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FORMATION AND COMPOSITION OF THE OCEANIC LITHOSPHERE OF THE LIGURIAN TETHYS: INFERENCES FROM THE LIGURIAN OPHIOLITES

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ABSTRACT

Ophiolites exposed along the Western Alpine - Northern Apennine (WA-NA) orogenic chain represent the oceanic lithosphere of the Ligurian Tethys which separated, during Late Jurassic - Cretaceous times, the Europe and Adria plates. WA-NA ophiolites show peculiar compositional, structural and stratigraphic characteristics: 1) mantle peridotites are both fertile, cpx-rich lherzolites, and depleted, cpx-poor peridotites; 2) gabbroic intrusives and basaltic volcanites have a MORB affinity and show a high-Ti character of primary magmas; 3) gabbroic rocks were intruded into mantle peridotites; 4) mantle rocks underwent decompressional, not adiabatic, subsolidus evolution, starting from subcontinental lithospheric mantle depths (spinel-facies conditions) towards the sea-floor. The Jurassic Ligurian Tethys was floored by an older peridotite-gabbro basement, subsequently covered by extrusion of discontinuous basaltic flows and by sedimentation of radiolarian cherts.

The Ligurian ophiolites represent the spatial association of: 1) old (Proterozoic and Permian) subcontinental lithospheric mantle peridotites; 2) Lower - Middle Jurassic MORB-type gabbroic rocks, intruded in the peridotites; 3) Upper Jurassic MORB-type basaltic volcanics, interlayered with radiolarian cherts, i.e. the first oceanic sediments. Present knowledge on the Western Alps ophiolites suggest that this association is well representative of the oceanic lithosphere of the Ligurian Tethys.

This peculiar ophiolitic association, which shows no cogenetic relationships between the different lithological components, cannot be reconciled with a mature oceanic lithosphere formed at present-day mid-oceanic ridges, where the mantle peridotites and the associated gabbroic-basaltic crust are linked by a direct cogenetic relationship. The large exposure of subcontinental mantle peridotites to the sea-floor, and the long history of subsolidus decompressional upwelling recorded by peridotites, are in favour of a geodynamic evolution driven by the passive extension of the Europe-Adria continental lithosphere. Passive extension caused: 1) the progressive exhumation and the tectonic unroofing at the sea-floor of the lithospheric subcontinental mantle, and 2) the passive upwelling of the asthenospheric mantle, which underwent decompressional partial melting and produced MORB-type parental melts for the gabbroic intrusions and for the basaltic extrusions.

During the late stages of lithosphere extension, most probably in Jurassic times and prior to complete oceanization, the conductive lithospheric mantle was permeated and impregnated by strongly depleted single melt increments and, later on, it was intruded by aggregated MORB melts. Melt impregnation is mainly confined to the more depleted, more “internal” peridotites massifs (i.e. Internal Ligurides and Lanzo South) which were, most probably, closer to the transition to more typical oceanic lithosphere (i.e. cogenetic mantle and crustal rocks), which has not, so far, been found in the ophiolites derived from the Ligurian Tethys Ocean.

INTRODUCTION

The oceanic lithosphere of modern major oceanic basins is formed at mid-ocean ridges where ascending limbs of the asthenosphere convection cells produce almost adiabatic uplift and decompressional partial melting of the asthenospheric mantle, which gives rise to basaltic melts and refractory mantle residua.

Such basalts have been variously termed: submarine basalts, ocean-floor basalts (OFB), abyssal basalts and mid-ocean ridges basalts (MORB), whereas the refractory mantle residua have been called oceanic or abyssal peridotites.

The oceanic lithosphere is composed of basaltic volcanics and gabbroic intrusives, which derive from the basaltic melts (the oceanic crust: layers 2 and 3) and by strongly depleted, residual peridotites (the oceanic mantle: layer 4) (for a more detailed description of the layered structure of the oceanic crust and mantle, see Wilson, 1989, and quoted references).

Topographically and structurally the mid-ocean ridges are very variable and this variability correlates well with the spreading rate of the ridge. Fast-spreading ridges (half spreading rates from 6-7 to more than 12 cm yr^{-1}) have rather smooth profiles, whereas slow-spreading ridges (half spreading rates 1-2 cm yr^{-1}) have jagged profiles and an axial rift valley.

As reported by Wilson (1989, and the quoted references), fast-spreading ridges have a large, steady-state permanent magma chamber beneath the axis of the ridge, which produces a continuous gabbroic layer, underneath the volcanic layer 2: the magma supply is rather continuous and the different magmatic batches mix in the convecting magma chamber (Fig. 1A): at present, it is questionable if there are large magma chambers at fast spreading ridges, and different models of the oceanic crust at fast spreading ridges have been proposed (see: Grove et al., 1992; Kelemen and Aharonov, 1998).

Slow-spreading ridges do not present a permanent subaxial magma chamber, and the upwelling magma is stored in rather small (a few km wide) ephemeral reservoirs (Fig 1B). These ridges show, moreover, both magmatic and amagmatic periods: the former are characterized by extrusion of basalt flows and intrusion of gabbroic bodies, whereas the latter, magma starved periods are characterized by dominant tectonic activity, frequently leading to the sea-floor exposure of oceanic mantle peridotites (see Cannat, 1993, and quoted references).

Ophiolites exposed along the Western Alpine - Northern Apennine orogenic chain represent the oceanic lithosphere of the Ligurian Tethys, which separated, during Late Jurassic - Cretaceous times, the Europe and Adria plates.

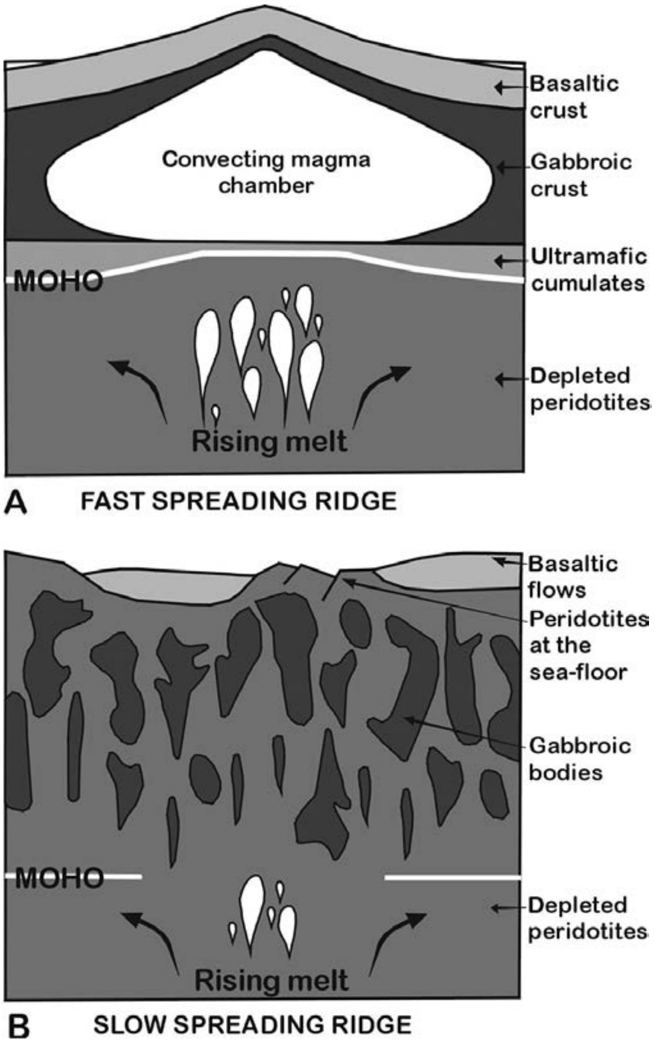

Fig. 1 - Hypothetical cross sections of mid-ocean ridges. (A) Fast spreading ridges, characterized by a permanent magma chamber, producing a continuous oceanic layer 3 (redrawn and modified after Wilson, 1989); (B) low spreading ridges, characterized by ephemeral magmatic intrusions producing discrete, dyke-like or sill-like gabbroic intrusion and a discontinuous magmatic crust (redrawn and modified after Cannat, 1993).

Western Alps - Northern Apennine ophiolites show peculiar compositional, structural and stratigraphic characteristics (references in Rampone and Piccardo, 2000, and Piccardo et al., 2001a):

1) mantle peridotites are both fertile, cpx-rich lherzolites, and depleted, cpx-poor peridotites;
2) gabbroic intrusives and basaltic volcanites have a MORB affinity and show a high-Ti character of primary magmas;
3) gabbroic rocks were intruded into mantle peridotites;
4) mantle rocks underwent decompressional, not adiabatic, subsolidus evolution, starting from subcontinental lithospheric mantle depths (spinel-facies conditions) towards the sea-floor;
5) mantle peridotites and gabbros were exposed to the sea-floor prior to extrusion of basalts and deposition of radiolarian cherts.

Accordingly, the Jurassic Ligurian Tethys was floored by an older peridotite-gabbro basement, subsequently covered by extrusion of discontinuous basaltic flows and by sedimentation of radiolarian cherts, i.e. the oldest oceanic sediments (Decandia and Elter, 1969; Piccardo, 1983; Lemoine et al., 1987) (Fig. 2).

The radiolarian cherts, which are interlayered and coeval to basalts, are not older than 160-150 Ma, in the whole Ligurian Tethys (De Wever and Caby, 1981; Marcucci and Passerini, 1991): a general agreement exists on the assumption that the inception of the oceanic stage in the Ligurian Tethys is not older than Late Jurassic.

A representative sampling of the diversity of the oceanic lithosphere which floored the Jurassic Ligurian Tethys is shown by the Ligurian ophiolites (Voltri Massif of the Ligurian Alps and Liguride Units of the Northern Apennine).

