Ofioliti, 2002, 27 (2), 119-131

THE EXTERNAL LIGURIAN UNITS (NORTHERN APENNINE, ITALY): FROM RIFTING TO CONVERGENCE OF A FOSSIL OCEAN-CONTINENT TRANSITION ZONE

Marroni M.*, **, Molli G.*, **, Montanini A.*, Ottria G.**, Pandolfi L.**** and **Tribuzio R.****,♣**

* *Dipartimento di Scienze della Terra, Università di Pisa, via S. Maria 53, 56126 Pisa, Italy (e-mail: gmolli@dst.unipi.it; marroni@dst.unipi.it).*

** *Istituto di Geoscienze e Georisorse, CNR , via S. Maria 53, 56126, Pisa, Italy (e-mail: pandolfi@dst.unipi.it).*

*** *Dipartimento di Scienze della Terra, Università di Parma, Parco Area delle Scienze, 43100 Parma, Italy (e-mail: ales01@ipruniv.cce.unipr.it).*

**** *Dipartimento di Scienze della Terra, Università di Pavia, via Ferrata 1, 27100 Pavia, Italy (e-mail: tribuzio@crystal.unipv.it).*

♣ *Istituto di Geoscienze e Georisorse, CNR, via Ferrata 1, 27100 Pavia, Italy.*

Keywords: *Ocean-continent transition, ophiolites, Ligurian Tethys. Northern Apennine.*

ABSTRACT

The External Ligurian Units of the Northern Apennine are interpreted as derived from the continent-ocean transition domain at the northern thinned continental margin of the Adria microplate, i.e. the External Ligurian domain. The evolution of this paleogeographic realm from pre-orogenic times to the Eo-alpine and Meso-alpine tectonics is presented here, through a review of stratigraphic, petrological and structural data. The tectono-metamorphic evolution started in the Late Carboniferous-Early Permian (about 290 Ma), with the emplacement at deep crustal levels of the gabbroic protoliths of mafic granulites. These lower continental crust rocks subsequently underwent Permo-Triassic tectonic exhumation and were finally exhumed at shallow crustal levels in middle Jurassic. The latter period was characterized by extensive brittle faulting at shallow crustal levels, giving rise to extensional allochtons formed by stretched slices of upper continental crust (mainly granitoids). At deep structural levels high temperature shearing of ophiolitic gabbros took place. Opening of the Ligurian Tethys is finally testified by the basalt emplacement and radiolarian chert sedimentation in the Late Jurassic.

During Late Cretaceous, development of Alpine intraoceanic subduction led to the inversion of the External Ligurian domain: the Eo-alpine deformation is recorded by syn-tectonic sedimentation of the *Complessi di Base* Auct., by development of very low-grade metamorphism and deformation at about 80 Ma. Middle Eocene deformation related with collision and indentation of the Adria with the Alpine accretionary wedge can be subdivided in two main stages: the first one (Ligurian Phase 1) implies large-scale, westward displacement of the EL Units, whereas the second stage (Ligurian Phase 2) is characterized by east-verging structures probably driven by the thinning of the preexisting nappe pile associated with exumation of underplated HP/LT Alpine units.

INTRODUCTION

In the western Tethys, the rifting processes related to opening of the Ligure-Piemontese oceanic basin led to conjugate passive continental margins characterized by an asymmetry in their structures and evolutionary paths (Lemoine et al., 1987; Stampfli and Marthaler, 1990; Dal Piaz, 1993; Hoogerduijn et al., 1993; Froitzheim and Manatschal, 1996, Marroni et al., 1998 and references). The characters and architecture of the ocean-continent transition areas associated with continental margins played an important role during plate convergence phases since the pre-existing discontinuities were reactivated by the contractional tectonics.

In the Alpine-Apennine framework (Fig. 1), the External Ligurian Units (hereafter referred as EL Units) are regarded as representative of the domain that joined the Ligure-Piemontese oceanic basin to the Adria Plate continental margin (e.g. Elter et al., 1966; Elter, 1975; Abbate et al., 1980; Zanzucchi, 1980; Galbiati, 1990; Vescovi, 1993, Rampone and Piccardo, 2000). This area, bears evidence of processes which began with post-Variscan/Triassic crustal attenuation, followed by Jurassic rifting and by later convergence starting from Late Cretaceous.

In this paper a review of the stratigraphical, petrological and tectonic framework of the EL Units from the Northern Apennine is proposed in order to provide a schematic picture for the evolution of an ocean-continent transition area of the Ligure-Piemontese oceanic basin during rifting, oceanization and convergence.

REGIONAL AND LITOSTRATIGRAPHIC SETTING

The Ligurian Units of Northern Apennine (Fig. 2) are remnants of the Ligure-Piemontese oceanic basin and its transition to the Adria continental margin. The Ligurian Units, occurring at the top of nappe pile, are recognized in two different lithostratigraphic and tectonic settings, corresponding to Internal Ligurian (IL) and External Ligurian (EL) (Elter et al., 1966; Elter, 1975). The IL Units are representative of the Ligure-Piemontese oceanic basin wherease the EL Units are interpreted as derived from the domain that joined the oceanic area to the Adria continental margin (Marroni et al., 2001 and references). The IL Units are interposed between the EL Units (Figs. 2 and 3), i.e. they can be observed in overthrust relationships with the EL Units of the Emilian Apennine and are in turn overlain by the Antola Unit (Elter and Pertusati, 1973). The main, large scale structures of the Ligurian Units are unconformably sealed by the Epimesoalpine successions, also known as Epiligurian Ranzano-Bismantova succession and Tertiary Piemontese basin or Langhe Basin (Laubscher et al., 1992), ranging in age from Middle Eocene to Late Miocene (Lorenz, 1969; Ricci Lucchi and Ori, 1985; Gelati and Gnaccolini, 1982; 1996; Bettelli et al., 1989; Mutti et al., 1995, Catanzariti et al., 1997). In Late Oligocene-Miocene time, the Ligurian Units and the overlying episutural successions are again deformed during thrusting onto the easternmost domain of the Adria plate, today represented by Subligurian, Tuscan and Umbrian-Marche Units (Elter, 1975 and following).

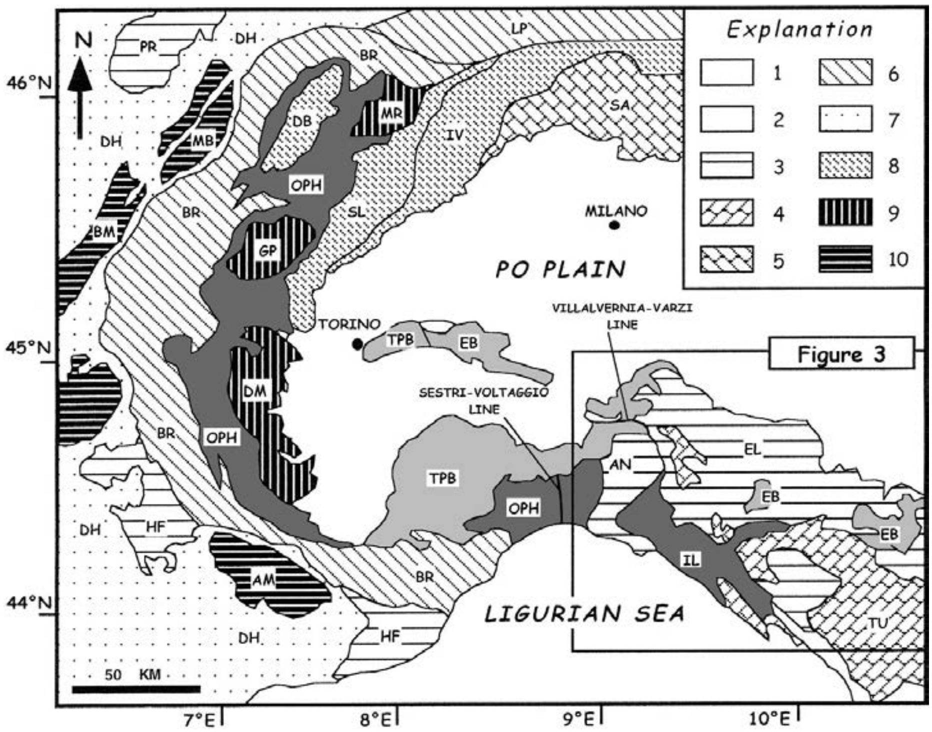

Fig. 1 - Tectonic sketch map of the Western Alps and Northern Apennine. 1- Post-orogenic sedimentary sequences of the Tertiary Piemonte (TPB) and Epiligurian (EB) Basins; 2- Alpine and Apennines Ophiolitic units [Internal Ligurian (IL), Sestri-Voltaggio, Voltri Group, Piemontese units of the Western Alps (OPH)]; 3- Helminthoid flysch and associated sedimentary complexes [External Ligurian (EL), Antola (AN), Autapie and Sanremo-Monte Saccarello (HF) and Prealpine (PR) Units]; 4- Canetolo and Umbrian-Tuscan Units (TU); 5- South Alpine cover Units (SA); 6- Briançonnais (BR) and Lower Penninic (LP) Units; 7- Dauphinois-Helvetic Units (DH); 8- Austro alpine Units [Sesia-Lanzo Zone (SL), Ivrea Zone (IV) and Dent Blanche (DB)]; 9- Internal crystalline massifs of the Western Alps [Dora Maira (DM), Gran Paradiso (GP) and Monte Rosa (MR)]; 10-External crystalline massifs of the Western Alps [Argentera Mercantour (AM), Belledonne (BM) e Mont Blanche (MB)]. The study area represented in Fig.3 is indicated.

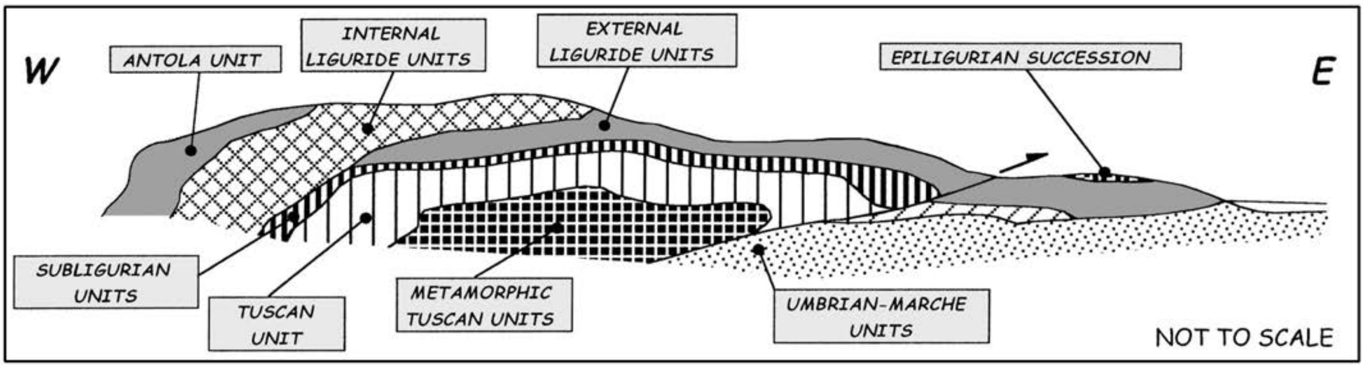

Fig. 2 - Schematic cross section of the Northern Apennine (redrawn from Elter, 1975).

