*Mem. Descr. Carta Geol. d'It.*
LXII (2003), pp. 15-46
16 figg.

# Contraints for an interpretation of the italian geodynamics: a review

# *Vincoli per una interpretazione della geodinamica italiana: una revisione*

SCROCCA D. (1), DOGLIONI C. (2), INNOCENTI F. (3)

ABSTRACT - To properly frame the seismic data acquired with the CROP Project, the geophysical and geological characteristics of the Italian region and a review of magmatism are briefly illustrated and commented.

A description of the crustal and lithospheric structure is coupled with a synthesis of the available geophysical data sets, namely: Bouguer gravity anomalies, heat flow data, magnetic anomalies, seismicity, tomography and present-day stress field. Several magmatic episodes with different geodynamic significance occurred in Italy. A review of magmatism in the Alps and in the Apennines is provided; igneous products are distinguished, in the Tyrrhenian and circum-Tyrrhenian region, in relation with the nature of the dominant magmatic source.

Finally, the tectonic evolution of the Alps and the Apennines is synthesised together with a comparison of the main morphological, structural and geodynamic features of these two orogens.

All these datasets highlight a complex geodynamic setting characterised, apart from the relatively stable foreland areas, by two very different orogens: the Alps and the Apennines.

The Alps represent a double-verging orogen with a long lasting geological evolution: this orogen shows a quite well developed lithospheric root and a documented overthrusting of the Adriatic plate over the European plate from Cretaceous to present.

The Apennines are rather a rapidly migrating thrust belt, developed mainly in Neogene times during the eastward roll-back of the subducting Adriatic plate; this orogen is associated with a back-arc basin (Tyrrhenian Sea) characterised in some part by oceanic crust and high heat flow.

KEY WORDS: Geodynamics, magmatism, tectonics, Italy

RIASSUNTO - Per un opportuno inquadramento dei dati sismici acquisiti nell'ambito del Progetto CROP negli ultimi anni, vengono sinteticamente descritte le principali caratteristiche geofisiche, magmatologiche e geologiche della regione italiana.

Le informazioni disponibili sulle struttura crostale e litosferica sono accompagnate da una sintesi dei dati relativi alle anomalie gravimetriche di Bouguer, al flusso di calore, alle anomalie magnetiche, alle caratteristiche sismologiche e al campo di stress attuale.

Inoltre, viene fornita una panoramica degli eventi magmatici che hanno caratterizzato la complessa evoluzione geodinamica della regione in esame. Una particolare attenzione è stata dedicata al magmatismo della regione tirrenica e circum-tirrenica; i prodotti ignei sono stati distinti in relazione alla natura della sorgente magmatica dominante.

Infine, sono state incluse una breve ricostruzione dell'evoluzione tettonica delle Alpi e degli Appenini ed un confronto tra le caratteristiche morfologiche, strutturali e geodinamiche di questi due orogeni.

Tutte queste differenti fonti di dati mettono in luce un quadro geodinamico caratterizzato, a parte le aree di avampaese relativamente stabili, dalla presenza di due orogeni molto differenti: le Alpi e gli Apennini.

Le Alpi rappresentano un orogene con doppia vergenza e una lunga evoluzione geologica; tale orogene è caratterizzato da radici litosferiche abbastanza sviluppate e dal documentato sovrascorrimento della placca adriatica su quella europea, avvenuto dal Cretacico all'attuale.

Gli Appennini, invece, sono una catena in rapida migrazione sviluppatasi prevalentemente durante il Neogene, in risposta all'arretramento flessurale della placca adriatica in subduzione; questa catena è associata con un bacino estensionale di retro-arco (il Mar Tirreno) che presenta in alcune zone una crosta oceanica ed un elevato flusso di calore.

PAROLE CHIAVE: Geodinamica, magmatismo, tettonica, Italia

(1) Istituto di Geologia Ambientale e Geoingegneria - CNR, c/o Dipartimento di Scienze della Terra, Università La Sapienza, P.le A. Moro 5 - 00185 Roma.
(2) Dipartimento di Scienze della Terra, Università La Sapienza, P.le A. Moro 5 – 00185 Roma.
(3) Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria 56 – 56127 Pisa

## 1. - INTRODUCTION

The geology of Italy is a lively system that can be traced from the early Paleozoic Hercynian orogen, throughout the Mesozoic opening of Tethys oceans to the later closure of these oceanic embayments, during the Alpine and Apenninic subductions. In spite of the long standing geological and geophysical studies, many unsolved questions remain about its structure and geodynamic evolution.

The huge amount of new NVR seismic data acquired with the CROP Project (about 1250 km onshore and more than 8740 km offshore) has brought a new valuable input to improve our understanding of this part of the Mediterranean region.

Aim of this contribution is to briefly review the main geophysical and geological features of the Italian region to properly frame this relevant data-set, now available to the scientific community. The final references, only partly cited in the text, are an updated collection of articles which might be helpful to the reader for further studies.

The present day geological and geomorphologic setting of the Italian peninsula is marked by the two orogens, the Alps to the north, and the Apennines along the peninsula and Sicily (fig. 1). Very limited areas in Italy have not been involved by the two orogenic waves, i.e. the Puglia region, part of the Iblean Plateau (SE-Sicily), a few areas in the Po and Venetian plains, and the Sardinia island. These foreland areas, even if not or weakly compressed by the orogenic waves, underwent subsidence or uplift movements connected to the migration of the Alpine or Apenninic fronts.

The present day Apenninic foredeep can be followed on the external side of the Apenninic chain from Southern Apennines to the Po Plain where it interferes with the older Southalpine foredeep.

Furthermore, the Apennines are characterised on their west side by the presence of a back-arc basin, the Tyrrhenian sea, developed from Miocene times.

Before describing the geodynamic and the tectonic evolution of the Alps and the Apennines, the available geophysical and geological data and a review of magmatism will be briefly illustrated and commented in the following chapters.

## 2. - GEOPHYSICAL DATA

### 2.1. - MOHO ISOBATHS

In the last decades several reconstructions of the Moho-discontinuity isobaths, based on seismic data, have been proposed for the Italian area or for part of it (among the others: CASSINIS, 1983; WIGGER, 1984; NICOLICH, 1989; NICOLICH & DAL PIAZ, 1992; NICOLICH, 2001).

Updated interpretation for part of the Italian region have then been proposed for the Alps (KISSLING, 1993; SCARASCIA & CASSINIS, 1997; WALDHAUSER *et alii*, 1998) and for the Ligurian, Tyrrhenian and Ionian Seas and adjacent on-shore areas (SCARASCIA *et alii*, 1994).

Overall, the Italian crust is generally continental apart in the Tyrrhenian abyssal plain where a 10 km thick Late Miocene - Pliocene oceanic crust is present (fig. 2), and in the Ionian Sea, where a Mesozoic oceanic crust is buried underneath a thick pile of sediments (CATALANO *et alii*, 2001).

Stable areas (Sardinia, Adriatic sea and Puglia) have Moho depths at about 30 km while the crust is thicker underneath the Alpine belt (45-55 km) and is thinner in west Tuscany and Latium (20-25 km).

Several different Moho discontinuities may be distinguished: a new forming Neogene-Quaternary Moho with low velocities in the Tyrrhenian basin and western Apennines (Tyrrhenian Moho), an old Paleozoic-Mesozoic Moho in the Padano-Adriatic-Iblean foreland areas (Adriatic Moho), and another Paleozoic-Mesozoic old Moho in the Alpine belt and Sardinia (European Moho). The available data outline a framework where the Adriatic Moho overrode the European Moho in the Alps while the Adriatic Moho underthrust the Tyrrhenian Moho to the south.

### 2.2. - LITHOSPHERE THICKNESS

The properties of the lithosphere-asthenosphere system and their lateral variations were clearly focussed in Italy and surrounding regions during the 1980's (CALCAGNILE & PANZA, 1980; PANZA *et alii*, 1980; PANZA, 1984; SUHADOLC *et alii*, 1990). A map of the lithospheric thickness, compiled by PANZA *et alii*, (1992) and based on an analysis on the surface waves dispersion, is represented in figure 3.

Although the distinction between the new lithosphere in the Tyrrhenian back-arc basin and the old subducting Apulo-Adriatic lithosphere has not been represented in this map, the main features of the lithosphere-asthenosphere system can be easily recognised.

The lithospheric thickness in foreland areas varies from 70 km in the northern Adriatic Sea to about 110 km to the south-east in Puglia. In the Tyrrhenian Sea, lithosphere thickness thins to 20-30 km. Along the Alps belt the lithosphere shows the higher thickness (up to 130 km in western Alps).

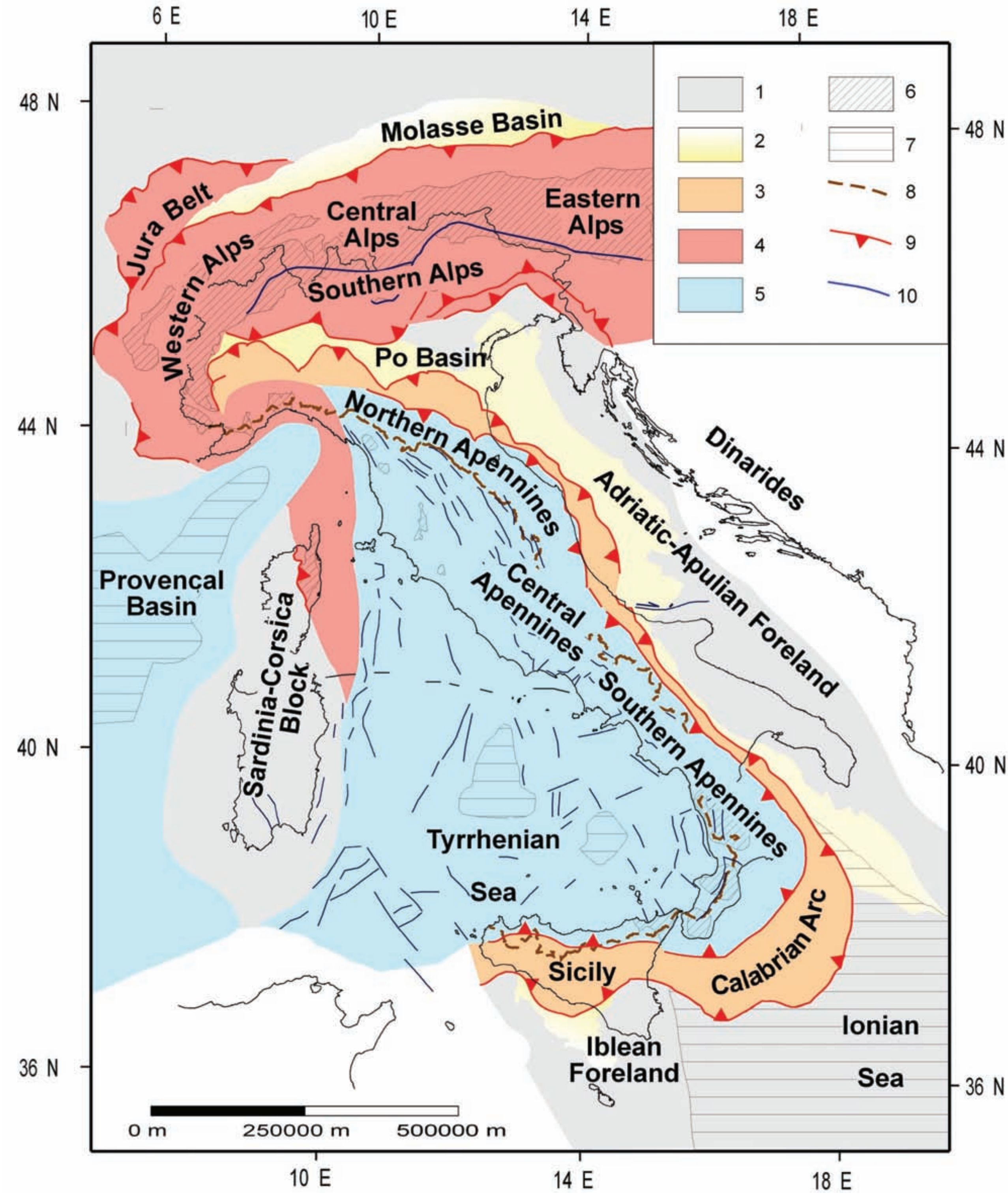


Fig. 1 – Synthetic tectonic map of Italy and surrounding seas; 1) Foreland areas; 2) foredeep deposits (delimited by the –1000 m isobath); 3) domains characterised by a compressional tectonic regime in the Apennines; 4) thrust belt units accreted during the Alpine orogenesis in the Alps and in Corsica;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

*– Schema tettonico dell'Italia e dei mari circostanti. 1) Aree d'avampaese; 2) depositi d'avanfossa (delimitati dall'isobata –1000 m); 3) domini caratterizzati da un regime tettonico compressivo negli Appennini; 4) settori strutturati in catena durante l'orogenesi alpina nelle Alpi e in Corsica; 5) aree interessate da una tettonica estensionale; queste aree possono essere considerate come un sistema di bacini retro-arco sviluppati in risposta all'arretramento flessurale della subduzione appenninica; 6) affioramenti del basamento cristallino e delle unita' metamorfiche alpine; 7) regioni caratterizzate da crosta oceanica; una crosta oceanica di neo-formazione è stata riconosciuta nel bacino provenzale (di età miocenica) e nel bacino tirrenico (di età plio-pleistocenica) mentre la presenza di una vecchia crosta oceanica mesozoica è ipotizzata per il bacino ionico; 8) spartiacque appenninico; 9) sovrascorrimenti principali; 10) faglie indifferenziate.*

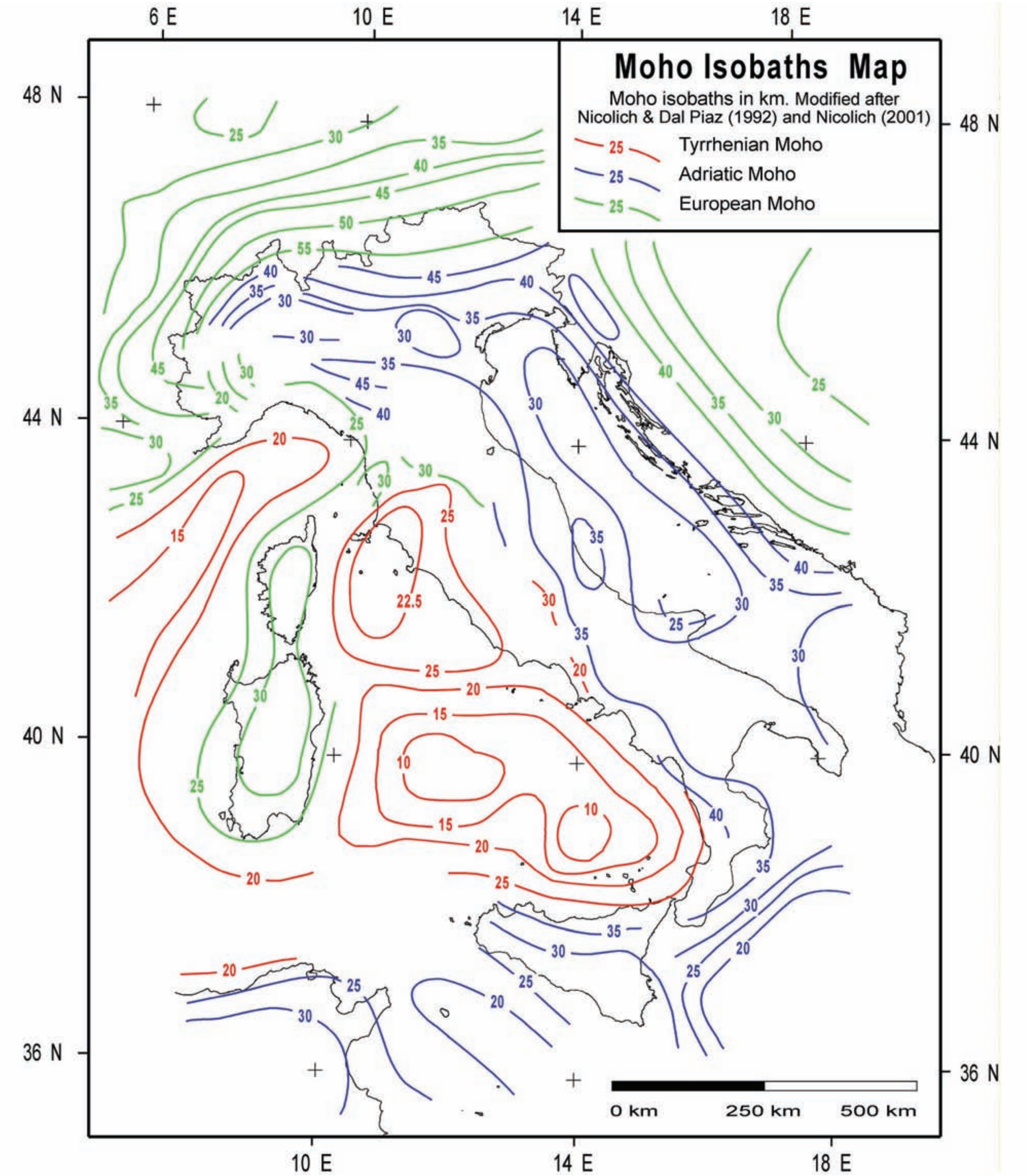


Fig. 2 – Moho Isobaths Map (modified after NICOLICH & DAL PIAZ, 1992 and NICOLICH, 2001). Three different Moho can be recognised: a new Neogene Moho (with low velocities) below the back-arc basins (Tyrrhenian Moho), an old Mesozoic Moho in the Apulo-Adriatic foreland areas (Adriatic Moho), and another old Moho below the alpine thrust belt and the Sardinia-Corsica block (European Moho).

*– Mappa delle isobate della Moho (modificata da NICOLICH & DAL PIAZ, 1992 e NICOLICH, 2001). Tre tipi di Moho differenti possono essere riconosciuti: una nuova Moho neogenica (caratterizzata da basse velocità) al di sotto del bacino di retro-arco (Moho tirrenica), una vecchia Moho mesozoica nei domini dell'avampaese apulo-adriatico (Moho adriatica) e una vecchia Moho al di sotto della catena alpina e del blocco sardo-corso (Moho europea).*

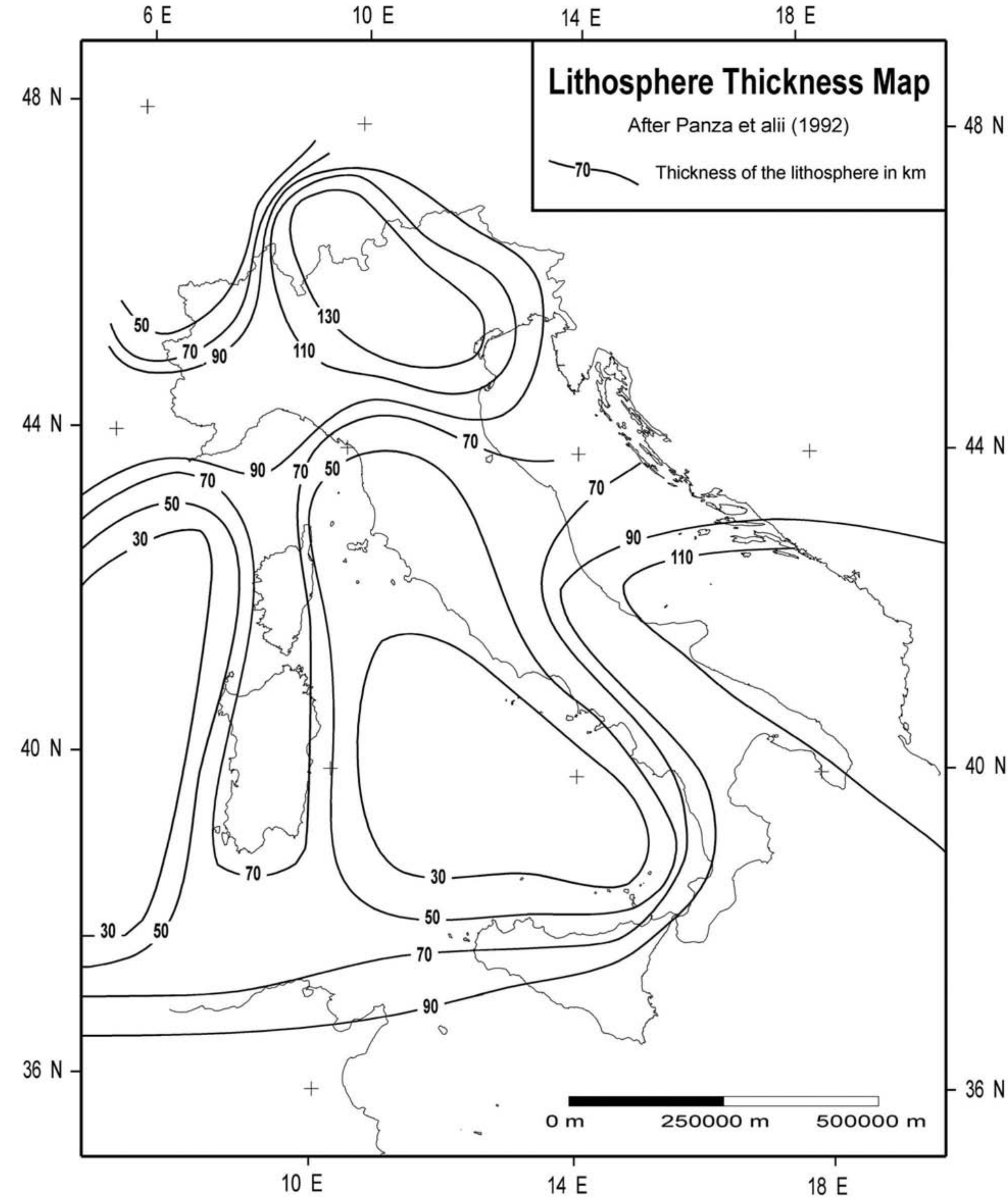


Fig. 3 – Lithosphere Thickness Map (after PANZA *et alii*, 1992). In this map the main features of the lithosphere-asthenosphere system can be recognised although the distinction between the new lithosphere in the back-arc basins (about 30 km thick) and the old subducting lithosphere (about 70-110 km in the apulo-adriatic foreland) has not been represented.