Voltri Massif ophiolites crop out as Europe-vergent tectonic units of high pressure meta-ophiolites (eclogitic metavolcanites and meta-gabbros and antigorite-olivine meta-peridotites). The Erro-Tobbio unit is composed of mantle peridotites which underwent subduction metamorphism and localized high-pressure recrystallization: it still preserves large volumes of the pristine mantle peridotites, showing mantle mineralogy and structural-textural features (Vissers et al, 1991; Hogerduijn Strating et al., 1993).

Since the early seventies (Decandia and Elter, 1972; Abbate et al., 1980), it has been recognized that Northern Apennine ophiolites crop out in two distinct structural units, the Internal and External Liguride Units, and that the Internal Liguride ophiolites have an atypical lithological sequence.

In the Internal Liguride Units, ophiolitic rocks show stratigraphic and structural relationships similar to those described for the whole Ligurian basin: they consist of a peridotite-gabbro basement stratigraphically covered by ophiolitic breccias, pillowed basaltic lava flows, and oceanic sediments (Radiolarian Cherts, Calpionella Limestones and Palombini Shales). Structural and stratigraphic knowledge indicates that the gabbroic bodies were intruded into the mantle peridotites and the peridotite-gabbro basement was exposed at sea-floor before basaltic extrusion and oceanic sedimentation. Mantle peridotites were partly serpentinized

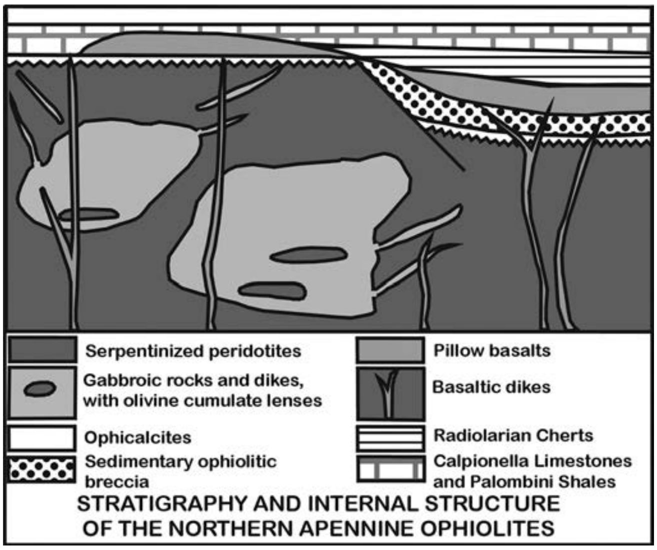

Fig. 2 - Hypothetical cross section showing the main stratigraphic and structural features of a typical Internal Liguride ophiolite section: it shows the sea-floor exposure of mantle peridotites, with an uppermost level of ophicalcites, which have been intruded by small gabbroic bodies. The mafic-ultramafic basament is discontinuously covered by ophiolitic breccias, pillowed basalts and the oceanic sedimentary cover (i.e. Radiolarian Cherts, Calpionella Limestones and Palombini Shales).

during sea-floor exposure: their uppermost level suffered intense fracturing and was transformed into ophicalcites.

In the External Liguride Units, the ophiolitic material is mostly represented by mantle peridotites and pillowed basaltic lava flows, which occur as huge slide blocks (olistoliths) within the Basal Complexes of Cretaceous-Eocene flysch sequences. They preserve, in places, primary stratigraphic relations with oceanic sediments and are associated to continental crust material (Marroni et al., 1998, and the quoted references).

Main aim of this paper is to review recent results of petrological and geochemical investigations on Ligurian ophiolites and to contribute to understanding of the geodynamic scenario from rifting to inception of the Jurassic Ligurian Tethys ocean.

PALEOGEOGRAPHY AND PRIMARY TECTONIC SETTING OF LIGURIAN OPHIOLITES

The Ligurian Tethys is believed to have developed by progressive divergence of the Europe and Adria blocks, in connection with the pre-Jurassic rifting and Upper Jurassic opening of the Northern Atlantic (Dewey et al., 1973; Lemoine et al., 1987), (Fig. 3).

Paleotectonic reconstructions of the Ligurian Tethys suggest that the Ligurian ocean was not wider than 400-500 km (Dercourt et al., 1986 ; Stampfli, 1993) and that plate convergence led to complete closure of the Ligurian Tethys in the Early Tertiary, when fragments of its oceanic lithosphere were emplaced as west-vergent thrust units in the Alps and east-vergent thrust units in the Apennine. Depending on their stratigraphic, structural and metamorphic characteristics, the different ophiolitic sequences of the Ligurian sector have been ascribed to different palaeogeographic settings in the Jurassic-Cretaceous Ligurian Tethys. The Voltri Massif ophiolites, which were subducted and recrystallized at eclogite facies conditions, were located west of the subduction zone, close to the European margin; the Northern Apennine ophiolites (Internal and External Ligurides), which underwent low-grade oceanic and orogenic metamorphism, were located east of the subduction zone, closer to the Adria margin (Fig. 4).

In the past, different interpretations of the main structural and petrological features of the Alpine-Apennine Jurassic ophiolites led to the development of different models for their primary tectonic setting. Particularly, the widespread occurrence of peridotites exposed at the sea-floor led some authors to suggest that these ophiolites were formed in a transform-zone setting (Gianelli and Principi, 1977; Lemoine, 1980; Weissert and Bernoulli, 1985).

Present knowledge on slow-spreading ridges of modern oceans indicate that they are frequently characterized by the direct exposure of serpentinized mantle peridotites on the sea-floor: peridotites are intruded by discrete gabbroic bodies and only partially covered by basaltic lava flows. Based on these features, some authors argued that Alpine-Apennine ophiolites represent mature oceanic lithosphere formed in a slow-spreading ridge setting (Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990; Lagabrielle and Lemoine, 1997).

On the other hand, the subcontinental origin of mantle peridotites from the Ligurian ophiolites was early stressed by some Authors (Decandia and Elter, 1969; 1972; Piccardo, 1976); they discussed the diversity of the Alpine-Apennine ophiolites compared with mature oceanic lithosphere of present-day oceanic basins. Based on the atypical association of fertile subcontinental-type lherzolitic mantle (i.e. the External Liguride lherzolites) and MORB magmatism, it was argued (Piccardo, 1977; Beccaluva and Piccardo, 1978) that the Ligurian ophiolites were formed during early stages of opening of the oceanic basin, following rifting, thinning, and break-up of the continental crust, and were therefore located in a marginal, pericontinental position of the Jurassic oceanic basin.

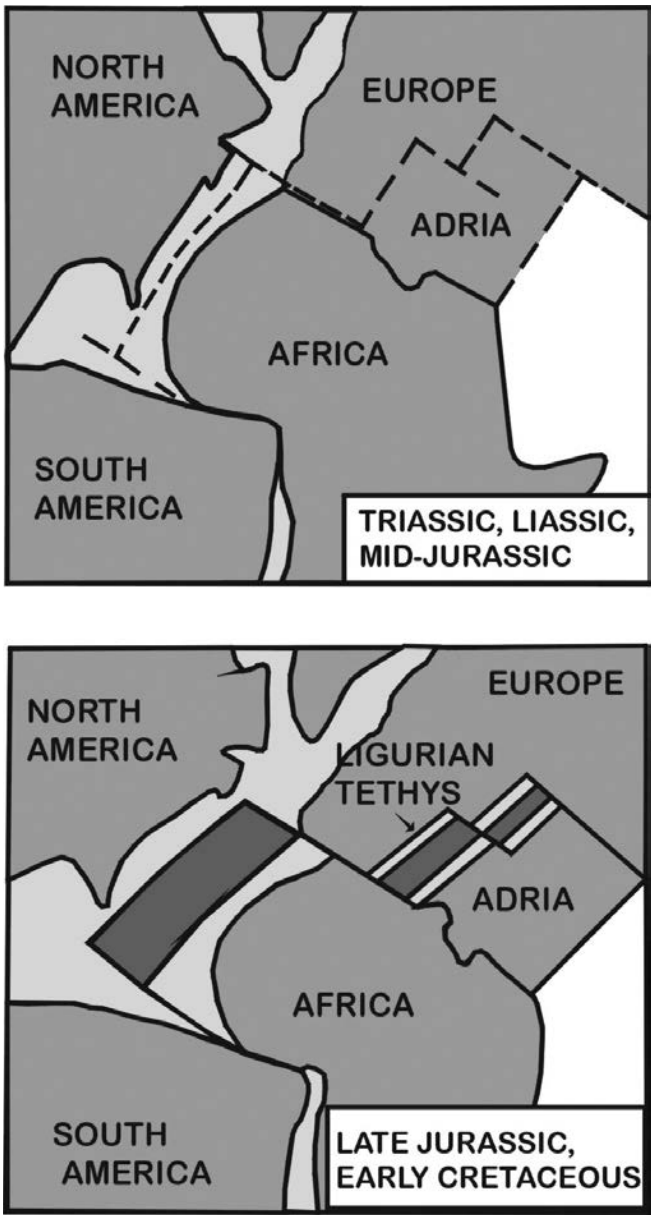

Fig. 3 - Mesozoic evolution of Central Atlantic and Ligurian Tethys oceans, from rifting to ocean formation (redrawn and modified after Lemoine et al., 1987).