Whereas the IL Units include an ophiolite sequence base of Late Jurassic to lower Paleocene sedimentary cover (Elter, 1975 and following), the EL Units display well-developed successions of Late Cretaceous-Middle Eocene age detached from their pre-Cretaceous substratum. The older parts of the EL successions mainly consist of Upper Cretaceous sedimentary deposits, reported in literature as C*omplessi di base* (Elter and Raggi, 1965; Elter et al., 1966, Zanzucchi, 1980 and many others). They are formed by turbidite and hemipelagic deposits associated with sedimentary melanges characterized by tectonic slices and slide blocks of ophiolites, continental crust rocks and Mesozoic sediments. The basal complexes locally preserve a gradual transition to Upper Cretaceous carbonate flysch known in literature as Helminthoid flysch. The Upper Cretaceous Helminthoid flysch is in turn overlain by Paleocene-Middle Eocene, mainly carbonate flysch, representing the youngest deposits within the EL successions.

Despite the ubiquitous occurrence of Upper Cretaceous-lower Tertiary carbonate flysch, the EL Units have been subdivided into two different groups according to the lithostratigraphic features of their basal complexes (Fig. 4). The first group ("Western successions") includes all the successions characterized by the occurrence of basal complexes with tectonic slices, slide blocks and debris flow deposits where mantle ultramafics and ophiolitic basalts are largely represented, whereas the second group ("Eastern successions") displays successions where the basal complexes indicate a continental affinity and the mafic and ultramafic rocks are scarce or lacking at all. According to these features, the first group ("Western successions") is considered to be placed "ocean-ward" near the Ligure-Piemontese oceanic domain, whereas the second group ("Eastern successions") can be located "continental-ward" at the distal edge of the Adria continental margin (Marroni et al., 2001 and references).

In both groups the Helminthoid flysch reveals the same stratigraphic: alternating thick calcareous turbidites, thin siliciclastic turbidites and minor carbonate-free hemipelagic background sediments. Sedimentological features of turbiditic beds are characterized by traction plus fall-out derived structures (ripples and climbing ripples) indicative of low density turbidity currents. These evidence together with absence of carbonate in hemipelagic background sediments are indicative of an abyssal plain environment located below the local $CaCO_3$ compensation level (Scholle, 1971). In the

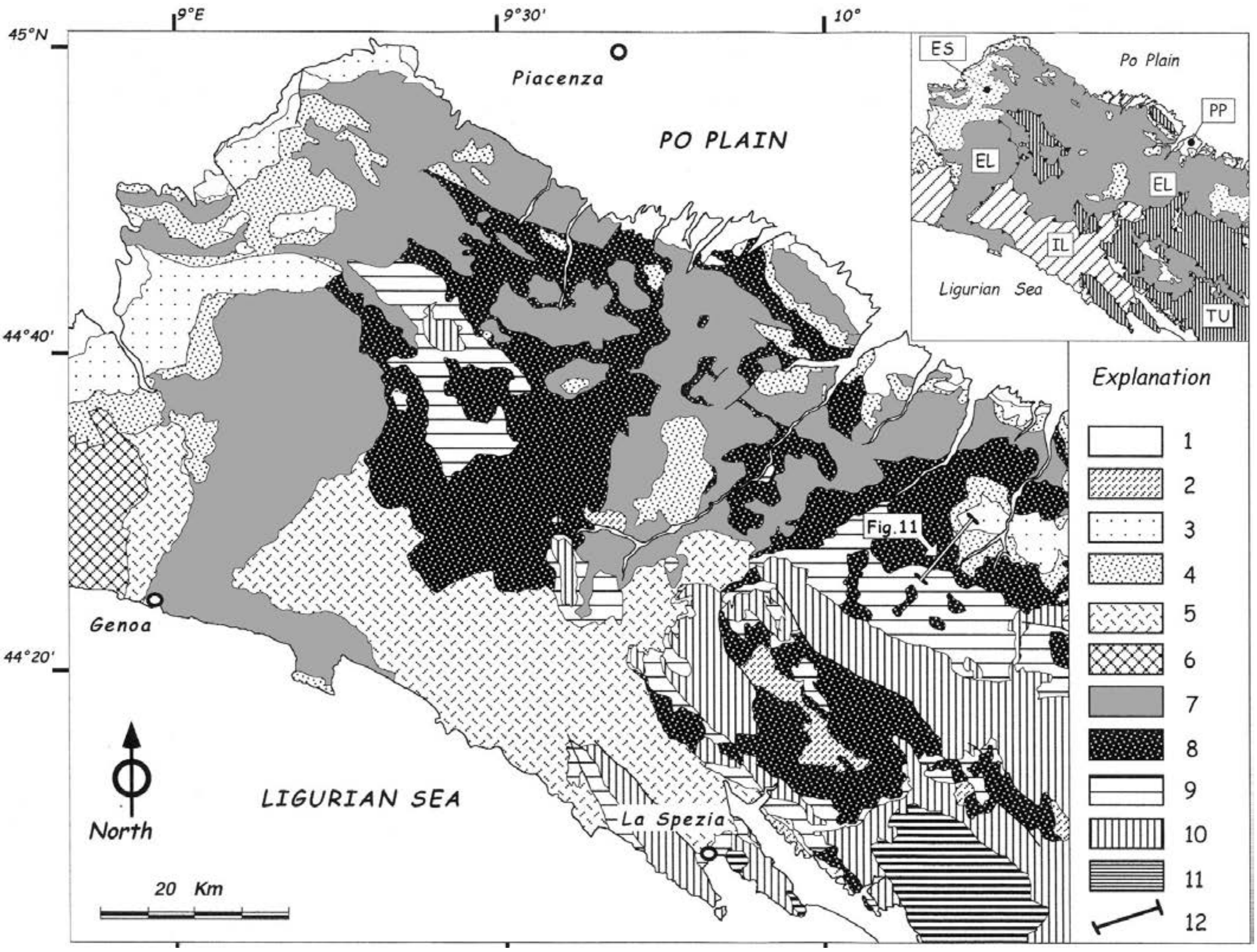

Fig. 3 - Tectonic sketch map of the Northern Apennine. 1- Plio-Quaternary deposits; 2- Plio-Pleistocene intramontane basins; 3- Miocene Epi-mesoalpine sedimentary sequences of the Tertiary Piemontese and Epiligurian basins; 4- Upper Eocene- Oligocene sedimentary sequences of the Tertiary Piemontese and Epiligurian basins; 5: Internal Ligurian Units; 6- Sestri-Voltaggio Zone and Voltri Group; 7- External "Eastern" Ligurian Units; - External "Western" Ligurian Units; 9- Subligurian Units ; 10- Tuscan Units; 11- Low-grade metamorphic Tuscan Units (Apuan Alps window); 12- Location of cross section of Fig. 11- (redrawn from Marroni et al. 2001).
Tectonic sketch map: PP- Plio-Pleistocene successions; ES- Tertiary Piedmontese and Epiligurian successions; IL- Internal Ligurian Units; EL- External Ligurian Units; TU- Tuscan and Umbrian Units.

Tertiary flysch the carbonatic supply decreases and the siliciclastic beds become abundant.

The "Western successions" (Figs. 3 and 4) include different units (Bettola-Caio, Orocco, Ottone, Mt.delle Tane and Groppallo Units, see Marroni et al., 2001) of Upper Cretaceous Helminthoid and Tertiary flyschs, characterized by Upper Cretaceous sedimentary melanges, e.g. Casanova, Mt. Ragola and Pietra Parcellara complexes. All these sedimentary melanges are characterized by tectonic slices and slide blocks associated with matrix- to clast-supported breccias and coarse grained, turbidite-derived rudites and arenites. The tectonic slices and slide blocks include subcontinental mantle rocks, gabbros and basalts, sometimes associated with lower and upper continental crust rocks, i.e. mafic and felsic granulites and granitoids.

The second group of EL Units, characterized by "Eastern successions" (Figs. 3 and 4) is represented by different units (e.g. the Media Val Taro, Cassio, Farini, Solignano, Antola and Sporno Units details in Marroni et al., 2001) which share: i) the lacking of ophiolites ii) the presence of deposits supplied by a continental margin (e.g. Conglomerati dei Salti del Diavolo), iii) tectonic slices of Middle Triassic-Jurassic carbonate platform sediments to be interpreted as remnants of the continental substratum (Sturani, 1973; Zanzucchi, 1980; Elter and Marroni, 1991).

In the following sections we analyze the features of the EL Units as recorded in their evolutionary paths during rifting, oceanization and convergence.

THE RIFTING OF THE CONTINENTAL LITHOSPHERE

The rifting process can be reconstructed through geochemical, petrological and structural data on the exhumed mantle and continental crust rocks. The continental crust rocks are mainly granulites and granitoids, which are representative of lower and upper crustal levels, respectively.

The subcontinental mantle rocks

The mantle ultramafic rocks mostly consist of fertile

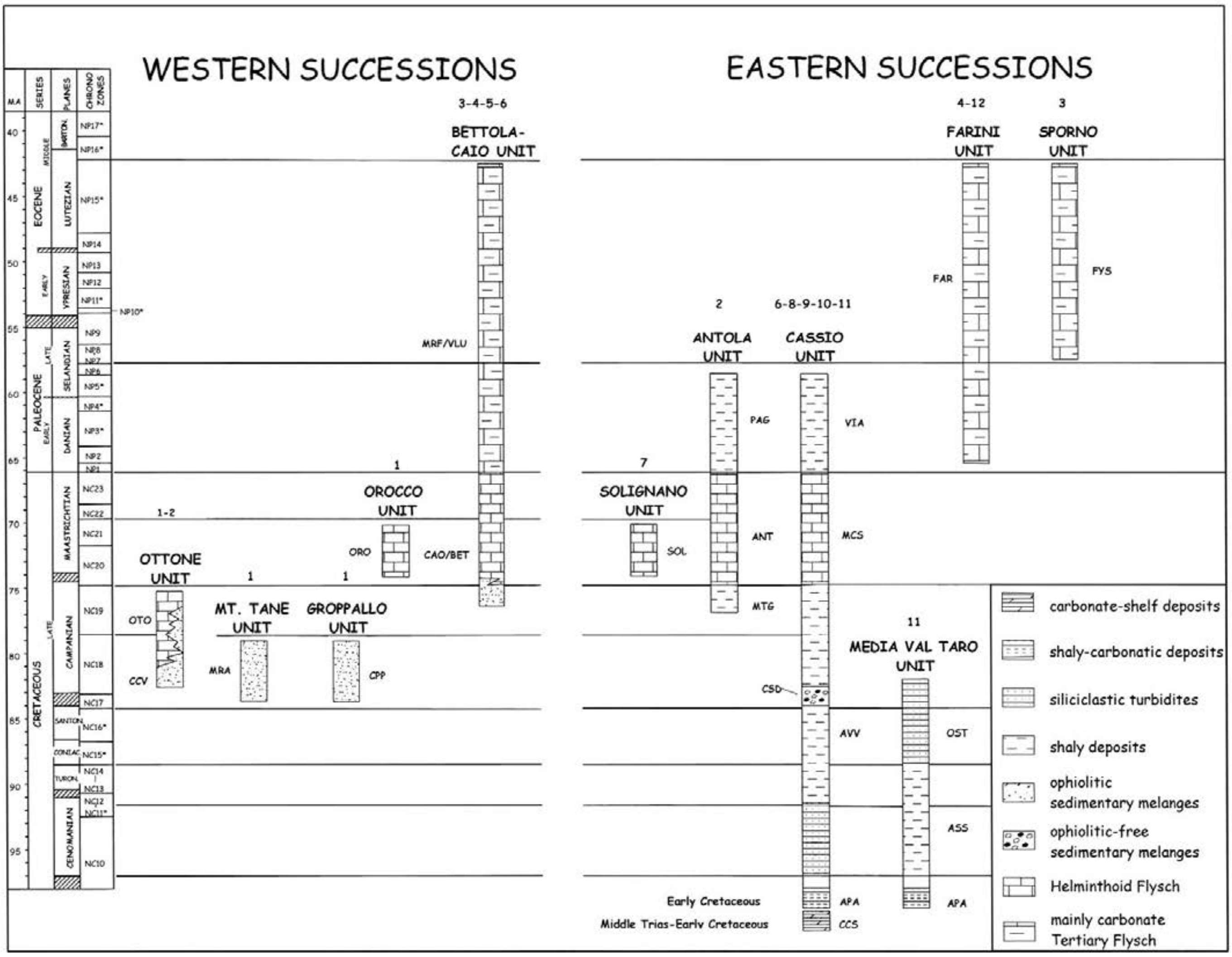

Fig. 4 - Age and lithological composition of the ocean- and continental-ward successions of the External Ligurian Units. Time scale from Cande and Kent (1992).

