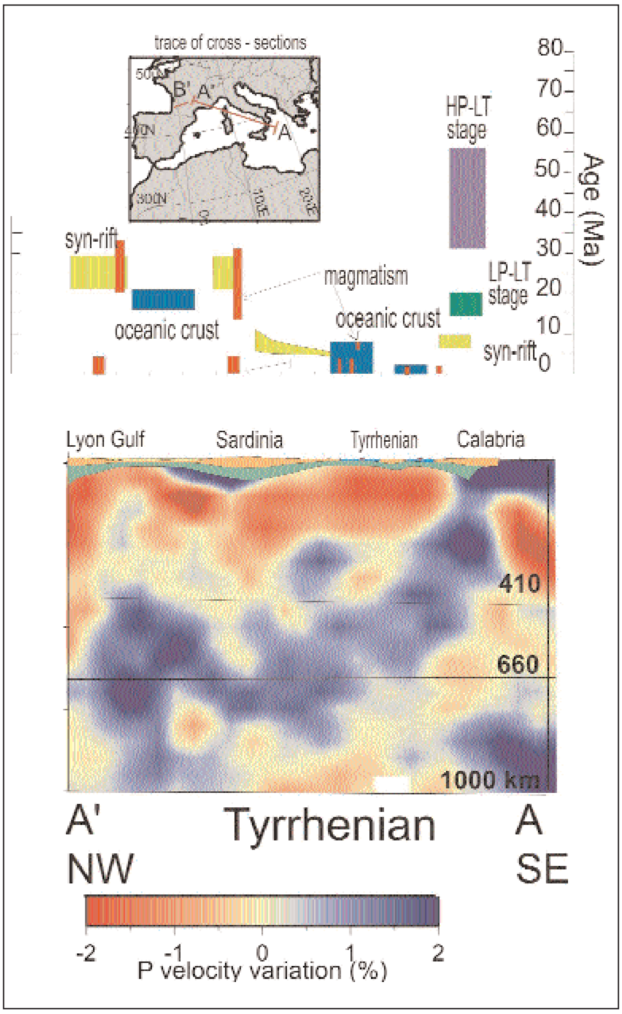

Fig. 2 - *Cross section of the studied area (location in the inset). (AA') From the Gulf of Lyon to Calabria. Crustal structure of section AA' is from from* Finetti & Del Ben (1982), Chamoot Rook *et alii* (1999). *Lithospheric structure is from* Suhaldoc & Panza (1989), Torné *et alii* (2000). *Tomographic cross sections are from model PM0.5* (Piromallo & Morelli, 2002). *The upper panels show the age and distribution of the geological record related to subduction (see text for references): metamorphism (blue and green boxes represent blueschist and greenschist facies, respectively), magmatism (red boxes represent volcanic and intrusive rocks), synrift deposits filling extensional basins (yellow box) and oceanic crust (light blue box).*

defined. Paleomagnetic data indicate that the arcuate shape was attained between the Late Miocene and the Pleistocene, during the opening of the Tyrrhenian sea. Significant counterclockwise rotation of the southern Apennines, in fact, occurred after the opening of the Liguro-Provençal basin (GATTACECA & SPERANZA, 2002), and part of this rotation (25°according to SAGNOTTI, 1992; SCHEEPERS *et alii*, 1993) should have occurred after the early Pleistocene. The Calabrian region itself rotated clockwise about 15°-25° during the Plio-Pleistocene (SCHEEPERS *et alii*, 1993; SCHEEPERS & LANGERAIS, 1994; SPERANZA *et alii*, 2000). Moreover, an overall clockwise rotation has been detected in the Sicilian belt (CHANNELL *et alii,* 1980, 1990, AIFA *et alii,* 1988; SCHEEPERS & LANGERAIS, 1993), but its timing and magnitude is still uncertain as it can be related to the complex rotational pattern of single thrust sheets (SPERANZA *et alii*, 1999).

In synthesis, the Tyrrhenian basin is characterized by extensional deformation, sedimentary basins, magmatic loci, and spreading centers which are distributed over a wide area (fig. 2). This contrasts with the Liguro-Provençal style of extension which shows a rather narrow margin (with the exception of the Gulf of Lyon), bordering the abyssal plain.

Over the whole, the Central Mediterranean basins show a rapid and intermittent episode of extension as the Tyrrhenian basin opened few million years after the drifting of the Liguro-Provençal basin. At the time extension initiate 30 Ma, we should expect that the subduction system was already developed enough to drive a vigorous retreating process.

2.2. - THE CALABRIA OROGENIC WEDGE

The nappe-structured belt of Calabria (fig. 1) is part of the peri-Mediterranean Alpine system progressively drifted and dispersed during the Neogene to Recent opening of the South Tyrrhenian basin and the subduction of the Ionian slab (DEWEY *et alii*, 1989; FACCENNA *et alii*, 2001a; HACCARD *et alii*, 1972). Here is preserved the oldest trace of the subduction process. However, the origin and tectonic significance of the Calabrian nappe architecture has been debated. In fact, kinematic data from Calabria have been used to support different interpretations of the Alps-Apennines linkage and the polarity of the subduction process in the Apennine region (see e.g. ; AMODIO MORELLI *et alii,* 1976; SCANDONE, 1982; BOULLIN, 1984; DIETRICH, 1988; CELLO *et alii,* 1996; DOGLIONI *et alii,* 1998; ROSSETTI *et alii,* 2001). These contrasting interpretations mainly derive from the kinematic stratification of the nappe pile, where both westward and eastward shear senses have been reported as responsible for nappe stacking (AMODIO MORELLI *et alii*, 1976; FAURE, 1980; DIETRICH, 1988).

The tectonic scheme generally accepted for the nappe architecture of Calabria is based on the synthesis of AMODIO MORELLI *et alii* (1976). In this scheme it is assumed that the Calabrian orogenic pile is the result of the eastward-verging overthrusting of an early westward-verging Alpine structured belt (Alpine Chain of AMODIO MORELLI *et alii,* 1976) onto the dominantly Meso-Cenozoic carbonate sequences that, originally part of the African and Adrian plate margin (Apennine Chain of AMODIO MORELLI *et alii,* 1976), presently constitute the major portions of the southern Apennine and Maghrebide chains. The Alpine Chain consists of the stacking of two main group of units: (i) Calabrian units (Calabride Complex of OGNIBEN, 1969), pre-Alpine (Paleozoic) in age, continental-derived metamorphic and igneous rocks and their Meso-Cenozoic sedimentary or weakly metamorphosed cover; and (ii) ophiolitic units (Liguride Complex of OGNIBEN, 1969), consisting of Cretaceous to late Oligocene ophiolite-bearing flyschoid sequences (BONARDI *et alii,* 1988, 1994) with local high-pressure/low-temperature (HP/LT) metamorphic signature (e.g. DE ROEVER 1972; SPADEA *et alii,* 1976; BECCALUVA *et alii,* 1982). This general picture, with no or few modifications, is also reported in more recent papers (BONARDI *et alii,* 1994; CELLO *et alii*, 1996; DOGLIONI *et alii,* 1998; THOMSON, 1994). In this scheme, it is thus assumed a priori that the present nappe contacts in Calabria are the results of overprinting compressional event, with no or little contribution of post-orogenic extension. In addition, it is also assumed that the high-pressure metamorphism (in both the Calabrian and Liguride complexes) occurred exclusively during the Alpine stage, i.e. during the westward-verging subduction linked to the eo-Alpine (Cretaceous and Paleocene) thickening phase, whereas the Apennine orogenesis produced only a reworking of the already structured high-pressure-belt (see also CELLO *et alii,* 1996, DOGLIONI *et alii,* 1998). This assumption strongly contrasts with the increasing amount of Tertiary ages (Eocene to Oligo-Miocene) that have been recently obtained for the orogenic metamorphism on the oceanic-derived units exposed in the northern Apennines ($^{40}Ar/^{39}Ar$ method on white micas of the Schistes Lustrées Nappe (BRUNET *et alii,* 2000; ROSSETTI *et alii,* 2000); and Calabria itself (ROSSETTI *et alii,* 2001). Fission track data on the Calabrian basement rocks also indicate a rapid un-roofing of this rock group between 30 to 18 Ma (THOMSON, 1994; 1998), once again confirming the Tertiary age of the main contacts within the nappe pile.