*– Mappa degli spessori litosferici (da* PANZA et alii*, 1992). Le principali caratteristiche del sistema litosfera-astenosfera possono essere riconosciute nonostante non sia rappresentata la distinzione tra la nuova litosfera nel bacino di retro-arco tirrenico (circa di 30 km di spessore) e la vecchia litosfera apulo-adriatica in subduzione (circa 70-110 km di spessore).*

Thicker lithospheric roots for the Alps (up to 200-220 km) has been proposed, using a different techniques, by BABUSKA *et alii* (1990) though, according to KISSLING (1993), the applied approach may led to over-speculative results.

### 2.3. - BOUGUER GRAVITY ANOMALIES

After the first realisations of Bouguer gravity maps for the Italian region (e.g. BALLARIN, 1963, MONGELLI *et alii*, 1975; SERVIZIO GEOLOGICO NAZIONALE, 1989), a recent compilation of data can be found in the Gravity Map of Italy (CNR, 1992), where a reduction density of d=2.4 g/cm$^3$ was used (fig. 4).

The main features observable in this map are: the positive gravimetric Bouger anomaly in Piemonte along the Ivrea-Verbano zone, the high positive anomalies that characterise the Tyrrhenian sea, and the alignment of negative gravimetric anomalies all along the Apenninic foredeep.

It is worth noting the clear shift between negative anomalies and topographic highs in the Apennines (MONGELLI *et alii*, 1975).

### 2.4. - HEAT FLOW DATA

Temperature distribution at depth and surface heat flow represent relevant factors that affect the physical properties of rock and the deformation processes of the lithosphere.

During the last decades several measurements of deep temperatures and surface heat flow have been carried out; on this base several heat flow maps have been compiled for Italy and surrounding regions (e.g. MONGELLI *et alii*, 1991; DELLA VEDOVA *et alii*, 1995 and references therein). An accurate heat flow map accompanied by new temperature maps at various depth have been produced by CATALDI *et alii*, (1995). Recently, DELLA VEDOVA *et alii* (2001) have published a new heat flow map trying to discriminate areas characterised by major contributions due to near-surface processes (fig. 5).

Heat flow values are very high (up to 200 mW/m2 or more) in the Tyrrhenian Sea and Western Apennines, particularly in Tuscany, while values decrease to 30-40 mW/m$^2$ in the foreland areas (Po Plain, Adriatic coast and Ionian Sea).

### 2.5. - MAGNETIC ANOMALIES DATA

In Italy, a systematic acquisition of magnetic data, both on-shore and off-shore, dated back to the 1970's. These magnetic surveys were developed both by AGIP and by scientific institutions (e.g.: OGS, CNR, ING) bringing to the release of different maps, sometimes showing relevant differences due to different acquisition methodology or data processing.

On one side, AGIP acquisition consisted in a series of aeromagnetic surveys and ended up with the compilation of an "Aeromagnetic map of Italy" (CASSANO *et alii*, 1986; SERVIZIO GEOLOGICO NAZIONALE, 1994). On the other side, the research activities produced through time several maps based on different data-set or data processing techniques (PINNA, 1987; MOLINA *et alii*, 1994; CHIAPPINI *et alii*, 2000).

### 2.6. – SEISMICITY

Seismicity in Italy is distributed all around the Alps and the Apennines. Few epicentres are located also in active areas in the foreland (offshore Puglia, north of the Gargano promontory) and in the southern Tyrrhenian Sea, where several intermediate and deep earthquakes occur (fig. 6).

Due to the rich historical documentation in Italy, several databases have been compiled to integrate all the available data about historical seismicity. One of the last compilation is represented by: "Catalogo Parametrico dei Terremoti Italiani", edited by some of the main institutions involved in seismological studies in Italy (CNR, ING, GNDT, SSN, SGA); it has been released in 1999 (http://emidius.itim.mi.cnr.it/CPTI/home.html).

Depth distribution of the south Tyrrhenian Sea earthquakes define an almost continuous Wadati-Benioff zone down to about 500 km that can be correlated with the subduction of the Ionian oceanic lithosphere (CAPUTO *et alii*, 1970; ANDERSON & JACKSON, 1987; GIARDINI & VELONÀ, 1991). Deep earthquakes and tomographic studies outline a quite steep slab (about 70° towards NW) with a tickness of about 80 km (SELVAGGI & CHIARABBA, 1995).

Also below the Northern Apennines some subcrustal earthquakes (depths < 100 km) have been recorded, suggesting a still active subduction (SELVAGGI & AMATO, 1992).

Available focal mechanism data (e.g. MONTONE *et alii*, 1999) show predominant normal faulting earthquakes all along the Apennines most elevated ridges, while thrust faulting is observed in the eastern Alps and in the external part of the Apennine accretionary prism (fig. 7).

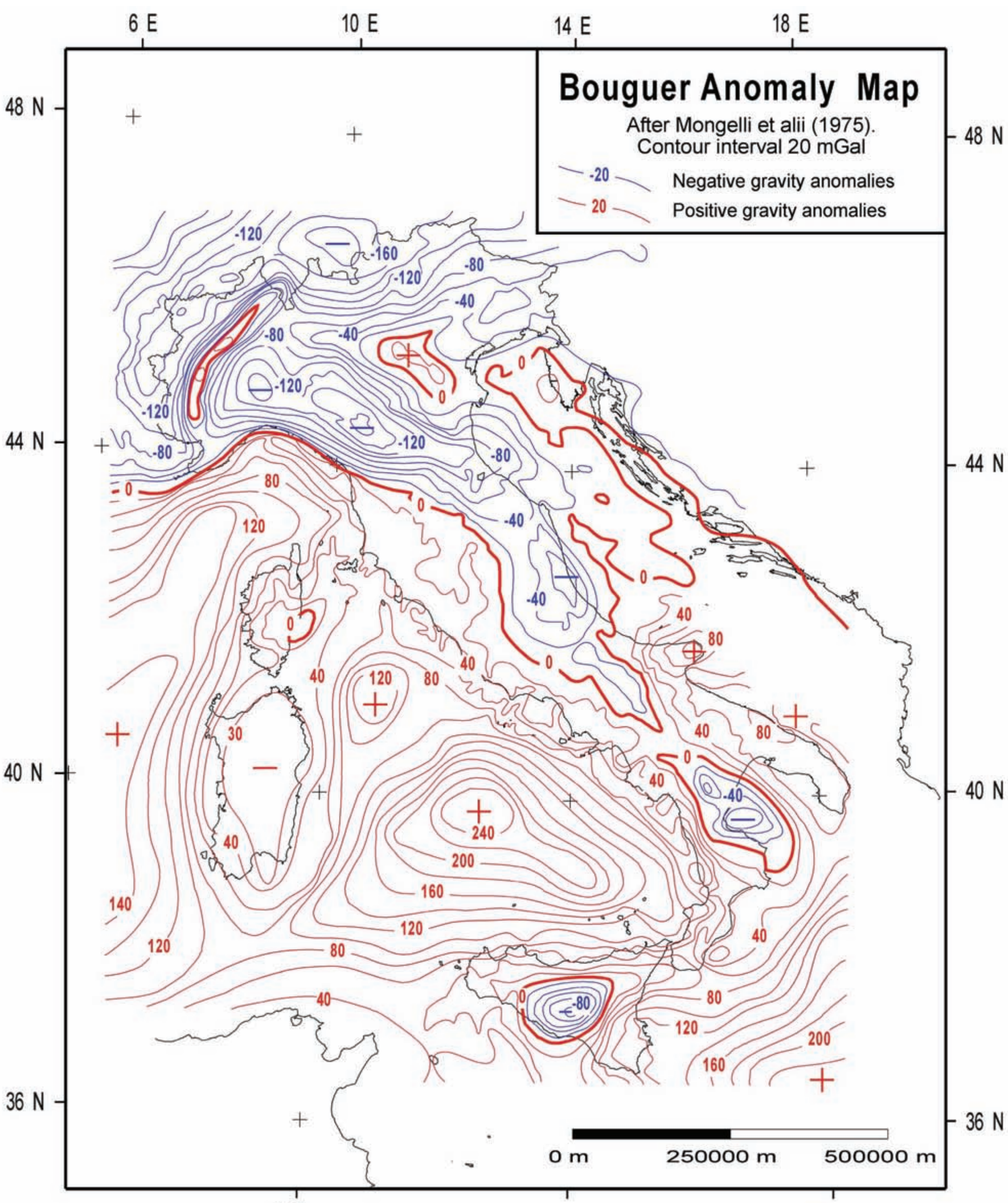


Fig. 4 – Bouguer gravity anomaly map (after MONGELLI *et alii*, 1975).
– *Mappa delle anomalie gravimetriche di Bouguer (da* MONGELLI et alii*, 1975).*

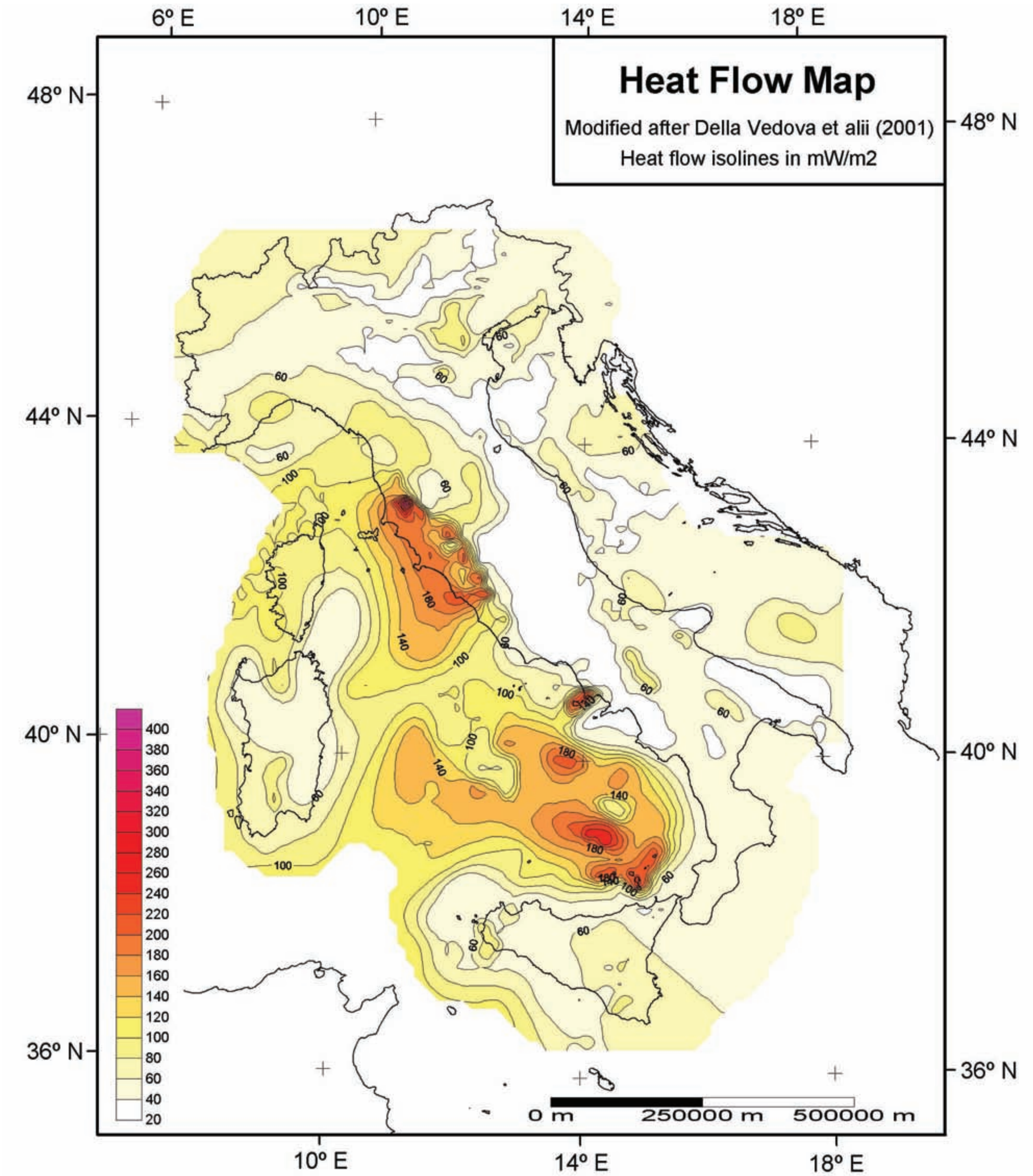


Fig. 5 – Heat flow map (modified after: MONGELLI *et alii*, 1991; CATALDI *et alii*, 1995; DELLA VEDOVA *et alii*, 2001).
– *Mappa del flusso di calore (modificato da: MONGELLI* et alii*, 1991; CATALDI* et alii*, 1995; DELLA VEDOVA* et alii*, 2001)*

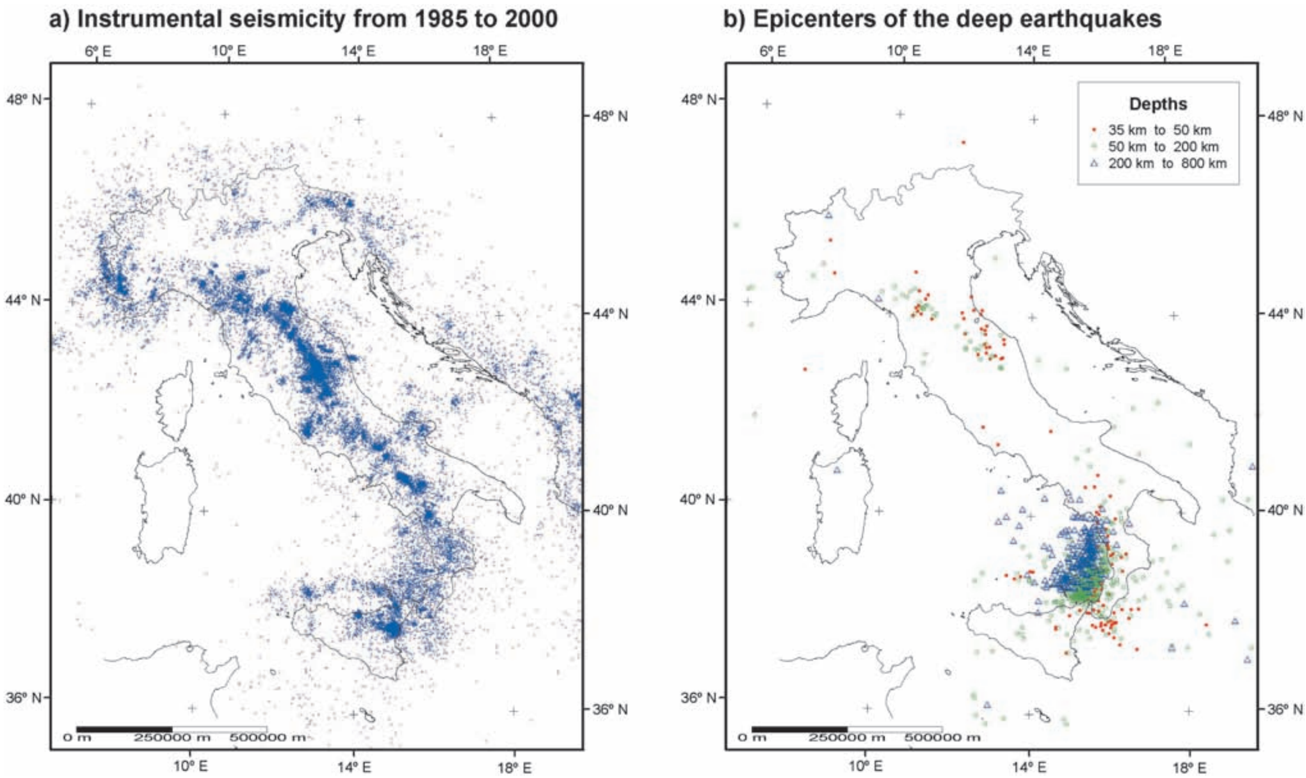


Fig. 6 – a) Epicentral map of the instrumental seismicity recorded between 1985 and 2000; b) epicenters of the deep eartquakes (depths > 35 km). Data according to VALENSISE & PANTOSTI (2001).

– *a) Distribuzione degli epicentri della sismicita' strumentale registrata tra il 1985 ed il 2000; b) epicentri dei terremoti profondi (profondita' > 35 km). Dati originali ripresi da* VALENSISE & PANTOSTI *(2001).*

## 2.7. - TOMOGRAPHY

Since the early 1990's, a better definition of the deep structure beneath the Italian region was provided by the development and the application of the modern tomographic techniques.

The tomographic images were elaborated either with an analysis, for the whole Mediterranean region, of huge amounts of bulletin regional and teleseismic data (SPAKMAN, 1990; SPAKMAN *et alii*, 1993; PIROMALLO & MORELLI, 1997) or, for the Italian peninsula, with a smaller quantity of more precise teleseismic data (AMATO *et alii*, 1993, 1998; LUCENTE *et alii*, 1999; AMATO & CIMINI, 2001).

High velocity anomalies are generally observable below the Alps, the Northern Apennines and the Calabrian arc, suggesting that the Adriatic continental lithosphere and the Ionian oceanic lithosphere are subducting westward almost vertically underneath the Apennines (fig. 8).

On the base of the weaker high velocity anomalies detected in their tomographic models below the Southern Apennines, the quoted Authors proposed different reconstructions of the deep structure of this part of the Apennines. AMATO *et alii*, (1993) and LUCENTE *et alii* (1999) speculate the presence of a "slabless window" at shallow depth (above 250 km) below the Southern Apennines, while SPAKMAN (1990) and SPAKMAN *et alii* (1993) suggest the existence of a continuous high velocity slab at depth, detached from its upper part except below the Calabrian arc. A slab break-off has been also suggested by topographic analysis (GVIRTZMAN & NUR, 2001). However, detailed tomographic studies focussed on the Southern Apennines (DE GORI *et alii*, 2001) have pointed out the presence of an almost continuos sub-vertical high velocity body, extending from 65 km down to 285 km, interpreted as Adriatic lithosphere in subduction beneath the Southern Apennines. According to DE GORI *et alii* (2001) the hypothesised "slabless window" was due to the poor resolution of previous studies in the shallow part of their models.