Explanation: OTO- Ottone Flysch; CCV- Casanova Complex; MRA- Mt. Ragola Complex; CCP- Pietra Parcellara Complex; ORO- Mt. Orocco Flysch; MRF/VLU- Marne Rosate Formation and Val Luretta Flysch; CAO/BET- Caio and Bettola Flysch; SOL- Solignano Flysch; PAG- Pagliaro Shale; ANT- Mt. Antola Flysch; MTG- Montoggio Shale; VIA- Viano Shale; MCS- Mt. Cassio Flysch; CSD- Salti del Diavolo Conglomerate; AVV- Varicoloured Shale; APA- Palombini Shale; CCS- Middle Trias to Lower Cretaceous continental substratum of Cassio Unit; OST- Ostia Sandstone; ASS- San Siro Shale; FAR- Farini d'Olmo Flysch; FYS- Mt. Sporno Flysch.

spinel lherzolites containing disseminated titanian pargasite (Beccaluva et al., 1984; Ottonello et al., 1984; Rampone et al., 1995). The relatively undepleted nature is shown by the relatively high amounts of clinopyroxene (10-15 vol %), high whole-rock Al_2O_3 contents and slight LREE depletion of clinopyroxene REE patterns. Temperature estimates for the spinel-facies assemblage point to relatively low values (mainly in the range 1000-1050°C), compatible with continental geothermal gradients (Beccaluva et al., 1984; Ottonello et al., 1984). The subcontinental origin of the lherzolites was confirmed by Sm-Nd, Rb-Sr and Re-Os isotope investigations (Rampone et al., 1995, Snow et al., 2000), that indicate a Proterozoic age as the time of accretion of the External Ligurian mantle to the subcontinental lithosphere.

The mantle lherzolites may contain pyroxenite bands (Piccardo, 1976; Beccaluva et al., 1984). Lherzolites and pyroxenites display partial recrystallization to plagioclase-bearing assemblages (Fig. 5A), locally accompanied by ductile deformation and development of tectonite and mylonite fabrics. Geothermometric investigations suggest that decompression to plagioclase-facies conditions was accompanied by slight cooling (Beccaluva et al., 1984; Rampone et al., 1995). Sm/Nd isochrons on plagioclase-clinopyroxene pairs from two lherzolite samples gave ages of 164±20 Ma, interpreted as the time of metamorphic re-equilibration under plagioclase-facies conditions (Rampone et al., 1995). The plagioclase-facies tectonites to mylonites are in places crosscut by doleritic dykes with MORB affinity (Venturelli et al., 1981; Vannucci et al., 1993, Marroni et al., 1998).

The lower crustal rocks

Mafic granulites commonly show a metamorphic foliation that developed during granulite-facies deformation. Rocks preserving relict gabbroic features at the hand-sample scale (Fig. 5B), such as igneous layering and coarse pyroxene porphyroclasts, are locally present (Marroni and Tribuzio, 1996). The mafic granulites (Fig. 5C) have variable compositions and commonly contain significant amounts of either olivine or Fe-Ti-oxide phases (see also Montanini, 1997). Their gabbroic protoliths were emplaced at deep crustal levels and underwent slow cooling and recrystallization under granulite-facies conditions. Pressure and temperature values of 0.7-0.8 GPa and 800-900°C have been estimated for the subsolidus re-equilibration of the gabbroic protoliths (Marroni and Tribuzio, 1996; Montanini, 1997). A gabbro-derived granulite gave a Sm-Nd clinopyroxene-plagioclase-whole-rock isochron of 291±9 Ma, interpreted as the age of the granulite-facies recrystallization during post-magmatic cooling, most likely close to the time of intrusion in the lower crust (Meli et al., 1996).

The protoliths of the mafic granulites can be subdivided into three main types: (1) olivine-bearing granulites characterized by symplectites of orthopyroxene, clinopyroxene and Al-spinel at the contact between olivine and plagioclase, (2) olivine-free, coarse-grained granulites displaying high modal abundances of clinopyroxene (clinopyroxene-rich granulites), (3) Fe-Ti oxide granulites showing relatively high modal amounts of ilmenite and magnetite (Montanini and Tribuzio, 2001). On the basis of mineralogy and whole-rock major and trace element compositions, the protoliths of the gabbro-derived granulites are recognized as cumulus rocks derived from variably evolved tholeiitic liquids (Montanini and Tribuzio, 2001). Whole-rock REE and Nd-Sr isotope compositions indicate that the parental liquids of the mafic granulite protoliths were tholeiites derived from a depleted mantle source. In particular, the Nd isotope compositions of olivine-bearing to clinopyroxene-rich granulites (Fig. 6) are consistent with those of residual mantle lherzolites from the ophiolites of the Northern Apennines (Rampone et al., 1998) and the Western Alps (Bodinier et al., 1991). These mantle rocks thus represent suitable refractory residua of the original sources that yielded the primary melts of the mafic granulite protoliths. The protoliths of the Fe-Ti-oxide-bearing mafic granulites can be related to the least evolved rocks through fractional crystallization and assimilation of crustal material.

Mafic granulites are in places associated with felsic granulites, but the original field relations between the two rock types are unclear. The felsic granulites commonly show quartz-feldspathic composition (Balestrieri et al., 1997); they probably represent anatectic and migmatitic rocks resulting from multi-stage melting of lower crustal basement rocks (Montanini and Tribuzio, 2001). The available petro-

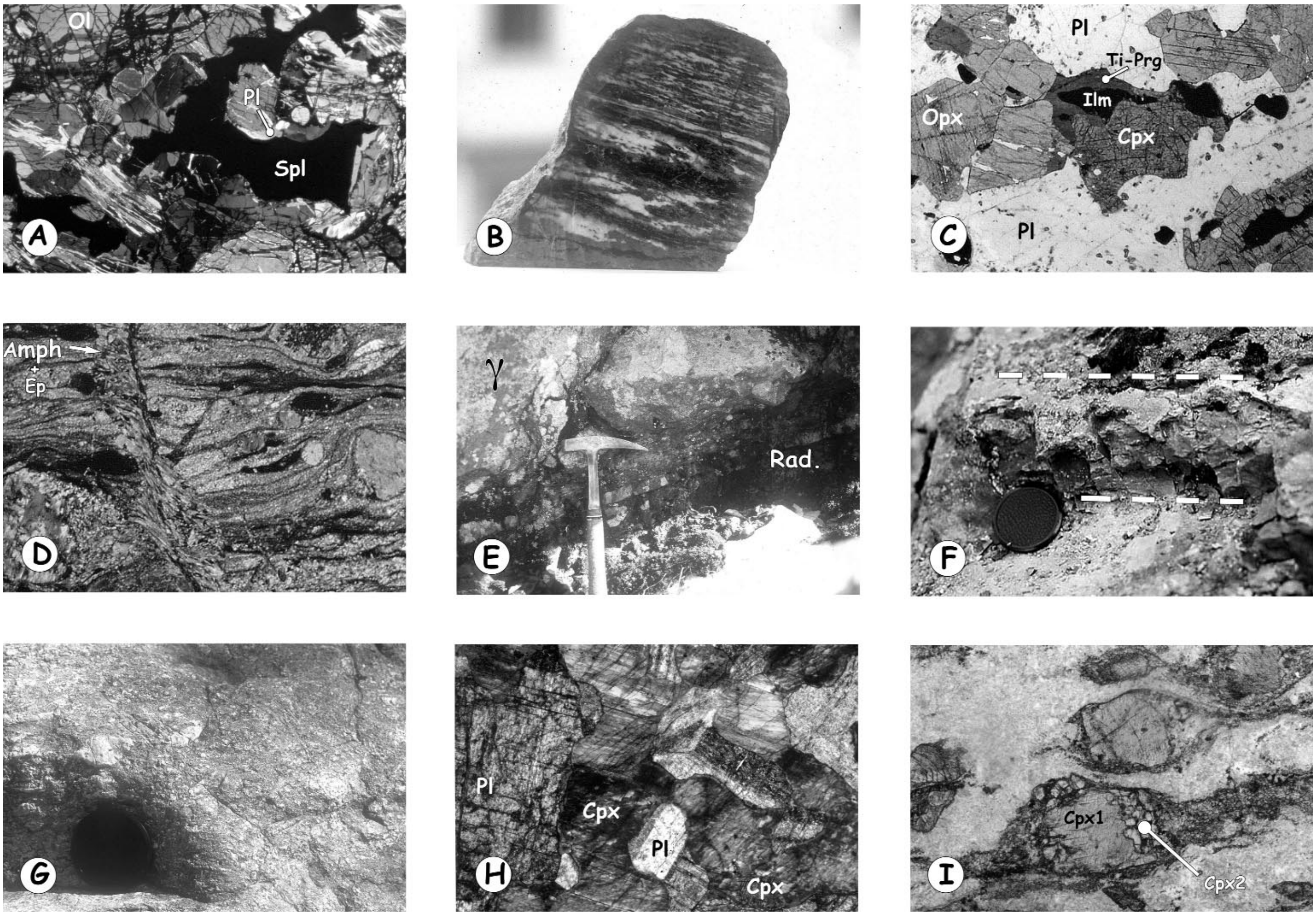

Fig. 5 - 5A- Spinel-plagioclase lherzolite (Mt. Nero peridotitic massif). Micrograph width: 1.5 mm. Crossed Nicols; 5B- hand specimen of mafic granulite; 5C- undeformed Fe-Ti oxide granulite with anhedral ilmenite rimmed by titanian pargasite. Micrograph width: 4.8 mm. Plane-polarized light; 5D- amphibolite facies mylonite cross-cutted by actinolite bearing vein, Crossed Nicols, micrograph width, 3 mm; 5E- primary contact between continental granite and the granitic cataclasite with Radiolarites. North of Mt. Penna, inverted sequence; 5F- mesoscopic appearance of green foliated ultracataclasite, North of Mt. Maggiorasca; 5G- mesoscopic appearance of green cataclasite, South Mt. Penna (microscopic view of 5F and 5G in Marroni et al., 1998); 5H- undeformed ophiolitic gabbro with subophitic texture. Micrograph width: 4.8 mm. Plane-polarized light; 5I- HT ophiolitic gabbro-mylonite, with sigma-type pyroxene porphyroclast and new recrystallized pyroxene; static green-amphibole recrystallization can be also observed. Micrograph width: 4,8 mm. Plane-polarized light. Mineral abbreviations according to Kretz (1983).