Further petrological-geochemical investigations on the Northern Apennine ophiolitic mantle ultramafics, demonstrated the depleted compositions of the Internal Liguride peridotites, and suggested the existence of a residua-melt relationship between peridotites and associated MORB magmatism (Ottonello et al., 1984). It was therefore asserted that the Internal Liguride ophiolites represent oceanic lithosphere produced during a more evolved stage of evolution of the

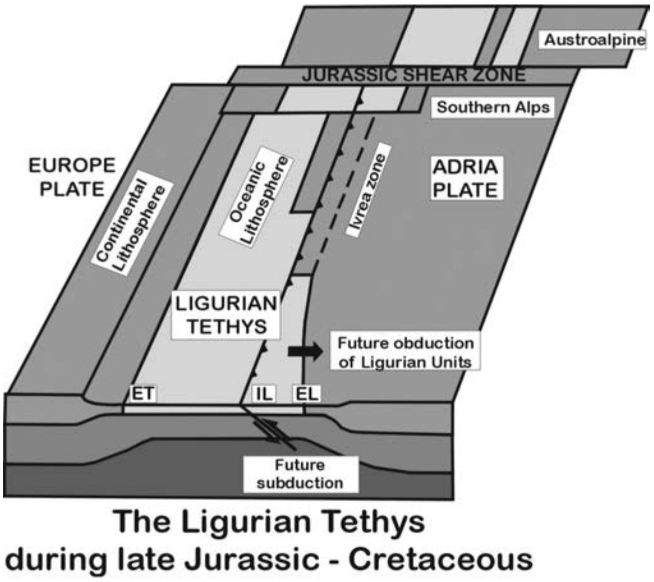

Fig. 4 - Generalized paleogeographic restoration of Upper Jurassic Ligurian Tethys, with location of the different Ligurian domains (redrawn and modified after Dal Piaz, 1995).

Ligurian Tethys (Beccaluva et al., 1984). The comparison with peridotites from different settings in modern oceanic basins emphasized close similarities between the External Liguride peridotites and the marginal and pre-rift fertile lherzolites, and between the Internal Liguride ultramafics and the depleted abyssal peridotites (Piccardo et al., 1990).

Petrological and geochemical studies on mantle peridotites developed in the last 10 years significantly contributed to the understanding of the primary tectonic setting of the Ligurian ophiolites.

PETROLOGY AND GEOCHEMISTRY

BASALTIC VOLCANICS

Basaltic volcanics are widespread in the Northern Apennine and Corsica ophiolites and in the Western Alps metamorphic ophiolites, where they have been transformed, during the alpine subduction, in metabasites which still preserve their primary geochemical affinity. Petrological and geochemical studies have provided clear evidence of the overall tholeiitic composition and MORB affinity, ranging from T-MORB to N-MORB, of the basaltic volcanics of the Northern Apennine ophiolites (Ferrara et al., 1976; Venturelli et al., 1981; Beccaluva et al., 1984; Ottonello et al., 1984; Rampone et al., 1998).

The Northern Apennine ophiolitic basalts display a large degree of differentiation: their REE compositions range from about 10xC1 to more than 40xC1. The most primitive Internal Liguride basalts show moderate LREE fractionation ($Ce_N/Sm_N = 0.6$) and HREE abundances at about 10xC1, the least differentiated External Liguride basalts display almost flat or slightly LREE-enriched REE spectra ($Ce_N/Sm_N = 0.9\text{-}1.0$) (Venturelli et al., 1981; Beccaluva et al., 1984; Ottonello et al., 1984; Marroni et al., 1998) (Fig. 5A).

Geochemical modelling indicates that the most primitive T-MORB and N-MORB-type basalts are consistent with magmas generated by variable degrees of fractional melting of a MORB-type asthenospheric mantle source (Vannucci et al, 1993).

Isotopic studies on the Northern Apennine basalts indicate that they have fairly homogeneous Nd isotopic ratios, consistent with their MORB affinity, but variable Sr isotopic ratios (up to 0.705821), which are related to oceanic sea-water alteration (Rampone et al., 1998).

Information on the age of the basaltic volcanic activity in the Ligurian Tethys has been derived by zircon U-Pb dating on acidic differentiates (plagiogranites l.s.) which are considered coeval to the basaltic volcanism: in fact, these acidic rocks cross-cut, in places, the contacts between the serpentinite-gabbro basement and the overlying sedimentary breccias (Borsi et al., 1996), or intrude the massive basalts and are, in turn, cut by basaltic dykes (Bortolotti et al., 1995). These data yield ages in the range 160-150 Ma (Bortolotti et al., 1991; 1995; Borsi et al., 1996; Ohnenstetter et al., 1981). These ages are completely consistent with the palaeontological ages of the radiolarian cherts (160-150 Ma) (De Wever and Caby, 1981; Marcucci and Passerini, 1991), which are frequently interlayered with the basaltic vulcanics.

GABBROIC INTRUSIVES

In the Western Alps - Northern Apennine (WA-NA) ophiolites the intrusive rocks occur as km-scale bodies intruded in mantle peridotites. The Internal Liguride gabbroic rocks well represent the intrusive rocks of the Alpine-Apennine ophiolites.

The dominant rock types are (Serri, 1980; Hebert et al., 1989; Piccardo, 1995; Tiepolo et al., 1997; Tribuzio et al., 2000):

- ultramafic cumulates (pl-cpx-bearing cumulus dunites);
- Mg-Al-gabbros (troctolites, ol-gabbros and cpx-gabbros);
- Fe-Ti-gabbros (Fe-Ti-oxide-bearing gabbros and diorites);
- plagiogranites (diorites and throndhjemites).

They show the crystallization sequence (olivine _ plagioclase _ clinopyroxene) and covariation of Fo content in olivine, An content in plagioclase and Mg-number in clinopyroxene, which are typical of low pressure crystallization of olivine tholeiites.

Olivine cumulates and olivine-gabbros of the Northern Apennine and Corsica ophiolites show bulk rock REE patterns generally flat, ranging from less than 1xC1 to 3xC1, with a slight LREE depletion and moderate Eu positive anomaly: their clinopyroxenes have rather flat HREE to MREE patterns, at about 9-10xC1, and LREE depletion ($Ce_N/Sm_N = 0.21\text{-}0.29$) (Rampone et al., 1998).

The REE composition of the computed liquids in equilibrium with these clinopyroxenes indicate a clear MORB affinity, in agreement with the Sr and Nd isotope ratios of some ol-gabbros and their clinopyroxenes (Fig. 5B).

Geochronological data (Sm-Nd systematics) on Ligurian ophiolitic gabbros yield ages of intrusion in the range 179-170 Ma for External Liguride gabbros from Tuscany (Tribuzio et al., 2001) and 164 Ma for an Internal Liguride gabbro from Eastern Liguria (Rampone et al., 1998) (Fig. 6). U-Pb zircon ages of 163-164 Ma are documented in some Western Alps ophiolitic metagabbros (i.e. Monviso Fe-gabbro, Lombardo et al., 2001; Allalin and Mellichen gabbros, Rubatto et al., 1998): older ages of intrusion (198 Ma, whole rock Sm-Nd systematics) are shown by the gabbroic rocks of the Montgenevre ophiolites (Costa and Caby, 2001).

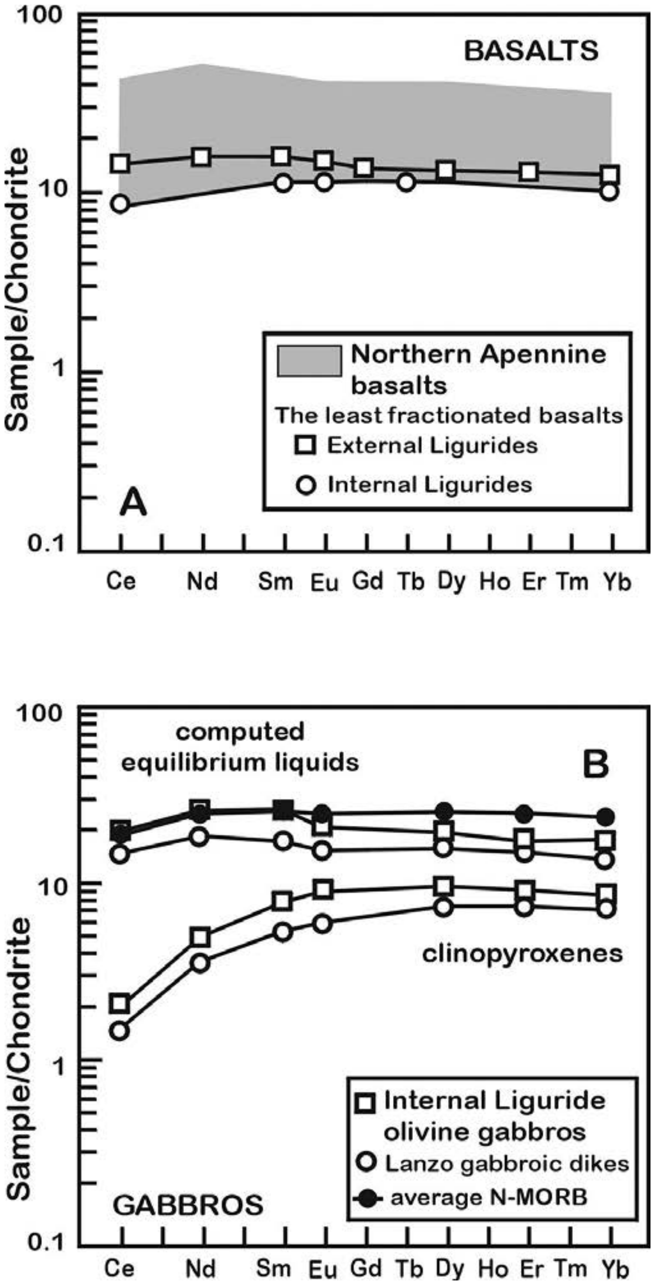

Fig. 5 - (A) C1-normalized REE patterns of the least fractionated IL and EL basalts (data from, respectively, Ottonello et al., 1984, and Vannucci et al., 1993): the grey field represents the fractionation interval covered by the whole Ligurian ophiolitic basalts. (B) C1-normalized REE patterns of the clinopyroxenes from a olivine gabbros from Internal Ligurides (data from Tribuzio et al., 1999) and Lanzo (data from Bodinier et al., 1991), and their computed equilibrium liquids: for comparison , REE pattern of an everage N-MORB is also reported.