## 2.8. - STRESS FIELD MAP

Another useful information to better frame the geodynamic evolution of the Italian peninsula is represented by the present-day stress field. Recently, MONTONE *et alii* (1999) have published a new map of the active stress in Italy based on data obtained with different methodologies (mainly borehole

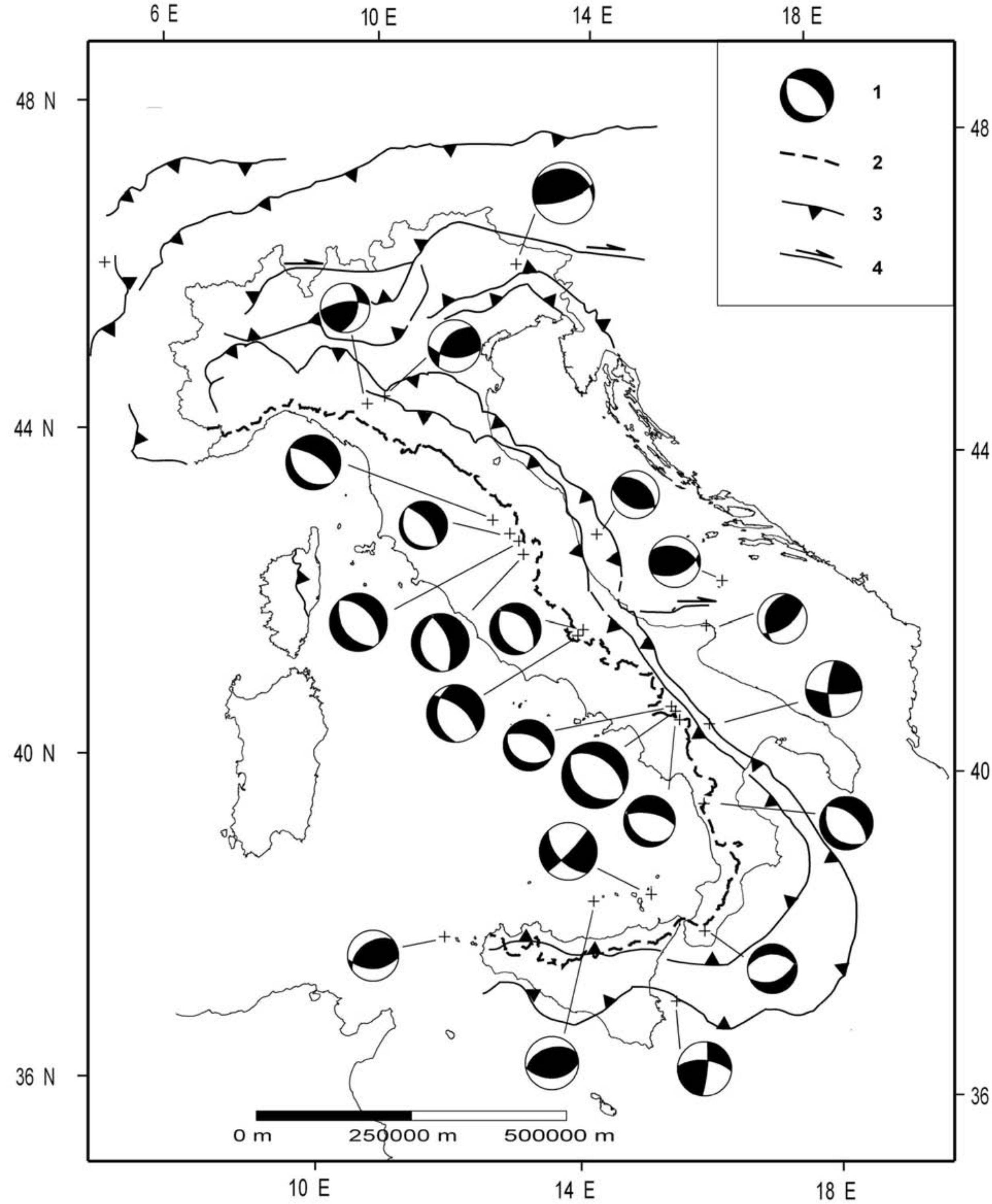


Fig. 7 – CMT solutions for great earthquakes in Italy (modified after MONTONE *et alii*, 1999). 1) CMT fault plane solutions; 2) Apenninic water divide; 3) thrusts; 4) wrench faults.

– *Soluzioni CMT per forti terremoti in Italia (modificata da* MONTONE et alii*, 1999). 1) Soluzione CMT; 2) spartiacque appenninico; 3) sovrascorrimenti; 4) faglie trascorrenti.*

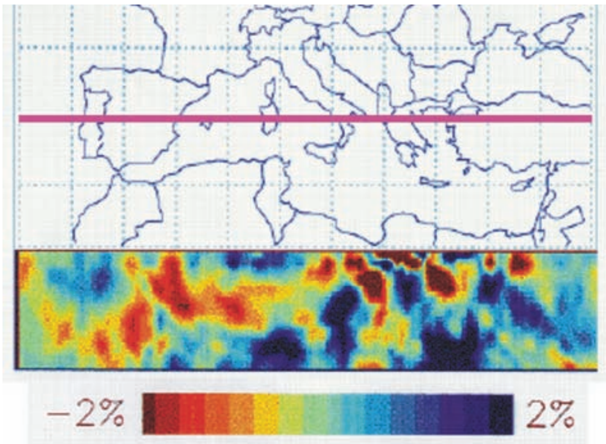


Fig. 8 – Tomographic image of the Italian region (after PIROMALLO & MORELLI, 1997). Top: profile location. Bottom: P-wave velocity structure in percent deviation from reference velocity model. Regardless the continuity of the slabs, which might be function of the reference velocity model, a steep high velocity body beneath the Apennines can be recognised.

*– Immagine tomografica della regione italiana (da PIROMALLO & MORELLI, 1997). In alto: ubicazione del profilo analizzato. In basso: sezione tomografica. Tralasciando le problematiche relative alla dibattutta continuità dello slab in subduzione, che può essere funzione del modello di velocità di riferimento adottato, nella sezione risulta evidente al di sotto degli Appennini un corpo molto inclinato ad alta velocità.*

breakouts and earthquakes fault plane solutions) and relative to different depth interval and tectonic units. Nevertheless, these data sets show a quite consistent picture characterised by the following first-order patterns (fig. 9).

Extensional tectonics affect large part of the Apennines, with vertical maximum stress and mainly NW-trending faults. A compressional regime is pointed out in the Eastern Alps and along the outer side of the Northern Apennines and in the Southern Tyrrhenian – northern Sicily area.

Unlike to previous stress compilations (PHILIP, 1987; REBAI *et alii*, 1992), in the stress map compiled by MONTONE *et alii* (1999) the Southern Apennines are characterised by an almost homogeneous stress field (AMATO & MONTONE, 1997) with a northeast directed minimum horizontal stress that, according to seismological data, is coincident with the $\sigma 3$ (AMATO & MONTONE, 1997). No clear evidences of NE oriented compression is reported in this map for the Southern Apennines, in spite of deformed Pleistocene sediments at the accretionary prism toe (PIERI *et alii*, 1997), and compressive focal mechanisms detected in the Matese area by MILANO *et alii* (1999).

## 3. - PALEOGEOGRAPHIC FRAMEWORK

The stratigraphy of Italy reflects the geodynamic evolution of the central Mediterranean. The Late Permian to Cretaceous sequences recorded the rifting and drifting history of the Tethys margins.

In particular, the geological units that form the present day Italian peninsula were mainly part of the passive margins of the western and northern Adriatic plate during the opening of the western Tethys or Ligure–Piemontese oceanic basin. Remnants of the European continental margin and of the Tethys oceanic domain can be identified in the Alps: examples of the first are the Helvetides while the Pennides are constituted by ophiolites and pelagic deposits of the Piemontese and Valais oceanic basins and by the interposed Briançonnais continental crust.

These margins underwent both tensional and transtensional tectonics: the typical basal succession with red beds, evaporites and carbonates gradually evolved through time.

During Permian and Triassic, in the Southern Alps, a general marine transgression towards the west resulted in fluvial continental facies covered by sabkhas, lagoons, shallow marine deposits, terrigenous infill, and volcanic episodes. In the Dolomites and Carnian Alps (Eastern Southern Alps), spectacular examples of atoll-like Ladinian and Carnian carbonate platforms prograding over adjacent coeval basins are very well exposed. After the deposition of terrigenous clastics and of peritidal sediments during Late Carnian times, the Late Triassic was characterised by the deposition of peritidal shallow water carbonates. Shaly interposed thick basins occurred in the Lombard Basin. Tensional or transtensional tectonics during the Late Permian-Triassic times controlled subsidence rates on horsts and grabens, and facies developments.

In the Apennines, the late Triassic is also represented by the Verrucano red beds and the Burano Anhydrite, an evaporitic layer seat of many Apenninic decollements. Cherts, limestones and marls deposited in the Southern Apennines in deep water conditions during the Upper Triassic (Lagonegro Basin).

During Jurassic times (BERNOULLI *et alii*, 1979; BERNOULLI, 2001), oolitic Bahamas-type carbonate platforms developed along the passive continental margin. Extensional tectonics affected broader areas and new basins formed. Early Jurassic basinal embayments in the Southern Alps and in the Apennines were filled by pelagic deposits made up of marls; during Middle-Late Jurassic nodular red limestones, cherts and carbonate resediments deposited in the same basins (fig. 10). At the end of Jurassic, three main paleogeographic environments were present:

1) an oceanic domain where radiolarites and basinal limestones were deposited above ophiolites (e.g. the Piemontese basin and the Ligure basin and possibly part of the Lagonegro basin which could have been the northward thinned passive continental margin prolongation of the present day Ionian Sea);

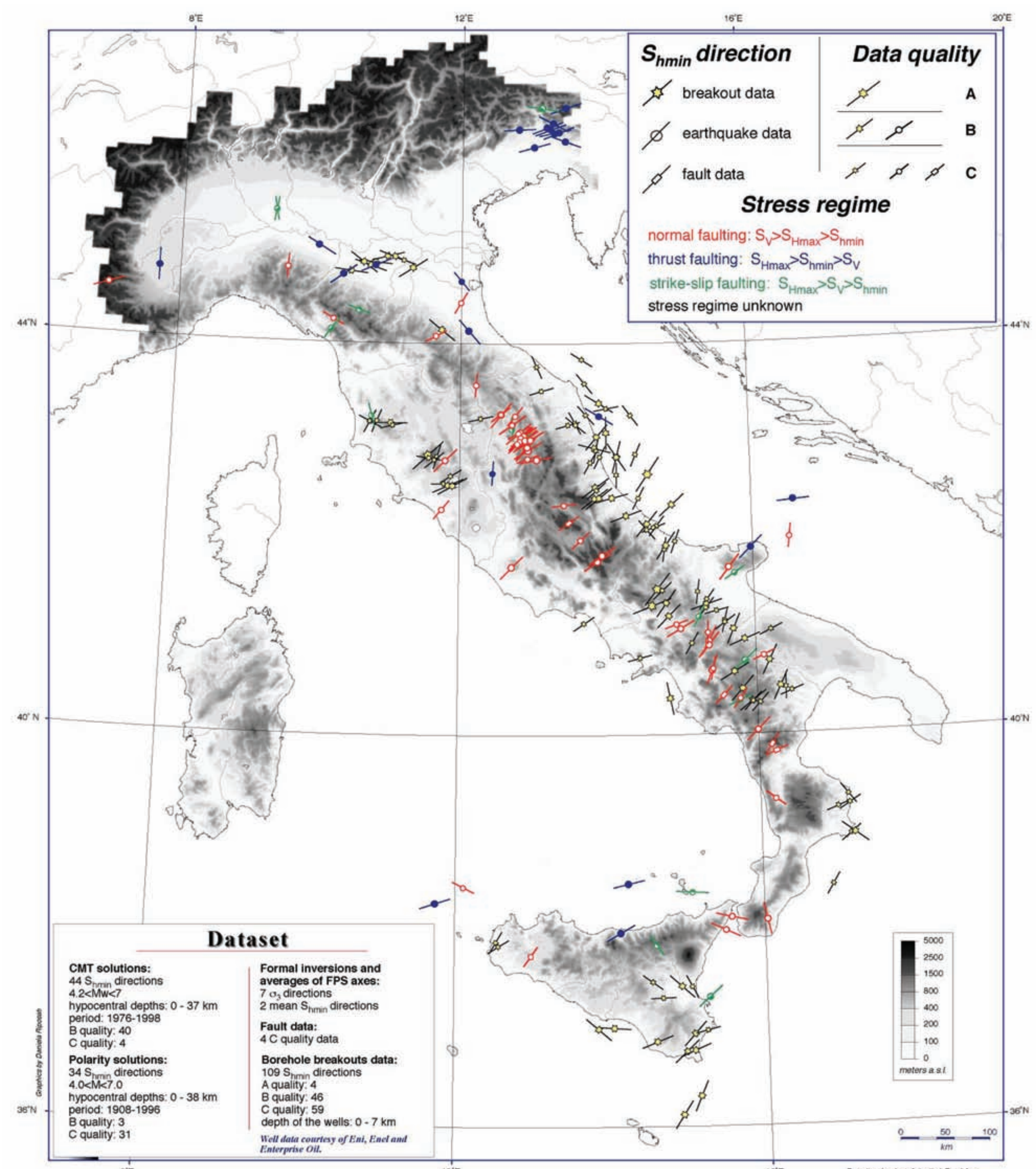


Fig. 9 – Active stress map of Italy (after MONTONE *et alii*, 1999), with minimum horizontal stress orientation (σ2 or σ3).
– *Mappa del campo di stress attivo in Italia (da* MONTONE et alii*, 1999), con orientazione dello stress minimo orizzontale (σ2 o σ3).*

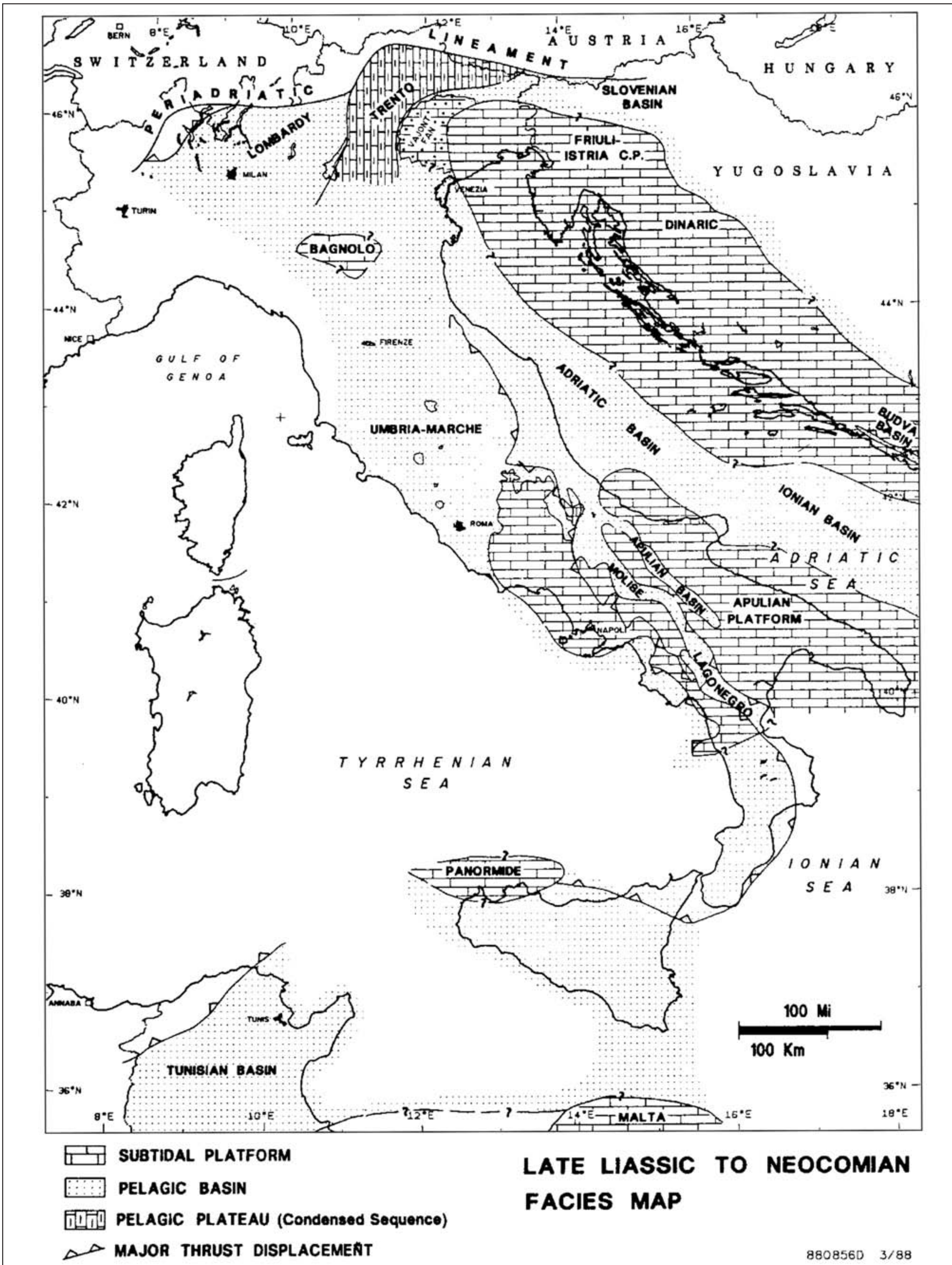


Fig. 10 – Late Liassic-Neocomian paleogeographic map (after ZAPPATERRA, 1990).
*– Mappa paleogeografica riferita al Lias superiore-Neocomiano (da ZAPPATERRA, 1990).*

2) a basinal domain following foundering of the continental margin, where carbonate pelagic and hemipelagic sedimentation dominated with deeper areas alternating with seamounts, showing condensed sedimentary section;
3) wide shelves characterised by a deposition of shallow marine carbonates. Some of the residual carbonate shelf areas persisted throughout the Cretaceous like the Apulian platform, the Friuli platform, and the Apenninic platforms.

Apulian plate, or African promontory, is a synonymous of Adriatic plate. The connection with Africa has been generally proposed on the basis of the paleomagnetic data showing a similar apparent polar wander path of the Adriatic Mesozoic values with those interpreted for Africa. However, the opening of the Ionian Sea during the Early Jurassic-Cretaceous had to generate an independent Adriatic plate with respect to Africa at least during the growth of the Ionian oceanic basin. The Ionian Sea is floored by 8-11 km of oceanic crust (De Voogd *et alii*, 1992) and 6-8 km of sedimentary cover of Mesozoic and Tertiary age. Low heat flow values (<40 mW/m2) and a thick lithospheric mantle (70-90 km) suggest an old age for this oceanic embayment. The Malta escarpment offshore east Sicily and the Salento offshore, southwest Puglia, appear to be two conjugate passive continental margins of Mesozoic age (Catalano *et alii*, 2001). As a consequence, the Ionian Sea in a section between Sicily and Puglia should be a complete oceanic section containing an aborted oceanic ridge of Mesozoic age whose relief is lost by thermal cooling and hidden by thick pelagic deposits, ranging in age from Jurassic to Tertiary, and by the overlapping Apennines thrust sheets. In this view, the continental extension that evolved to form the oceanic crust in the Ionian Sea should have began at least during the Triassic, a very early history of the Ionian rift.

## 4. - MAGMATISM

Several magmatic episodes with different geodynamic meaning occured in Italy.

Older magmatic episodes are related to the Hercynian orogeny, developed between Devonian and Early Permian times. A late orogenic calcalkaline magmatic phase during Late Carboniferous - Early Permian generated abundant granitic batholiths or plutons (e.g. Mont Blanc, Monte Rosa in the Western Alps, Baveno in the western Southern Alps, Doss del Sabion, Brixen and Cima d'Asta in the Dolomites, central-eastern Southern Alps, Barbagia and Gallura granites in Sardinia, Sila and Serre in Calabria, etc.) and ignimbritic effusions as those of the Piastrone Porfirico Atesino in Trentino-Alto Adige (central Southern Alps). The only sector of the outcropping Hercynian orogen not or little superimposed by the Alpine or Apenninic thrust belts is situated in Sardinia; it has also been drilled in some wells in the Adriatic plate.

### 4.1. - The Apennines magmatism

The magmatism related to the Apenninic orogenic cycle developed since Mesozoic up to present. The Mesozoic igneous products are found as: i) intraplate alkaline volcanism sparsely recorded in the Jurassic carbonate sequence in southern Tuscany and in the Mesozoic sedimentary units of the Pelagian block (Boccaletti & Manetti, 1972; Rocchi *et alii*, 1998); ii) as ophiolitic units in Northern Apennines, Corsica and Calabria, representing relicts of Jurassic oceanic crust formed by thinning and rifting of continental lithosphere that eventually generated an oceanic basin (the Ligure-Piemontese basin). The ophiolitic suites testify the occurrence of a MORB seafloor similar to the present normal oceanic crust (the so-called Northern Apennines Internal Ligurides) together with a peri-continental Proterozoic mantle covered by Jurassic MORB volcanics (External Ligurides) (Rampone & Piccardo, 2000).