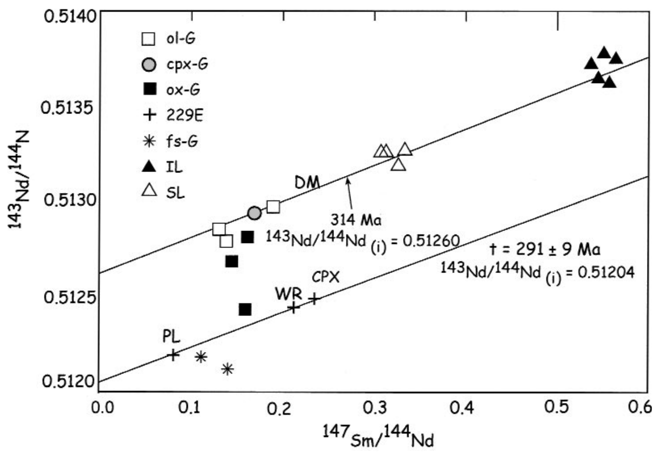

Fig. 6 - $^{143}Nd/^{144}Nd$ vs. $^{147}Sm/^{144}Nd$ diagram for the External Ligurian mafic granulites (Montanini and Tribuzio, 2001) and spinel-facies clinopyroxenes from mantle rocks of the Northern Apennines (IL- Internal Ligurian Units, Rampone et al., 1995) and Western Alps (SL- Southern Lanzo lherzolites, Bodinier et al., 1991). Abbreviations: ol-G= olivine-bearing granulites, cpx-G= clinopyroxene-rich granulite, ox-G= Fe-Ti-oxide-bearing granulite, fs-G= felsic granulite. Isochron data (whole-rock, plagioclase and clinopyroxene) for a sample of contaminated Fe-Ti oxide granulite (229E) are after Meli et al. (1996).

logical and geochronological data suggest a common tectono-metamorphic evolution for the mafic and felsic granulites (Marroni et al., 1998). Their exhumation to upper crustal levels in Late Triassic-Middle Jurassic is testified by a pre-Alpine retrograde evolution to subgreenschist facies conditions, which is accompanied by development of deformations progressively changing from plastic to brittle (Fig. 5D). In particular, radiometric data (Ar-Ar amphibole cooling age of 228 Ma; Meli et al., 1996) imply that high-temperature, granulite facies ductile shear zones developed before the Middle Triassic.

The upper crustal rocks

The granitoids are mostly represented by peraluminous biotite-bearing granodiorites and two-mica leucogranites (Marroni et al., 1998). The two-mica leucogranites locally contain Mn-rich garnet (Sps = 48-64 mol %), thus indicating an emplacement at shallow crustal levels ($P < 0.3$ GPa). The compositions of both granodiorites and leucogranites point to an orogenic affinity; their peraluminous character suggests involvement of anatectic liquids in their origin (Marroni et al., 1998). K-Ar and Rb-Sr muscovite ages of 310-280 Ma were interpreted to represent intrusion ages (Ferrara and Tonarini, 1985).

The granitoids locally preserve primary contacts with ophiolitic basalts and Upper Jurassic radiolarian cherts (Fig. 5E; Pagani et al., 1972; Molli, 1996). In particular, the granitoids show to have been intruded by basaltic dykes or capped by basaltic flows and radiolarian cherts, thus indicating the exposure at the sea floor during the Jurassic. These primary contacts allow to recognize brittle deformations (Fig. 5F,G) in localized low-angle shear zones, which predated the basalt emplacement and occurred under subgreenschist-facies conditions (Molli, 1996; Marroni et al., 1998). K-Ar and Rb-Sr biotite cooling ages of 220-230 Ma (Ferrara and Tonarini, 1985 and references) suggest that such a cataclastic deformation occurred after the Middle Triassic.

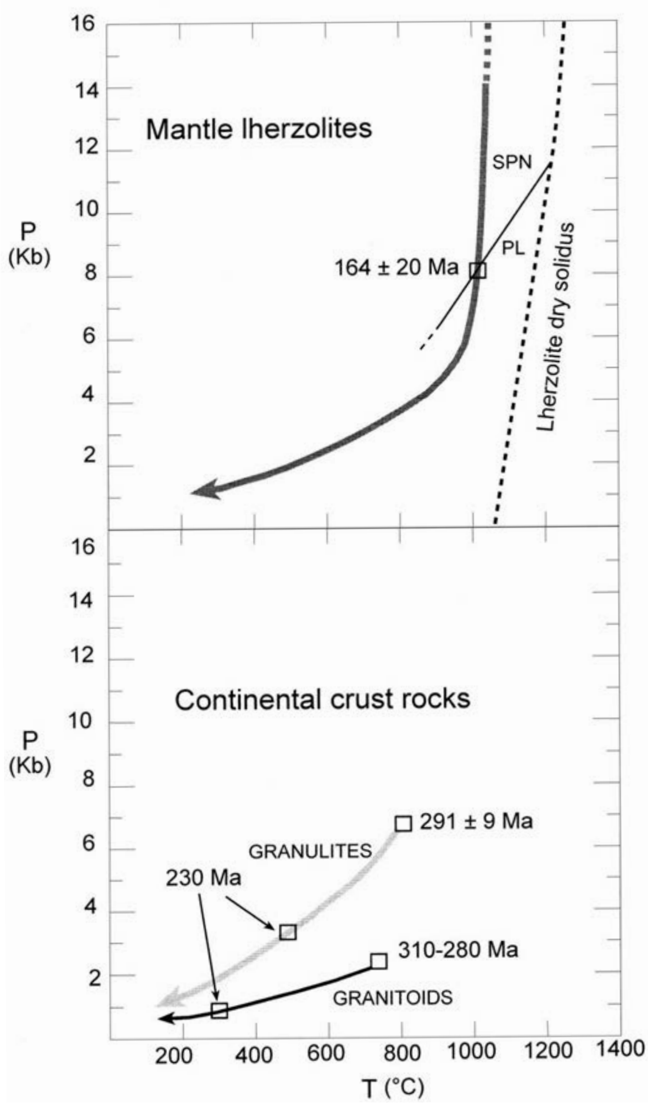

Fig. 7 - Schematic P-T-path for the pre-oceanic evolution of mantle peridotites (a) and continental crust rocks (b) from the External Ligurian domain. Trajectory of mantle rocks inferred from the literature data (Beccaluva et al., 1984; Rampone et al., 1995); P-T-t paths of granulites and granites redrawn after Marroni et al. (1998).

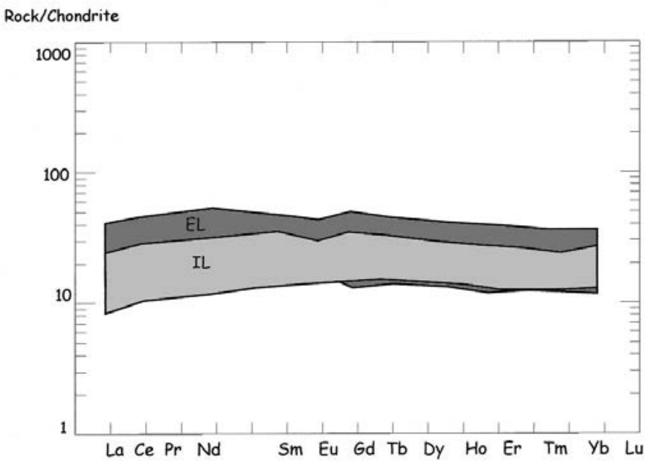

Fig. 8 - Whole-rock rare earth element patterns of basaltic rocks from the Northern Apennine ophiolites, normalized to chondrite abundances (Anders and Ebihara, 1982). Data sources: EL- External Ligurian Units (Venturelli et al., 1981; Vannucci et al., 1993; Marroni et al., 1998 and author's unpublished data), IL- Internal Ligurian Units (Venturelli et al., 1981; Ottonello et al., 1984; Rampone et al., 1998).

The pressure-temperature-time (P-T-t) evolution

The schematic P-T-t paths showing the pre-oceanic evolution of lower and upper continental crustal rocks is reported in Fig. 7A. It describes the evolution of a segment of Adria continental lithosphere during the Permo-Triassic and Jurassic attenuation.

The emplacement of mafic granulite protoliths occurred in Late Carboniferous-Early Permian times (at about 290 Ma). Such a process was most likely related to the post-Variscan extensional regime which led to asthenosphere upwelling and lithospheric thinning (Costa and Rey, 1995; Müntener et al., 2000). Mafic and associated felsic granulites show evidence for an early retrogression stage characterized by the overprinting of amphibolite- over granulite-facies ductile shear zones (Fig. 5A), most likely active between Permian and Middle Triassic (~ 230 Ma) and coupled with decreasing pressure conditions (Marroni et al., 1998). The subsequent retrograde evolution is accompanied by cataclastic deformations (Fig. 5D) starting from the amphibolite/greenschist transition (Montanini, 1997).

The upper continental crust rocks underwent deformation in localized, shallower cataclastic shear zones over a time span between 230 and 160 Ma age, as constrained by biotite cooling ages and by the overlying undeformed radiolarites, MORB-type basaltic flows and dyke intrusions.

The schematic P-T-t path of the subcontinental mantle (Fig. 7B) shows that it was not originally coupled with the associated External Ligurian granulites. In particular, the mantle lherzolites were under spinel-facies conditions at about 230 Ma, as suggested by the age of about 164 Ma reported by Rampone et al. (1995) for the equilibration in the plagioclase facies, while the granulites were most likely at shallow crustal levels. On the other hand, the P-T-t evolution of the External Ligurian granulites is similar to that of other mantle slivers of the Ligurian Tethys, namely the Erro-Tobbio ophiolitic mantle (Vissers et al., 1991), where the transition to plagioclase-facies conditions occurred at about 300 Ma (Piccardo et al., 2001).

THE OCEANIZATION AND THE CONFIGURATION OF THE CONTINENT-OCEAN TRANSITION

The oceanization process and the configuration of the continent-ocean transition can be inferred by the study of ophiolitic gabbros, basalts and sedimentary cover, and by their relations with the continental crust rocks.

The ophiolitic gabbros and basalts: inception of the MORB-type magmatism

The gabbroic rocks are rare and occur as decametric to hectometric slide-blocks and bodies intruding the mantle lherzolites, and decametric to hectometric slide-blocks (Marroni et al., 1998). Locally, the latter are crosscut by bodies of Fe-Ti oxide-bearing microgabbro and doleritic dykes, and covered by radiolarian cherts. The gabbroic rocks (Fig. 5H) include troctolites to olivine-bearing Mg gabbros, and minor Fe-Ti oxide-bearing diorites. Their petrological and geochemical features (Marroni et al., 1998; Tribuzio et al., 2000; Montanini et al., 2001) are comparable with those observed for the MOR-type gabbroic rocks of the Internal Ligurian ophiolites (Serri, 1980; Hébert et al., 1989; Tiepolo et al., 1997; Rampone et al., 1998). The gabbroic rocks thus testify the injection of MOR-type magmas in subcontinental mantle, probably during exhumation to ocean floor. A similar evolution was proposed for the mantle-gabbro associations from the coeval ophiolites of the Platta Nappe (Western Alps) and for the modern West Iberian ocean-continent transition (Cornen et al., 1999; Scharer et al., 2000). The External Ligurian gabbroic rocks are locally affected by high-temperature shear zones (Fig. 5F), which show the syn-kinematic crystallization of neoblastic clinopyroxene + plagioclase ± titanian pargasite ± ilmenite (Marroni et al., 1998; Montanini et al., 2001).