The available intrusion ages of the Western Alps - Northern Apennine ophiolitic gabbroic rocks (i.e. 198-163 Ma) are relatively older than the Upper Jurassic (160-150 Ma) opening of the Ligurian Tethys.

MANTLE PERIDOTITES

Most of the ophiolitic peridotites from the Ligurian Tethys (Liguria, Corsica, Lanzo) are spinel-facies lherzolites showing presence and enrichment of plagioclase.

Plagioclase formation in ophiolitic Alpine-Apennine spinel peridotites has been referred to: 1) in situ partial melting at plagioclase-facies conditions (Boudier and Nicolas, 1972); 2) subsolidus recrystallization from spinel- to plagioclase-facies conditions (Bezzi and Piccardo, 1971; Piccardo, 1976; Pognante et al., 1985; Rampone et al., 1993; 1995; 1996); 3) impregnation by a percolating exotic melt (Rampone et al., 1997; Rampone and Piccardo, 2000; Piccardo et al., 2001a; 2001b; 2002) .

The proper understanding of the genetic process of plagioclase is crucial, since it may furnish important information on the evolution experienced by the peridotites and, accordingly, on the upwelling mechanisms which led to their sea-floor exposures.

In fact:

1) in situ partial melting supports the hypothesis of an adiabatic, diapiric mantle upwelling with partial melting due to decompression;
2) metamorphic transition from spinel- to plagioclase-facies conditions supports the hypothesis of a subsolidus mantle decompression during passive lithospheric extension;
3) plagioclase enrichment by melt impregnation indicates accumulation, entrapment and crystallization in the lithospheric mantle of melts deriving from the upwelling asthenosphere.

Subsolidus metamorphic transition is evident in the External Liguride and Erro-Tobbio peridotites (Piccardo, 1976; Rampone et al., 1993; Hoogerdujin Strating et al., 1993; Romairone, 1999). This process ihave been recognized on the basis of structural and petrographic features: i.e. the development of: i) exsolution lamellae of orthopyroxene and plagioclase within spinel-facies clinopyroxenes; ii) olivine + plagioclase coronas or aggregates surrounding spinel or at the spinel-pyroxenes boundaries, according to the metamorphic reaction spinel + pyroxenes _ olivine + plagioclase. This subsolidus reaction has been monitored by trace element partitioning in the External Liguride lherzolites (Rampone et al., 1993). In the case of subsolidus decompressional recrystallization, temperatures recorded by the new granoblastic plagioclase-bearing assemblages are slightly to significantly lower than the equilibration temperature of the spinel-facies assemblage. This indicates that pristine spinel peridotites followed a decompressional evolution under decreasing temperature, consistently with an evolution as the foot-wall of an extensional system.

Melt impregnation is evident in the most refractory Lanzo South, Internal Liguride and Corsica peridotites (Romairone, 1996; Rampone et al., 1997, 2001; Piccardo et al., 2002). It has been identified on the basis of peculiar microstructures, i.e. presence of: i) plagioclase blebs or veins along grain boundaries or crosscutting mantle minerals; ii) partial dissolution of mantle clinopyroxene and replacement by orthopyroxene, and development of orthopyroxene + plagioclase symplectites surrounding mantle clinopyroxenes; iii) undeformed, granular gabbroic microdomains and veinlets, made of plagioclase + orthopyroxene ± clinopyroxene + olivine, frequently showing magmatic textures and crosscutting deformed mantle minerals. Impregnated peridotites are frequently enriched in plagioclase (up to 15% by volume) and orthopyroxene with respect to plagioclase-recrystallized peridotites. In the case of melt percolation and impregnation, temperatures recorded by the plagioclase-bearing gabbroic granular domains, and frequently also by the spinel-facies porphyro-

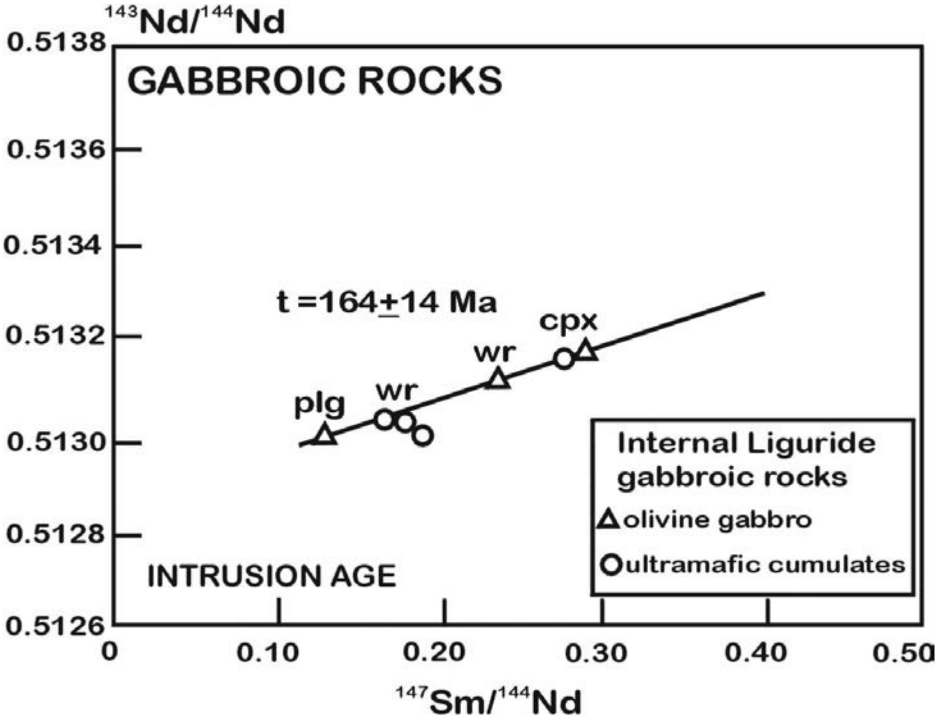

Fig 6 - ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd diagram for olivine gabbros and ultramafic cumulates of the Internal Liguride mafic intrusives (whole rocks [wr], clinopyroxene [cpx] and plagioclase [plg] (data from Rampone et al., 1998).

clastic relics, in these plagioclase-enriched peridotites, are slightly to significantly higher than the equilibration temperature of the spinel-facies assemblage in the not-enriched plagioclase-free peridotites (Piccardo et al., 2002) from the same peridotite body. This indicates that pristine spinel peridotites were significantly heated during melt migration and impregnation.

Field, structural and petrographic evidence indicates that the subsolidus spinel- to plagioclase-facies transition and melt percolation and entrapment occurred at deeper conditions, where mantle rheology still allowed plastic deformation and melt migration via porous flow. The subsequent dyke intrusion of aggregated MORB melts, parental to the gabbroic dykes, occurred at shallower levels, where the upwelling lithospheric mantle reached more rigid and fragile conditions because of the conductive heat loss.

THE EXTERNAL LIGURIDE PERIDOTITES

The External Liguride mantle peridotites are dominantly spinel lherzolites with isotropic granular to tectonite-mylonite fabrics. They are characterized by rather fertile composition, with only slight depletion in fusible components.

Their fertile character is indicated by: (1) the lherzolitic modal composition (clinopyroxene up to 10-15 % by volume); (2) relatively high bulk rock Al_2O_3 (2.86-4.00 wt%) and CaO (2.33-3.39 wt%) contents, with a few samples approaching the primitive mantle values; (3) clinopyroxene REE spectra showing only moderate LREE depletion (Ce_N/Sm_N = 0.6-0.8) and absolute concentrations at 10-16xC1 (Fig. 7A); (4) the relatively high Na, Ti, Sr and Zr contents in clinopyroxenes and whole rocks (Piccardo, 1976; Rampone et al., 1995).

The majority of the External Liguride lherzolites display a complete static equilibrium recrystallization under spinel-facies conditions. Disseminated Ti-pargasite amphiboles occur in structural and chemical equilibrium with the spinel-bearing assemblage: these amphiboles show LREE-depleted spectra (Fig. 7A) and very low Sr, Zr, Ba and K contents. Thermobarometric estimates on the spinel-facies assemblages yield T in the range 1000-1100°C. This equilibrium recrystallization is interpreted as the stage of annealing recrystallization at the conditions of the regional geotherm, after accretion of the External Liguride mantle section to the conductive lithosphere (i.e. isolation from the convective asthenospheric mantle).

Present-day Sr and Nd isotope ratios plot within the depleted end of the MORB field (Rampone et al., 1995), similarly to other subcontinental orogenic lherzolites from the Western Mediterranean area (Pyrenees and Lanzo Nord).

Sm-Nd model ages are in the range 1.9-1.7 Ga (assuming a CHUR mantle source) and 2.4-2.1 Ga (assuming a DM and a CHUR mantle sources), indicating Proterozoic ages of accretion to the subcontinental lithosphere (Rampone et al., 1995) Fig. 8A and B).

THE INTERNAL LIGURIDE PERIDOTITES

The Internal Liguride mantle ultramafics are depleted peridotites, with granular and tectonite-mylonite fabrics: they consist of clinopyroxene-poor (5-10% by volume) lherzolites.