Alkaline intraplate, OIB-type magmatism of Maastrichtian to Paleogene age is sporadically found in carbonate units of the Adria plate (e.g. Eocene melasyenite and melagabbros of Punta delle Pietre Nere). However, the first igneous products related to the Africa-Europe convergence are of Oligocene age and occur as volcanoclastites in synorogenic turbidites in Northern Apennines or as portion of well-developed magmatic arc in Sardinia (Serri *et alii*, 2001), due to the W-directed Apennine subduction.

In the Northern Apennines during the Lower Miocene, after the closure of the Ligurian basin, the Alpine continental collision lasted, whereas in the Southern Apennines-Calabria the oceanic subduction switched from the Alpine E-directed to the Apennine W-directed, with the consumption and roll-back of the oceanic Ionian lithosphere. Thus, along the Apennine chain, after Miocene times the nature of the subducting slab varied from continental (Northern and Southern Apennines) to oceanic (Calabria), to continental again (Sicily). The features of magmatism in Tyrrhenian and circum-Tyrrhenian region reflect the complexity of the

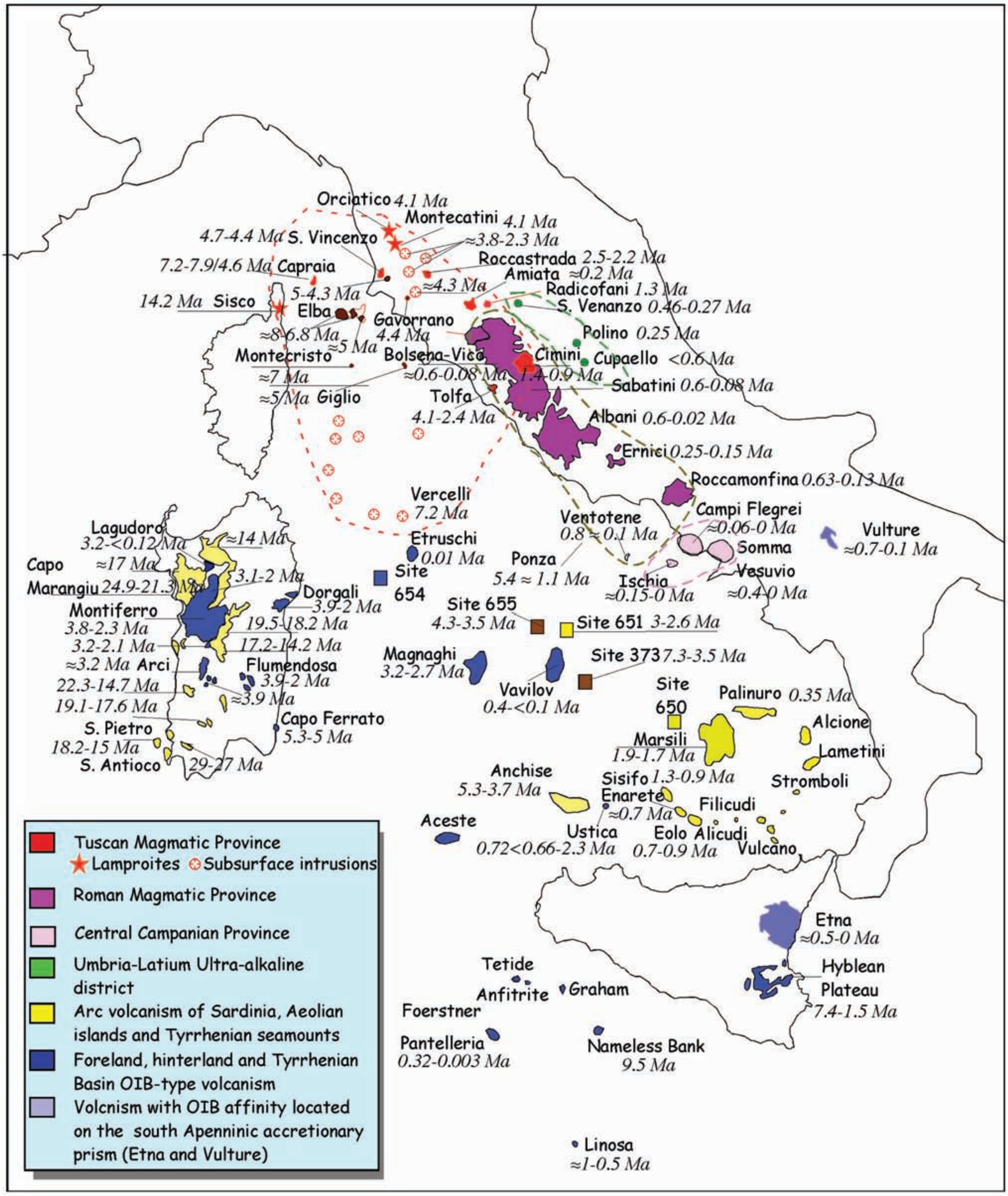


Fig. 11 – Distribution of Cenozoic igneous products in Tyrrhenian and circum- Tyrrhenian region. Dashed lines include the products of the Tuscan Magmatic Province (red), Roman Magmatic Province (brown), Umbria-Latium ultra-alkaline District (green) and Central Campanian Province (pink).

*– Distribuzione dei prodotti ignei Cenozoici nella regione Tirrenica e circum-Tirrenica. Le linee tratteggiate in rosso, marrone, verde e rosa includono i prodotti, rispettivamente, delle Province Magmatiche Toscana, Romana, del Distretto Ultra-alcalino Umbro-laziale e della Provincia Centro-campana.*

geodynamic context, exhibiting a great variability of petrogenetic affinity. Figure 11 show the distribution of the igneous products of mainly Neogene-Quaternary age distinguished in relation with the nature of the dominant magmatic source, largely following the interpretation of SERRI *et alii* (2001). From north to south, the following sectors are recognized:

1) Tuscan Magmatic Province (TMP) (INNOCENTI *et alii*, 1992), which includes igneous products of northern Corsica (Sisco), the Tuscan Archipelago, northern Tuscany and Latium (Mt. Cimini and Tolfa). The Province comprises also the not exposed acidic plutons of northern Tyrrhenian Sea and western Tuscany.
2) Roman Magmatic Province (RMP) (WASHINGTON, 1906) includes: volcanic systems of Vulsini, Vico, Sabatini, Colli Albani, Ernici and Roccamonfina.
3) Umbria-Latium Ultra-alkaline District (ULUD) (STOPPA & LAVECCHIA, 1992) which comprises the explosive and effusive products generally derived by the low-volume monogenic volcanoes of San Venanzo, Cupaello and Polino.
4) Central Campanian Province (CCP), where the Campanian volcanic centres of Campi Flegrei, Somma-Vesuvio and Ischia are included (SERRI *et alii*, 2001).
5) Southern Apenninic-Calabrian Arc-System (SAAS) and Tyrrhenian Basin (TB) comprehending the volcanic products of the active volcanic arc of Aeolian Islands and Tyrrhenian seamounts, the calc-alkaline Miocene products of Sardinia and those drilled in central Campania.
6) African-Adriatic Foreland (AAFL) and European Hinterland (EHL). This sector includes the igneous products of Hyblean Plateau in eastern Sicily, the exposed and submerged volcanoes of Sicily Channel and the Pliocene alkaline volcanics from Sardinia, located in the EHL. This association comprises also the two volcanoes, i.e. Mt. Etna and Mt. Vulture, both placed on the accretionary prism toe of the Apennines.

The TMP constitutes the most complex and time extended magmatic association of the whole Apenninic Arc. The dominant products are represented by a late Miocene complex of nested Christmas-tree laccoliths in central and western Elba (DINI *et alii*, 2002; ROCCHI *et alii*, 2002), by the shallow plutons exposed in Tuscan Archipelago and Campiglia, or buried in southern Tuscany, (FRANCESCHINI *et alii*, 2000; GIANELLI & LAURENZI, 2001) and by the plutons identified as submarine relieves or sediment-covered intrusions in northern Tyrrhenian Sea (ZITELLINI *et alii*, 1986). These rocks are S-type, peraluminous granitoids varying in age between late Miocene and Pliocene. Minor occurrences of rhyolites and trachydacites are considered as the early Pliocene (San Vincenzo) and Pleistocene (Mts Cimini and Mt. Amiata) counterparts of the intrusive magmatism.

Petrological and geochemical features of the intrusive bodies reflect mixing processes between melts generated in the crust (dominant) and basic magmas of mantle origin. Rocks with composition similar to pure crustal melts have rarely been identified: f.i. laccoliths of leucogranites in Isola d'Elba and Isola del Giglio (WESTERMAN *et alii*, 1993; DINI *et alii*, 2002); rhyolites of S.Vincenzo (FERRARA *et alii*, 1989) and Roccastrada (PINARELLI, 1991).

The petrogenetic affinity of mantle-derived component is difficult to be defined. In the case of granitoid rocks of Tuscan Archipelago, isotopic and geochemical data suggest that the mantle magma had a composition similar to the Miocene subalkaline magma erupted in the Island of Capraia, which is considered derived by mantle-wedge melting during the subduction phase of Adria Plate (DINI *et alii*, 2002; POLI, 1992). Mixing processes are also dominant in the eastern Quaternary products of TMP (Mt. Amiata and Mt. Cimini) for which it has been assumed a basic end-member formed by a potassium-rich magma (PINARELLI, 1991). Therefore, it seems that subcrustal magma, interacting with continental crust, changes geochemical features with time, becoming more alkaline and potassium-rich.

In TMP, mafic products with lamproitic affinity, characterized by relatively high silica content, high Mg#, high Ni and LILE contents, have also been found. They are considered to have been generated in the lithosphere at relatively low depth by a residual mantle which underwent a contamination by upper crust materials (CONTICELLI & PECCERILLO, 1992; PECCERILLO, 1999).

Products of RMP are extended from Vulsini to the north down to Roccamonfina and Ventotene to the south. These Pleistocene products typically include potassium-rich undersaturated rocks containing leucite (high potassium series, HKS, APPLETON, 1972, or undersaturated trend of SERRI *et alii*, 1993). The most primitive rocks are fairly rich in CaO and $Al_2O_3$ with low $TiO_2$ and high LILE contents, and show well-defined Ta and Nb negative anomalies in spider diagrams. Products of the undersaturated trend are locally associated to nearly saturated rocks with lower $K_2O$ contents (potassium series, KS, APPLETON, 1972 or saturated trend, of SERRI *et alii*, 1993), as for example at Ernici and

Roccamonfina. Geochemical and isotopic data suggest that primitive rocks of the undersaturated trend (HKS) were related with fertile mantle, metasomatised by components deriving from subducted K-rich crustal material; whereas, products of the saturated trend (KS) could have been formed from a geochemically similar source to that which generated HKS but at lower depth (PECCERILLO & PANZA, 1999) or by a phlogopite-rich harzburgitic mantle probably confined in the mechanical layer of the lithosphere (SERRI *et alii*, 2001).

CCP rocks were erupted from the active volcanic complexes of Somma-Vesuvio, Campi Flegrei and Ischia-Procida. They include ultra-alkaline, leucite-rich undersaturated products, and K-alkaline saturated rocks (both undersaturated and saturated trends). Available data suggest distinct geochemical features of CCP rocks with respect to RMP products, consistent with an origin from a dominant fertile OIB-type source, probably contaminated by terrigenous subducted sediments (BECCALUVA *et alii*, 1991; AYUSO *et alii*, 1998) even if some isotope data, especially derived by the Hf-Nd systematics, suggest that the crustal component was dominated by pelagic sediments (GASPERINI *et alii*, 2002).

Circum-Tyrrhenian arc volcanism comprises the active arc of the Aeolian Islands, several seamounts localised in the Tyrrhenian Basin at N and NW of the active arc and the Miocene products from Sardinia. These latters represent the relict of a magmatic arc, varying in age between 32 and 13 Ma, which was formed as a consequence of W-directed subduction of oceanic lithosphere (BROTZU, 1997). The Sardinia volcanics constitute an association dominated by calc-alkaline products which are associated, especially in the southern part of the island, to high-K calc-alkaline rocks and tholeiites (DOSTAL *et alii*, 1982; DOWNES *et alii*, 2001). Submarine volcanic centers of Burdigalian-Langhian age have been found offshore in south-western Corsica and are considered as belonging to the Sardinia arc system (SERRI *et alii*, 2001).

The Aeolian active arc is constituted by seven islands and by numerous seamounts which enlarge it towards east and west. The arc structure can be divided in two main sectors by the NNW-SSE alignment of Vulcano, Lipari and partly Salina islands; the eastern sector (Panarea and Stromboli) is shifted toward south with respect to the western one (Alicudi, Filicudi and Salina). Erupted products form a complex association including tholeiitic, calc-alkaline, high-K calc-alkaline, shoshonitic and potassic rocks (FRANCALANCI *et alii*, 1993). Leucite-bearing alkaline rocks are mainly localized in the eastern sector of the structure, and dominate the most recent products (<0.1 Ma) and those actually erupted at Stromboli and Vulcano. The depth of the Benioff plane underneath the islands is estimated around 200-300 km. A great number of seamounts occur on the inner arc and on its western extension; they represent relicts abandoned during southeastward arc migration, considered as a consequence of the roll-back of the Ionian oceanic lithosphere (SERRI *et alii*, 2001). The western side of the arc is marked by the occurrence of the Island of Ustica, formed by Na-alkaline rocks deriving from a mantle source with a well-defined OIB affinity but slightly modified by a subduction-related component (CINQUE *et alii*, 1988). The occurrence of OIB-like volcanism inside the Aeolian arc system is still an open geodynamic problem.

Based on geochemical and isotopic data, rocks from Aeolian arc are generally interpreted as deriving from the super-slab mantle wedge, geochemically heterogeneous and variously enriched by a subduction component. Potassic rocks of Stromboli reflect a complex petrogenesis: in fact they are considered by some authors (e.g., PECCERILLO & PANZA, 1999) to be generated by a mantle source geochemically similar to that of Vesuvio and Campi Flegrei, whereas others suggested that their geochemical features derive from a source modified by a component related to the subducted sediments (e.g., ELLAM *et alii*, 1988) and/or by a major involvement of continental lithosphere (TONARINI *et alii*, 2001).

Since late Miocene the Africa foreland was affected by an OIB-type igneous activity, which is essentially localized between the Sicily Channel and the eastern margin of Sicily (Iblean Plateau).

The volcanics in Sicily Channel are related to the main grabens of the area and have been erupted from different centers which originated Pantelleria and Linosa islands, and numerous submarine relieves or banks. The volume of emitted products is relatively modest, therefore the rift system has to be considered a low volcanicity continental rift. Products of Pantelleria and Linosa form a slightly alkaline series, ranging in composition from alkali-basalts to peralkaline rhyolites (pantellerites), while in the northern part of the area dredged rocks have a more variable composition ranging from basanites to tholeiites (CALANCHI *et alii*, 1989). This volcanism, which is still active (Foernster and Graham Bank), began in the late Miocene (9.5 Ma, Nameless Bank; BECCALUVA *et alii*, 1981) and reached its maximum intensity during Plio-Pleistocene.

In Sicily, the oldest products of the Iblean Plateau have been dated back to late Miocene (7.5 Ma), while the youngest to early Pleistocene (~1.7 Ma; TRUA *et alii*, 1997). The eruption rate is generally low (<~70 $km^3$/Ma), with a peak of activity during Plio-Pleistocene (about 280 $km^3$/Ma; ROCCHI *et alii*, 1998). The erupted products are relatively primitive and show compositions ranging from highly alkaline (nephelinites, basanites, alkali-basalt) to subalkaline (tholeiites); their geochemical and isotopic features suggest an origin from the lower part of the lithosphere (TBL) enriched heterogeneously by infiltrations of low-grade astenospheric melts (BECCALUVA *et alii*, 1998). Such metasomatic mantle process, probably associated to $CO_2$-rich fluids, is also testified by the composition of mantle xenoliths found in Miocene tuff-breccia and diatremic-pipes, and in some Quaternary alkaline lavas from the northern margin of the Iblean Plateau; moreover the evolution of Nd and Sr isotopes suggest that metasomatic process developed between 100 and 200 Ma (TONARINI *et alii*, 1996).

Products with a marked OIB affinity also occur in the hinterland of the Apenninic Chain, in the hangingwall of the Apennines subduction. Such Plio-Pleistocene activity is mainly localized in Sardinia where extensional tectonics developed in relation with the opening of South-Tyrrhenian Basin. This includes two smaller basins (Vavilov and Marsili basins) floored by oceanic crust and varying in age between 4.5 and 1.8 Ma, to which are associated big seamounts as Magnaghi, Vavilov, and Marsili mainly generated by OIB-MORB transitional sources.

Volcanic rocks of Sardinia belong to tholeiitic, transitional and alkaline series with intraplate affinity; they are associated to large volcanic complexes (Montiferro and Mt. Arci), basaltic plateau (central and central-western Sardinia), or to small monogenic centers (f.i. Capo Ferranto). Geochemical and isotopic data indicate the occurrence of an heterogeneous enriched mantle showing an evident HIMU imprint, which is considered plume-derived (GASPERINI *et alii*, 2002) or alternatively to an astenospheric mantle modified by a subduction-related component (LUSTRINO *et alii*, 2000).

Two important volcanoes, Etna and Vulture (fig. 11), stand out among the products with intraplate affinity of the southern Apennine. They show very peculiar structural position and geochemical features. In fact, both volcanoes are localized on accretionary prism close to important lithospheric discontinuities of the subducting plate (DOGLIONI *et alii*, 2001).

The activity of Mt. Etna began since 500 Ky ago and, after an initial phase marked by tholeiitic rocks, has produced slightly Na-alkaline volcanics with a prevalence of hawaiitic terms; such products made up different nested edifices which have shifted from east to west until Mongibello, which is presently active. Structural and geochemical data suggest that the source of Etnean magmas is represented by astenospheric mantle risen as consequence of the formation of a slab-window generated by larger roll-back of the oceanic ionian plate with respect to the continental sicilian one (DOGLIONI *et alii*, 2001). The distribution of mobile elements in the fluid phase and the isotopic composition of B, Sr and Nd support the hypothesis that a mantle source was contaminated by $H_2O$-rich fluids derived by the adjoining Ionian plate (TONARINI *et alii*, 2001).

Vulture is a Quaternary strato-volcano characterized in the summit area by the occurrence of a caldera partially obliterated by a flank failure and the presence of two recent maar structures (GUEST *et alii*, 1988; LA VOLPE & PRINCIPE, 1991; STOPPA & PRINCIPE, 1998). The basal activity is essentially ignimbritic and dated back around 0.7 Ma. Erupted products are highly undersaturated and include basanites, tephrites, foidites, phonolites, and trachytes, with hayuna as typical feldspatoid; melilitites and carbonatites are minor occurrences. During the youngest phase of activity, around at 0.13 Ma, a violent explosive hydromagmatic phase occurred which generated the carbonatitic and melilitic tuffs (STOPPA & WOLLEY, 1997); calcite–carbonatitic intrusive ejecta have been found in older pyroclastic units (ROSATELLI *et alii*, 2000). The genesis of Vulture products is still unclear, even though available geochemical data support the hypothesis of derivation from a OIB-type mantle source, modified by a subduction related component (DE FINO *et alii*, 1986; MELLUSO *et alii*, 1996; BECCALUVA *et alii*, 2002). Overall, the geochemical features of Etna and Vulture volcanoes and their resembling structural position express a comparable geodynamic significance.

### 4.2. - THE ALPINE MAGMATISM

Igneous rocks of the Alpine domain are mainly related to the Hercynian and Alpine orogens, even if minor occurrence attributed to the Caledonian orogenesis have been recognized. Late Carboniferous-Permian calc-alkaline granitoid plutons are widespread from western to central Alps (f.i. Mont Blanc, Monte Rosa, Baveno to Doss del Sabion, Brixen and Cima d'Asta in the Dolomites) and are associated with large ignimbrite covers in central Southern Alps. All these products are part of the alpine crystalline basement involved by the alpine thrusts (DOGLIONI & FLORES, 1997).