Based on coupled structural and petrographical investigations on the nappe stack exposed in the Sila Piccola Massif, we recently proposed an alternative tectonic scenario for the orogenic tectonic evolution of Calabria. ROSSETTI *et alii* (2001) documented the occurrence of a major top-to-the-W/NW semi-brittle to brittle extensional shear zone separating an upper tectonic complex from a lower one, each complex showing different Alpine metamorphic and structural signatures (fig. 3). The upper tectonic complex consists of a nappe-like structure, piling up the Calabrian, ophiolitic and Appenine carbonate rock units and recording a main top-to-the-E compressional shear. The lower tectonic complex consists of a polymetamorphic high-pressure-low-temperature (Mg-carpholite-bearing)

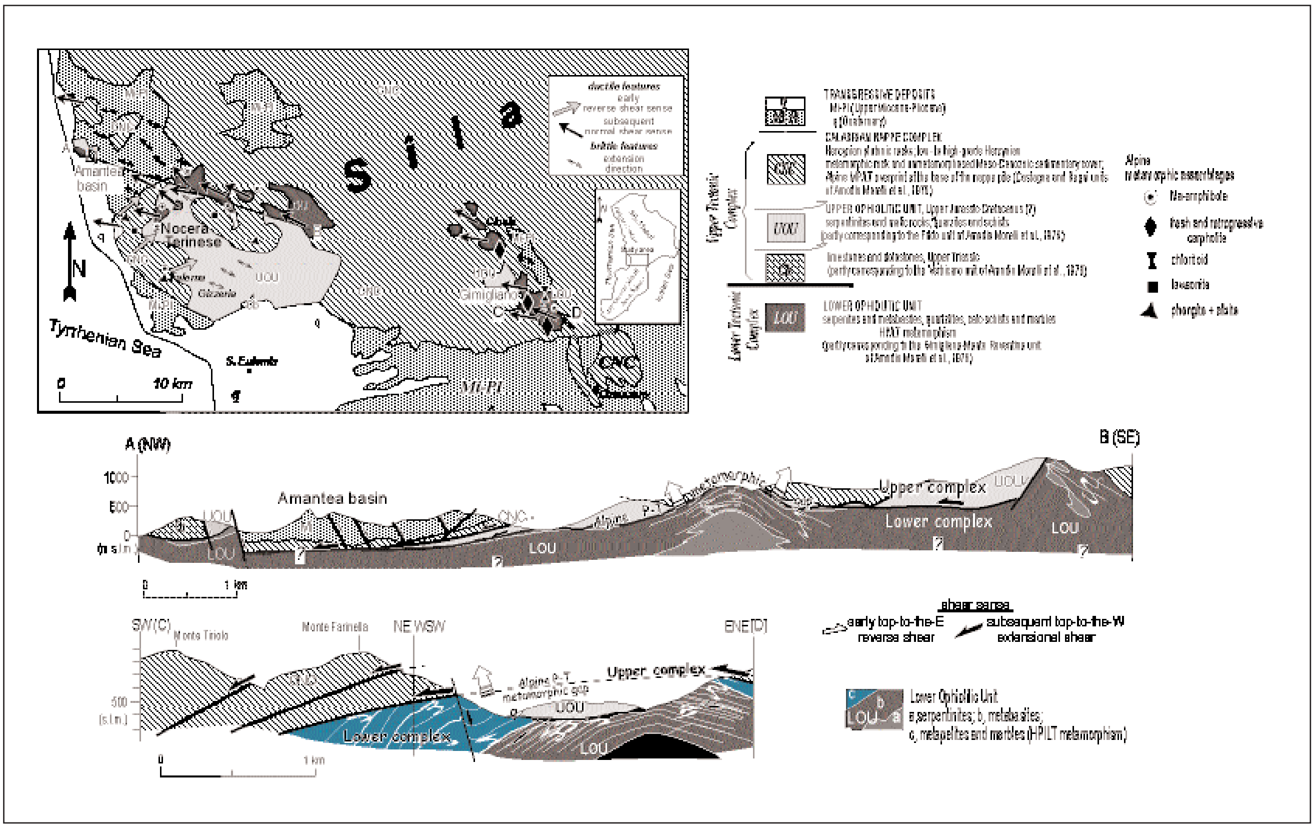

Fig. 3 - *Geological sketch map and related profiles showing the arrangment of the nappe stack of the Calabria orogenic wedge. Note the geometry of the flat-lying extensional detachment fault.*

ophiolite-bearing metamorphic sequence.

P-T estimates range from 0.5 to 0.8 GPa for pressure and less than 350°C for temperature in the continental-derived basement rocks (PICCARRETA, 1981; ROSSETTI *et alii,* 2001) and from 0.9 to 1.2 GPa for pressure and less than 450°C for temperature in the oceanic-derived rocks (SPADEA *et alii*, 1976; CELLO *et alii,* 1991; ROSSETTI *et alii*, 2001). Radiometric ages of the Alpine metamorphism range from Paleocene to Upper Oligocene times for the Calabride continental-derived rocks. BORSI & DUBOIS (1968) obtained ages ranging between 65 and 56 Ma (whole rock K/Ar and Rb/Sr methods), SCHENK (1980) of ~ 43 Ma (Rb/Sr method on pre-alpine biotites), BONARDI *et alii* (1987) of 25-30 Ma (Rb/Sr method on phengites). Ages of Alpine metamorphism for the oceanic-derived units are constrained at the Eocene-Oligocene boundary. ROSSETTI *et alii* (2001) obtained ages of ~35 Ma (Ar^{40}/Ar^{39} method on phengites) BECCALUVA *et alii* (1981) obtained ages ranging from ~ 48 to ~ 30 Ma (K/Ar method whole rock). Fission track data on the Calabride complex indicates a rapid unroofing of these rock types from 30 to 18 Ma (THOMPSON, 1998).

Top-to-the-northeast compressional shearing, syn- to post-kinematic to blueschist metamorphism, has been reported from the Variscan basement rocks of the upper plate (ROSSETTI *et alii,* 2001). These data, coupled with the ones derived from the same units (DIETRICH, 1988) and oceanic-derived units (MONACO, 1993) indicate a major northeastward-directed thickening event, locally experienced under blueschist metamorphic conditions. Ductile to brittle top-to-the west extensional shear (probably active since Late Oligocene) accompanied exhumation of the lower complex rocks, reworking the previous nappe contacts with shear localisation along the upper/lower tectonic complex discontinuity. A similar tectonic configuration has been previously described by PLATT & COMPAGNONI (1990) for the Calabrian units exposed in the Aspromonte region and for the Liguride Complex. Tectonic evolution of Calabria is thus reinterpreted as the effect of superimposed westward-directed extension onto a previously eastward-structured compressional belt.

Finally, domino-like style of extension controls the early tectono-sedimentary evolution of the Middle-Upper Miocene post-orogenic tectonic depressions, lying at the top of the brittle westward extending upper-plate nappe stack (MATTEI *et alii,* 2002). Maximum extension directions as deduced by fault slip data sets are subparallel to the stretching direction of the westward-verging attenuation shear zones (fig. 3).

Summing up, *HP/LT*, subduction-related metamorphism affecting both upper- and lower-plate rocks is indicative of active underthrusting before and during the back-arc extension, from Paleocene to Early Miocene. The continuous formation of blueschist units thus better supports a model of continuous subduction at least from the beginning of the Tertiary.

3. - THE CENTRAL MEDITERRANEAN SUBDUCTION ZONE: DEEP STRUCTURE

The Calabrian Arc is the only region of the Mediterranean in which crustal, intermediate depth and deep earthquakes are recorded all along an approximately continuous dipping plane. Seismicity is distributed along a narrow (~200 km) and steep (~70°) Benioff plane, SW-NE striking and NW dipping, down to about 500 km (e.g. ANDERSON & JACKSON, 1987; SELVAGGI & CHIARABBA, 1995)

The presence of seismicity on a well defined Benioff zone reveals a direct trace of the past and 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, and, if any, of an aseismic slab and to detect the presence of low seismic velocity areas.