Basaltic rocks are widespread and mostly represented by tectonic slices and slide-blocks of massive and pillow lavas, locally covered by radiolarian cherts and sedimentary ophiolite breccias (Pagani et al., 1972). Basaltic rocks also occur as dykes crosscutting mantle lherzolites and gabbroic rocks (Marroni et al., 1998). In both lavas and dykes, the igneous assemblage consists of plagioclase + clinopyroxene ± olivine + ilmenite. The igneous minerals are commonly extensively replaced by greenschist- to subgreenschist- facies assemblages, possibly partly related to interaction with seawater-derived fluids, in agreement with their relatively high $^{87}Sr/^{86}Sr$ ratios (0.7049-0.7054; Rampone et al., 1998). Incompatible trace elements reveal normal to transitional MORB affinity for the basalts (Venturelli et al., 1981; Ottonello et al., 1984; Vannucci et al., 1993; Marroni et al., 1998; Rampone et al., 1998). Nd isotope compositions are close to typical depleted mantle, with initial ε_{Nd} of about 8.3. The origin of basalts was ascribed to a depleted asthenospheric mantle in the spinel stability field (Venturelli et al., 1981; Ottonello et al., 1984; Vannucci et al., 1993).

The basalts from External and Internal Ligurian ophiolites are associated with radiolarian cherts of middle Bathonian-early Callovian and middle Bathonian to early Oxfordian age, respectively (Chiari et al., 2000). The two groups of basalts (Fig. 8) have broadly similar incompatible trace element bulk compositions (Venturelli et al., 1981; Ottonello et al., 1984; Marroni et al., 1998). On the other hand, Vannucci et al. (1993) showed that the External Ligurian basalts are slightly less LREE-depleted than the Internal Ligurian basalts, on the basis of the clinopyroxene trace element compositions. Such compositional variations have been related to small differences in the fractional melting degree of the mantle source (Vannucci et al., 1993).

The External Ligurian Domain: reconstruction of the Upper Jurassic ocean- continent transition at the southern margin of Ligurian Tethys

The tectonic setting of the EL domain, prior to Late Cretaceous can be reconstructed through the characteristics of the basal complexes in both continent-ward and ocean-ward successions (Fig. 9). The analysis of tectonic slices and of slide blocks composition allow the reconstruction the pre-Upper Cretaceous substratum of the ocean-ward successions. The integration of the available data indicates that the substratum was formed by subcontinental mantle tectonically associated with slices of lower and upper continental crust. Radiolarian bearing cherts overlying both oceanic as well as continental crust rocks testifying that the setting has been achieved during oceanization. No significant difference in age can be inferred for the inception of radiolarian sedimentation in true oceanic (IL) and pericontinental domains (EL) of the Ligurian Tethys (Chiari et al., 2000 and

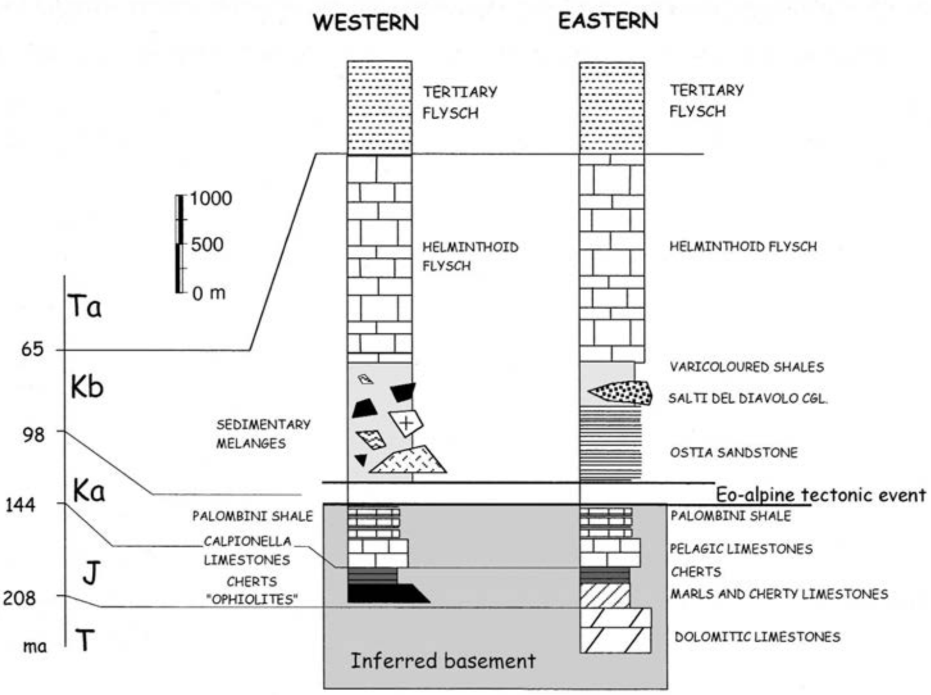

Fig. 9 - Proposed reconstruction of the "Western" and "Eastern" successions of the External Ligurian Units, (redrawn from Marroni et al., 2001).

references). In addition, available data indicate that the basaltic magmatism associated with the EL and IL ophiolites has similar petrological features, suggesting a common depleted asthenospheric mantle source.

In the continental-ward successions, the pre-Upper Cretaceous deposits are represented only by the slices recognized at the base of the Cassio Unit succession. These slices are made up of a Middle Triassic to Lower Cretaceous, mainly carbonate succession whose original basement was likely represented by the metamorphic and magmatic rocks recognized in the Salti del Diavolo Conglomerate (Elter et al., 1966; Baldacci et al., 1972). This succession records the transition from platform to pelagic deposits in a basin probably controlled by extensional faults as suggested by the occurrence of large volumes of sedimentary breccias recognized at the top of the Triassic dolostones or into the pelagic limestones. Sinking of the basin and the associated normal faults were probably representative of the extension that affected this area of the Adria continental margin during the rifting phases (Vercesi and Cobianchi, 1998). As a whole, the pre-Upper Cretaceous substratum of the continental-ward succession was represented by a continental crust belonging to the Adria passive margin.

The pre-Upper Cretaceous setting reconstructed from EL Units reveals important differences existing between the continental-ward and ocean-ward successions (Fig. 9). The substratum of the ocean-ward succession is representative of the ocean-continent transition, consisting of subcontinental mantle, continental crust rocks and ophiolites, whereas the continental-ward successions were placed over a thinned continental basement at the distal edge of the Adria Plate, according to the interpretation of Marroni et al. (1998; 2001).

THE CONVERGENCE EVOLUTION

In the following parts we describe the tectonic evolution of the EL domain during the contractional tectonics from the inception of oceanic closure (Eoalpine events) to the main phase of deformation (Ligurian phases).

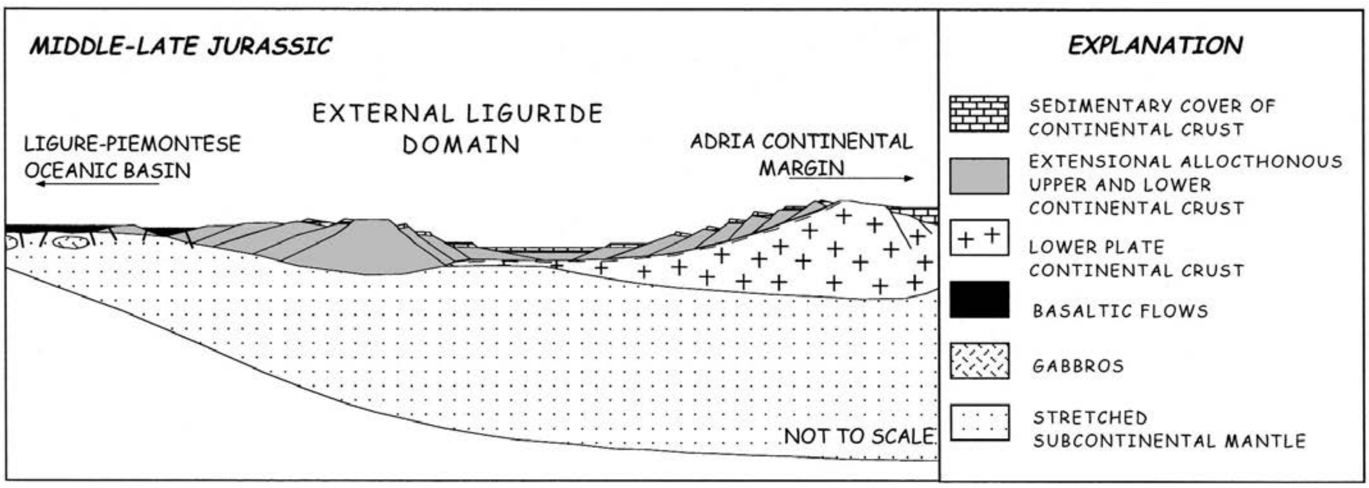

Fig. 10 - Reconstruction of the Adria continental margin at the transition with the oceanic basin in the learliest Late Jurassic during the sedimentation of the Radiolarian cherts.

The Upper Cretaceous tectonics

The occurrences of sedimentary melanges in the ocean-ward successions was interpreted as the evidence for an Upper Cretaceous tectonic phase (Elter and Raggi, 1965; Elter et al., 1966; Grandjacquet and Haccard, 1977; Treves, 1984; Bertotti et al., 1986; Gardin et al., 1994; Vai and Castellarin, 1992, Vescovi et al., 1999). This hypothesis is supported by the presence of tectonic slices, slide blocks and the widespread occurrence of sedimentary deposits related to processes like cohesive debris flows, hyperconcentrated flows and high density turbidity currents, which suggest a basin located close to the source area.

Further evidence for a Upper Cretaceous tectonics are provided by the radiometric dating of igneous and metamorphic rocks found as slide blocks in the sedimentary melanges. For instance, the partial annealing of fission tracks in zircons from quartzo-feldspathic granulites indicates that temperature must have exceeded 200°C at about 80 Ma during a thermal event of Late Cretaceous age (Balestrieri et al., 1997). This is consistent with the slight metamorphic overprint under subgreenschist facies conditions responsible for the development of chlorite and sericite in the quartzo-feldspathic granulites. In addition, the mafic granulites provided an $^{40}Ar/^{39}Ar$ plagioclase pseudoplateau around 80 Ma (Meli et al., 1996), which can be related to the development of a metamorphic overprint in the pumpellyite-actinolite facies (Marroni and Tribuzio, 1996; Montanini, 1997). Furthermore, K/Ar ages of the ophiolitic basalts record an Upper Cretaceous event at 83±5 Ma (Beccaluva et al., 1981).

The tectonic slices and slide blocks in the ocean-ward successions thus show evidence for metamorphism and deformation achieved at about 80 Ma, corresponding to Santonian-early Campanian time span. In the continental-ward successions, unconformities in the basal complexes can be related to the same tectonic activity (see also Vai and Castellarin, 1992 and Vescovi, 1993). The Ostia Sandstone and the Salti del Diavolo Conglomerate can be similarly interpreted as deposits related to the reactivation of former Jurassic faults during the Santonian-Campanian tectonics (Vescovi, 1993; Gardin et al., 1994).

The Middle Eocene tectonics

The presence of Middle Eocene deformation in the Ligurian Units of the Northern Apennine has been well known since Elter et al. (1966); this deformation collectively named "Ligurian Phase" includes several deformation structures developed at high structural levels. The age of these deformations has been constrained using the youngest sediments involved in tectonic structures, the local presence of Epiligurian and Epimesoalpine deposits unconformably covering tectonic contacts and/or structures, as well as the overprinting relationships of the tectonic elements. However, the structures related to the "Ligurian phase" are frequently overprinted by the subsequent Miocene (i.e. Apenninic), east-verging deformations and the Middle Eocene thrust surfaces have been generally reactivated during the subsequent tectonic events.

Only in few areas the structural relationships between the EL Units sealed by the Epiligurian deposits are still preserved allowing the analysis of structures of the Ligurian phase. Even if the structural data are scarce, the restoration from Miocene, NE verging apenninic deformations allows the recognition of a preexisting polyphase structural setting well witnessed by the relationships among the different Ligurian Units (Fig. 3 and 10).