They show: (1) significantly depleted bulk and mineral compositions, particularly for Ti, Na and LREE; (2) bulk rock C1-normalized REE patterns characterized by a progressive depletion from HREE to MREE at concentration levels never exceeding 1xC1; (3) clinopyroxene compositions characterized by very low Ti and Na contents and REE spectra steeply plunging at LREE and almost flat from HREE to MREE, at 7-10xC1. Geochemical modelling indicates tha the Internal Liguride peridotites are refractory residua after low-degree fractional melting of an asthenospheric mantle source, which produced MORB-type melts

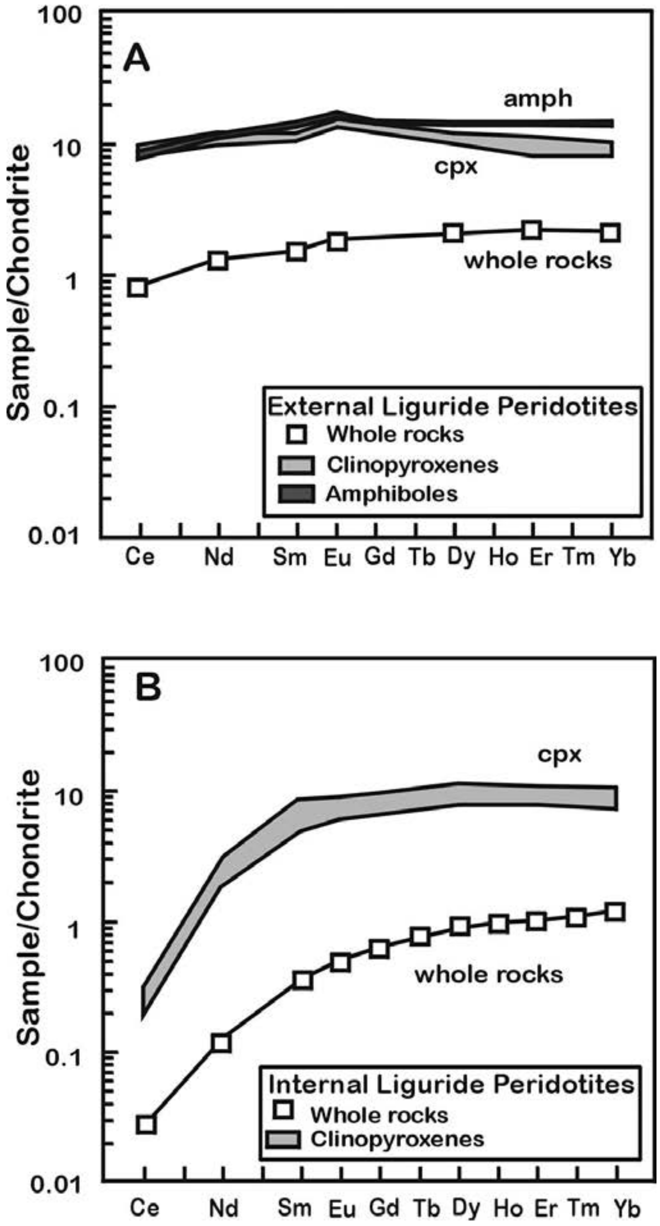

Fig. 7 - Representative C1-normalized REE patterns for whole rock, clinopyroxens (cpx) and pargasitic amphiboles (amph) from (A) the External Liguride lherzolites (data from Rampone et al., 1995), and (B) the Internal Liguride peridotites (data from Rampone et al., 1996).

(Rampone et al., 1996) (Fig. 7B).

The majority of the Internal Liguride peridotites display a complete static equilibrium recrystallization acquired after the partial melting event: thermobarometric estimates for this granular, spinel-facies equilibration yield T in the range 1150-1200°C. This equilibration is interpreted as due to accretion of the Internal Liguride residual mantle to the conductive lithosphere, after partial melting.

Present-day Sr and Nd isotope ratios indicate that their $^{87}Sr/^{86}Sr$ ratios are consistent with a MORB-type mantle, but their $^{143}Nd/^{144}Nd$ ratios are very high and plot significantly above the MORB field. Sm-Nd model ages, calculated assuming a depleted mantle (DM) source, yield a Permian age (275 Ma) for the partial melting event (Rampone et al., 1996) (Fig. 9A).

Permian ages of depletion by partial melting is also recorded by other Western Alpine subcontinental and ophiolitic peridotites: a Permian age (about 270 Ma) of partial melting has been inferred for the subcontinental Balmuccia peridotites (Ivrea Zone) (Voshage et al., 1988), which plot along the isochron defined by the Internal Liguride peridotites: the Lanzo South ophiolitic peridotites also plot on this trend (Fig. 9B).

Prior to gabbroic dyke intrusion, the Internal Liguride peridotites have been percolated by strongly depleted MORB melts, which gave rise to widespread plagioclase enrichment and melt/mantle clinopyroxene reactions (Rampone et al., 1997). The impregnating plagioclases are highly calcic and strongly depleted in the most incompatible elements (LREE, Sr), with respect to minerals in equilibrium with average MORB.

THE ERRO-TOBBIO PERIDOTITES

The Erro-Tobbio mantle peridotites are spinel lherzolites with granular to tectonite-mylonite fabrics, the latter confined to km-scale shear zones where plagioclase- and amphibole-facies assemblages are developed during deformation.

The Erro-Tobbio peridotites show variably depleted compositions, as evidenced by: (1) the decrease in modal clinopyroxene (from 10 to 3% by volume), accompanied by a decrease in Al_2O_3 (from 3.3 to 1.1 wt%) and CaO (from 2.7 to 1.1 wt%); (2) the bulk-rock REE patterns rather flat, from HREE to MREE, at less than 2xC1, with a significant LREE fractionation (Ce_N/Sm_N = 0.05-0.11); (3) the low contents of fusible components (Al, Ti, Sr, Zr, Y) in clinopyroxenes; (4) the clinopyroxene REE patterns, that are flat from HREE to MREE, at 7-11xC1, and are strongly fractionated for the LREE (Ce_N/Sm_N = 0.06-0.09) (Ernst and Piccardo, 1979; Romairone, 1999, Piccardo et al., 2001) (Fig. 10A).

The compositional features indicate that the Erro-Tobbio peridotites are refractory residua after variable degrees of fractional melting starting from a MORB-type asthenospheric mantle source .

The Erro-Tobbio peridotites were completely recrystallized at spinel-facies conditions and temperatures in the range 920-1090°C: this indicates annealing equilibration to intermediate geothermal gradients during accretion to the conductive subcontinental lithosphere.

The subsequent partial reequilibration at plagioclase-facies (T in the range 940-1000°C) and amphibole-facies (T in the range 850-970°C) conditions, and the later partial serpentinization, indicate that the Erro-Tobbio peridotites underwent a subsolidus, non-adiabatic, decompressional evolution from lithospheric mantle depths towards shallow levels, leading to their sea-floor exposure during opening of the Ligurian Tethys (Hoogerdujin Strating et al., 1993).

Spinel-facies clinopyroxenes show rather homogeneous present-day Nd isotope ratios, which are slightly higher than those of typical MORB mantle, and Sr isotope ratios rather high and variable, due to sea-water alteration (Romairone, 1999).

Prior to intrusion of gabbroic bodies and dykes, the Erro-Tobbio peridotites were percolated by basaltic melts, which produced localized zones of replacive dunites, and, later on, impregnated by basaltic melts which generated localized plagioclase enrichments.

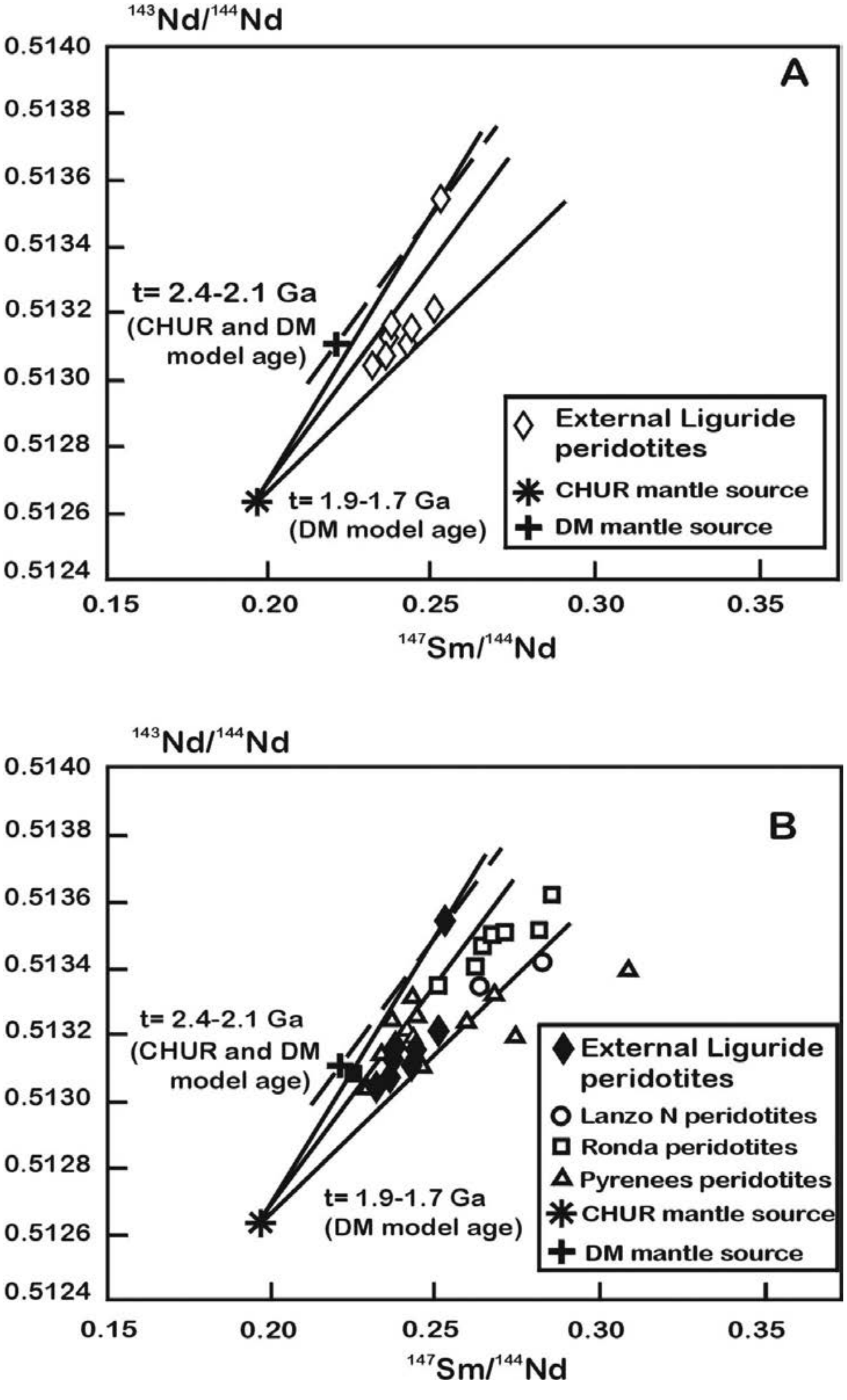

Fig. 8 - ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd diagram for the External Liguride peridotites (A) (data from Rampone et al., 1995), compared with data from other subcontinental orogenic peridotites (B) (Ronda, Reisberg et al., 1989; Pyrenees, Downes et al., 1991, Mukasa et al., 1991; Lanzo North, Bodinier et al., 1991). All data are from clinopyroxene separates. The DM (Depleted Mantle) and CHUR source ratios are, respectively, ^{143}Nd/^{144}Nd = 0.513114, ^{147}Sm/^{144}Nd = 0.222 and ^{143}Nd/^{144}Nd = 0.512638, ^{147}Sm/^{144}Nd = 0.1967 (see: Rampone et al., 1995, for more detailed explanations).