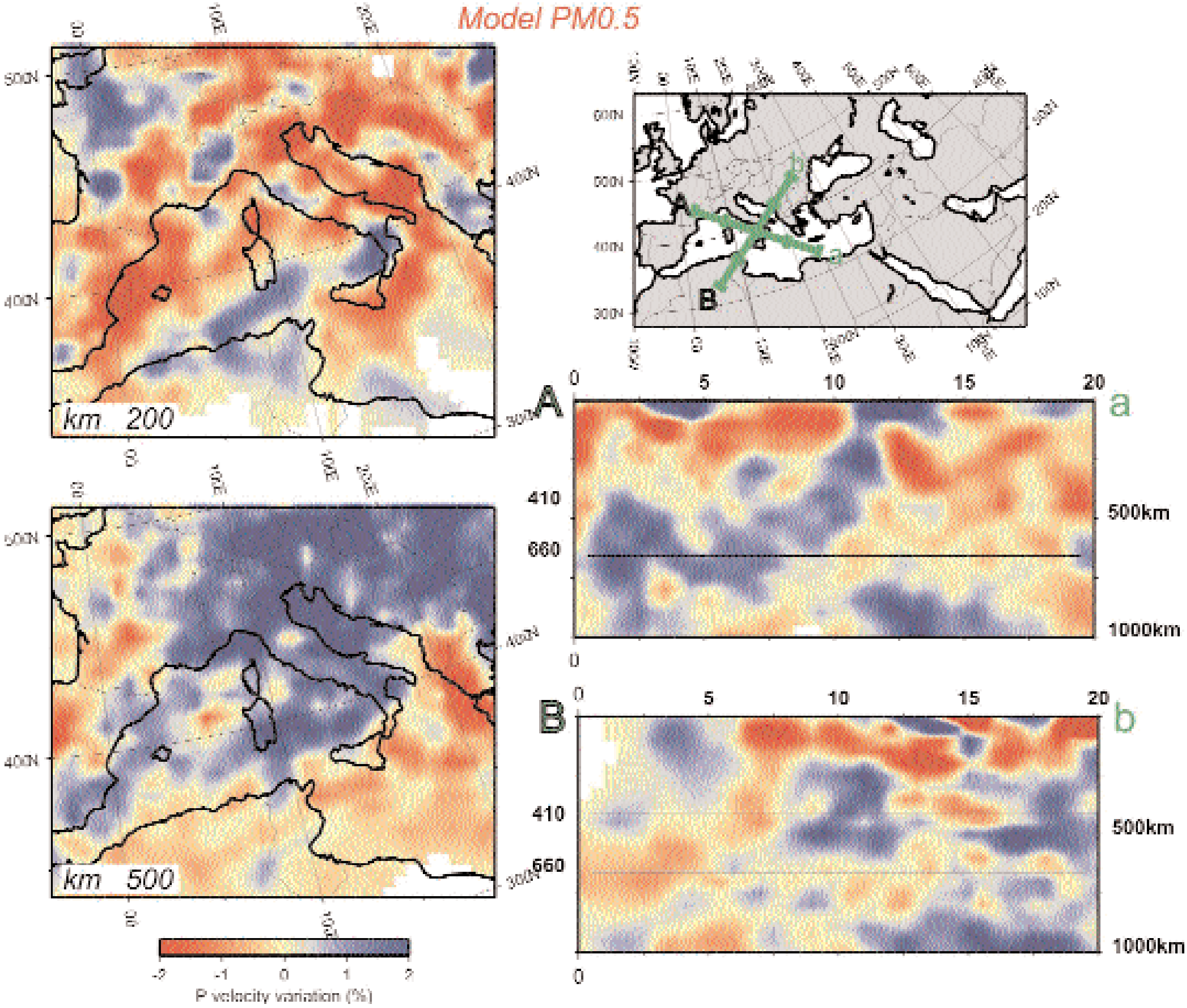

Fig. 4 - *Map views of tomographic results at 200 km and 500 km, and cross-sections (Aa, Bb) from model PM0.5* PIROMALLO & MORELLI (2002). *Velocity anomalies are displayed in percentages with respect to the reference model sp6* (MORELLI & DZIEWONSKI, 1993).

3.1. - Tomographic model PM0.5

We focus here on a limited area of the recent high-resolution, large-scale tomographic model built for the whole Euro-Mediterranean region (Piromallo & Morelli, 2003). The model (PM0.5) is obtained through the inversion of the large dataset constituted by the collection of over 30 years of P-wave delay times by the International Seismological Centre (ISC). After accurate data selection and relocation (52,000 relocated events using more than 5,000,000 observations), first arrival residuals of both regional (epicentral distance $\Delta \leq 28°$) and teleseismic ($\Delta > 28°$) rays from shallow earthquakes (focal depth $h \leq 50$ km) are used to compute summary residuals as input data to the inversion (Piromallo & Morelli, 1997; 2003). The velocity model is parameterized over a three-dimensional cartesian grid, with horizontal node spacing of roughly 55 km in both directions and 50 km vertical spacing, down to 1000 km depth. Standard ray tracing and inverse problem solution techniques are applied. The perturbation to the velocity field is computed and displayed with respect to the global reference velocity model sp6 (Morelli & Dziewonski, 1993).

Resolution sensitivity analyses, performed with input velocity anomalies of different spatial wavelength and shape, indicate that structures with spatial extent ranging from ~100 km to ~600 km are fairly resolved all over large part of the inversion domain. In the best sampled regions, features with size smaller than 100 km (and larger than 55 km, the nominal model resolution) are also detectable. However, smaller-scale details may sometimes result unstable in the inversion. Crustal structure is instead not explicitly modeled and therefore poorly or not resolved at all, implying that features at crustal depths may result unreliable.

3.2. - Images of the Southern Tyrrhenian area

The whole PM0.5 model is displayed by means of maps at different depth layers in Piromallo & Morelli (2003), therefore we refer to this paper for a comprehensive view. We show here in figure 4 a zoom in of the model into the region of interest, the Southern Tyrrhenian area, at two representative horizontal layers, at 200 and 500 km. The layer at 200 km depth roughly marks the limit between two depth ranges in which the seismic velocity of the region is characterised by a different structure. Below 200 km depth, the high velocity anomaly in correspondence of the Calabrian Arc joins into a continuous belt with the southern Apennines to the N and with the Sicily-Maghrebides chain to the SW (Piromallo & Morelli, 2003; Faccenna *et alii,* 2003).

Moving from 200 km depth to the surface, instead, high velocity anomalies along the peninsula appear disconnected from each other, interrupted by wide gaps of low velocity anomalies (below the southern Apennines and the Sicily Channel). Therefore, the Calabrian Arc is the only place where, along a segment whose lateral extent reaches ~300 km, the high velocity structure is vertically continuous all over the depth range, from the surface to the transition zone. The map at 500 km depth of figure 4, located in the middle of the transition zone, shows another representative layer, in which we can clearly see how the Calabrian fast anomaly merges into a broader positive anomaly, spreading all over central Europe and the western Mediterranean. This large-scale high velocity anomaly which characterizes the transition zone (Piromallo *et alii,* 2001), probably gathers the material from different portions of subducted slabs. Below the western Mediterranean we find the traces of Betic-Alboran, Algerian, Apenninic and Calabrian slabs (Faccenna *et alii,* 2003), while below central Europe fast velocity material likely comes from the Alpine-Carpathians subduction.

The vertical profile Aa (figs. 2, 4) cross-cuts the positive anomaly of the Calabrian Arc, approximately parallel to the direction of maximum extension of the Tyrrhenian basin. The high velocity structure can indeed be followed continuously, starting from a shallow horizontal portion, located on the Ionian side of the arc, which connects to a feature that deepens steeply to the NW into the mantle, down to 400 km, and then bends almost horizontal in the transition zone, lying on the 660 km discontinuity. Below the Tyrrhenian Basin a low velocity anomaly is detected, from the surface down to the top of the transition zone at 400 km, overlain by the fast shallow anomaly of the Sardinia-Corse block. In the eastern portion of the cross-section, note also the pronounced slow anomaly at intermediate depths, just behind the slab-like fast one.

Cross-section Bb (fig. 4), orthogonal to the previous profile, intersects the Calabrian fast anomaly along-strike, imaging the slab as a trapezoidal structure and showing its limited lateral extent. On its left side a very strong slow anomaly, is located in the shallower 150 km below the Sicily Channel and western Sicily. On the top right side of the trapezoid, another pronounced slow anomaly, below the Southern Apennines, and, further to the east, the fast slab-like body deepening below the Hellenides are imaged.

Overall, the three-dimensional image that we can derive from tomography for the Calabrian fast anomaly is that of a spoon-like structure, with a handle that is dipping to the NW at a steep angle and the cup which bends almost horizontally in the transition zone.

3.3. - Comparison with other models

All P-wave tomographic models available for the Southern Tyrrhenian area, based upon different datasets and techniques, are consistent in detecting a continuous fast velocity feature, steeply dipping below the Calabrian Arc: joint regional and teleseismic tomography with ISC P first arrivals (Spakman *et alii*, 1993; Piromallo & Morelli, 1997; 2003), teleseismic tomography with Italian National Seismic Network

(RSNC) P and PKP first arrivals (AMATO *et alii*, 1993; LUCENTE *et alii*, 1999), deep earthquake tomography with RSNC plus local networks P arrivals (SELVAGGI & CHIARABBA, 1995), and teleseismic tomography with RSNC P direct and secondary arrivals (CIMINI & DE GORI, 2001). This slab-like feature is unanimously interpreted as the signature of subducted lithosphere. Differences in the imaged structure among these models arise instead moving northward, below the southern Apennines, or in the Tyrrhenian and Ionian domains, mainly due to the combined effect of the ray-sampling/model inversion volume and of the pattern of heterogeneous structures which characterizes the area.