According to Elter and Pertusati (1973), an early stage of top-west thrusting (Ligurian phase 1) can be assumed in order to explain the regional overlaying of the continental-ward Antola Unit on the IL Units (Fig. 2). If the Antola Unit, as well as the other EL continental-ward units, were derived from the distal edge of the Adria continental margin, its occurrence at the top of the IL Units would require a large-scale westward displacement. The mesoscopic evidence of this deformation can be observed in the Antola Unit and its basal fault zone where cataclastic fault rocks show a northwest sense of shear (Marroni et al., 1998). An

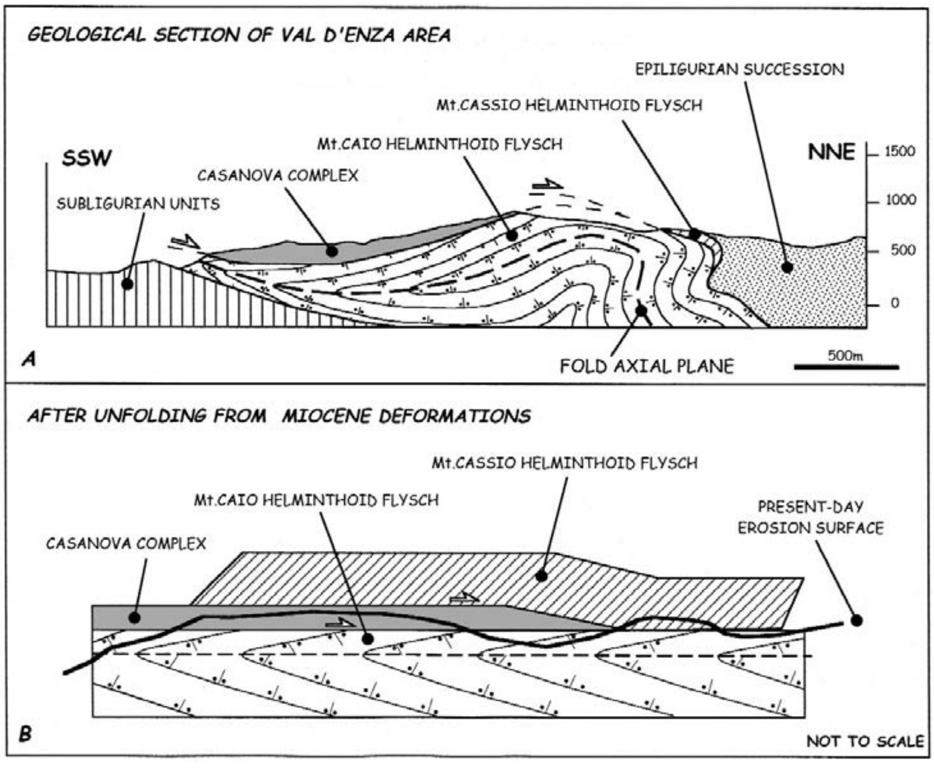

Fig. 11 - Geological section of the Val d'Enza area. The relationships between Casanova Complex, Mt. Caio and Mt. Cassio Flysch sealed by Epiligurian succession are shown at the present-day and after unfolding from Miocene deformations. To locate the section see Fig.3.

early stage of top-west thrusting is also suggested by the occurrence of the Cassio Unit at the top of the EL ocean-ward units, as recognized in the Val Nure and Val Taro areas as well as in others areas of the Northern Apennine (Daniele and Plesi, 1999). In addition, in Val Taro and Val Nure areas Plesi et al. (1993) and Cerrina Feroni et al. (1994) have recognized well developed top-west thrusts that, subsequently deformed by east-verging folds and thrusts, can be interpreted as the record of the first phase affecting the EL domain.

The second stage (Ligurian Phase 2) is well testified by numerous east-verging, large-scale folds with about NW-SE axis and subhorizontal axial planes recognized in some of the EL Units (Cerrina Feroni et al., 1989; Costa et al., 1991; Cerrina Feroni et al., 1994; Costa et al., 1995). The best example can be found in the Val d'Enza area where the relationships between Caio and Cassio Units are sealed by the

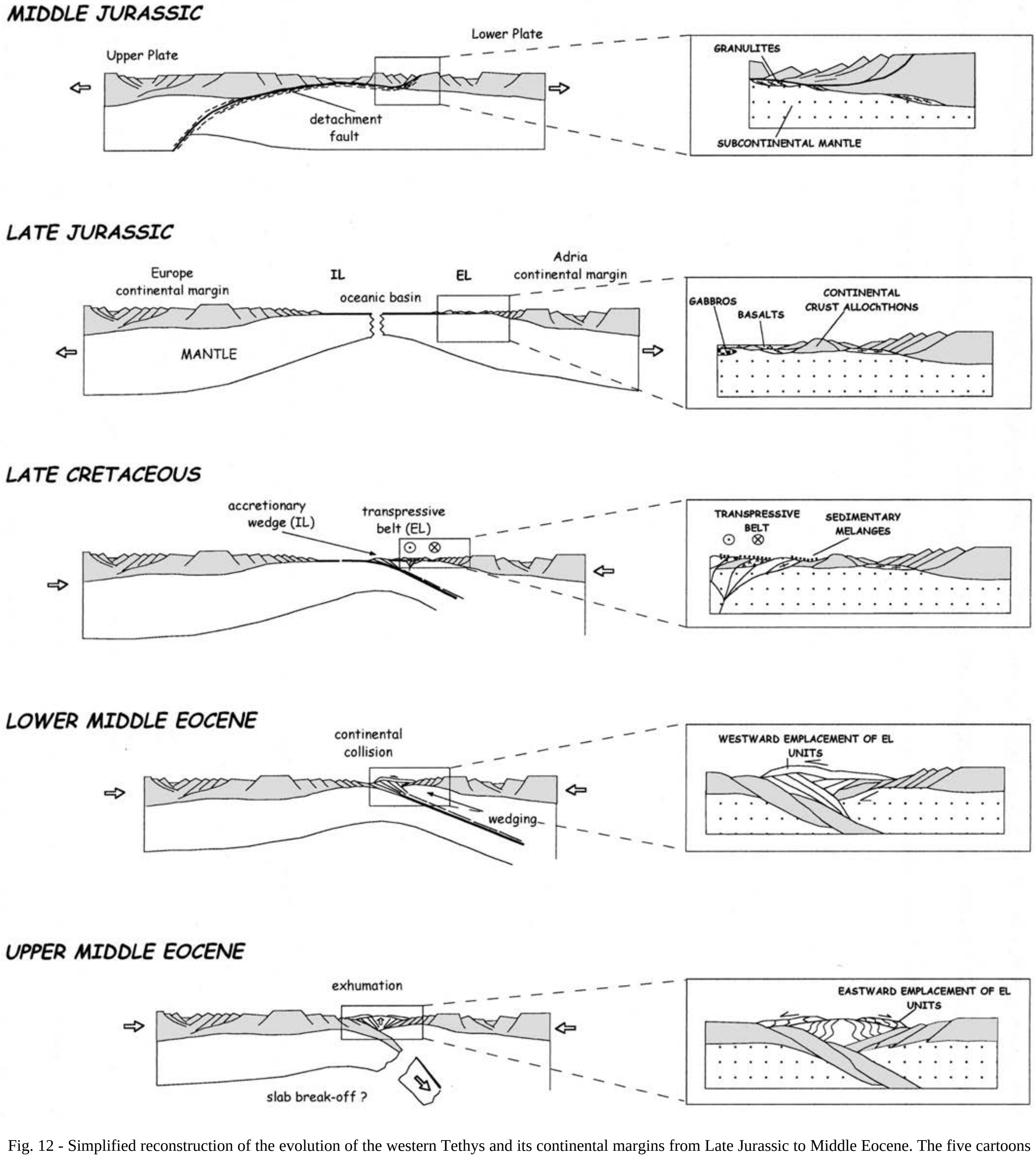

Fig. 12 - Simplified reconstruction of the evolution of the western Tethys and its continental margins from Late Jurassic to Middle Eocene. The five cartoons show the rifting stage (Middle Jurassic), the drifting stage (Late Jurassic), the intraoceanic subduction stage (Late Cretaceous) and the continental collision stages (Early and late Middle Eocene). Following von Blackenburg and Davies (1995) the slab break-off of the subducted slab is hypothized in the Late Middle Eocene. The location of Internal (IL) and External (EL) Ligurian Units is indicated. The right side shows close-up of the area corresponding to External Ligurian Domain. Not to scale; see the text for further explanation.

Epiligurian deposits (Fig. 11). After restoration from Miocene deformations, i.e. east-verging overturned folds, the Cassio Unit overlays the Caio one, that, in turn, appears to be deformed by northeast verging, overturned folds with WNW-ESE axis and subhorizontal axial plane. In addition, the restoration reveals that the shear surface between the Caio and Cassio Units cuts down in the stratigraphic succession as suggested by the lack of the basal complexes leading to the direct superposition of two Helminthoid flysch sequences (Fig. 11). Extensional geometries, producing local cut-down sections or footwall plucking are evident in the westernmost part of the EL Units and have been described in association with the late stage of development of northeast-verging structures in the EL Units in the Val Taro area (Plesi et al., 1993). Moreover, Meccheri et al. (1982) and Costa et al. (1991) described hinge line rotation of the main folds of about 80° in the large scale structure in the Val Ceno and Val Taro area. As a whole, the structures of the Ligurian phase 2 include overturned folds with subhorizontal axial planes, shear surfaces cutting down in the stratigraphic sequence, passive rotation of the linear structural elements. These structural features are coherent with the gravitational spreading and tectonic transport from the internal, westernmost areas represented by the Alpine accretionary prism toward the external Adria continental margin. This interpretation is in agreement with large scale gravity tectonic as main mechanism for this type of deformation (Elter, 1960; 1975; Van Wamel, 1987), as well as with more recent reconstructions of the deformation history in the IL Units related with exhumation-related extensional tectonics (Hoogerdujing Strating, 1991; Marroni and Pandolfi, 1996).

To sum up, the "Ligurian deformational event" seems to be consisting of two stages: the first one (Ligurian Phase 1) implies large-scale, westward displacement of the EL Units, whereas the second stage (Ligurian Phase 2) is characterized by east-verging deformations probably driven by the thinning of the preexisting nappe pile.

CONCLUSIONS

The pre-Upper Cretaceous configuration of the EL domain was characterized by two sub-areas with different features, which were achieved during the opening of the Jurassic Ligurian Tethys. The sub-domain near to the oceanic basin, representing the pristine substratum of the ocean-ward successions, was characterized by exposure of subcontinental mantle overlain by highly faulted slices of the upper and lower continental crust, i.e. the extensional allochthons of the upper plate (Lister et al., 1986; Froitzheim and Manatschal, 1996). Eastward, this area grades to the continental crust original substratum of the continental-ward successions, probably representing the distal edge of the Adria continental margin.

From the Late Jurassic to Early Cretaceous the EL domain was characterized by a continuous pelagic sedimentation. During the Late Cretaceous, probably in Santonian to early Campanian the inception of convergence-related deposits marked a main change related with the subduction of the oceanic lithosphere below the Adria continental margin and its transition to oceanic basin (Elter and Pertusati, 1973, Grandjacquet and Haccard, 1977). This tectonics, probably developed in a transpressive system, mainly affecting the ocean-ward basin coinciding with a crustal weakness zone at the boundary between oceanic and continental crust. In this setting, the faults inherited from Jurassic rifting were subjected to inversion tectonics leading to a stack of thrust sheets which were the source of of Cretaceous sedimentary melanges.