THE MONTE MAGGIORE (CORSICA) PERIDOTITES

The Monte Maggiore mantle ultramafics are strongly depleted peridotites, with spinel-facies granular assemblage: they are clinopyroxene-poor, refractory spinel lherzolites, locally enriched in plagioclase (Jackson and Ohnenstetter, 1981; Romairone, 1996; Rampone et al., 1997; 2001) .

Clinopyroxenes have almost flat MREE to HREE patterns, at less than 7xC1, and LREE fractionation ($Ce_N/Sm_N = 0.03$, $Ce_N/Yb_N = 0.02$, $Ce_N = 0.10$) (Fig. 10B): Monte Maggiore peridotites are the most depleted of the Ligurian Tethys ophiolitic peridotites, and closely resemble abyssal peridotites from modern oceans.

Monte Maggiore peridotites show widespread records of melt percolation and impregnation evidenced by plagioclase enrichment (Romairone, 1996; Rampone et al., 1997): sometimes small cumulate pockets are formed by the impregnating melts (Rampone et al., 1997; Piccardo and Rampone, 2001a and 2001b). The impregnating melts were SiO_2-saturated: the silica saturation was likely the result of reactive porous flow processes between melts and country

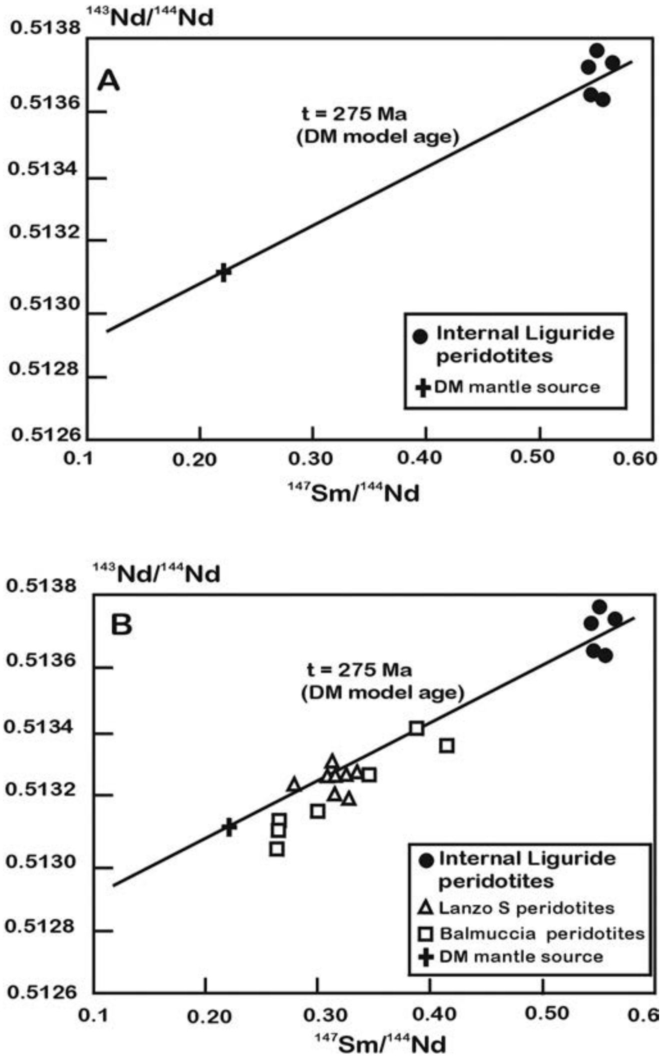

Fig. 9 - ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd diagram for the Internal Liguride peridotites (A) (data from Rampone et al., 1996), compared with data from the Balmuccia (Ivrea Zone, Voshage et al., 1988) and Lanzo South (Bodinier et al., 1991) peridotites (B).

peridotite during upwelling from deeper levels. The migrating melts were progressively saturated in pyroxenes, reaching major element compositions similar to low pressure melts (Kelemen et al., 1995).

The impregnating, magmatic plagioclase is extremely poor in the most incompatible trace elements (LREE,Sr,Zr), and show a negative LREE fractionation, which is unusual, compared to plagioclase from MORB. The percolating melts show an overall MORB affinity with a strongly depleted signature, more depleted with respect to any erupted MORB (Rampone et al., 1997; Piccardo and Rampone, 2001a and 2001b).

The intrusive pods consist of orthopyroxene-rich ultramafic-mafic cumulates (i.e. plagioclase peridotites, olivine gabbronorites, gabbronorites, noritic anorthosites), with cumulus olivine (Fo 90), clinopyroxene and orthopyroxene (Mg# 89-90), and interstitial plagioclase (An 81-94). Cumulus clinopyroxenes and interstitial plagioclases are strongly depleted in the more incompatible elements (LREE,Sr,Zr,Ti) (Piccardo and Rampone, 2001a and b), with respect to minerals in equilibrium with an average MORB and to minerals of typical oceanic and ophiolitic MORB-type gabbros. The calculated liquid in equilibrium with magmatic clinopyroxene shows a strongly LREE-fractionated REE pattern, significantly different from any erupted MORB. Geochemical modelling indicates that the impregnating liquids most probably consisted of unmixed depleted single melt increment produced by 5-7% melting degree from a fractional melting process on a slightly depleted spinel-facies asthenospheric mantle source (Rampone et al., 1997; Piccardo and Rampone, 2001a and 2001b).

The orthopyroxene-rich intrusive pods are similar, as for petrography and mineral chemistry, to the unique suite of oceanic cumulates from MAR, DSDP Site 334 (Ross and Elthon, 1993), composed of orthopyroxene-rich mafic-ultramafic rocks, for which a parental liquid strongly depleted in Na, Y, Sr, Ti and Zr, relative to the lowest abundances in N-MORBs, has been estimated.

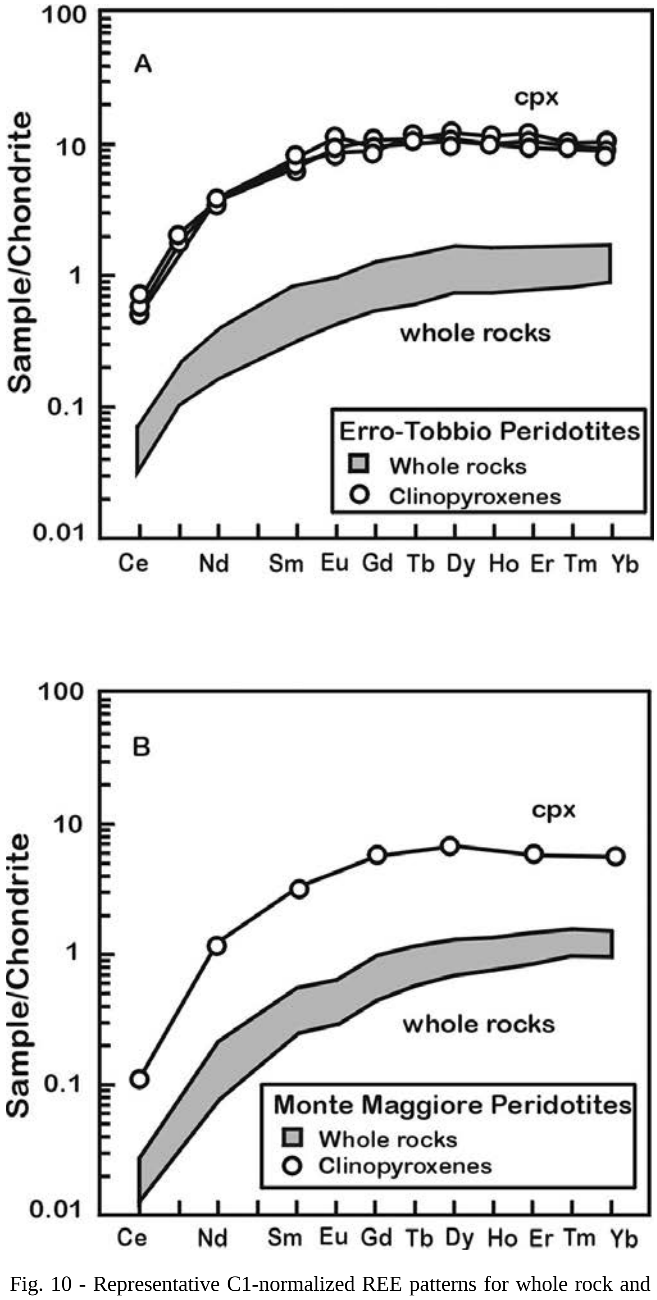

Fig. 10 - Representative C1-normalized REE patterns for whole rock and clinopyroxens (cpx) from (A) the Erro-Tobbio peridotites (data from Romairone, 1999) and (B) the Monte Maggiore peridotites (data from Rampone et al., 1997, and unpublished).