Teleseismic rays have quasi-vertical ray paths in the uppermost mantle and bottoming depths in the lower mantle, while regional ray paths have a larger horizontal component and turning points ranging in the upper mantle (down to 750 km), with discontinuous depth distribution due to the presence of upper mantle velocity interfaces (i.e. PIROMALLO & MORELLI, 1997). For these reasons there is a substantial difference, mainly at shallow depths, in the coverage provided by rays travelling in the two distance ranges, that result somehow complementary in space: teleseismic rays being confined to regions right below stations and events, especially in the shallower layers, while regional rays more extensively sampling the regions in between the ray foci. Therefore, while teleseismic tomography mainly detects features with a vertical extent, joint tomography of regional and teleseismic residuals is able to image, in addition, horizontally lying structures (SPAKMAN *et alii*, 1993; PIROMALLO & MORELLI, 1997; 2003). This explains why results of studies based on teleseismic data alone (see for comparison) fail in imaging features with horizontal rather than vertical extent (for example the fast Ionian lithosphere, fast Adriatic lithosphere, slow Tyrrhenian province of fig. 2). Moreover, below the central Apennines, where model PM0.5 detects a strong positive anomaly in the top 200 km (see fig. 4), teleseismic studies obtain an almost unperturbed/slightly positive model, likely due to limited vertical resolution at these depths.

The power of models built through joint inversion of regional and teleseismic data, like PM0.5 (PIROMALLO & MORELLI, 2003), with respect to tomography performed with teleseismic data alone, resides in that the combination of the two datasets results in the avalability of a large number of criss-crossing rays, with an ample range of incidence angles, which contribute to a more uniform illumination of the investigated volume and better constrain the resulting model.

4. - THE CENTRAL MEDITERRANEAN SUBDUCTION ZONE: KINEMATICS

To calibrate the tectonic evolution of the Central Mediterranean and to reconstruct the rifting and spreading events of the backarc Tyrrhenian and Liguro-Provençal basins we use the geological data illustrated before. In particular, to identify the main tectonic episodes and to estimate the amount of backarc extension, we subtract from the present geological cross-section (fig. 2) the oceanic crust and, using an area balancing technique, we restore the thinned continental crust to the thickness of its shoulders (fig. 2). The restoring technique is based on the assumption that the locus of extension at the surface corresponds to the locus of maximum crustal thickening (pure shear mechanism) and that the pre-rift thickness of the crust was about 30-35 km, as presently observed on the basin shoulders in Sardinia and in Provençal area (~30 km, see FINETTI & DEL BEN, 1986; CHAMOT-ROOKE *et alii*, 1999) where the amount of extension is considerably lower with respect to the basin itself. In addition, we neglect the role of erosion and possible lower crustal flow that might complicate the relationships. For these reasons, large error bars have been adopted. We estimated the amount of back-arc extension by reconstructing the

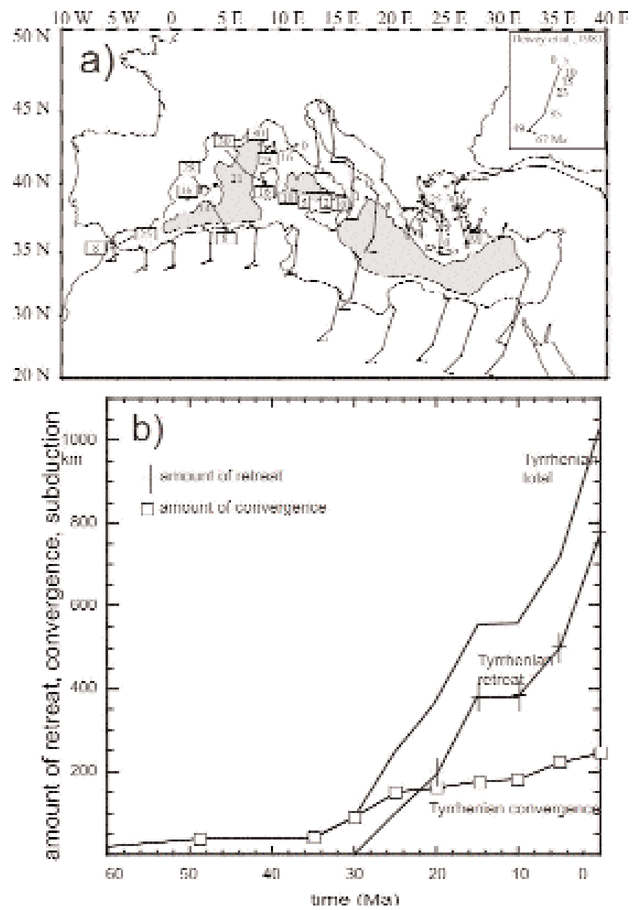

Fig. 5 - *(a) Displacement trajectories of Africa and Apulia motion with respect to stable Eurasia (calculated from* DEWEY *et alii* (1989), *see inset for stages division) and displacement trajectories related to back-arc extension (numbers are million years). (b) Amount of relative convergence, extension and total amount of subduction calculated along the cross-section of figure 2 perpendicular to the trench in the last 64 Ma.*

main tectonic events at the scale of the crust in different steps. Figure 5 shows the amount of extension attained by the Southern Tyrrhenian (steps at 3, 5, 7, and 10 Ma), and the Liguro-Provençal basin (step at 16, 23, and 30 Ma).

We note that the total amount of extension (~780 km) is partitioned roughly equally between the two basins, with alternating episodes of rifting (~7 Ma) and oceanic spreading (~5 Ma). In addition, we note that the rate of extension is reduced at the end of spreading of the Liguro-Provençal basin: rifting in the Tyrrhenian initiated after a small pause of few Ma and progressively accelerated.

We also find that the volcanic arc-trench gap is rather wide (~400 km) in comparison to the present-day. This suggests, in agreement with the paleo-reconstruction of BECCALUVA *et alii*, 1989 and SERANNE, 1999, that the slab attained a shallow dip prior to and after the opening of the Liguro Provençal basin. In addition, slab steepening has been proposed by JOLIVET *et alii*, 1999 and BRUNET *et alii,* 2000 along the northern section of the Tyrrhenian sea to account for the decreasing time gap between the HP compressional event and the onset of extension and magmatism.

The amount and velocity of extension estimated here is in good agreement with previous evaluations. Along the southern section of the Liguro-Provençal basin, the rifting event was estimated to be 150±20 km (CHAMOT-ROOKE *et alii*, 1999) while the amount of spreading was estimated to be 150 km (MAUFFRET *et alii*, 1995), 230 (BURRUS, 1984), and 230 ± 20 km (CHAMOT-ROOKE *et alii*, 1999; fig. 5). For the Tyrrhenian Sea, the total extension evaluated by MALINVERNO & RYAN, 1986 is on the order of 330-350 km. In the southern section of the Tyrrhenian Sea, similar values have been estimated by PATACCA *et alii*, 1990 and SPADINI *et alii*, 1995. Furthermore, the total amount of extension along the whole southern section agrees well with previous studies (GUEGUEN *et alii*, 1998).

The amount of convergence at the trench has been estimated by calculating the component of the Africa-Eurasia convergence perpendicular to the paleo-trench. Several kinematic reconstructions were proposed for the Mediterranean region to define the way the African plate converges toward Eurasia (e.g., DEWEY *et alii*, 1989; DERCOURT *et alii*, 1993). All of these models basically agree that Africa moved slowly relative to stable Eurasia with counterclockwise rotation, moving NE up to ~ 40 Ma, then N-S, and finally NNW (fig. 5). The relative velocity of a point located half way along the northern African coast was probably slower than 3 cm/yr during the last 80 Myrs, halving during the last 20-30 Ma (JOLIVET & FACCENNA, 2000). These numbers agree with another recent estimate of absolute plate motion for Africa (SILVER *et alii*, 1998). Geodetic data indicate that Africa currently moves N20°W at a rate of 0.7 cm/yr in the Central Mediterranean (WARD, 1994).