In late Campanian-Maastrichtian time, the main feature of the EL domain was the deposition in both ocean- and continental-ward domains of the Helminthoid flysch followed in the Paleocene-Early Eocene by the Tertiary carbonate flysch. As a whole, the EL domain was characterized until the Middle Eocene of a continuous, long-lived sedimentation without evidences of syn-sedimentary tectonics.

The EL domain was subsequently affected by a main tectonic event in the Middle Eocene during the continental collision between the Adria and European Plates. This tectonic event includes two different phases. The first phase includes a west-ward emplacement of the EL Units onto the ophiolitic units of the accretionary prism testified by the present-day structural overlapping of the Antola Unit onto the IL units (Fig. 11; lower Middle Eocene stage). The geometry of the EL units with the continental-ward units overlying the ocean-ward ones also implies a top-west thrusting. During this phase, the EL Units are thrust at high structural levels and detached from their pristine substratum, that probably was subjected to indentation with the internal areas of the orogenic wedge. This indentation was probably made easier by the configuration of the EL domain substratum, characterized by a thick litospheric mantle and a thinned continental crust which suffered inversion tectonics. This phase of wedging reflects that shortening related to continental collision occurred between the Adria and European continental margins in the Middle Eocene. The second tectonic phase, consisting of northeast-verging folds and top-northeast shear surfaces, seems consistent with an extensional tectonics that affected the pre-existing stack of thrust sheets producing thinning of the nappe pile (Fig. 11; upper Middle Eocene stage). This extensional tectonics can be recognized in the whole Alpine-Apennine boundary framework as testified by the broadly coeval exhumation of the IL Units (Hoogerduin Strating, 1991; Marroni and Pandolfi, 1996) and the high pressure/ low temperature metamorphic units of the Voltri group (Vanossi et al., 1984; Crispini, 1996).

Acknowledgements

This research was supported by M.U.R.S.T. and C.N.R., Istituto di Geoscienze e Georisorse, Pisa funds. Careful reviews by G. Manatschal and M. Scambelluri are gratefully acknowledged.

REFERENCES

Abbate E., Bortolotti V. and Principi G., 1980. Apennine ophiolites: a peculiar oceanic crust. Ofioliti, 5 (1): 59-96.

Anders E. and Ebihara M., 1982. Solar system abundances of the elements. Geochim. Cosmochim. Acta, 46: 2363-2380.

Baldacci F., Cerrina Feroni A., Elter P., Giglia G. and Patacca E., 1972. Il margine del paleocontinente nord-apenninico dal Cretaceo all'Oligocene: nuovi dati sulla ruga Insubrica. Mem. Soc. Geol. It., 11: 367-390.

Balestrieri M.L., Bigazzi G., Marroni M. and Tribuzio R., 1997. Quartzo-feldspathic granulites from External Liguride Units (northern Apennine): tectono-metamorphic evolution and thermochronological constraints from zircon fission-track data. C. R. Acad. Sci. Paris, 324: 87-94.

Beccaluva L., Chiesa S. and Delaloye M., 1981. K/Ar age determinations on some Tethyan ophiolites. Rend. S.I.M.P., 37: 869-880.

Beccaluva L., Macciotta G., Piccardo G.B. and Zeda O., 1984. Petrology of lherzolitic rocks from the Northern Apennine ophiolites. Lithos, 17: 299-316.

Bernoulli D., Bertotti G. and Froitzheim N., 1990. Mesozoic faults and associated sediments in the Austroalpine-south Alpine passive continental margin. Mem. Soc. Geol. It., 45: 25-38.

Bertotti G., Elter P., Marroni M., Meccheri M. and Santi R,.(1986. Le argilliti a blocchi di M. Veri: Considerazioni sulla evoluzione tettonica del bacino ligure nel Cretaceo sup. Ofioliti, 11 (3): 193-220.

Bettelli G., Bonazzi U. and Panini F., 1989. Schema introduttivo alla geologia delle Liguridi dell'Appennino Modenese e delle aree limitrofe. Mem. Soc. Geol. It., 39: 91-125.

Bodinier J.L., Menzies M.A. and Thirlwall M.F., 1991. Continental to oceanic mantle transition - REE and Sr-Nd isotopic geochemistry of the Lanzo Lherzolite Massif. J. Petrol., Spec. Lherz. Issue, p. 191-210.

Cande S.C., Kent D.V., 1992. A new Geomagnetic Polarity Time Scale for late Cretaceous and Cenozoic. J. Geoph. Res. 97, 13): 917-951.

Catanzariti R., Rio D. and Martelli L., 1997. Late Eocene to Oligocene calcareous nannofossil biostratigraphy in Northern Apennines: the Ranzano Sandstone. Mem. Sci. Geol., Padua, 49: 207-253.

Cerrina Feroni A., Elter P., Plesi G., Rau A., Rio D., Vescovi P. and Zanzucchi G., 1991. Il Foglio 217 Neviano degli Arduini nel quadro delle geologia dell'Appennino Emiliano-romagnolo: dati nuovi, problemi e prospettive. Mem. Descr. Carta. Geol. It., 44: 111-120

Cerrina Feroni A., Fontanesi G. and Martinelli P., 1989. La struttura a sinclinale coricata del Flysch di M. Caio tra la Val Cedra e la Val Parma nell'Appennino Settentrionale. Mem. Accad. Sci. Lunigianense, 57/58: 43-44.

Cerrina Feroni A., Martinelli P. and Ottria G., 1994. L'edificio strutturale della media Val Nure (Appennino settentrionale): nuovi dati strutturali e biostratigrafici. Atti Ticinensi Sci. Terra, Ser. spec., 1: 105-115.

Chiari M., Marcucci M. and Principi G., 2000. The age of the radiolarian cherts associated with the ophiolites in the Apennines (Italy) and Corsica (France): a revision. Ofioliti, 25: 141-146.

Conti M., Marcucci M. and Passerini P., 1985. Radiolarian cherts and ophiolites in the Northern Apennines and Corsica: age correlations and tectonic frame of siliceous deposition. Ofioliti, 10: 201-225.

Cornen G., Girardeau J. and Monnier C., 1999. Basalts, underplated gabbros and pyroxenites record the rifting process of the West Iberian margin. Mineral. Petrol., 67: 111-142.

Costa E., De Nardo E.T., Mattioli A. and Ronchi P., 1991. Evoluzione tettonica delle Liguridi: le strutture di M. Carameto e M. Dosso (Val Ceno, Provincia di Parma). Mem. Descr. Carta. Geol. It., 44: 375-386.

Costa E., Frati G. and Villa G., 1995. Note illustrative della Carta geologico-strutturale delle Liguridi Esterne nell'area tra la media Val Ceno e la Val d'Arda (Provv. di Parma e Piacenza). Atti Ticinensi. Sci. Terra, 3: 3-29.

Costa S. and Rey P., 1995. Lower crustal rejuvenation and growth during post thickening collapse: insights from a crustal cross section through a Variscan metamorphic core complex. Geology 23: 905-908.

Crispini L., 1996. Analisi strutturale dei metasedimenti del Gruppo di Voltri. Tesi Dottorato Univ. Genova. 264 pp.

Dal Piaz G.V., 1993. Evolution of Austro-Alpine and Upper Penninic Basement in the Northwestern Alps from Variscan Convergence to Post-Variscan Extension. In: Von Raumer J.F. and Neubauer F. (Eds.), Pre-Mesozoic geology in the Alps. Springer, p. 325-342.

Daniele G. and Plesi G., 1999. The Ligurian Helminthoid Flysch Units of the Emilian Apennines:stratigraphic and petrographic features, paleogeographic restoration and structural evolution. Geodin. Acta, 13 (5): 313-334.

Desmurs L., Manatschal G. and Bernoulli D., 2001. The Steinmann Trinity revised: mantle exhumation and magmatism along an ocean-continent tranistion: the Platta nappe, eastern Switzerland. In: Wilson R.C.L., Taylor B. and Froitzheim N. (Eds.), Non volcanic rifting of continental margins: a comparison of evidence from land and sea. Geol. Soc. London Spec. Publ., 187: 235-266.

Elter P., 1960. I lineamenti tettonici dell'Appennino a NE delle Apuane. Boll. Soc. Geol. It., 79 (2): 273-312.

Elter P., 1975. L'ensemble ligure. Bull. Soc. Géol. France, 17: 984-997.

Elter P. and Raggi G., 1965. Contributo alla conoscenza dell'Appennino Ligure: 3) Tentativo di interpretazione delle brecce ofiolitiche cretacee in relazione ai movimenti orogenetici nell'Appennino ligure. Boll. Soc. Geol. It., 84: 1-12.

Elter G., Elter P., Sturani P. and Weidmann M., 1966. Sur la prolungation du domaine ligure de l'Apennin dans le Monferrat e les Alpes et sur l'origine de la Nappe de la Simme s.l. des Prealpes romandes et chaiblaisiennes. Bull. Lab. Géeol. Min. Geophis. et Musée Géol. Univ. Lausanne, 176: 279-377.

Elter P., Ghiselli F., Marroni M., Ottria G. and Pandolfi L., 1993. Il profilo Camogli - Ponte dell'Olio: assetto strutturale e problematiche connesse. Studi Geol. Camerti, Vol. Spec. 1993/2: 9-15.

Elter P. and Pertusati P.C., 1973. Considerazioni sul limite Alpi-Appennino e sulle relazioni con l'arco delle Alpi Occidentali. Mem. Soc. Geol. It., 12: 359-394.

Elter P. and Marroni M., 1991. Le Unità Liguri dell'Appennino Settentrionale: sintesi dei dati e nuove interpretazioni. Mem. Descr. Carta. Geol. It., 44: 121-138.

Ferrara G. and Tonarini S., 1985. Radiometric geochronology in Tuscany: results and problems. Rend. S.I.M.P., 40: 111-124.

Froitzheim N. and Manatschal G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geol. Soc. Amer. Bull., 108: 1120-1133.

Galbiati B., 1990. Considerazioni sulle fasi iniziali dell'orogenesi nell'Appennino Settentrionale. Atti Ticinensi Sci. Terra, 33: 255-266.

Gardin S., Marino M., Monechi S. and Principi G., 1994. Biostratigraphy and sedimentology of Cretaceous Ligurid Flysch: paleogeographical implication. Mem. Soc. Geol. It., 48: 219-235

Gelati R. and Gnaccolini M., 1982. Evoluzione tettonico-sedimentaria della zona limite tra Alpi ed Appennini tra l'inizio dell'Oligocene ed il Miocene medio. Mem. Soc. Geol. It., 24: 183-191.

Gelati R. and Gnaccolini M., 1996. The stratigraphic record of Oligocene-early Miocene events at the south-western end of the Piedmont Tertiary Basin. Riv. Ital. Paleont. Strat., 102: 65-76

Grandjacquet C. and Haccard D., 1977. Position structurale et role paleogeographique de l'Unité du Bracco au sein du contexte ophiolitique liguro-piémontais (Apennin, Italie). Bull. Soc. Géol. France, 19 (4): 901-908.

Hébert R., Serri G. and Hekinian R., 1989. Mineral chemistry of ultramafic tectonites and ultramafic to gabbroic cumulates from the major oceanic basins and Northern Apennines ophiolites (Italy) - A comparison. Chem. Geol., 77: 183-207.

Hermann J., Müntener O., Trommsdorff V. and Hansmann W., 1997. Fossil crust-to-mantle transition, Val Malenco, Italian Alps. J. Geophys. Res., 102: 20123-20132.

Hoogerduijn Strating E.H., 1991. The evolution of the Piemonte-Ligurian ocean, A structural study of the ophiolite complexes in Liguria (NW Italy). Ph.D. Dissert., Uthecht Univ., 127 pp.