In Triassic times, a relatively widespread magmatism developed in the Southern Alps; it is recorded as: i) magmatic clasts and tuff layers in Anisian-Ladinian sandstones ("Pietra verde" in NE Friuli); ii) subvolcanic bodies sometimes passing to true volcanic facies, as lava flows and lava breccia intercalated in Triassic marine sedimentary sequences, iii) plutons and dyke swarms (from Brescian Prealps, Val Trompia and Val Camonica, and from Recoaro to Predazzo-Monzoni area in the Dolomites). In spite of intense alteration process affecting the rocks of this association, it has been recognized a variable composition ranging from calc-alkaline to shoshonites. A calc-alkaline suite with composition ranging from andesites to rhyolites has been identified mainly in the "Pietra Verde" succession, whereas K-rich shoshonitic products are found in a southernmost belt from Brescian Prealps to Dolomites. These latters are dominated by shoshonitic basalts, shoshonites and latites with minor trachytes or by their intrusive equivalents (PISA *et alii*, 1979; SLOMAN, 1989; CORAZZATO *et alii*, 2001). The geodynamic context in which the Triassic association developed is enigmatic. In fact, the entire association displays a subduction-related geochemical signature as stressed by the high LILE/HFSE ratios and by the Nb, Ta and, in a lesser extent, Zr, Hf and Ti negative anomalies in the MORB-normalized spidergrams (SLOMAN, 1989), even if evidence of a Triassic convergent system are considered meager. Thus, two main models have been put forward. The former considers the igneous association as an orogenic magmatic arc (CASTELLARIN *et alii*, 1979; CASTELLARIN *et alii*, 1988), expression of the southward subduction of European plate. The latter model claims that igneous activity is related to a Triassic rifting tectonic phase (BECHSTADT *et alii*, 1978; CORAZZATO *et alii*, 2001) possibly preceding the Jurassic oceanic opening; thus, the orogenic geochemical imprinting of erupted products could have been produced in the mantle source by a pre-triassic subduction episode (SLOMAN, 1989).

The oldest igneous products related to orogenic Alpine cycle are represented by remnants of the Jurassic oceanic lithosphere separating the European plate from Africa-Adria (Ligurian Tethys) and forming ophiolitic units partially preserved mainly in the western Alps (e.g. LEMOINE *et alii*, 1987). Such units are metamorphic, since they have been involved in the Alpine subduction (Cretaceous) and the subsequent continental collision; furthermore, they contain either fragments of the Ligurian oceanic crust and parts of subcontinental upper mantle, exhumed as consequence of the rifting preceding the opening of the Ligurian Tethys, as documented also in northern Apennines (PICCARDO *et alii*, 1997; RAMPONE & PICCARDO, 2000).

The magmatism strictly related to the Alpine Orogenesis developed essentially in the Eocene-Miocene interval. Middle Eocene-Oligocene products of andesitic-dacitic composition have been drilled in various wells at the margin of the Po Plain (POLINO *et alii*, 2001). Traces of an extensive volcanic activity are also found as andesitic clasts and volcanoclastic layers in the external Alpine flysches (Taveyanne sandstones; RUFFINI *et alii*, 1995b) and intercalated in the sedimentary sequence of Tertiary Piedmonte Basin and Monferrato (RUFFINI *et alii*, 1995a). The volcanic centers generating the explosive, mainly subaerial, volcanism are not found in surface; nevertheless, they have been identified as plurikilometric subsurface edifices, under the Po plain, by geophysical methods (CASSANO *et alii*, 1986). Overall, these products are generally strongly altered; however, the phenocryst assemblages and the glass relics reveal an orogenic association whose petrogenetic affinity varies from calc-alkaline to shoshonitic/ultrapotassic (D'ATRI *et alii*, 1999), resembling that of the dykes and plutons emplaced in Southern Alpine domain (DAL PIAZ *et alii*, 1988). The intrusive and subvolcanic bodies are located along the Insubric tectonic lineament and display emplacement ages spanning from Early Eocene to Lower Miocene, with a climax between 29 and 32 Ma (VON BLANCKENBURG & DAVIES, 1995). The geochemical features of these products indicate a subduction-related affinity, with a minor influence due to crustal contamination, at least in the more primitive mantle-derived rocks (WILSON & BIANCHINI, 1999).

Intraplate volcanism occur in the South-Eastern Alps from Late Paleocene to Late Oligocene extending from Lessini Mts. to Marostica and Berici Hills up to Euganean Hills (DE VECCHI & SEDEA, 1995; ZANTEDESCHI, 1994). The four districts are roughly NNW-SSE trending. Scarcely differentiated mafic lavas dominate in the Lessini, Marostica and Berici areas, where Na-alkaline basalts, basanites, nephelinites and minor subalkaline tholeiitic basalts are present, sometimes including mantle xenoliths (SIENA & COLTORTI, 1989). In the southernmost area (Euganean Hills) more evolved products, up to trachytic and rhyolitic composition, were erupted after an early phase characterized by the presense of basic rocks with alkaline, transitional and tholeiitic intraplate affinity (MILANI *et alii*, 1999).

## 5. - TECTONIC EVOLUTION

The inversion of relative motion between European and Adriatic plates began during Cretaceous (PFIFFNER *et alii*, 1997; POLINO *et alii*, 1990) and generated compression at the western margin or dextral transpression at the northern margin of the Adriatic plate (LAUBSCHER, 1983).

The development of the Alps is due to the thrusting toward the west and north-west of the Adriatic plate over the European plate while the Apennines have been generated by the subduction of the Adriatic plate toward the west. The spatial and temporal evolution of the Alps and later of the Apennines during the Tertiary is recorded by the clastic sediments, flysches and molasse, which overlaid diachronously the earlier passive margin sequences. Alpine and Apenninic foredeeps were fed by the relative orogens and migrated through time with the coeval lateral migration of thrust belts.

### 5.1. - ALPS

The main paleogeographic units of the Alps are from northwest to southeast: Helvetides, Pennides, Austroalpine and Southern Alps (figs. 1, 12). The last two were part of the Adriatic continental margin, to the south and east of the Tethys, while the first two are made up of fragments of the European margin and of the Tethys ocean.

The convergence in the Alps began during the Early Cretaceous with the subduction toward the east or southeast, underneath the Austroalpine and Southern Alps continental lithosphere, of the oceanic embayment interposed between the European and Adriatic margin. The first nappes formed during this early deformation called eo-Alpine phase. Blue schists and eclogites facies recorded this eo-Alpine HP/LT event in the Penninic and Austroalpine units of the western Alps at 130-40 Ma. This is considered the prograde part of the alpine metamorphic P-T-t path.

The collision with the overthrusting of the Adriatic plate over the European plate is dated at the Eocene, and it is referred as the meso-Alpine phase. The convergence continued with high intensity during the Neogene (neo-Alpine phase), and it is still active as indicated by the deformation of Plio-Pleistocone sequences and the present seismicity.

Austroalpine and Penninic units are thrust-sheets arranged in antiformal stack duplexes, with a strong ductile component. Stretching lineations show mainly E-W component of the slip vectors during Cretaceous and Eocene times. Thrusts and ductile milonitic zones are generally folded. The Southern Alps show instead a more brittle deformation, with thrust planes arranged with classic imbricate fan geometries. Austroalpine and Southern Alps are separated by the Insubric Line, a composite feature active at least since the Oligocene.

The roughly E-W segments of the Insubric Line are characterized by dextral transpression during Oligocene and Neogene, whereas the oblique NNE-SSW segments are thrusts or conjugate antithetic sinistral Riedel shears (Canavese and Giudicarie Lines). The E-W striking central Eastern Alps and Southern Alps are considered the right lateral transpressive arm of the Alpine orogen.

The Penninic units can be interpreted as the ophiolitic remnants of the Piemontese oceanic basin. The Dora Maira, Gran Paradiso and Mt. Rosa areas represent the "internal" massifs of the Alpine edifice, whereas the "external" Alpine massifs are the Argentera, Pelvoux-Belledonne (in France), Mt. Blanc and Aar-Gottardo (in Switzerland). The internal massifs are basement nappes of the Adriatic continental margin (Austroalpine), whereas the external massifs are basement nappes of the European continental margin (Helvetides). Penninic units of the Tauern window (e.g. calceschists) outcrop in northern Alto-Adige.

The Southern Alps show a general S-SE vergence. The other Alpine units are vergent toward the European plate, westward and northwestward. The Southern Alps have an inherited Mesozoic architecture from west to east, the Canavese zone (transition with the ocean Tethys or Ligure-Piemontese to the west), the Lugano horst, the Lombard basin, the Trento horst, the Belluno basin, and the Friuli platform (fig. 12).

These schematic subdivisions are sometimes a misleading mixture of paleogeographic and paleostructural features. In fact the term platform indicates shallow water carbonate platform environment, which may or may not have drowned during the Middle Jurassic (e.g. the Trento Platform, where the Liassic carbonate platform is covered by the pelagic Ammonitico Rosso). Thickness variations of the sedimentary cover which more precisely identify horsts and grabens also occur within the former main paleogeographic units. Toward the east the Vardar ocean was also bordering the Adriatic plate. These Mesozoic features were mainly N-S trending, and have been cut obliquely by the Southern Alps thrusts.

The Giudicarie belt, in the central Southern Alps, is a major structural undulation characterized by sinistral transpression occurred at the hinge zone

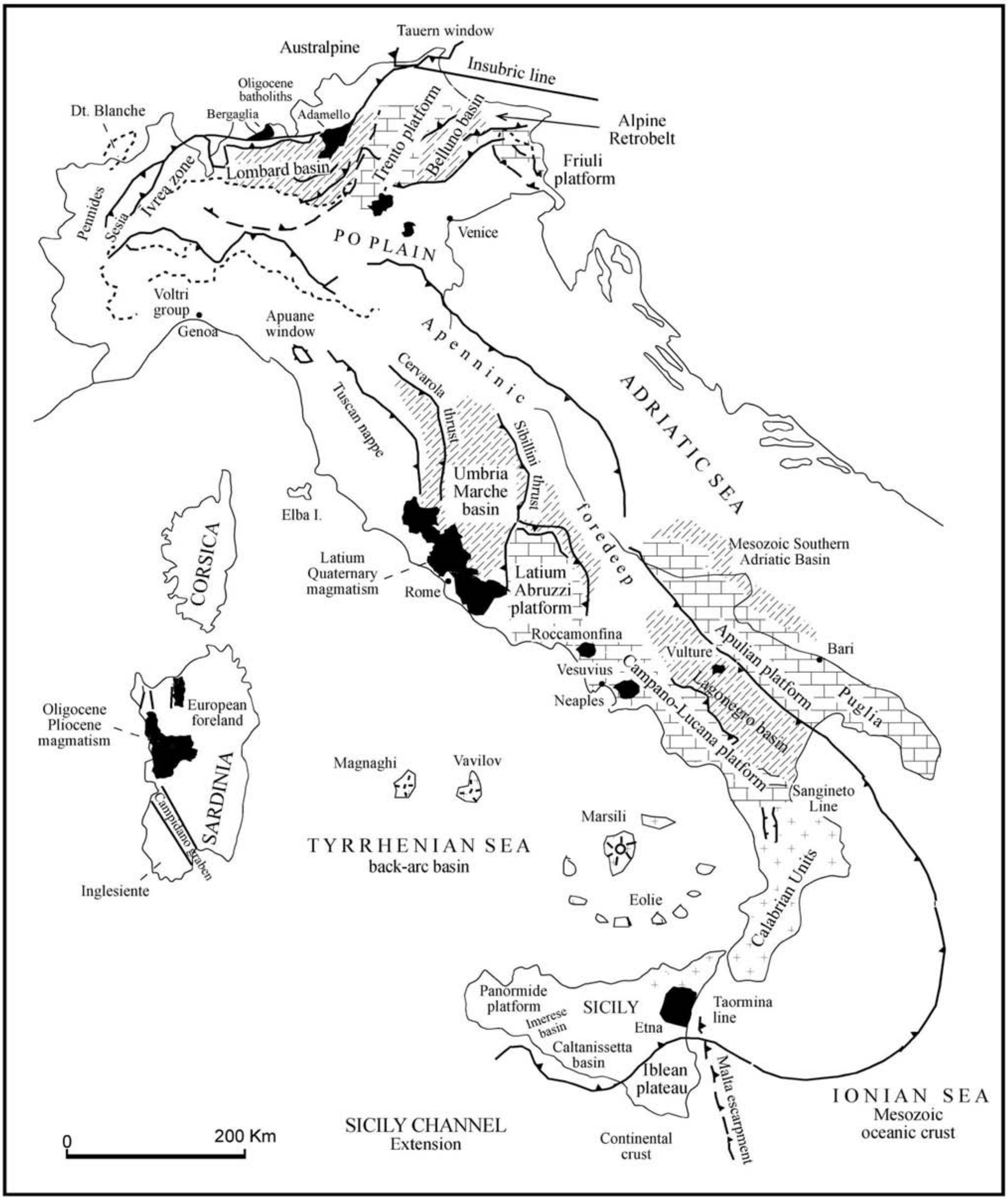


Fig. 12 – Location map of the main paleogeographic and structural units mentioned in the text.
*– Posizione delle principali unità paleogeografiche e strutturali citate nel testo*

between the Mesozoic Trento platform to the east and the Lombard basin to the west.

Since the onset of the inversion, from passive to active continental margin, the paleogeographic zones changed their configuration, and the foredeep of the Southern Alps formed in an E-W trend. To the east of the Southern Alps, during Late Cretaceous and Paleogene, the Alps interfered with the Dinarides, an orogen due to the underthrusting of the Adriatic plate under the eastern European plate, after the consumption of the interposed Vardar ocean (an eastern arm of the Tethys ocean). Eocene thrusts and foredeep of the NNW-SSE trending Dinarides are preserved in north-eastern Italy. The western front of the Southern Alps is buried underneath the Po Plain, due to the southward tilting operated on the orogen by the advancing wave of the Apenninic foredeep (DOGLIONI, 1993).

### 5.2. - APENNINES

The Apenninic history follows the "Alpine" evolution until the Late Eocene. They underwent a similar Mesozoic paleogeography and later inversion but during the Oligocene a W-dipping subduction started to the east of the Alpine belt, east of the Sardinia-Corsica, before and during its counterclockwise rotation (GUEGUEN *et alii*, 1998).

During the Neogene, the Apennines accreted the sediments of the Adriatic plate Mesozoic passive continental margin, and of the Ionian oceanic basin associated to the eastward roll-back of the subduction hinge (MALINVERNO & RYAN, 1986; PATACCA & SCANDONE, 1989). The Apennines migrated northeastward in the Northern Apennines, eastward in the Central and Southern Apennines, and southeastward in Calabria and Sicily (figs. 1, 12).

The main Mesozoic paleogeographic and structural subdivisions in the Apennines are the following (figs. 10, 12). In the northern part, from west to east, the Ligurian basin (largely oceanic) and the Tuscan zone with platform facies until the Liassic, followed by pelagic sedimentation like in the adjacent Umbro-Marchigiano basin. To the south-east is the Latium-Abruzzi platform. In the southern Apennines, from west to east, the main paleogeographic zones are the Western (or Apennine) platform, the Lagonegro-Molise basins and the Apulian platform. To the east of the Apulian platform another basin developed during the Mesozoic (e.g. the East Gargano basinal sediments), and this was coeval to the opening of the southern Adriatic basin (BERTOTTI *et alii*, 2001).

The forward propagation of thrusts piled up the paleogeographic domains, having in the hangingwall of the thrusts units originally located westward relative to the footwall, e.g. the Liguride units thrusting the Tuscan nappe, which in turn was thrust onto the Cervarola unit, mainly composed of foredeep sediments, having in the footwall the Umbro-Marchigiano basin. To the south, the Campano-Lucana platform was thrust onto the Lagonegrese pelagic units, which in turn was thrust onto the Apulian platform. This setting occurred because thrust planes were running in some cases parallel to the pre-existing paleogeographic zones. In Sicily similar Mesozoic subdivisions are indicated by the Panormide platform, Imerese basin, Trapanese platform, Sicanian basin, Saccense, and Iblean platforms. The Trapanese, Saccense and Iblean carbonate platforms drowned to pelagic facies during the Middle Jurassic (CATALANO *et alii*, 1993).

Like in the Alps, the inversion due to the subduction regimes generated new paleogeographic zones superimposing with different angles the earlier subdivisions: e.g. the Plio-Pleistocene Apenninic foredeep, running from Monferrato in Piemonte, through the Po Plain (fig. 1), the Adriatic sea, the Bradanic trough, the Ionian sea, and the Caltanissetta basin in Sicily.

The Alpine units in Calabria and NE Sicily are bounded by the Sangineto Line to the north in Calabria, and by the Taormina Line in NE Sicily (Peloritani). Apart those Calabrian and Sicilian outcrops, the basement in the Apennines is visible in the Apuane window, in the Montagnola Senese, Elba Island, Argentario (Tuscany), and in other smaller outcrops on the west coast.

The Apennines are cross-cut by several grabens developed, starting from Neogene times, during the eastward migration of an extensional tectonic wave.

The main steps of the Apennines evolution may be considered the Eo-Alpine phase (Cretaceous) and Liguride phase (Paleocene-Eocene), with Alpine W-vergence and structural style, and the Sub-Liguride phase (Oligocene). The Tuscan phase (Tortonian) is considered the one during which the main nappes emplaced (Ligurides, Tuscan nappe, Cervarola nappe); during the Tuscan phase the Apuane area underwent metamorphism. However, the Apennines continued to move throughout the Pliocene and Pleistocene, with a frontal active accretionary wedge and an internal elevated ridge in extensional regime.

Several problems concerning Apenninic paleogeography are still open, e.g. the extension and oceanic nature of the Ionian-Lagonegro basin, the shape and distribution of the Mesozoic carbonate platforms (e.g. D'ARGENIO, 1988; PATACCA *et alii*, 1992; MARSELLA *et alii*, 1995), and their significance in the Apenninic kinematics where paleogeographic zones have partly become structural units. It is also under debate the amount of

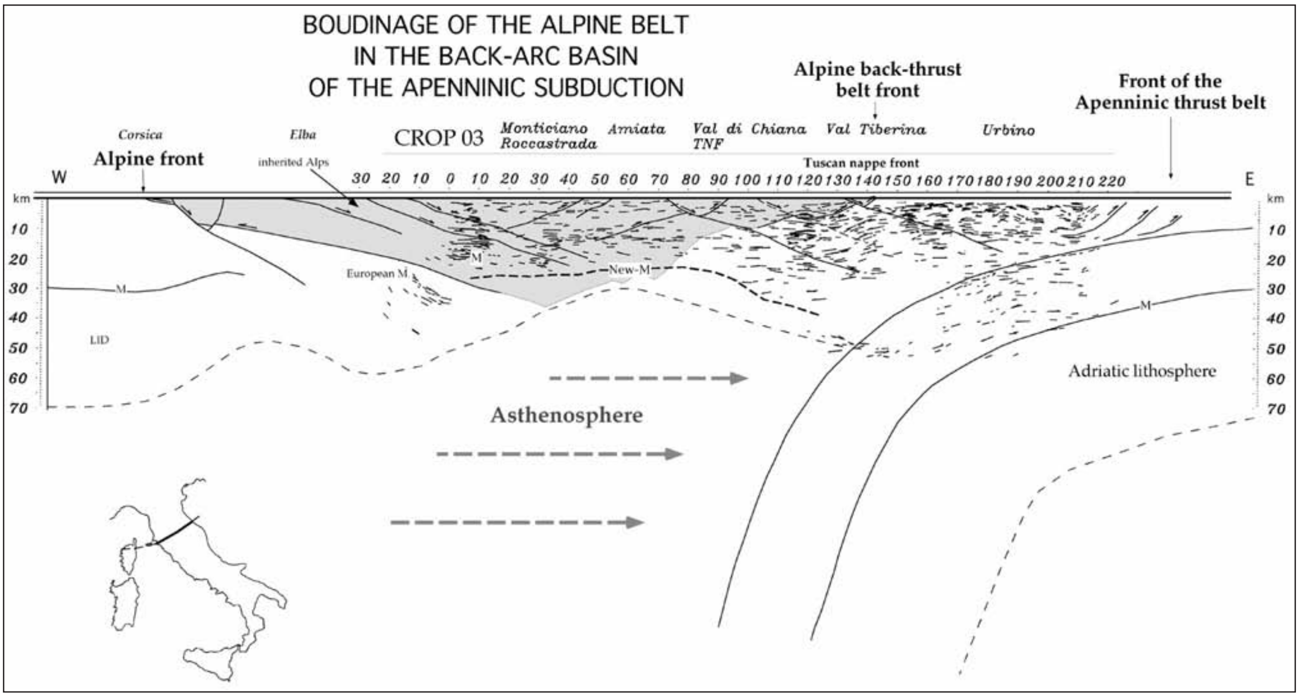


Fig. 13 – Line drawing and interpretation of the CROP 03 seismics (after DOGLIONI *et alii*, 1998). In shadow is the Alpine orogen stretched by the back-arc extension of the west-directed Appenninic subduction.