THE LANZO PERIDOTITES

The Lanzo mantle ultramafics are variably depleted peridotites: they range from clinopyroxene-poor, refractory spinel-facies lherzolites to fertile plagioclase-bearing lherzolites. They crop out in three bodies (i.e. Northern, Central and Southern), separated by shear zones (Boudier, 1978). Clinopyroxenes show REE patterns with more or less marked LREE negative fractionation: Ce_N/Yb_N = 0.2-0,4 (La_N 1-2) in the Northern and Central Bodies, Ce_N/Yb_N = 0.13-0.17 (La_N 0.3-0.4) in the Southern Body (Bodinier et al., 1991) (Fig. 11A and B). Lanzo ultramafics carry pyroxenite layers and gabbroic dykes: their clinopyroxenes have REE patterns, similar to clinopyroxenes from N-MORB.

The Lanzo massif has been interpreted (Nicolas, 1984) as an asthenospheric diapir emplaced in the lithosphere during the opening stage of the Ligurian Tethys. Based on the trace element distribution, it has been inferred that the southern part of Lanzo massif underwent more advanced partial melting (from 6 to 20%), starting from garnet-facies conditions, while the northen part sufferent lower degrees of melt extraction (<6%). More recently, Pognante et al. (1985) stated that the Lanzo ultramafics might be a section of sub-continental lithosphere with a polyphase history of partial melting and decompression during rifting, that was later intruded in the Jurassic by N-MORB type melts.

The widespread presence of plagioclase in both Northern and Southern Domains has been variably interpreted as record of: i) in situ partial melting, ii) percolation of indigenous or exotic melts (Nicolas, 1984; Bodinier et al., 1991).

Based on isotopic data, Bodinier et al. (1991) inferred that the Northern Body has been derived from the asthenosphere near the Proterozoic-Phanerozoic boundary, thus representing a fragment of old subcontinental lithosphere; by contrast, these Authors consider the Southern Body a piece of the Phanerozoic asthenosphere which rose up as a high-temperature diapir during the opening of the Ligurian Tethys.

Ongoing research (Piccardo et al., 2002) reveals that the plagioclase enrichment in the Lanzo South Body is most probably due to melt impregnation. The mantle protoliths of the Lanzo South plagioclase-enriched spinel peridotites were depleted lherzolites, showing protogranular textures and spinel-facies assemblages, which indicate an early complete equilibrium recrystallization at lithospheric mantle depths, at temperatures of about 1000-1100°C. These peridotites were percolated via pervasive porous flow and were impregnated by melts which crystallized as undeformed gabbroic micro-granular aggregates between deformed mantle minerals. The peculiar composition of the magmatic plagioclase (i.e. exceptionally low Sr contents and variably LREE-depleted REE spectra) suggests that the impregnating melts were variably depleted in highly incompatible elements, with respect to average MORB. Lanzo South peridotites underwent, later on, melt migration along dunite channels: the migrating melts crystallized euhedral clinopyroxene megacrysts, which are in equilibrium with melts with MORB affinity. Geothermometric calculations on minerals from the plagioclase-enriched peridotites indicate that the Lanzo South peridotites were significantly heated (up to 1250°C) during diffuse melt percolation. Chemical and thermal evidence indicates, accordingly, that the Lanzo South peridotites record the thermo-chemical erosion of the subcontinental lithospheric mantle by the upwelling asthenosphere.

Later on, Lanzo South peridotites were intruded by variably fractionated MORB melts, parental to the Mg-rich and Fe-rich gabbroic dykes.

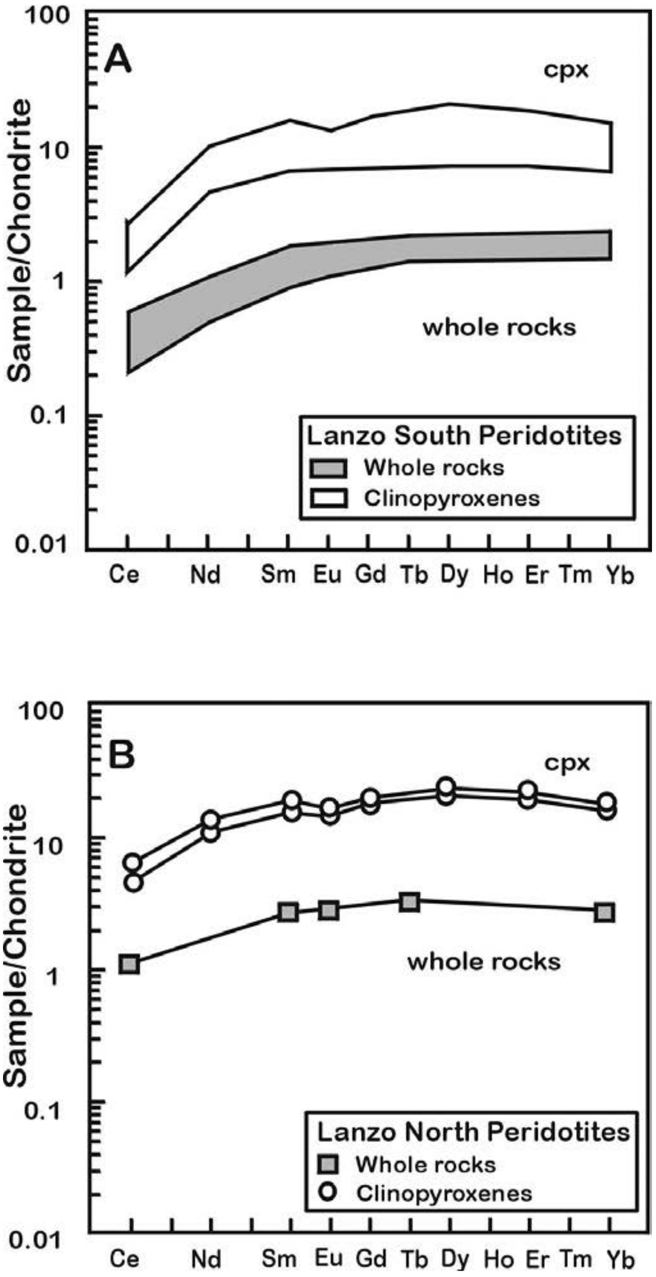

Fig 11 - Representative C1-normalized REE patterns for whole rock and clinopyroxens (cpx) from (A) the Lanzo South peridotites and (B) the Lanzo North peridotites (data from Bodinier, 1988; Bodinier et al., 1991).

DISCUSSION

Field and petrological-geochemical data indicate that the subcontinental lithospheric mantle, represented by the Liguria, Corsica and Lanzo ophiolitic peridotites, was: i) early accreted to the subcontinental lithosphere, ii) progressively exhumed to shallow levels, and percolated and impregnated by upward migrating melts and, ii) later intruded by aggregated MORB melts, parental to the gabbroic dykes.

During the lithospheric extension which governed the rifting and opening of the Ligurian Tethys, the Alpine-Apennine ophiolitic peridotites were continuously upwelling and underwent progressive cooling by conductive heat loss and modification of their rheological characteristics. Melt intrusion in a more fragile regime (the gabbroic dykes) occurred when these mantle sections were at shallower levels in the conductive lithosphere. Progressive change in rheology of the lithospheric mantle during upwelling was accompanied by variation in the melt dynamics: early single melt increments survived unmixed and migrate isolated by diffuse porous flow, whereas subsequently the different melt fractions were more efficiently mixed and completely aggregated, most probably, in shallow crustal magma chambers. These aggregated MORBs underwent differentiation within these ephemeral magma chambers and formed variably fractionated magmas, which migrated along fractures in the shallow and fragile uppermost mantle, to form the gabbroic dykes with MORB affinity.

THE PRE-OCEANIC EVOLUTION RECORDED BY THE LIGURIAN OPHIOLITIC PERIDOTITES.

The Ligurian ophiolitic peridotites show records of subsolidus tectonic-metamorphic evolution from subcontinental lithospheric depths to the ocean floor, after accretion to the conductive subcontinental lithosphere (Fig. 12). The fertile External Liguride peridotites were accreted during Proterozoic times, the depleted Internal Liguride peridotites were accreted during Permian times, after partial melting on an asthenosphere mantle source.

Main records of this subsolidus decompressional evolution are: (1) the development of km-scale tectonite-mylonite extensional shear zones; (2) the subsolidus recrystallization of plagioclase- and amphibole-bearing assemblages; (3) the late serpentinization related to sea-water alteration.

The plagioclase-facies reequilibration has been dated by Sm-Nd systematics on plagioclase-clinopyroxene pairs: they give 273-313 Ma for the Erro-Tobbio peridotites (Romairone, 1999) (Fig. 13B) and 165 Ma for the External Liguride peridotites (Rampone et al., 1995) (Fig. 13A). These two isochron data point to clinopyroxene-plagioclase equilibration in the Permian and the Jurassic, respectively. Available geochronological data indicate that the decompressional evolution of the lithospheric mantle of the Europe-Adria system was already active since Late Carboniferous - Permian times, whereas a continuous extensional process till the Upper Jurassic opening of the Ligurian Tethys is, so far, a working hypothesis (Rampone and Piccardo, 2000; Piccardo et al., 2001).

Some evidence on the continuous lithospheric extensional evolution in the Ligurian sector of the Tethys is given by the continental crust material, and particular by the gabbro-derived mafic granulites, which are linked to the External Liguride peridotites (Marroni and Tribuzio, 1996; Montanini et al, 1998; Marroni et al., 1998; Montanini and Tribuzio, 2001). The gabbroic protoliths of these granulites were intruded during Early Carboniferous - Late Permian times (about 290 Ma, Meli et al., 1996), and they underwent decompressional retrogression from granulite to amphibolite facies between Permian and Middle Triassic (Meli et al., 1996; Marroni et al., 1998).