In order to estimate the net convergence rate (the rate at which the plates moved perpendicularly to the trench), we reconstruct the orientation of the trench in time (fig. 5). Paleomagnetic data indicate that Iberia accomplished a significant rotation (22° ± 14°) with respect to Europe between 132 and 124 Ma (VAN DER VOO, 1993; MOREAU *et alii,* 1997). After this episode, the rotation of the Iberian peninsula slowed down and was followed by translation (~120 Ma) during the initial phase of the opening of the Bay of Biscay (~85 Ma; JOLIVET, 1996, and references therein). At that time, the trench was therefore oriented NE-SW running parallel to the former Iberian passive margin. Subsequently, the trench position remained rather stable, turning to N-S only after the rotation of the Sardinia-Corsica block (~21-16 Ma;), and then turning again to its present-day position during the Southern Tyrrhenian spreading episodes (~5-2 Ma). The trench was therefore oriented roughly parallel to the motion of Africa during most of the subduction process. With the numbers from DEWEY *et alii*, 1989, we can estimate that the total amount of net convergence produced by the motion of Africa since 80 Ma is ~240 km with an average rate of 3 mm/yr. We note that the motion of the Adria microplate cannot contribute significantly to increase the convergence because its Tertiary motion can be assumed to be coherent with Africa (CHANNEL*,* 1986). We therefore observe that the net convergence velocity on the Central Mediterranean trench appears to be very low when compared with other subduction zones worldwide (JARRARD, 1986).

Figure 5 shows that the total amount of subduction during the Tertiary is on the order of 1000 km. This value derives from the sum of the contribution given by the Africa-EurAsia shortening (on the order of 200 km) and of the one given by the retreat of the trench (on the order of 800 km).

5. - THE CENTRAL MEDITERRANEAN SUBDUCTION ZONE: TECTONICS

On the basis of the geological and kinematic constraints, tied with tomographic images, we are able to reconstruct the evolution of the Calabrian slab in six main steps from 35 Ma to present-day (fig. 6). The main assumption behind this model is that the high velocity anomalies, imaged by tomography, are related to cold subducted material. This assumption is supported by the fact that seismicity is lined up over the high velocity anomalies and that the expected amount of subduction is in good agreement with the one measured from the tomographic images. The reconstruction is then performed subtracting from the present-day high velocity anomaly the estimated amount of subduction.

Around 35 Ma, the Calabrian slab constitutes a segment of the wider subducting slab, extending for more than 1500 km from southern Iberia to the Ligurian region (fig. 6). It dips towards NW and consumes the land-locked Jurassic oceanic basin (LE PICHON *et alii*, 1988). The position of the trench,

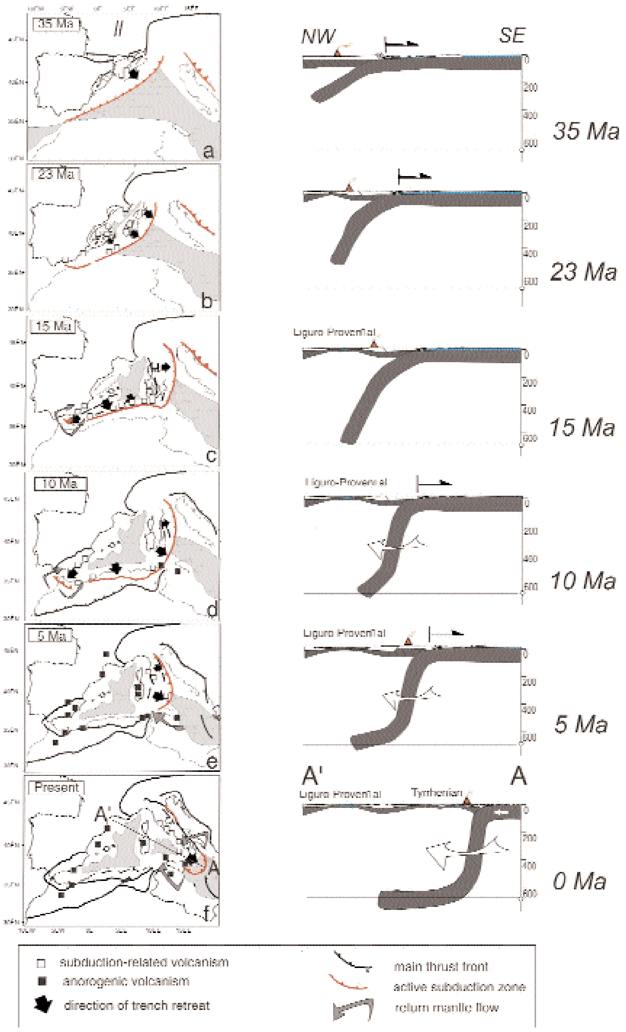

Fig. 6 - *Reconstruction of the evolution of the Mediterranean region in relative (Eurasia fixed) reference frame in six stages, from 35 to present-day. Oceanic domains are marked in grey. The location of the magmatic centers and their bearing with subduction process are marked with black (anorogenic) and white (subduction-related) squares. Cross sections illustrate the evolution of the subduction process along the the Tyrrhenian (inspired from the tomographic cross section AA' of Figure 2). Black arrows indicate the net motion of the trench, large white arrows indicate possible lateral flow of the mantle. Small volcanoes indicate the approximate position of the arc, if any.*

running along the Iberia margin, has been reconstructed by restoring back the amount of back-arc extension. The trench terminates to the north-east in correspondence of the Ligurian region, where subduction flips dipping southward beneath the Alps, and to the south-west in correspondence of the Gibraltar region where the Tethyan seaway gets narrow or even disappears (fig. 6). At this time, the subducting slab was probably continuous and already well developed, reaching a depth of 300-400 km and dipping at rather shallow angle. Therefore, the infant stage of the slab should be traced back at least up to the Paleogene, as attested by evidences of blueschist metamorphism in Calabria.

At about 30 Ma, the back-arc extensional process starts over the Mediterranean (JOLIVET & FACCENNA, 2000). It initiates in the north-eastern sector, in the Liguro-Provençal area. Calc-alkaline volcanism spreads over the region, attesting the efficiency of the subduction process. This large-scale re-organization of the subduction process over the whole Mediterranean region has been related to an increment of the retrograde motion of the slab under the concurrent action of increased slab pull level and of the decrease in the Africa rate of motion (JOLIVET & FACCENNA, 2000).

From 30 to 23 Ma (fig. 6) back-arc extensional processes propagate southward from the Liguro-Provençal basin to the Valencia and to the Alboran basin. Extensional processes localise not only in the backarc region, but also induce the collapse of the previously thickened orogenic wedges with the formation of large-scale flat-lying detachments in Calabria (ROSSETTI *et alii,* 2001). The formation of this structure and the exhumation of the deep-seated units attest a change in the evolution of the subduction wedge. The velocity of subduction, mainly related to the slab retrograde motion, progressively increases, reaching its maximum in southern Sardinia (fig. 6), and produces the formation of a first smooth arc, in front of the oceanic seaway. Calc-alkaline subduction related volcanism is widespread over the whole region from Sardinia to the Valencia and Alboran region.

Between 21 and 16-15 Ma (fig. 6), the Liguro-Provençal basin completes its opening phase with the peak of extension and during the rapid counter-clockwise rotation of the Sardinia block. Around 16-15 Ma, the retrograde migration of the western Mediterranean slab stops. No appreciable extension takes place during this time interval in the central-western Mediterranean basins. The geometry of the trench already attains a sharp curvature in the proto-Calabrian area possibly related with the lateral extent of the Tethyan oceanic seaway. Reconstruction of slab geometry reveals that at that time the subducted lithosphere already reaches and interacts with the deeper part of the transition zone (fig. 6). The interaction and deformation of the slab at its arrival at the 660-km discontinuity is proposed as a primary cause for the sudden decrease in the rate of rollback (FACCENNA *et alii*, 2001b)

Around 12-10 Ma (fig. 6) the locus of extension jumps southward from the Liguro-Provençal to the Tyrrhenian region.

Between 10 and 5 Ma (fig. 6) rifting migrates eastward inside the Tyrrhenian domain. There, the velocity of extension increases leading to the emplacement of an isolated oceanic spreading centres from about 5 Ma onward. From this moment we also observe the opening of the Sicily channel rift system, that can suggest that the Calabrian slab separates from the African one, following different directions: southward in northern African and southeastward in Calabria, where the trench retreats faster, consuming the oceanic seaway lithosphere. The formation of the slab window is marked by a change in the nature of volcanism, and alkali-basalts are emplaced during the late Miocene- Pliocene in northern Tunisia and in Sardinia.