– *Line drawing e interpretazione del profilo sismico CROP 03 (da* DOGLIONI et alii*, 1998). E' evidenziato l'orogene alpino assottogliato dall'estenzione di retro-arco connessa alla subduzione appenninica (diretta verso W).*

involvement of the basement in the Apenninic accretionary wedge, and whether the Adriatic plate basement is entirely subducted or not. Is there continental crust under the Apennines or is it lost by the Apenninic subduction? Are the Apenninic basement outcrops only remnants of the earlier Alpine tectonics?

The Tyrrhenian Neogene back-arc basin includes several smaller basins developed on the continental shelf, slope, and bathyal plain which arrives to 3,000-3,600 m depth (SCANDONE, 1980; MOUSSAT *et alii*, 1986; KASTENS *et alii*, 1990; SARTORI *et alii*, 1989; PASCUCCI *et alii*, 1999). Horsts and grabens are mainly N-S trending, with several transfer zones, disturbing the cylindricity of the stretching. Several kilometers thick peri-Tyrrhenian Neogene basins are located off-shore Sardinia (Sardinia basin), Calabria and Sicily. On the Tyrrhenian sea floor there are outcrops of the Hercynian basement, abyssal oceanic tholeiites (dated 6 Ma), and sedimentary basins filled with Miocene clastics, Messinian evaporites and Pliocene-Quaternary clastics. Where oceanic, the crust of the Tyrrhenian basin is even less than 8 km thick. Diapiric structures occur in the central part of the deeper Tyrrhenian basins, where thick Messinian halite is present.

The Sicily channell is due to extension between Sicily and Tunisia (Africa) active since Neogene times. This is responsible for the Pantelleria, Malta and Linosa basins, NW-SE trending grabens, parallel to similar features outcropping in Tunisia and the offshore Pelagian shelf (TORELLI *et alii*, 1992; TORELLI *et alii*, 1995; CATALANO *et alii*, 2000).

## 5.3. - ALPS VS APENNINES

Thrust belts are the typical expression of subduction zones. Analysing the geological and geophysical signature of thrust belts world-wide, two different end-members can be recognised which display pronounced and systematic differences (LAUBSCHER, 1988; ROYDEN & BURCHFIEL 1989; DOGLIONI, 1992; ROYDEN, 1993; DOGLIONI *et alii*, 1999).

The first group (e.g. Apennines, Carpathians) is characterised by the presence of a back-arc basin, low structural and topographic relief, mainly sedimentary Mesozoic-tertiary rock involved, one deep foredeep (high subsidence rates), and low to none metamorphism (fig. 13).

The second group (e.g. Alps, Himalayas) shows instead a conjugate retrobelt, high structural and topographic relief, widespread outcrops of crys-

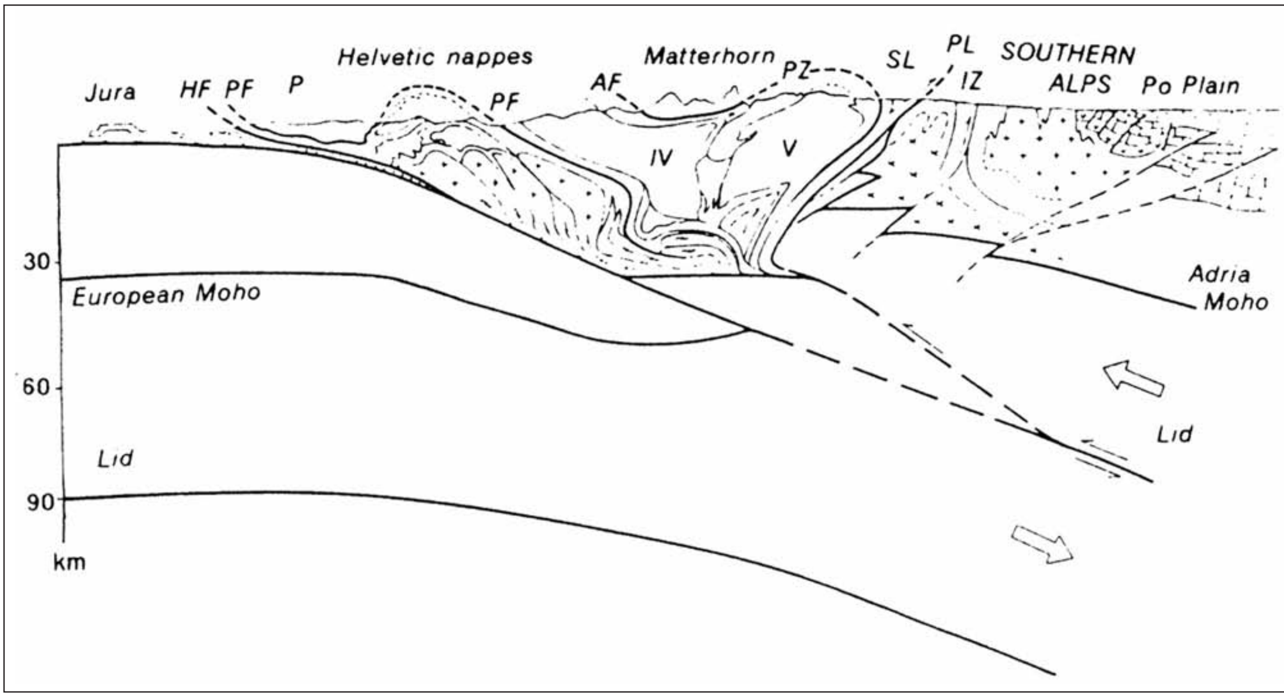


Fig. 14 – Geological profile across the Western Alps (after Dal Piaz, 1997).
– *Profilo geologico attraverso le Alpi Occidentali (da Dal Piaz, 1997).*

talline basement, two shallow foredeep (low subsidence rate), and medium to high grade metamorphism (fig. 14).

The Alps and Apennines, being representative of these two end-members, provide a stimulating opportunity to compare structural differences between thrust belts.

### 5.3.1. – *Back-Arc Basin vs Retrobelt*

The most impressive difference between the two orogens is the presence of a back-arc basin only to the west of the Apennines, i.e. the Tyrrhenian Sea, while the Southern Alps represent the retrobelt of the Alps.

The Apennines relief is marked by extension or, more exactly, the uplift of the belt is controlled by tensional regime; on the contrary, in the Alps the uplift of the orogen is due to thickening of the crust-lithosphere system generated by compression, even if there are evident tensional manifestations of normal faulting in its core.

Tensional faulting in the Alps is probably determined by orogenic overthickening and by interference with other geodynamic factors (e.g. the Oligocene extension of the Rhine and Rhone grabens or the interference with the opening of the Pannonian Basin in the Eastern Alps).

The Neogene extension in the Apennines has a different character from the extension in the Alps. The geodynamic context, timing, and uplift rates are strongly different; in fact, the extension in the Apennines ridge cannot be considered as the collapse of the orogen. The Apennines are characterized by a frontal active accretionary wedge, below sea-level, whereas the main elevated ridge is instead in uplift and extension.

More to the west, toward the Tyrrhenian sea, seismicity decreases and the subsidence is mainly related to thermal cooling. There is a clear eastward migration of rifting in the Tyrrhenian itself, from Early Miocene in the western part to Plio-Pleistocene in the east. Similarly, continental rifting and related magmatism show an eastward migration throughout the Apennines, coeval with compression in adjacent thrust-fold belts to the east.

These different tectonic fields moved, and are still moving, eastward expanding the Apenninic arc at velocities of 1 to 7 cm/yr, rates comparable with other arcs related to W-directed subduction. The eastward roll-back of the Adriatic lithosphere (Malinverno & Ryan, 1986, Patacca & Scandone, 1989; Doglioni, 1991) accompanied this migration.

Fragments of the Alps outcrop in the Apennines belt (e.g. Calabria, Pontine islands, Tuscany, Elba island). They have also been found scattered and disrupted on the floor of the Tyrrhenian basin and they may be interpreted buried below the western Apennines. Those indicate that the extension and shape of the Alps during their Cretaceous-Eocene subduction-collision history was continuous toward the south. A frontal thrust belt and the relative conjugate retrobelt of the Alps have been overprinted since Oligocene on by the Apenninic wave, and the Alps are therefore part of the core of the western Apennines (fig. 13).

### 5.3.2. - *Topography and Structural Relief*

Another macroscopic difference between Alps and Apennines is the morphology. The average altitude is obviously higher for the Alps: the highest mountain in the Alps is the Mont Blanc (4810 m), while in the Apennines is the Gran Sasso d'Italia (2914 m). The average altitude of the Alps is 1200-1300 m, while for the Apennines is about 400-600 m.

The Alps have also a much higher structural relief. The erosion eliminated a large part of the uplifted thrust sheets that would have reached some tens of kilometres of altitude if they could have maintained their original position. Such structural elevation is also marked by the extensive outcrops of metamorphic rocks which are not present in the Apennines. Blue schists and eclogite facies rocks bearing coesite, a mineral indicating very high pressure (30 kbar; CHOPIN, 1984) show that now at the surface in the Alps are rocks previously formed at depth of several tens of kilometres (even 100 km).

On the other hand, the Apennines exhibit predominant outcrops of sedimentary cover (see, for instance, BALLY *et alii*, 1986), and only a few scattered occurrences of metamorphic rocks, mainly relicts of the Hercynian basement uplifted during the earlier Alpine phase. In contrast with the Alps, the Apennines did not have a thick pile of nappes above them (CORRADO, 1995) to have been eroded. In other words, they have a very low structural elevation, which is at least a few tens of kilometres lower with respect to the Alps.

In the Apennines, very often the highest peaks are shifted to the 'east' relative to the divide. This could be associated to the faster 'eastward' retreat of the Apennines slab relative to the erosion rates (SALUSTRI GALLI *et alii*, 2002).

### 5.3.3. - *Foredeep Basins*

Another stunning difference between the Alps and the Apennines is that paradoxically the Alps have shallower foredeeps and lower subsidence rates in spite of their higher topographic relief and consequent higher lithostatic load (DOGLIONI, 1993).

In the Alpine foredeep (Molasse Basin; PFIFFNER, 1986) the Oligocene base reaches 4000 m (BIGI *et alii*, 1992); subsidence rates in the Alpine foreland range from 0 to 200 m/Ma. The Southern Alps propagated south-southeastward between the Late Cretaceous (western part) and the Pliocene. The Southalpine foredeep had subsidence rates which rarely exceeded the 300m/Ma (MASSARI, 1990), determined by dividing the entire thickness of the flysch and molasse deposits by their duration of deposition (2-6 km of sediments deposited in 15-40 or more Ma). In the eastern part of the Southalpine foredeep, the Dinaric foredeep also interferes with its effects of subsidence since at least the Paleocene up to the Early Miocene.

In contrast with the Alps, the Apennines have a very pronounced foredeep, with the Pliocene base even at 8.5 km (BIGI *et alii*, 1992) and indicating subsidence rates ranging between 1000-1600 m/Ma. Much part of the Apenninic foredeep is located on top of the accretionary wedge, and not only to its front. This means that the so-called piggy-back basin is often the real foredeep for the Apennines. Clastic supply in the Apenninic foredeep is provided not only by the Apenninic accretionary wedge, but also by the Alps and Dinarides surrounding the Adriatic plate.

Moreover, significant differences in the mean dip of the foreland monocline between the Alps and the Apennines, as well as variations along a given belt, have been pointed out (MARIOTTI & DOGLIONI, 2000; fig. 15)

## 6. - CONCLUSIONS

Alps and Apennines are diachronous and have very different rates of evolution and vitality. The Alpine subduction began during Early Cretaceous and continued until the Pliocene, with slower later reactivations. The Apenninic-Tyrrhenian system is instead a very recent feature because it mainly formed during the last 10-15 Ma. However, within the Apennines there are structures related to earlier subduction phases, i.e. the W-directed subduction connected to the back-arc opening of the Provencal Basin during Late Eocene-Early Miocene times, but in particular, this system inverted the earlier Alpine orogen.

The Italian peninsula and Sicily are mainly formed by an asymmetric disrupted thrust belt (the Apennines) surrounding a corresponding asymmetric back-arc basin. The Italian asymmetry may be interpreted as the result of an irregular subduction

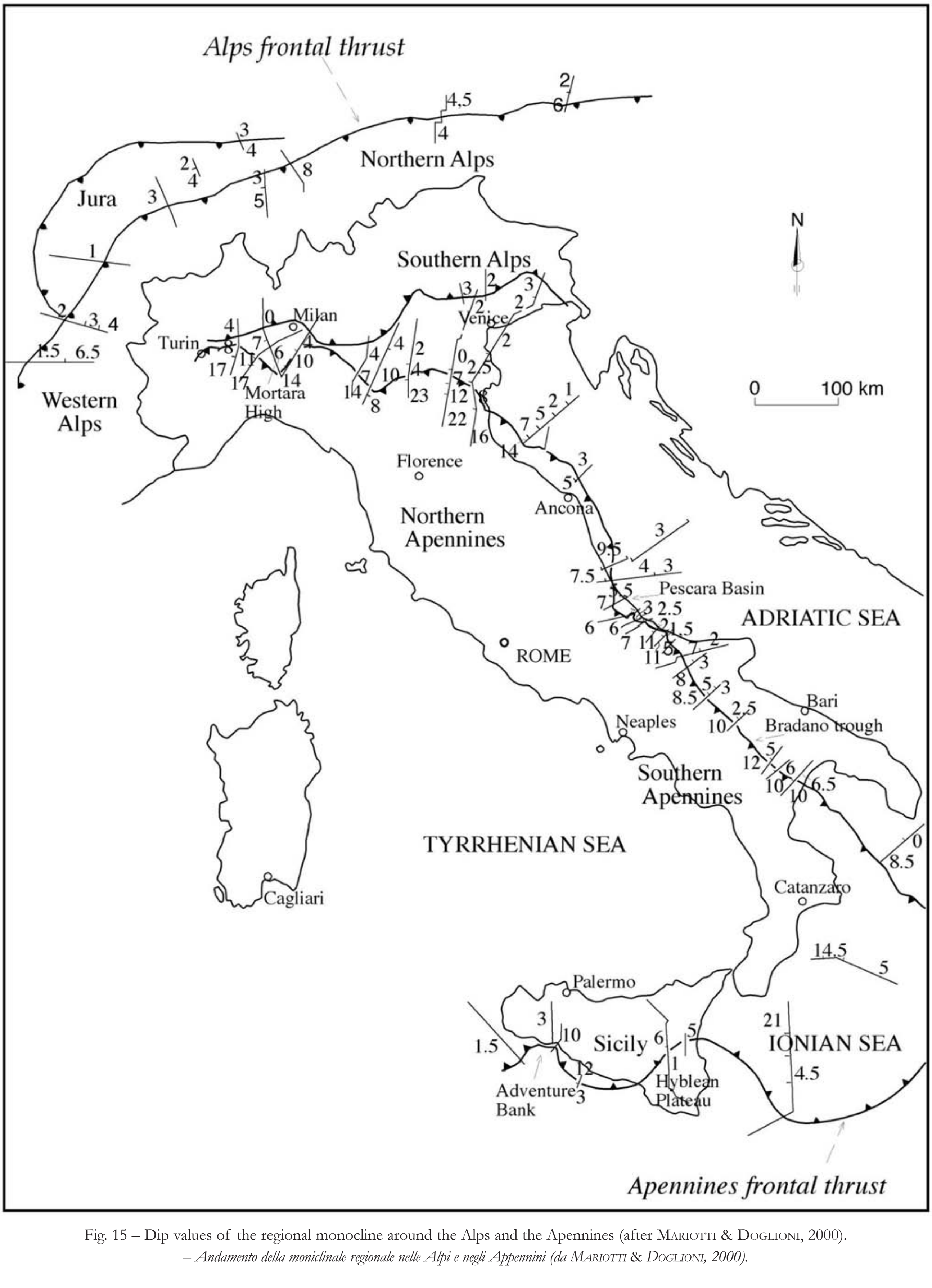


Fig. 15 – Dip values of the regional monocline around the Alps and the Apennines (after MARIOTTI & DOGLIONI, 2000).
*– Andamento della moniclinale regionale nelle Alpi e negli Appennini (da MARIOTTI & DOGLIONI, 2000).*

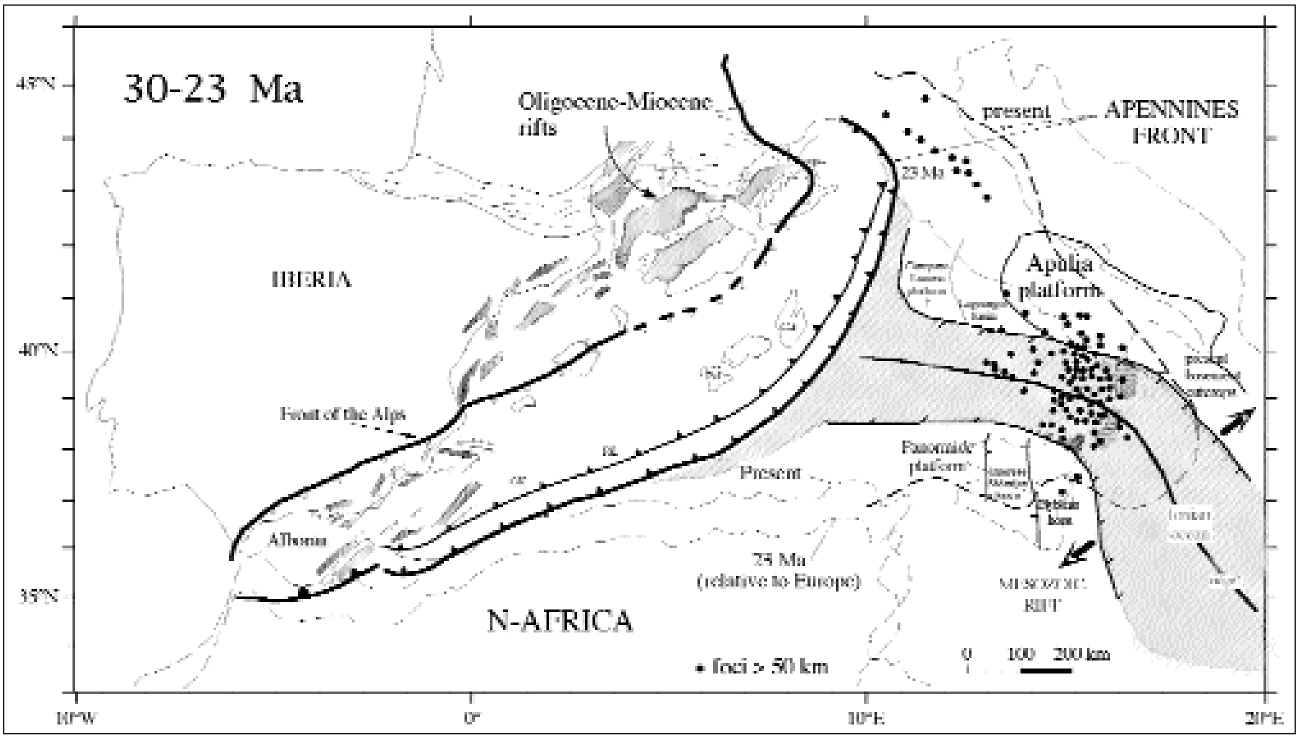


Fig. 16 – Late Oligocene-Early Miocene palaeogeography of the central-eastern Mediterranean, with the preserved Mesozoic palaeogeography in the Apennines foreland to the east (after CATALANO *et alii*, 2001). The 330 km wide Ionian Mesozoic Ocean had to be transferred to the west-north-west, since the restoration of the southern Apennines thrust sheets implies thinned but still continental crust to the north of the Ionian Sea. The present seismicity, deeper than 50 km (after AMATO *et alii*, 1993) closely matches the oceanic palaeogeography. Note also the correspondence between the oceanic nature of the subducting plate and the outcrop of basement rock in the hanging-wall in Calabria and NE Sicily.