Hoogerdujin Strating E.H., Rampone E., Piccardo G.B., Drury M.R. and Vissers R.L.M., 1993. Subsolidus emplacement of mantle peridotites during incipient rifting and opening of the Mesozoic Tethys (Voltri Massif, NW Italy). J. Petrol., 34: 901-927.

Kretz R., 1983. Symbols for rock-forming minerals. Am. Mineral. 68: 277-279.

Laubscher H.P., Biella G.C., Cassinis R., Gelati R., Lozey A., Scarascia S. and Tobacco I., 1992. The Ligurian Knot. Tethys. Geol. Rundsch, 81: 275-289.

Lemoine M., Tricart P. and Boillot G., 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): in search of a genetic model. Geology, 15: 622-625.

Leoni L., Marroni M., Sartori F. and Tamponi M., 1995. The grade of metamorphism in the metapelites of the Internal Ligurid Units (Northern Apennines, Italy). Europ. J. Mineral., 8: 35-50.

Lister G.S., Etheridge M.A. and Symonds P.A., 1986. Detachment faulting and the evolution of passive margin. Geology, 14: 246-250

Lorenz C., 1969 Contribution à l'étude stratigraphique de l'Oligocène inférieur des confins Ligure-Piémontais (Italie). Atti Ist. Geol. Univ. Genova, 6 (2): 253-888.

Marroni M. and Tribuzio R., 1996. Gabbro-derived granulites from External Liguride units (Northern Apennine, Italy): implications for the rifting processes in the Western Tethys. Geol. Rundsch., 85: 239-249.

Marroni M. and Pandolfi L., 1996. The deformation history of an accreted ophiolite sequence: the Internal Liguride units (Northern Apennines, Italy). Geodin. Acta, 9(1): 13-29.

Marroni M., Molli G., Montanini A. and Tribuzio R., 1998. The association of continental crust rocks with ophiolites (Northern Apennines, Italy): implications for the continent-ocean transition. Tectonophysics, 292: 43-66.

Marroni M., Molli G., Ottria G. and Pandolfi L., 2001. Tectono-sedimentary evolution of the External Liguride units (Northern Apennine, Italy): insights in the pre-collisional history of a fossil ocean-continent transition zone. Geodin. Acta, 14: 307-320.

Martelli L., Cibin U., Di Giulio A. and Catanzariti R., 1998. Litostratigrafia della Formazione di Ranzano (Priaboniano-Rupeliano, Appennino Settentrionale e Bacino Terziario Piemontese). Boll. Soc. Geol. It., 117: 151-185.

Meccheri M., Clerici A. and Costa E., 1982. Analisi mesostrutturale delle deformazioni plicative in alcuni affioramenti delle Arenarie di Ostia (Appennino Parmense) . Boll. Soc. Geol. It., 101: 3-16.

Meli S., Montanini A., Thoni M. and Frank W., 1996. Age of mafic granulite blocks from the External Liguride Units (Northern Apennine, Italy). Mem. Sci. Geol. Padua, 48: 65-72.

Molli G., 1996. Pre-orogenic tectonic framework of the Northern Apennine ophiolites. Ecl. Geol. Helv., 89: 163-180.

Montanini A., 1997. Mafic granulites in the Cretaceous sedimentary mélanges from the Northern Apennine (Italy): petrology and tectonic implications. Schweiz. Miner. Petr. Mitt., 77: 43-64.

Montanini, A. and Tribuzio, R., 2001. Gabbro-derived and felsic granulites from the Northern Apennines (Italy): evidence for emplacement of tholeiitic basalts in the post-Variscan lower crust. J. Petrol., 42: 2259-2277.

Montanini. A., Tribuzio R. and Vernia L., 2001. Gabbroic rocks from a fossile continent-ocean transition: the example of the External Liguride ophiolites (Northern Apennines, Italy). EUG 11 Meeting, Strasburgo, 2001, Abstr., p. 729.

Müntener O, Hermann J and Trommsdorff V. 2000. Cooling history and exhumation of lower-crustal granulite and upper mantle (Malenco, Eastern Central Alps). J Petrol., 41: 175-200.

Mutti E., Papani L., Di Biase D., Davoli G., Mora S., Segadelli S. and Tinterri R., 1995. Il Bacino Terziario epimesoalpino e le sue implicazioni sui rapporti tra Alpi ed Appennino. Mem. Sci. Geol. Padua, 47: 217-244.

Ottonello G., Joron J.L. and Piccardo G.B., 1984. Rare Earth and 3d transition element element geochemistry of peridotitic rocks: II. Ligurian peridotites and associated basalts. J. Petrol., 25: 373-393.

Pagani G., Papani G., Rio D., Torelli L:, Zanzucchi G. and Zerbi N., 1972. Osservazioni sulla giacitura delle ofioliti nelle alte valli del T. Ceno e del F. Taro. Mem. Soc. Geol. It., 11: 531-546.

Piccardo G.B., 1976. Petrologia del massiccio lherzolitico di Suvero (La Spezia). Ofioliti, 1: 279-318.

Piccardo G.B., Rampone E., Romairone A., Scambelluri M., Tribuzio R. and Beretta C., 2001. Evolution of the Ligurian Tethys: inference from petrology and geochemistry of the Ligurian Ophiolites. Per. Mineral., 70: 147-192.

Piccardo G.B., Rampone E. and Vannucci R., 1990. Upper Mantle evolution during continental rifting and ocean formation: evidences from peridotites bodies of the Western Alpine (Northern Apennines sistem). Mem. Soc. Géol. France, 156: 323-333.

Plesi G., Bianchi L., Chicchi S. and Daniele G., 1993. Le Unità Liguri ed Emiliane della media Val di Taro e la loro evoluzione strutturale. Atti Ticinensi Sci. Terra, 36: 183-229.

Rampone E., Piccardo G.B., Vannucci R., Bottazzi P. and Ottolini L., 1993. Subsolidus reactions monitored by trace element partitioning: the spinel- to plagioclase-facies transition in mantle peridotites. Contrib. Mineral. Petrol., 115: 1-17.

Rampone E., Hoffmann A.W., Piccardo G.B., Vannucci R., Bottazzi P. and Ottolini L., 1995. Petrology, mineral and isotope geochemistry of the External Liguride peridotites (Northern Apennine, Italy). J. Petrol., 36: 81-105.

Rampone E., Hofmann A.W. and Raczek I., 1998. Isotopic contrasts within the Internal Liguride ophiolite (N. Italy): the lack of a genetic mantle-crust link. Earth Planet. Sci. Lett., 163: 175-189.

Rampone E. and Piccardo G.B., 2000. The ophiolite-oceanic lithoshere analogue: New insights from the Northern Apennines (Italy). Geol. Soc. Am. Spec. Pap., 349: 21-34.

Ricci Lucchi F. and Ori G.G., 1985. Syn-orogenic deposits of migrating basin system in the NW Adriatic Foreland. Foreland basins Symp., Fribourg, Allen P.H. and Homewood P. (Eds.), p. 137-176.

Scharer U., Girardeau J., Cornen G. and Boillot G., 2000. 138-121 Ma astenospheric magmatism prior to continental break-up in the North Atlantic and geodynamic implications. Earth Planet. Sci. Lett., 181: 555-572.

Scholle P.A., 1971. Sedimentology of fine-grained deep-water carbonate turbidites. Monte Antola flysch (Upper Cretaceous, Northern Apennines, Italy). Geol. Soc. Am. Bull., 82: 629- 658.

Serri G., 1980. Chemistry and petrology of gabbroic complex of the northern Apennine ophiolites. In: A. Panayiotou (Ed.), Ophiolites, Proceed. Intern. Ophiolite Symp., Cyprus 1979. Geol. Surv. Dept., Cyprus, p. 296-313.

Stampfli M. and Marthaler G.M., 1990. Divergent and convergent margins in the North-Western Alps confrontation to actualistic models. Geodin. Acta, 4 (3): 159-184.

Snow J.E., Schmidt G and Rampone E., 2000. Os isotopes and highly siderophile elements (HSE) in the Ligurian ophiolites, Italy. Earth Planet. Sci. Lett., 175: 119-132.

Sturani C., 1973. Considerazioni sui rapporti tra Appennino Settentrionale ed Alpi Occidentali. Rend. Acc. Lincei, 183: 119-142.

Tiepolo M., Tribuzio R. and Vannucci R., 1997. Mg- and Fe-gabbroids from Northern Apennine ophiolites: parental liquids and igneous differentiation processes. Ofioliti 22: 57-69.

Treves B., 1984. Orogenic belts as accretionary prisms: the example of northern Apennines (Northern Italy). Ofioliti, 9 (3): 577-618.

Tribuzio R., Tiepolo M. and Vannucci R., 2000. Evolution of gabbroic rocks from the Northern Apennine ophiolites (Italy): comparison with the lower oceanic crust from modern slow-spreading ridges. In: Dilek J., Moores E., Elthon D. and Nicolas A. (Eds.), Ophiolites and oceanic crust: New insights from field studies and Ocean Drilling Program. Geol. Soc. Am. Mem., Spec. Paper, 349: 129-138.

Vai G.B. and Castellarin A., 1992. Correlazione sinottica delle unità stratigrafiche nell'Appennino Settentrionale. Studi Geol. Camerti, Vol. Spec. 1992/2: 171-186.

Vannucci R., Rampone E., Piccardo G.B., Ottolini L. and Bottazzi P., 1993. Ophiolitic magmatism in the Ligurian Tethys: an ion microprobe study of basaltic clinopyroxenes. Contrib. Mineral. Petrol., 115: 123-137.

van Wamel W.A., 1987. On the tectonics of the Ligurian Apennines (Northern Italy). Tectonophysics, 142: 87-98.

Vanossi M., Cortesogno L., Galbiati B., Messiga B., Piccardo G. and Vannucci R., 1984. Geologia delle Alpi Liguri: dati, problemi, ipotesi. Mem. Soc. Geol. It., 28: 5-77.

Venturelli G., Capedri R.S., Thorpe R.S. and Potts P.J., 1981. Rare earth and trace elements characteristic of ophiolitic metabasalts from the Alpine-Appenine belt. Earth Planet. Sci. Lett., 53: 109-123.

Vercesi P.L. and Cobianchi M., 1998. Stratigrafia di un frammento di margine continentale giurassico: la successione di C.se Caldarola (Appennino Piacentino). Boll. Soc. Geol. It., 117: 537-554.

Vescovi P., 1993. Schema evolutivo per le Liguridi dell'Appennino Settentrionale. Atti Ticinensi Sci. Terra, 36: 89-112.
Vescovi P., Fornaciari E., Rio D. and Valloni R., 1999. The Basal complex stratigraphy of the Helminthoid Monte Cassio Flysch: a key to the Eoalpine tectonics of the Northern Apennines. Riv. It. Paleont. Stratigr., 105: 101-128.
Vissers R.L.M., Drury M.R., Hoogerdujing Strating E.H. and Van der Wal D., 1991. Shear zones in the upper mantle: a case of study in an Alpine lherzolite massif. Geology, 19: 990-993.
von Blackenburg F. and Davies J.H., 1995. Slab breakoff: a model for the syncollisional magmatism and tectonics in the Alps. Tectonics, 14: 120-131
Zanzucchi G., 1980. I lineamenti geologici dell'Appennino parmense. Note illustrative alla carta e sezioni geologiche della Provincia di Parma e zone limitrofe (1:100.000). Vol. dedicato a S. Venzo, Ed. STEP, Parma, p. 201-233.

Received, January 8, 2002
Accepted, July 24, 2002