At present (fig. 6), the remnant of the once vigorous western Mediterranean subduction zone is preserved only in the narrow tongue below Calabria and perhaps in the northern Apennine (SELVAGGI & AMATO, 1992). Despite the presence of a well defined Wadati-Benioff zone (SELVAGGI & CHIARABBA, 1995), some arguments on the morphology of the accretionary prism off Calabria could suggest that the subduction process below Calabria is progressively decaying (CHAMOT-ROOKE, personal comunication).

6. - TESTING IN LABORATORY THE KINEMATICS OF THE CENTRAL MEDITERRANEAN SUBDUCTING SYSTEM

To test the tectonic reconstruction of subduction proposed here and back-arc extension we have performed 3-D laboratory experiments. In particular, the aim of this experimental program is to investigate the kinematics of a retreating subduction during the free sinking of the slab into the mantle and its interaction with the upper/lower mantle boundary.

6.1. - MODELS: ASSUMPTIONS AND LIMITATIONS

Our experiments are set up in the following framework:

1. - Viscous rheology. We model the slab as a viscous body assuming that the lithosphere behaves like a viscous fluid, characterized by large temporal- and spatial-scale, such as is the case for subduction (TAO & O'CONNELL, 1993). We further simplify slab behavior by using a Newtonian fluid whereas laboratory data indicate that upper mantle materials obey a creep power law of deformation (e.g. BRACE & KOHLSTEDT, 1980). Since a Newtonian material has a stronger response to deformations than a power-law fluid (RANALLI, 1995), the velocities observed in laboratory should be considered as a lower bound.

2. - No net plate convergence. The system is driven only by the slab pull force to simulate the Central Mediterranean conditions where the average net convergence of the incoming African plate at the trench has always been very low (DEWEY *et alii*, 1989; DERCOURT *et alii*, 1993)

3. - The system is isothermal. For experimental constraints we consider a simplified system governed only by the negative buoyancy of the subducting lithosphere; no positive buoyancy from plumes is included. The negative buoyancy is implemented chemically. This implies that the mantle is convectively neutral so that the only moment within it is that caused by the lithosphere/slab system. Moreover it is assumed that the density contrast of the slab is preserved during the whole subduction process. This situation is equivalent to quasi-adiabatic conditions. Our velocity of the subduction process is much higher than 1 cm/y. Under these conditions, we effectively neglect temperature changes during subduction (WORTEL, 1982; BUNGE *et alii*, 1997). Another consequence is that we neglect the role of the endothermic phase changes at the transition zone (CHRISTENSEN & YUEN, 1985; TACKLEY, 1993; PYSKLYWEC & MITROVICA, 1998). The possible effect of impediment for the slab to penetrate into the lower mantle is here reproduced only by the increase in viscosity with depth.

4. - The system does not include an overriding plate. This simplification has two consequences. The first consequence is that we assume that the subduction fault is weak with a viscosity comparable with the upper mantle viscosity. This choice is able to reduce the time scale of the subduction process but not its general behavior (KING & HAGER, 1990). The second consequence is that the overriding plate is assumed to passively move with the retreating trench. Therefore, this experimental setting can be considered as appropriate for all the natural cases, including the central Mediterranean, where the motion of the overriding plate towards the trench is lower than the velocity of trench retreat.

6.2. – SETUP

Following the approach used in previous analogue studies, the rheology of the lithosphere, upper- and lower mantle is approximated by linear viscous multi-layer regions (KINCAID & OLSON, 1987; GRIFFITHS & TURNER, 1988; GRIFFITHS *et alii*, 1995; GUILLOU-FROTTIER *et alii*, 1995; FACCENNA *et alii*, 1996; FACCENNA *et alii*, 1999). The analogue materials, a silicone putty-honey composite, are selected to scale to the slab–mantle system, as described by FACCENNA *et alii* (1999). A lower mantle layer has been added as a new feature. Silicone putty is a visco-elastic material. For the applied experimental strain-rate the silicone putty can be considered as a quasi-Newtonian fluid where stress increases linearly with strain rate (WEIJERMARS, 1986). It is composed of a pure polymeric substrate (polidimethylsiloxane-PDMS) with galena powder to vary both density and viscosity. The upper mantle has been modeled by honey, which is a Newtonian low-viscosity fluid. The increase in viscosity in the lower mantle has been reproduced by a mixture of pure honey and glucose syrup. The viscosity and density of each layer are constant and are considered as average effective values. Parameters and values for nature and the experimental system are listed in table 1.

The multilayered system is arranged in a rectangular Plexiglas tank (34 cm high, 58 cm long and 14 to 30 cm wide). Vertical walls are lubricated by a homogeneous layer of Vaseline in order to minimize edge effects. Experiments were performed 2-6 times to ensure reproducibility. Each experiment was monitored using a sequence of photographs taken in time intervals (from 1 to 4 minutes) in the lateral and top view.

Tab. 1 - *Scaling of parameters in nature and in laboratory for a reference model.*

PARAMETER			NATURE	REFERENCE MODEL
g	Gravitational acceleration	m s^{-2}	9.81	9.81
	Thickness			
h	Oceanic lithosphere	m	70000	0.012
H	Upper mantle		660000	0.11
	Scale factor for lenght		L_{model}/L_{nature}=1.6 10^{-7}	
	Density			
ρ_l	Oceanic lithosphere	kg m^{-3}	3300	1482
ρ_{um}	Upper mantle		3220	1383
ρ_{lm}	Lower mantle		3220	1383
	Density contrast (ρ_l-ρ_{um})		80	99
	Density ratio (ρ_l/ρ_{um})		1.025	1.072
	Viscosity			
η_l	Oceanic lithosphere	Pa s	4 10^{23}	1.6 10^{5}
η_{um}	Upper mantle		4 10^{21}	459
η_{lm}	Lower mantle		1.2 10^{23}	1.8 10^{4}
	Viscosity ratio (η_l/η_{um})		10^{2}	3 10^{2}
t	**Characteristic time**	s	3.1*10^{13} *(1Ma)*	60 *(1min)*

6.3. – RESULTS

We show here the results of two experiments (out of 50 performed) characterized by the same lithospheric structure but by a different upper/lower mantle condition: experiment 1, with a uniform mantle configuration, and experiment 2 with a layered configuration with a lower mantle 30 times more viscous than the upper mantle (tab. 2 fig. 7).

In both cases we identify a distinct sequences of phases:

Phase I: Subduction initiation

To start the process, the silicone plate is initially manually bent inside the syrup to reach the critical amount of a gravitational unstable wedge corresponding to about 150-200 km in nature. More detailed problems linked to initiation of subduction are beyond the scope of these experiments (MCKENZIE, 1977; MUELLER & PHILLIPS, 1991; ERICKSSON & ARKANI-HAMED, 1993).

Phase II: Free falling slab

Once the subduction instability is formed, the plate starts to sink into the mantle increasing progressively its dip to about 70°-90° while both velocity of trench motion and back-arc opening accelerate. Confirming the laboratory and numerical modeling of BECKER *et alii*, 1999, we find that during the free fall descent into the mantle the slab length

Tab. 2 - *Physical parameters used in the selected experiments. The rheogical parameters are measured at room temperature.*

Experiment	Oceanic lithosphere	Upper mantle	Lower mantle
1	$h=0.012$ m $\rho=1482$ kg m^{-3} $\eta=1.6\times10^5$ Pa s	$H=0.11$ m $\rho=1383$ kg m^{-3} $\eta=459$ Pa s	$\rho=1383$ kg m^{-3} $\eta=459$ Pa s
2	$h=0.012$ m $\rho=1482$ kg m^{-3} $\eta=1.6\times10^5$ Pa s	$H=0.11$ m $\rho=1383$ kg m^{-3} $\eta=459$ Pa s	$\rho=1383$ kg m^{-3} $\eta=1.5\times10^4$ Pa s
3	$h=0.012$ m $\rho=1482$ kg m^{-3} $\eta=1.6\times10^5$ Pa s (laterally free)	$H=0.11$ m $\rho=1383$ kg m^{-3} $\eta=459$ Pa s	$\rho=1383$ kg m^{-3} $\eta=1.5\times10^4$ Pa s

H(t) scales exponentially as:

$$H(t) \propto H_0 \exp\left(C \frac{\Delta\rho g r^3}{\eta_o R^2} t\right) \quad (1)$$

where $\Delta\rho$ is the density contrast between the ocean and the upper mantle, g the gravitational acceleration, r the bending radius, R the width of the plate, H_0 the initial length and η_o the viscosity of the oceanic plate. The scaling indicates that the subduction process results mainly from the balance between two opposite actions: the negative buoyancy of the subducted material and the resisting viscous dissipation due to the bending at the trench.