*– Ricostruzione paleogeografica del Mediterraneo centro-orientale riferita all'Oligocene superiore – Miocene inferiore, con evidenziata la paleogeografia mesozoica dell'avampaese appenninico (da CATALANO* et alii*, 2001). L'Oceano Ionico Mesozoico caratterizzato da un ampiezza di circa 330 km doveva essere ubicato a ovest-nord-ovest poiché la retrodeformazione della catena a sovrascorrimenti dell'Appennino meridionale implica una crosta assottigliata ma ancora continentale a nord del Mare Ionio. La distribuzione della sismicità recente, più profonda di 50 km (da AMATO* et alii*, 1993), coincide con la paleogeografia delle zone oceaniche. Da notare anche la corrispondenza tra la natura oceanica della placca in subduzione e gli affioramenti di rocce del basamento in Calabria e Sicilia nord-orientale.*

beneath Northern and Southern Apennines: in fact, the Adriatic lithosphere is continental in origin with respect to the Ionian oceanic lithosphere, possibly a relict of the Mesozoic Tethys. Due to this asymmetry the Apenninic arc and its Puglia foreland assumed the shape of a "boot", typical term descriptive the Italian peninsula.

Three types of lithosphere with different characteristics, but pertaining to the same Adriatic plate, can be recognised (Figs. 1 & 3):

– in the Northern and Central Apennines, thin continental lithosphere at the surface in the foreland, and probably thinner at depth along the slab;

– in the Southern Apennines, thick continental lithosphere in the foreland, whereas probably old oceanic lithosphere constitutes the slab at depth to the west (northern prolongation of the Ionian Mesozoic basin);

– in the southern sector, offshore Calabria, old oceanic Ionian lithosphere both in the foreland and at depth.

The northward decreasing extension of the Tyrrhenian basin may be interpreted as a function of the northward decreasing capability to subduct of the thicker northern Adriatic continental lithosphere.

The main transition is between parallels 40° and 41°. The differences in composition and thickness of the Apenninic subducting slab are in fact also recorded by the peri-Tyrrhenian magmatism and by the present seismicity.

The Apennines result in a greater shortening in the Calabrian arc and a corresponding maximum back-arc extension in the southern Tyrrhenian sea. In the Central-Northern Apennines shortening is decreasing linearly northward from 170 to 35 km according to BALLY *et alii*, (1986), and the extension in the Tyrrhenian sea is linearly decreasing northward as well, confirming that extension and compression are genetically linked.

In conclusion, the present shape of the Italian peninsula (Apennines) reflects an asymmetric Late Oligocene - Quaternary subduction controlled by the inherited Mesozoic lateral thickness and composition variations of the Adriatic-Ionian lithosphere (fig. 16).

REFERENCES


AMATO A., ALESSANDRINI B., CIMINI G.B., FREPOLI A. & SELVAGGI G. (1993) – *Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity.* Ann. Geofis., **36**, (2): 201-214.

AMATO A. & CIMINI G.B. (2001) – *Deep structure from seismic tomography*. In: VAI G.B. & MARTINI I.P. (Eds.): *"Anatomy of an orogen: the Apennines and adjacent Mediterranean basins"*. Kluwer Academic Publishers: 33-45, Dordrecht, The Netherlands

AMATO A., MARGHERITI L., AZZARA R., BASILI A., CHARABBA C., CIACCIO M.G., CIMINI G. B., DI BONA M., FREPOLI A., LUCENTE F.P. & NOSTRO C. (1998) - P*assive seismology and deep structure in central Italy.* In: PLOMEROVA J., LIEBERMANN R.C. & BABUSKA V. (Eds.): "*Geodynamics of lithosphere and Earth's mantle; seismic anisotropy as a record of the past and present dynamic processes".* Pure Appl. Geoph., **151** (2-4): 479-493.

AMATO A. & MONTONE P. (1995) – *State of stress in Southern Italy from borehole breakout and fochal mechanism data.* Geophys. Res. Lett., **22**: 3119-3122.

AMATO A. & MONTONE P. (1997) – *Present day stress field and active tectonics in southern peninsular Italy*. Geophys. J. Int., **130**: 519-534.

ANDERSON H. & JACKSON J. (1987) – *The deep seismicity of the Tyrrhenian Sea.* Geophys. J. R. Astron. Soc., **91**: 613-637.

APPLETON, J.D., (1972) - P*etrogenesis of potassium-rich lavas from the Roccamonfina volcano, Roman Region., Italy*. J. Petrol., **13**: 425-456.

AYUSO R.A., DE VIVO B., ROLANDI G., SEAL II R.R. & PAONE A. (1998) - *Geochemical and isotopic Nd–Pb–Sr–O variations bearing on the genesis of volcanic rocks from Vesuvius, Italy.* J. Volcanol. Geotherm. Res., **82**: 53–78.

BABUSKA V., PLOMEROVA J. & GRANET M. (1990) – *The deep lithosphere in the Alps: a model inferred from P residuals*. Tectonophysics, **176**: 137-165.

BALLARIN S. (1963) – *Il campo della gravita' in Italia: carte delle anomalie topografiche-isostatiche.* Commis. Geodet. It. Mem., No. **17**.

BALLY A.W., BURBI L., COOPER C. & GHELARDONI R. (1986) - *Balanced sections and seismic reflection profiles across the central Apennine.* Mem. Soc. Geol. It., **35**: 257-310.

BECCALUVA L., COLTORTI M., DI GIROLAMO P., MELLUSO L., MILANI L., MORRA V., & SIENA F. (2002) - *Petrogenesis and evolution of Mt. Vulture alkaline volcanism (Southern Italy).* Mineral. Petrol., **74**: 277-297.

BECCALUVA L., DI GIROLAMO P. & SERRI G. (1991) - *Petrogenesis and tectonic setting of the Roman volcanic Province, Italy*. Lithos, **26**: 191-221.

BARCHI M., MINELLI G. & PIALLI G. (1998) – *The CROP03 profile: a synthesis of results on deep structures of the Northern Apennines.* Mem. Soc. Geol. It., **52**: 383-400.

BECCALUVA L., MACCIOTTA G., DI GIROLAMO P. & SAVELLI C. (1981) - *Upper Miocene submarine volcanism in the Strait of Sicily (Banco Senza Nome)*. Bull. Volcanol., **44**: 573-581.

BECCALUVA L., SIENA F., COLTORTI M., DI GRANDE A., LO GIUDICE A., MACCIOTTA G., TASSINARI R. & VACCARO C. (1998) - *Nephelinitic to Tholeiitic Magma Generation in a Transtensional Tectonic Setting:an Integrated Model for the Iblean Volcanism, Sicily.* J. Petrol., **39**: 1547-1576.

BECHSTADT T., BRANDNER R., MOSTLER H. & SCMIDT K. (1978) - *Aborted rifting in the Triassic of the eastern and southern Alps.* Neues Jahrbuch Geol. Paloent. Abhandl., **2**: 157-178.

BERNOULLI, D. (2001) - *Mesozoic-Tertiary carbonate platforms, slopes and basins of the external Apennines and Sicily*. In: VAI G.B. & MARTINI I.P. (Eds.): "*Anatomy of an orogen: the Apennines and adjacent Mediterranean basins*". Kluwer Academic Publishers: 307-325, Dordrecht, The Netherlands.

BERNOULLI D., KÄLIN O. & PATACCA E. (1979) - *A sunken continental margin of the Mesozoic Tethys: the Northern and Central Apennines*. Publ. Spec. Assoc. Sedimentol. France, **1**, 197-210.

BERTOTTI G., PICOTTI V., CHILOVI C., FANTONI R., MERLINI S. & MOSCONI A. (2001) - *Neogene to Quaternary sedimentary basins in the south Adriatic (central Mediterranean): Foredeeps and lithospheric buckling.* Tectonics, **20** (5): 771-787.

BIGI G., COSENTINO D., PAROTTO M., SARTORI R. & SCANDONE P. (1992) - *Structural Model of Italy. Scale 1:500,000*. Quaderni de "La Ricerca Scientifica", **114** (3). CNR

BOCCALETTI M. & MANETTI, P. (1972) - *Traces of Lower Middle Liassic volcanism in crinoidal limestones of the Tuscan Sequence in the Montemerano area (Grosseto, Northern Apennines).* Eclogae Geol. Helvetiae, **65**: 119-129.

BROTZU P. (ed) (1997) - *The calcalkaline volcanism in Sardinia.* Per. Mineral., **66**: 1-231.

CALANCHI N., COLANTONI P., ROSSI P.L., SAITTA M. & SERRI G. (1989) - *The Strait of Sicily continental rift systems: physiography and petrochemistry of the submarine volcanic centres.* Marine Geology, **87**: 55-83.

CALCAGNILE G. & PANZA G.F. (1980) – *The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions.* Pure Appl. Geophys., **119**: 865-879.

CAPUTO M., PANZA G. F. & POSTPISCHL D. (1970) – *Deep structure of the Mediterranean Basin. J.* Geophys. Res., **75**: 4919-4923.

CAROZZO M.T., LUZIO D., MARGIOTTA C. & QUARTA T. (1992) – *Gravity Map of Italy, Scale 1:500,000*. Quaderni de "La Ricerca Scientifica", **114** (3), CNR

CASSANO E., FICHERA R. & ARISI ROTA F. (1986) – *Rilievo aeromagnetico d'Italia. Alcuni risultati interpretativi.* Atti del 5° Convegno del GNGTS, Roma, CNR: 939-958.

CASSINIS R. (1983) – *Seismicity and crustal structure in the italian region: a preliminary zoning*. Boll. Geofis. Teor. Appl., **25** (97): 3-26.

CASTELLARIN A., LUCCHINI F., ROSSI P.L., SELLI L. & SIMBOLI G. (1988) - *The Middle Triassic magmatic-tectonic arc development in the Southern Alps.* Tectonophysics, **146:** 79-89.

CASTELLARIN A., LUCCHINI F., ROSSI P.L., SIMBOLI G., BOSELLINI A. & SOMMAVILLA E. (1979) - *Middle Triassic Magmatism in Southern Alps II: A Geodynamic Model.* Riv. Ital. Paleont. Strat., **85**: 1111-1124.

CATALDI R., MONGELLI F., SQUARCI P., TAFFI L., ZITO G. & CALORE C. (1995) – *Geothermal ranking of the italian territory.* Geothermics, **24**: 115-129.

CATALANO R., DI STEFANO P., NIGRO F. & VITALE F. (1993) - *Sicily mainland and its offshore: a structural comparison.* In: MAX M.D. & COLANTONI P. (Eds.): *"Geological development of the Sicilian-Tunisian Platform.* Unesco Report in Marine Science, **58**: 19-24.

CATALANO R., DOGLIONI C. & MERLINI S. (2001) - *On the Mesozoic Ionian basin.* Geophys. J. Int., **144**: 49-64.

Catalano R., Franchino A., Merlini S. & Sulli A. (2000) - *A crustal section from the eastern Algerian Basin to the Ionian ocean (central Mediterranean).* Mem. Soc. Geol. It., **55**: 71-85.

Chiappini M., Meloni A., Boschi E., Faggioni O., Beverini N., Carmisciano C. & Marson I. (2000) – *Shaded relief magnetic anomaly map of Italy and surrounding marine areas.* Ann. Geophys., **43** (5): 983-989.

Chopin C. (1984) - *Coesite and pure pyrope in high grade blueschists of the Western Alps: A first record and some consequences.* Contrib. Mineral. Petrol., **86**: 107-118.

Cinque A., Civetta L., Orsi G. & Peccerillo A. (1988) - *Geology and geochemistry of the island of Ustica (southern Tyrrhenian Sea).* Rend. Soc. It. Mineral. Petrol., **43**: 987-1002.

Cippitelli G. & Merlini S. (2001) - *Structural styles inferred by seismic profiles.* In: Vai G.B. & Martini I.P. (Eds.): *"Anatomy of an orogen: the Apennines and adjacent Mediterranean basins".* Kluwer Academic Publishers: 441-454, Dordrecht, The Netherlands.

Consiglio Nazionale delle Ricerche (1992) - *Structural Model of Italy and Gravity Map.* Progetto Finalizzato Geodinamica. Quaderni de "La Ricerca Scientifica", **114** (3) (9 sheets) CNR.

Conticelli S. & Peccerillo A. (1992) - *Petrology and geochemistry of potassic and ultrapotassic volcanism in central Italy: petrogenesis and inferences on the evolution of the mantle sources.* Lithos, **28**: 221-240.

Corazzato C., Groppelli G., Natoli E. & Pasquarè G. (2001) - *Il Gruppo di Montecampione: stratigrafia dei corpi subvulcanici tra la Val Camonica e la Val Trompia (Alpi meridionali, Lombardia).* Atti Ticinesi di Scienze della Terra, **42**: 141-152.

Corrado S. (1995) - *Optical parameters of maturity of organic matter dispersed in sediments: first results from the Central Apennines (Italy).* Terra Nova, **7**: 338-347

D'Argenio B. (1988) – *L'Appennino campano-lucano. Vecchi e nuovi modelli geologici tra gli anni sessanta e gli inizi degli anni ottanta.* Mem. Soc. Geol. It., **41**: 3-15.

D'Atri A., Dela Pierre F., Lanza R. & Ruffini R. (1999) - *Distinguishing primary and resedimented vitric volcaniclastic layers in the Burdigalian carbonate shelf deposits in Monferrato (NW Italy).* Sed. Geol., **129**: 143–163.

Dal Piaz G.V. (1997) - *Alpine geology and historical evolution of the orogenic concept.* Mem. Sc. Fis., **21**: 49-83.

Dal Piaz G.V., Del Moro A., Martin S. & Venturelli G. (1988) - *Post-Collisional Magmatism in the Ortler-Cevedale Massif (Northern Italy*). Jb. Geol. Bundesanstalt. Wien, **131**: 533-551.

De Fino M., La Volpe L., Peccerillo A., Piccarreta G. & Poli G. (1986) - *Petrogenesis of Monte Vulture volcano (Italy): inferences from mineral chemistry, major and trace element data.* Contrib. Mineral. Petrol., **92**: 135-145.

De Gori P., Cimini G.B., Chiarabba C., De Natale G., Troise C. & Deschamps A. (2001) – *Teleseismic tomography of the Campanian volcanic area and surrounding Apennine belt.* J. Volcanol. Geotherm. Res., **109**: 55-75.

Della Vedova B., Bellani S., Pellis G. & Squarci P. (2001) - *Deep temperatures and surface heat flow distribution.* In: Vai G.B. & Martini I.P. (Eds.): *"Anatomy of an orogen: the Apennines and adjacent Mediterranean basins".* Kluwer Academic Publishers: 65-76, Dordrecht, The Netherlands.

Della Vedova B., Lucazeau F., Pasquale V., Pellis G. & Verdoya M. (1995) - *Heat flow in the tectonic provinces crossed by the southern segment of the European Geotraverse.* In: Balling N. & Decker E.R. (Eds.): *"Heat flow and thermal regimes of continental lithosphere".* Tectonophysics, **244**: 57-74.

De Vecchi G. & Sedea R. (1995) - *The Paleogene basalts of the Veneto Region (NE Italy).* Mem. Sci. Geol., **47**: 253-274.

De Voogd B., Truffert C., Chamot-Rooke N., Huchon P., Lallemant S. & Le Pichon X. (1992) - *Two-ship deep seismic soundings in the basins of the Eastern Mediterranean Sea (Pasiphae cruise).* Geophys. J. Int., **109**: 536-552.

Dini A. , Innocenti F., Rocchi S., Tonarini S. & Westerman D.S. (2002) - *The magmatic evolution of the late Miocene laccolith-pluton-dyke granitic complex of Elba Island, Italy.* Geol. Magazine, **139** (3): 257-279.

Doglioni, C. (1991) - *A proposal of kinematic modelling for W-dipping subductions - Possible applications to the Tyrrhenian-Apennines system.* Terra Nova, **3:** 423-434.

Doglioni C. (1992) – *Main differences between thrust belts.* Terra Nova, **4**: 152-164.

Doglioni C. (1993) - *Some remarks on the origin of foredeeps.* Tectonophysics, **228**: 1-22.

Doglioni C. (1994) - *Foredeeps versus subduction zones.* Geology, **22** (3): 271-274.

Doglioni C. & Flores G. (1997) - *Italy.* In: Moores & Fairbridge (Eds.): *Encyclopedia of European and Asian Regional Geology.* Chapman & Hall: 414-435. New York.

Doglioni C., Harabaglia P., Merlini S., Mongelli F., Peccerillo A., & Piromallo C. (1999) – *Orogens and slabs vs. their direction of subduction.* Earth Science Rev., **45**: 167-208.

Doglioni C., Innocenti F. & Mariotti G. (2001) - *Why Mt. Etna?* Terra Nova, **13**: 25-31.

Doglioni C., Mongelli F. & Pialli G.P. (1998) - *Boudinage of the Alpine belt in the Apenninic back-arc.* Mem. Soc. Geol. It., **52**: 457-468.

Doglioni C., Mongelli F. & Pieri P. (1994) - *The Puglia uplift (SE Italy): An anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere.* Tectonics, **13**: 1309-1321.

Dostal J., Coulon C. & Dupuy C. (1982) - *Cainozoic andesitic rocks of Sardinia (Italy).* In: R. Thorpe S. (Ed.): *"Andesites".* John Wiley & Sons: 353-370, Chichester

Downes H., Thirlwall M.F. & Trayhorn S.C. (2001) - *Miocene subduction-related magmatism in southern Sardinia: Sr-Nd- and oxygen isotopic evidence for mantle source enrichment.* J. Volcanol. Geotherm. Res, **106**: 1-21.

Ellam R.M., Menzies M.A., Hawkesworth C.J., Leeman W.P., Rosi M. & Serri G. (1988) - *The transition from calc-alkaline to potassic orogenic magmatism in the Aeolian Islands, Southern Italy.* Bull. Volcanol., **30**: 386-398.

Ferrara G., Petrini R., Serri G. & Tonarini S. (1989) - *Petrology and isotope-geochemistry of San Vincenzo rhyolites (Tuscany, Italy).* Bull. Volcanol., **51**: 379-388.

Francalanci L., Taylor S.R., McCulloch M.T. & Woodhead J. (1993) - *Petrological and geochemical variations in the calc-alkaline rocks of Aeolian arc (Southern Tyrrhenian Sea, Italy).* Contrib. Mineral. Petrol., **113**: 300-313.

Franceschini, F., Innocenti F., Marsi A., Serri G. & Tamponi M. (2000) - *Petrography and chemistry of the buried Pliocene Castel di Pietra pluton (Southern Tuscany, Italy).* N. Jb. Paläeont. Abh., **215**: 17-46.

GASPERINI D., BLICHERT-TOFT J., BOSCH D., MACERA P. & ALBARÈDE F. (2002) - *Upwelling of deep mantle material through a plate window: evidence from the geochemistry of Italian basaltic volcanics*. J. Geophys. Res., in press.

GIANELLI G. & LAURENZI M.A. (2001) - *Age and Cooling Rate of the Geothermal System of Larderello*. Geothermal Resources Council Transactions, San Diego: 731-735.

GIARDINI D. & VELONA' M. (1991) – *The deep seismicity of the Tyrrhenian Sea*. Terra Nova, **3**: 57-64.

GUEGUEN F., DOGLIONI C. & FERNANDEZ M. (1998) – *On the post-25 Ma geodynamic evolution of the western Mediterranean*. Tectonophysics, **298**: 259-269.

GUEST J.E., DUNCAN A.M. & CHESTER D.K. (1988) - *Monte Vulture Volcano (Basilicata, Italy): an analysis of morphology and volcaniclastic facies*. Bull. Volcanol., **50**: 244-257.

GVIRTZMAN Z. & NUR A. (2001) - *Residual topography, lithospheric structure and sunken slabs in the central Mediterranean*. Earth Plan. Sci. Letters, **187** (1-2): 117-130.

INNOCENTI F., SERRI G., FERRARA G., MANETTI P. & TONARINI S. (1992) - *Genesis and classification of the rocks of the Tuscan Magmatic Province: thirty years after Marinelli's model*. Acta Vulcanol., **2**: 247-265.

KASTENS K.A., MASCLE J., *et alii* (1990) – *Proc. ODP, Sci. Results,* **107**: College Station TX (Ocean Drilling Program), 772 pp.

KISSLING E. (1993) - *Deep structure of the Alps; what do we really know?*. In: SNIEDER R., CERMAK V. & POUPINET G. (Eds.): *"Structure and evolution of the European lithosphere and upper Mantle"*. Phys. Earth Planet. Interiors, **79** (1-2): 87-112.

KOSTOULA T., JONES A., DOWNES H., BEARD A. (1999) - *Geochemistry and isotopic composition of mantle xenoliths from Vulture volcano, S. Italy*. Ofioliti, **24**: 120.

LAUBSCHER H.P. (1983) - *The Late Alpine (Periadriatic) intrusions and the Insubric Line*. Mem. Soc. Geol. It., **26:** 21-30.

LAUBSCHER H.P. (1988) - *The arcs of the Western Alps and the Northern Apennines: an updated view*. Tectonophysics, **146**: 67-78.

LA VOLPE L. & PRINCIPE C. (1991) - *Monte Vulture Volcano (Basilicata, Italy): an analysis of morphology and volcanoclastic facies: discussion*. Bull. Volcanol., **53**: 222-227.

LEMOINE M., TRICART P. & BOILLOT G. (1987) - *Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines)*. Geology, **15**: 622-625.

LUCENTE F.P., CHIARABBA C., CIMINI G. B. & GIARDINI D. (1999) – *Tomographic constraints on the geodynamic evolution of the italian region*. J. Geophys. Res., **104**: 20307-20327.

LUSTRINO M., MELLUSO L. & MORRA V. (2000) - *The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy)*. Earth Planet. Sci. Letters, **180**: 259-270.

MALINVERNO A. & RYAN W.B.F. (1986) - *Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere*. Tectonics, **5**, 227-245.

MARIOTTI G. & DOGLIONI C. (2000) - *The dip of the foreland monocline in the Alps and Apennines*. Earth Planet. Sci. Letters, **181**: 191-202.

MARSELLA E., BALLY A.W., CIPPITELLI G., D'ARGENIO B. & PAPPONE G. (1995) – *Tectonic history of the Lagonegro Domain and Southern Apennine thrust belt evolution*. Tectonophysics, **252**: 307-330.

MASSARI F. (1990) – *The foredeeps of the northern Adriatic margin: evidence of diachroneity in deformation of the southern Alps*. Riv. It. Paleont. Strat., **96**: 351-380.

MELLUSO L., MORRA V. & DI GIROLAMO P. (1996) - *The Mt. Vulture volcanics complex (Italy): evidence for distinct parental magmas and for residual melts with melilite*. Mineral. Petrol., **56**: 225-250.

MILANI L., BECCALUVA L. & COLTORTI M. (1999) - *Petrogenesis and evolution of the Euganean magmatic complex, Veneto region, north-east Italy*. Eur. J. Mineral., **11**: 379-399.

MILANO G., DIGIOVAMBATTISTA R. & ALESSIO G. (1999) - *Earthquake swarms in the Southern Apennines chain (Italy): the 1997 seismic sequence in the Sannio–Matese mountains*. Tectonophysics, **306**: 57–78.

MOLINA F., ARMANDO E., BALIA R., BATTELLI O., BOZZO E., BUDETTA G., CANEVA G., CIMINALE M., DE FLORENTIIS N., DE SANTIS A., DONNALOIA M., ELENA A., ILICETO V., LANZA R., LODDO M., MELONI A., PINNA G., SANTARATO G. & ZAMBRANO R. (1994) – *Geomagnetic survey of Italy. Repeat station network and magnetic maps*. Progetto Finalizzato Geodinamica. Publication ING, N. 554.

MONTONE P., AMATO A. & PONDRELLI S. (1999) - *Active stress map of Italy*. J. Geophys. Res., **114** (B11): 25,595-25,610.

MONGELLI F., LODDO M. & CALCAGNILE G. (1975) - *Some observations on the Apennines gravity field*. Earth Planet. Sci. Letters: **24**, 385-393.

MONGELLI, F., ZITO, G., DELLA VEDOVA, B., PELLIS, G., SQUARCI, P. & TAFFI, L. (1991) - *Geothermal Regime of Italy and surrounding Seas*. In: "*Exploration of the deep continental crust",* Springer-Verlag: 381-394, Berlin.

MOUSSAT E., REHAULT J.P. & FABBRI A. (1986) - *Rifting et évolution tectono-sédimentaire du Bassin tyrrhenien au cours du Néogène et du Quaternaire*. Giorn. Geol., **48** (1/2): 41-62.

NICOLICH R. (1989) – *Crustal strcuture from seismic studies in the frame of the European Geotraverse (southern segment) and CROP Projects*. In: BORIANI A., BONAFEDE M., PICCARDO G. B. & VAI G. B. (Eds.): "*The lithosphere in Italy. Advances in Earth Science Research."*. Atti Convegni Lincei, **80**: 41-61.

NICOLICH R. (2001) - *Deep seismic transects*. In: VAI G.B. & MARTINI I.P. (Eds.): "*Anatomy of an orogen: the Apennines and adjacent Mediterranean basins*". Kluwer Academic Publishers: 47-52, Dordrecht, The Netherlands.

NICOLICH R. & DAL PIAZ G.V. (1992) - *Moho isobaths. Structural Model of Italy. Scale 1:500,000*. Quaderni de "La Ricerca Scientifica", **114** (3), CNR.

OGNIBEN L., PAROTTO M. & PRATURLON A. (1975) - *Structural Model of Italy*. Quaderni de "La Ricerca Scientifica", **90**: pp.502. CNR

PANZA G.F. (1984) - *Structure of the lithosphere-asthenosphere system in the Mediterranean region*. In: KAHLE H.G., MUELLER S. & WILSON P. (Eds.): *"Crustal dynamics in the Alpine-Mediterranean region"*. Ann. Geophys., **2**:137-138.

PANZA G.F., MUELLER S. & CALCAGNILE G. (1980) - *The gross features of the lithosphere-asthenosphere system in Europe from seismic surface waves and body waves*. In: PANZA G.F., MUELLER S. & WIELANDT E. (Eds.): *" Generation and propagation of seismic waves"*. Pure Appl. Geophys., **118**: 1209-1213.

PANZA G.F., SCANDONE P., CALCAGNILE G., MUELLER S. & SUHADOLC P. (1992) – *The lithosphere-asthenosphere system in Italy and surrounding regions*. Quaderni de "La Ricerca Scientifica", **114** (3), CNR.

Pappalardo L., Piochi M., D'Antonio M., Civetta L., Petrini R. (2002) - *Evidence for Multi-stage Magmatic Evolution during the past 60 kyr at Campi Flegrei (Italy) deduced from Sr, Nd, and Pb Isotope Data.* J. Petrol., **43**: 1415-1434.

Pascucci V., Merlini S. & Martini P. (1999) - *Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy).* Bas. Research, **11**: 337-356.

Patacca E. & Scandone P. (1989) - *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab.* In: Boriani A., Bonafede M., Piccardo G. B. & Vai G. B. (Eds.): "*The lithosphere in Italy. Advances in Earth Science Research*". Atti Convegni Lincei, **80**: 157-176.

Patacca E. & Scandone P. (2001) – *Late thrust propagation and sedimentary response in the thrust-belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene).* In: Vai G.B.& Martini I.P. (Eds.): *"Anatomy of an Orogen: the Apennines and the adjacent Mediterranean Basins".* Kluwer Academic Publishers: 401-440, Dordrecht, The Netherlands.

Patacca E., Scandone P., Bellatalla M., Perilli N. & Santini U. (1992) - *The Numidian-sand event in the southern Apennines.* Mem. Sci. Geol., **43**: 297-337.

Peccerillo A. (1999) - *Multiple mantle metasomatism in central-southern Italy: Geochemical effects, timing and geodynamic implications*. Geology, **27**: 315-318.

Peccerillo A. & Panza G.F. (1999) - *Upper mantle Domains beneath Central-Southern Italy: Petrological, geochemical and Geophysical Constraints.* Pure. Appl. Geophys., **156**: 421-443.

Pialli G., Barchi M. & Minelli G. (Eds.) (1998) – *Results of the CROP03 deep seismic reflection profile.* Mem. Soc. Geol. It., **52**: 657 pp.

Pfiffner O.A. (1986) - *Evolution of the north Alpine foreland basin in the Central Alps.* In: "*Foreland Basins*". Spec. Publ. Int. Assoc. Sedimentol., **8:** 219-228.

Pfiffner O.A., Lehner P., Neitzmann P., Mueller St. & Steck A. (Eds.) (1997) - *Results of NRP 20; deep structure of the Swiss Alps.* Birkhaeuser Verlag, Basel, Switzerland.

Philip H. (1987) – *Plio-Quaternary evolution of the stress field in in Mediterranean zones of subduction and collision*. Ann. Geophys, **5B**: 301-319.

Piccardo G., Rampone E., Robbiano A., Scambelluri M. & Vallis F. (1997) - *Pre-Alpine and Alpine Evolution of the Erro-Tobbio Peridotite, Voltri Massif, Western Liguria.* Ofioliti, **22**: 153-162.

Pieri P., Vitale G., Beneduce P., Doglioni C., Gallicchio S., Giano S.I., Loizzo R., Moretti M., Prosser G., Sabato L., Schiattarella M., Tramutoli M. & Tropeano M. (1997) – *Tettonica quaternaria nell'area bradanico-ionica.* Il Quaternario, **10**: 535-542.

Pinarelli L. (1991) - *Geochemical and isotopic (Sr, Pb) evidence of crust-mantle interaction in acidic melts. The Tolfa-Cerveteri-Manziana volcanic complex (Central Italy): a case history.* Chem. Geol., **92**: 177-195.

Pinna E. (1987) – *Italy, Total Magnetic Field Anomaly.* Selca Editore, Firenze.

Piromallo C. & Morelli A. (1997) - *Imaging the Mediterranean upper mantle by P-wave travel time tomography.* Ann. Geophys., **40** (4): 963-979.

Pisa G., Castellarin A., Lucchini F., Rossi P.M., Simboli G., Bosellini A. & Sommavilla E. (1979) - *Middle triassic Magmatism in Southern Alps I: A Review of General data in the Dolomites.* Riv. Ital. Paleont. Str., **85**: 1093-1110.

Poli G. (1992) - *Geochemistry of Tuscan Archipelago Granitoids, central Italy: the role of hybridization processes in their genesis.* J. Geol., **100**: 41-56.

Polino R., Dal Piaz G.V. & Gosso G. (1990) - *Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps.* Mém. Soc. Géol. France, **156**: 345-367.

Polino R., Fantoni R., Rogledi S. & Ruffini R. (2001) - *Testimonianze del vulcanismo oligocenico collisionale nel "retroforeland" alpino.* In: Geoitalia 2001: 68-70, Chieti.

Rampone E. & Piccardo G. (2000) - *The ophiolite-oceanic lithosphere analogue: New insights from the Northern Apennines (Italy).* In: Dilek Y., Moores E.M., Elthon D., Nicolas A. (Eds.): "*Ophiolites and Oceanic crust: New Insights from Fields studies and the Ocean Drilling Program*". Geol. Soc. Am. Spec. Paper: 21-34, Boulder, Colorado.

Rebai S., Philip H. & Taboada A. (1992) – *Modern tectonic stress field in the Mediterranean region: evidence for variation in stress directions at different scales.* Geophys. J. Intern., **110:** 106-140.

Rocchi S., Longaretti G. & Salvadori M. (1998) - *Subsurface Mesozoic and Cainozoic magmatism in southern-eastern Sicily: distribution, volume and geochemistry of magmas.* Acta Vulcanol., **10**: 395-408.

Rocchi S., Westerman D., Dini A., Innocenti F. & Tonarini S. (2002) - *Two-stage growth of laccolith at Elba Island (Italy).* Geology, **30** (11): 983-986.

Rosatelli G., Stoppa F. & Jaones A.P. (2000) - *Intrusive calcite-carbonatite occurrence from Mt. Vulture volcano, southern Italy.* Mineral. Mag., **64**: 615-624.

Royden L.H. (1993) – *The tectonic expression of slab pull at continental convergent boundaries.* Tectonics, **12**: 303-325.

Royden L.H. & Burchfiel B.C. (1989) – *Are systematic variations in thrust belt style related to plate boundary processes? (the western Alps versus the Carpathians).* Tectonics, **8**: 51-62.

Ruffini R., Cadoppi P., d'Atri A. & Novaretti A. (1995a) - *Ash layers in the Monferrato (NW Italy): records of two types of magmatic source in Oligocene-Miocene time.* Eclogae Geol. Helv., **88**: 347-363.

Ruffini R., Cosca M.A., d'Atri, A. Hunziker J.C. & Polino R. (1995b) - *The volcanic supply of the Taveyanne turbidites (Savoie, France): A riddle for Tertiary Alpine volcanism.* Acc. Naz. Sci., Scritti Doc., **14**: 359-376.

Salustri Galli C., Torrini A., Doglioni C. & Scrocca D. (2002) - *Divide and highest mountains vs subduction in the Apennines.* Studi Geol. Camerti, Nuova Serie **1**:143-153.

Sartori R. & ODP Leg 107 Scientific Staff (1989) - *Drillings of ODP Leg 107 in the Tyrrhenian Sea: Tentative Basin Evolution Compared to Deformations in the Surroundings Chains.* In: Boriani A., Bonafede M., Piccardo G. B. & Vai G. B. (Eds.): "*The lithosphere in Italy. Advances in Earth Science Research*". Atti Convegni Lincei, **80**: 139-156.

Scandone P. (1980) - *Origin of the Tyrrhenian Sea and Calabrian Arc.* Boll. Soc. Geol. It., **98**: 27-34.

Scarascia S. & Cassinis R. (1997) – *Crustal structures in the central-eastern Alpine sector; a revision of the available DSS data.* Tectonophysics, **271** (1-2): 157-188.

Scarascia S., Lozej A. & Cassinis R. (1994) – *Crustal structures of the Ligurian, Tyrrhenian and Ionian seas and adjacent onshore areas interpreted from wide-angle seismic profiles.* Boll. Geofis. Teor. Appl., **36** (141-144): 5-19.

Schmid S.M. & Kissling E. (2000) - *The arc of the western Alps in the light of geophysical data on deep crustal structure.* Tectonics, **19** (1): 62-85.

SELVAGGI G. & AMATO A. (1992) – *Subcrustal earthquakes in the northern Apennines (Italy): Evidence for a still active subduction?* Geophys. Res. Lett., **19**: 2127-2130.

SELVAGGI G. & CHIARABBA C. (1995) – *Seismicity and P-wave velocity image of the Southern Tyrrhenian subduction zone*. Geophys. J. Int., **121**: 818-826.

SERRI G., INNOCENTI F. & MANETTI P. (1993) - *Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy.* Tectonophysics, **223**: 117-147.

SERRI G., INNOCENTI F. & MANETTI P. (2001) - *Magmatism from Mesozoic to Present: petrogenesis, time-space distribution and geodynamic implications.* In: VAI G.B.& MARTINI I.P. (Eds.): *"Anatomy of an Orogen: the Apennines and the adjacent Mediterranean Basins".* Kluwer Academic Publishers: 77-104, Dordrecht, The Netherlands.

SERVIZIO GEOLOGICO NAZIONALE (1989) – *Gravimetric Map of Italy, scale 1:1.000.000. 2 sheets.* Servizio Geologico d'Italia, Istituto Poligrafico e Zecca dello Stato, Roma.

SERVIZIO GEOLOGICO NAZIONALE (1994) – *Carta Aeromagnetica d'Italia, scale 1:1.000.000.* Servizio Geologico d'Italia, Istituto Poligrafico e Zecca dello Stato, Roma.

SIENA F. & COLTORTI M. (1989) - *Lithospheric mantle evolution: Evidences from ultramafic xenoliths in the Lessinian volcanics (northern Italy).* Chem. Geol., **77**: 347-364.

SLOMAN L.E. (1989) - *Triassic shoshonites from the Dolomites, northern Italy; alkaline arc rocks in a strike-slip setting.* J. Geophys. Res., **94**: 4655-4666.

SPAKMAN W. (1990) - *Tomographic images of the upper mantle below central Europe and the Mediterranean.* Terra Nova, **2**: 542-553.

SPAKMAN W., WAN DER LEE S. & VAN DER HILST R. (1993) – *Travel-time tomography of the European-Mediterranean mantle down to 1400 km.* Phys. Earth Planet. Interiors, **79**: 3-74.

STOPPA F. & LAVECCHIA G. (1992) - *Late Pleistocene ultra-alkaline magmatic activity in the Umbria-Latium region (Italy): An overview.* J. Volcanol. Geotherm. Res., **52**: 277-293.

STOPPA F. & PRINCIPE C. (1998) - *Eruption style and petrology of a new carbonatitic suite from Mt. Vulture, Southern Italy: The Monticchio Lakes Formation.* J. Volcanol. Geotherm. Res., **80**: 137-153.

STOPPA F. & WOLLEY A.R. (1997) - *The Italian carbonatites: field occurrence, petrology and regional significance.* Mineral. Petrol., **59**: 43-67.

SUHADOLC P., PANZA G.F. & MUELLER S. (1990) - *Physical properties of the lithosphere-asthenosphere system in Europe.* Tectonophysics, **176**: 123-135.

TONARINI S., ARMIENTI P., D'ORAZIO M. & INNOCENTI F. (2001) - *Subduction-like fluids in the genesis of Mt. Etna magmas: evidences from boron isotopes and fluid mobile elements.* Earth Planet. Sci. Letters, **142**: 471-483.

TONARINI S., D'ORAZIO M., ARMIENTI P., INNOCENTI F. & SCRIBANO V. (1996) - *Geochemical features of eastern Sicily lithosphere as probed by Hyblean xenoliths and lavas.* Eur. J. Mineral., **8**: 1153-1173.

TORELLI L., GRASSO M., MAZZOLDI G., PEIS D. & GORI D. (1995) - *Cretaceous to Neogene structural evolution of the Lampedusa Shelf (Pelagian Sea, central Mediterranean).* Terra Nova. **7** (2): 200-212.

TORELLI L., TRICART P., ZITELLINI N., ARGNANI A., BOUHLEL I., BRANCOLINI G., DE CILLIA C., DE SANTIS L. & PEIS D. (1992) - *Une Section sismique profonde de la chaine Maghrebides-Apennins, du bassin Tyrrhenien a la plateforme Pelagienne (Mediterranée centrale).* Comptes Rendus Acad. Sci., **315** (5): 617-622.

TRUA T., LAURENZI M.A. & ODDONE M. (1997) - *Geochronology of the Plio-Pleistocene Hyblean volcanism (SE Sicily): new 40Ar/39Ar data.* Acta Vulcanol., **9**: 167-176.

TRÜMPY R. (1982) - *Alpine Paleogeography: a Reappraisal.* In: HSU K.J (Ed.): *"Mountain buiding processes".* Academic Press: 149-156.

VALENSISE G. & PANTOSTI D. (Eds.) (2001) – *Database of Potential Sources for Earthquakes Larger than 5.5 in Italy.* Ann. Geof., Suppl. to vol. **44** (4): pp. 180, with CD-ROM, INGV.

VON BLANCKENBURG, F. & DAVIES J.H. (1995) - *Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps.* Tectonics, **14**: 120-131.

WALDHAUSER F., KISSLING E., ANSORGE J. & MUELLER S. (1998) - *Three-dimensional interface modelling with two-dimensional seismic data; the Alpine crust-mantle boundary.* Geoph. J. Intern., **135** (1): 264-278.

WASHINGTON H.S. (1906) - *The Roman comagmatic region.* Carnegie Inst. WASHINGTON, **57**: 1-199.

WESTERMAN D.S., INNOCENTI F., TONARINI S. & FERRARA G. (1993) - *The Pliocene Intrusions of the Island of Giglio (Tuscany).* Mem. Soc. Geol. It., **49**: 345-363.

WIGGER P.J. (1984) – *Die Krustenstruktur der Nordapennins und angrenzender Gebiete mit besondere Berücksichtigung der geotermischen Anomalie der Toskana.* Berl. Geowiss. Abh., Reihess Heft, **9**: 1-87.

WILSON M. & BIANCHINI G. (1999) - *Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions.* In: DURAND B., JOLIVET L., HORVATH F., SÉRANNE M. (Eds.): *"The mediterranean Basins: tertiary Extension within the Alpine Orogen".* Geol. Soc. London, Spec. Publ., **156**: 141-168.

ZANTEDESCHI C. (1994) - *New Rb-Sr radiometric data from Colli Euganei (North-Eastern Italy).* Mem. Sci. Geol., **46**: 17-22.

ZAPPATERRA E. (1990) - *Carbonate paleogeographic sequences of the Periadriatic region.* Boll. Soc. Geol. It., **109**: 5-20.

ZITELLINI N., TRINCARDI F., MARANI M., TRAMONTANA M. & BARTOLE R. (1986) - *Neogene tectonics of the Northern Tyrrhenian Sea.* Giorn. Geol., **48**: 25-40.