As a kinematic consequence the descending slab has always a retrograde migration which produces a significant mass flow in the mantle directed from region of high pressure to region of lower pressure.

Phase III: Interaction slab/transition zone

When the slab reaches and anchors at the upper/lower mantle discontinuity, it decreases its dip to 50° while subduction and trench migration are temporarily delayed for about 5-10 Ma. The lithospheric system, then, bends laterally attaining an arcuate shape which allows the lateral escape of mantle material. From this moment subduction and trench migration resume while, simultaneously, the lower portion of the subducted lithosphere starts to bend and to lie down on the transition zone, the dip of the slab steepens again to 70° and the locus of back-arc extension jumps trenchward.

Phase IV: Steady-state subduction

The system reaches a steady-state configuration characterized by slab reorganization and a constant trench retreat velocity.

We find that at the observed timescales, the general features of the subduction evolution are relatively insensitive to the choice of viscosity imposed for the 660 km discontinuity. We obtain both the episodicity and the stagnant behavior of the slab lying on the 660 km discontinuity by imposing any viscosity ratio between the lower and the upper mantle higher than 10 (FUNICIELLO *et alii*, 2003). In any case, phase III is strongly dependent on the lateral boundary conditions. To test it, in experiment 3 we double the width of the box leaving constant the width of the plate. It ensures lateral circulation of the mantle during the whole process. As predicted by previous calculation (DVORKIN *et alii*, 1993), the process increases remarkably its velocity (rate similar to experiments 1), but the general picture is preserved. In particular, the subduction process is interrupted only for few Ma during the slab-660 km discontinuity interaction and the final dip of the slab is higher.

7. - REMARKS ON THE DYNAMICS OF THE CENTRAL MEDITERRANEAN SUBDUCTION SYSTEM

The comparison between laboratory simulation and the kinematics of the system permits to drawn some considerations on the dynamics of the Central Mediterranean

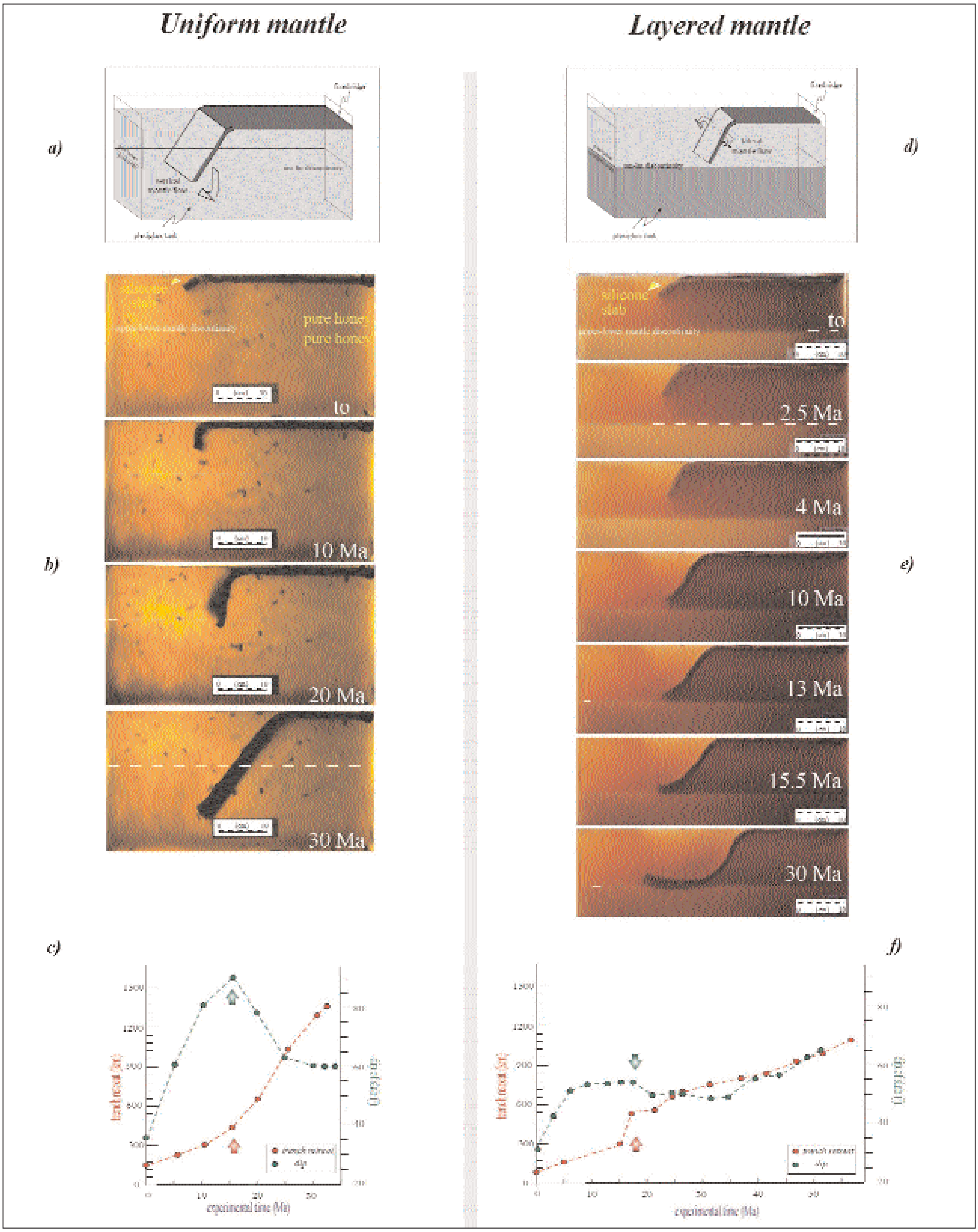

Fig. 7 - *(a) Set up of the experiment 1 characterized by a uniform mantle configuration; (b) lateral view of four stages of evolution of the experiment 1; (c) plot of amount of trench retreat and dip versus time for the experiment 1. The arrow indicates the time of interaction with the 660 km discontinuity. Hereafter 1 minute and 1 centimeter in the experiment correspond to 1 Ma and 60 km; (d) set up of the experiment 2 characterized by a layered configuration with a lower mantle 30 times more viscous than the upper mantle; (e) lateral view of four stages of evolution of the experiment 2; (f) plot of amount of trench retreat and dip versus time for the experiment 2.*

subduction zones, respecting the separation in three different steps, as in the experiments.

Phase I, 60-35 My: subduction initiation. In this initial phase, lithospheric subduction is entirely pushed by the slow plate convergence. About 300-400 km of cold lithosphere subducts at low angle, reaching a depth of 150 km and allowing the development of arc-volcanism. This means that until a critical gravity anomaly is reached, subduction will not be driven by gravity, but only by the incoming plate velocity. During this phase, the orogenic structure in the subduction wedge is dominated by thrusting of the nappe pile at different depth. The strong coupling between the plates prevents the exhumation of the deepest blue-schist units. It is difficult to estimate the velocity of subduction during this phase because it is difficult to define the exact age for the initiation of subduction. Pressure-Temperature estimate for the 35 Ma old blue-schist units gives a quite cold gradient typical of vigorous subduction process.

Phase II, 30-16 My. The presence of arc volcanism signals that a sufficient length of subducted lithosphere is available to allow the gravitational pull to become the driving force of the subduction. Back-arc opening starts, aided by (i) the weakening of the lithosphere due the volcanic activity in the back-arc region, and (ii) the decrease of the confining horizontal compression on the Alpine orogen associated to the decrease in absolute motion of the African plate (JOLIVET & FACCENNA, 2000). Subduction velocity rapidly increases up to 4 cm/y during the rifting and spreading phases of the opening of the Liguro-Provençal basin.

The progressive increase of subduction velocity during phase II (starting at 35 My ago) can be matched by the results of laboratory experiments simulating the free falling of a slab into the mantle under the effect of gravitational pull and can be fit by the equation (1) (FACCENNA *et alii*, 2001a) (fig. 8).

In particular, this result indicates that the time-scale of the process is highly influenced by choice of the viscosity of the slab/mantle system, but the general trend of the process is respected. Our results also show than when the subduction is gravity-driven in an unrestricted upper mantle the pattern is not sensitive to lower mantle conditions. We observe that after the first phase of shallow- dipping subduction initiation, the gravity-driven slab increases its dip to about 70° while both slab sinking and back-arc opening accelerates (fig. 5). Confirming the laboratory and numerical modeling of BECKER *et alii* (1999), we find that during the free fall descent into the upper mantle the slab length *H(t)* scales exponentially with the load exerted by the subducted lithosphere and resisted mainly by the viscous dissipation due to bending of the oceanic lithosphere at the trench.

Phase III, 16 My-present: interaction slab/transition zone. At about 16 My ago in the absolute time scale in figure 7, the slab hits the 660 discontinuity and impinges in the lower mantle. In the simpler case of a whole, undifferentiated mantle (exp.1; fig. 7), the subducting slab sinks freely into the lower mantle, increasing its depth and the rate of back-arc opening. A single exponential scaling reproduces accurately this behavior, but cannot in any way reproduce the reduction of the rate of subduction recorded 16 Ma ago at the end of the Liguro-Provençal opening, nor the second episode of Tyrrhenian opening. Only a restricted upper mantle convection characterized by a viscosity ratio higher than 10 between lower and upper mantle (exp.2 in fig. 7 and 8) can simulate this process. When the slab reaches and anchors at the 660 km boundary subduction and trench migration stop; then, under the pull of its own weight, the slab/lithospheric system starts to bend laterally attaining an arcuate shape allowing lateral escape of mantle material. From this moment, the lower portion of the subducted lithosphere deforms at depth. After 5 My the slab tip lies horizontally in the transition zone, the locus of back-arc extension jumps trenchward following the new, steep configuration of the slab and subduction and trench migration resume. The experimental curve 2 fits well the geologic timing in figure 8, showing that indeed the episodic trench migration in the Mediterranean can be explained by the interaction between the subducting slab and the transition zone.

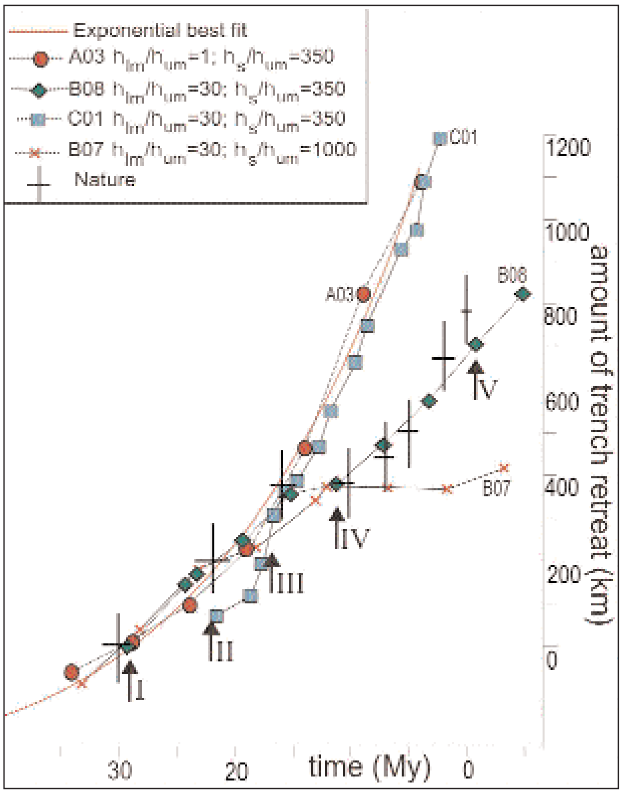

Fig. 8 - *Diagram comparing the geological timing of trench migration in the Central Mediterranean during the last 40 Myr with the results from different models. We show four laboratory experiments (A03, B08, B07, C01) using the scaling rules listed in table 1 (1 Myr corresponds to about 1 min of experiment, and 60 km correspond to 1 cm) and in table 2; the timing of the five snapshots I-V of curve B08 displayed in Figure 7e are marked. We also show the best-fitting exponential curve to experiment A03, simulating a gravity-driven subduction in a homogeneous mantle.*

As illustrated before, the importance of the convection process in restricted mantle configuration is further illustrated by the result of another set of experiments, settled with an unbounded upper mantle circulation: this experiment preserved the general picture but the process increases remarkably its velocity. In particular, the subduction process is interrupted only for few My during the slab-660 km interaction and the final dip of the slab is higher.

In the Central Mediterranean, a partially bounded upper mantle circulation provides a good fit to the timing history of the episodic back-arc opening (exp.2 is marginally slower than the geological curve in figure 8), in agreement with the continuous surface geological signature and with the high-velocity anomaly imaged in the transition zone along the entire Calabrian Arc-Apennine line, but also with the possible partial lateral detachment of the slab proposed for the last evolutionary phase of subduction (WORTEL & SPAKMAN, 2000). We speculate that the formation of the Sicily channel rift zone, for example, could represent the superficial feature of a deep process related to the lateral escape of the mantle material from beneath the slab.

This tectonic model has a number of geological implications.

(i) First, the non-steady evolution of subduction process in the Central Mediterranean founds direct correlation with the evolution of the subduction zone. The phases distinguished here at the scale of the mantle are also reflected in the evolution of the inner orogenic wedge. The exhumation of the high –pressure units are, for example, attained during the maximum acceleration of the extensional process during the opening of the Liguro-Provençal region. This means that the overall re-organization of the subduction process has a direct influence on the evolution of the subduction wedge itself, corroborating previous ideas (JOLIVET *et alii,* 1999). The end of the exhumation event, in fact, corresponds with the stasis of the extensional process that occurred between 16 and 12 Ma. The period of stasis of extension and the re-organisation of subduction process is also recorded by volcanism. The volcanic activity of the arc with a calk-alcaline imprinting, in fact, stopped at the end of the Sardinia-Corsica drifting and is resumed after few million years in the Tyrrhenian region (ARGNANI & SAVELLI, 1999).

(ii) The entrance of the continent at trench, probably attained at 35-40 Ma, did not cause any decrease in the rate of subduction. In fact, soon after the entrance at trench of the small continental margin the subduction process accelerates causing back-arc extension. This fact can be probably justified by the small dimension of the subducting continent compared to the already subducted negatively buoyant oceanic lithosphere. Analytical (RANALLI *et alii,* 2000) and laboratory experiments (REGARD *et alii*, 2003), for example indicate that the only subduction of more than 200-300 km of light continental material material is indeed able to reduce and stop the subduction process.

(iii) The opening of the Sicily channel can be related to the necessity for the mantle to laterally escape from beneath the slab. In fact, the formation (late Messinian-Pliocene) of this rift zone is coeval with the break-up of the Tyrrhenian crust and the acceleration of slab retreat.

The model proposed here bears interesting insights on the way the slab deforms and on the way the mantle convects over the geological time-scale. Our model indicates that the evolution of the subduction process is a non-steady state process punctuated by an intermittent evolution related to the interaction between the slab and the deep mantle layers. In particular, the episodic evolution of back-arc basins is here interpreted as an effect of the restricted convection process related to an increase of viscosity with depth. This idea is in agreement with the finding of different tomographic models that the high velocity anomaly below the Central-Western Mediterranean region is restricted in the upper mantle and lying over the 660-km discontinuity.

The model presented can be used to interpret the gross evolution of the Central Mediterranean slab. We identify the interaction between slab and mantle as the key to interpret the non-steady evolution of the retreating slab and its intermittent behaviour. This model fits the geometry of the slab, as imaged by tomography, and the timescale of the retreating process. In addition, we propose an alternative mechanism to explain the opening of the Sicily channel rift system.

The validity of this model should be tested by other independent data sets. For example, shear wave splitting can shed light on the mantle pathway around the Calabrian slab. In our model, for example, we should expect a strong imprinting of the seismic anisotropy of the mantle with fast polarization that turns around the slab and converges, in western Sicily, towards the Tyrrhenian region. In addition, structural analysis could contribute to constrain the kinematics of the Sicily channel rift system that seems to be characterised by the superimposition of different deformational episodes (CELLO *et alii*, 1985; JONGSMA *et alii*, 1987; GRASSO *et alii,* 1990; ARGNANI*,* 1993). Finally, testing the different phases of evolution of the model as proposed in figure 6 can be also done by including dynamic topography produced by the motion of the slab and its coupling with the mantle, and this can be compared with the curve of subsidence in the southern Tyrrhenian region.

This model with its inherent semplicity does not account for the very recent evolution of the Calabrian subduction zone. During the last 700 kyr the Calabrian arc, in fact, underwent rapid uplift. The GIUNCHI *et alii* (1996) simulation illustrates that uplift of the calabrian arc can be justified by the unlocking of the subduction zone during its retreat. We believe that the reconstruction of the present-day velocity field can reveal if the Calabrian Arc is indeed still retreating at high rate, as it has done during the Pliocene, or most probably, if we are assisting to its final decay.

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