THE POST-VARISCAN LITHOSPHERE EXTENSION OF THE EUROPE-ADRIA SYSTEM

Passive lithosphere extension was, for a long time, inferred as the leading mechanism for the opening of the Jurassic Ligurian Tethys (i.e. Elter, 1972; Piccardo, 1976; Lemoine et al., 1987; Piccardo et al., 1990; 1994) (Fig. 14A and B).

Geological-structural knowledge on the Western Alps indicates that the Europa-Adria system, following Variscan convergence, underwent Upper Palaeozoic onset of lithosphere extension (Dal Piaz, 1993; Dal Piaz and Martin, 1998,

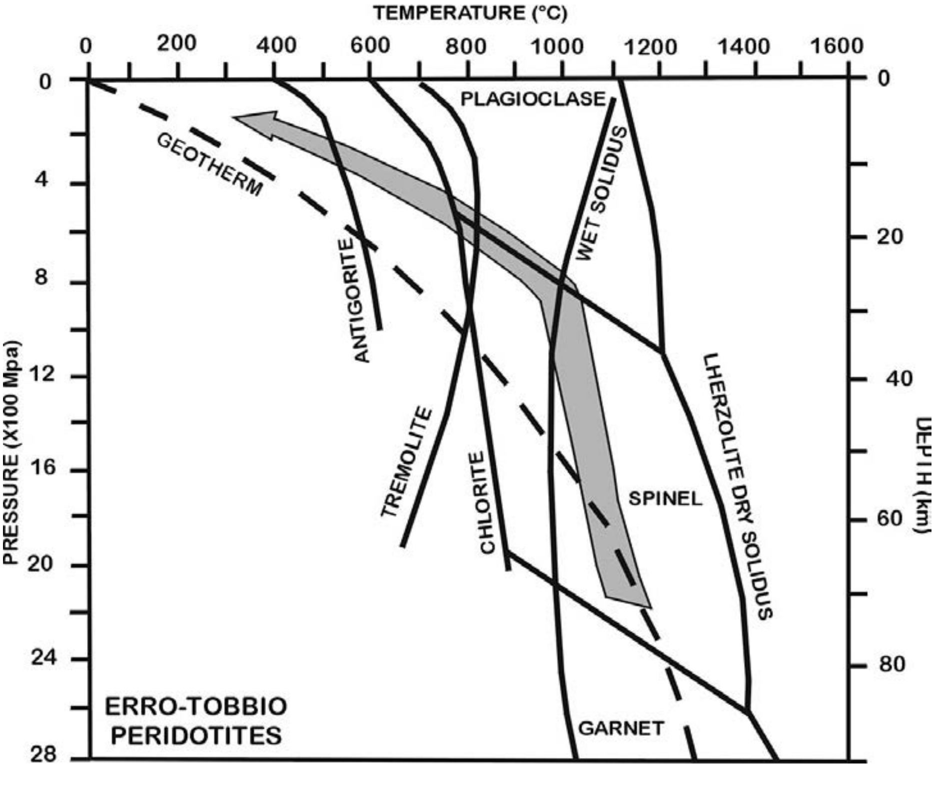

Fig. 12 - Pressure - Temperature path showing the mantle evolution of the Erro-Tobbio peridotite (redrawn after Hoogerduijn Strating et al., 1993).

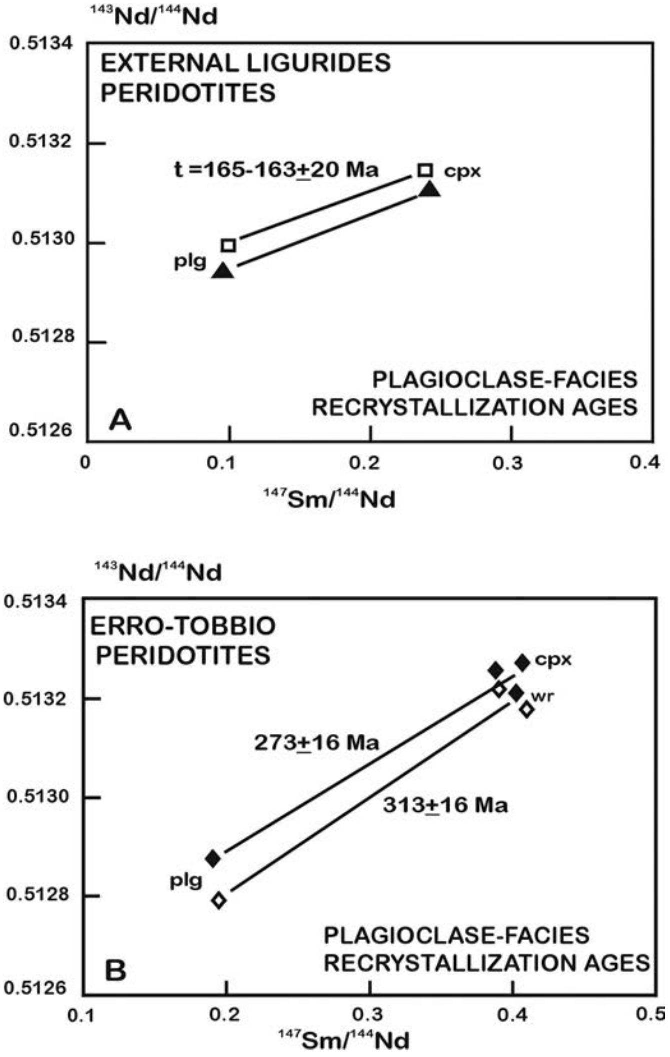

Fig. 13 - ^{143}Nd/^{144}Nd vs ^{147}Sm/^{144}Nd diagram for clinopyroxene (cpx) and plagioclase (plg) separates and whole rocks (Wr) from: (A) the External Liguride peridotites (data from Rampone et al., 1993) and (B) the Erro-Tobbio plagioclase tectonites (data from Romairone, 1999).

and references therein) through simple shear mechanisms along deep low-angle detachment zones, evolving to an asymmetric continental rift and Upper Jurassic oceanic opening. This may account for the decompressional partial melting of the asthenospheric mantle, the production of MORB-type melts and their intrusion as gabbroic bodies since Permian.

Lithosphere extension and asthenosphere partial melting during the pre-oceanic rift evolution of the Europe-Adria system are recorded by the Ligurian mantle peridotites, which were exposed at the sea-floor during the opening of the Jurassic Ligurian Tethys.

In fact, this post-Variscan composite evolution is testified by (Fig. 15):

- the Upper Carboniferous and Jurassic subsolidus decompressional evolution (spinel- to plagioclase- to amphibole-facies transition) recorded by the subcontinental lithospheric mantle sections of the Erro-Tobbio and External Liguride peridotites, respectively;
- the Permian decompressional partial melting of an asthenospheric mantle source recorded by the Internal Liguride residual peridotites.

The decompressional asthenosphere partial melting, which was active since Permian times, is, moreover, testified by the presence of :

- huge post-Variscan Permian gabbroic bodies, which derived by MORB-type mantle parental magmas and were intruded into the extending lithosphere of the Adria margin (Austroalpine Units of the Western Alps);
- the Lower to Middle Jurassic ophiolitic MORB-type gabbros, intruded into the extending subcontinental mantle, which was later exposed at the sea-floor during Upper Jurassic opening of the Ligurian Tethys.

CONCLUSIVE REMARKS

The Ligurian ophiolites represent the spatial association of:

- old (Proterozoic and Permian) subcontinental lithospheric mantle peridotites;
- Lower - Middle Jurassic gabbroic rocks, intruded in the peridotites;
- Upper Jurassic MORB-type basaltic volcanites, interlayered with radiolarian cherts, i.e. the first oceanic sediments.

Present knowledge on the Western Alps ophiolites suggest that this association is well representative of the oceanic lithosphere of the whole Ligurian Tethys.

This peculiar ophiolitic association, which shows no cogenetic relationships between the different lithological components (Rampone et al., 1998; Tribuzio et al., 2001), cannot be reconciled with a mature oceanic lithosphere formed at present-day mid-oceanic ridges (Rampone and Piccardo, 2000; Piccardo et al., 2001), where the mantle peridotites and the associated mafic crust are linked by a direct cogenetic relationship (Snow et al., 1994).

Moreover, the large exposure to the sea-floor of subcontinental mantle peridotites and the subsolidus decompressional upwelling recorded by the peridotites are in favour of a geodynamic evolution driven by the passive extension of the Europe-Adria continental lithosphere.

Passive lithosphere extension caused:

1) the progressive exhumation and the tectonic unroofing at the sea-floor of the lithospheric subcontinental mantle, and
2) the passive upwelling of the asthenospheric mantle, which underwent decompressional partial melting and produced MORB-type melts, which percolated and impregnated the overlain lithospheric mantle and, later, intruded as gabbroic bodies and dykes and extruded as basaltic lava flows.

The passive extension of the lithosphere is the most suitable geodynamic process to account for the tectonic denudation at the sea-floor of large sectors of subcontinental mantle, as deduced from analogue geophysical modelling for mantle exhumation at continent-ocean boundary (Brun and Beslier, 1996).

The presence of a subcontinental peridotite basement and of relics of stretched continental crust, which have been later injected by MORB-type basaltic dykes, strongly recall the present setting in the Northern Red Sea embryonic ocean (Bonatti et al., 1983; Piccardo, 1995; Piccardo et al., 1994; 2002), whose origin has been related to passive and asymmetric extension of the Nubian-Arabian lithosphere (Bohannon et al., 1989; Voggenreiter et al., 1988). The as-

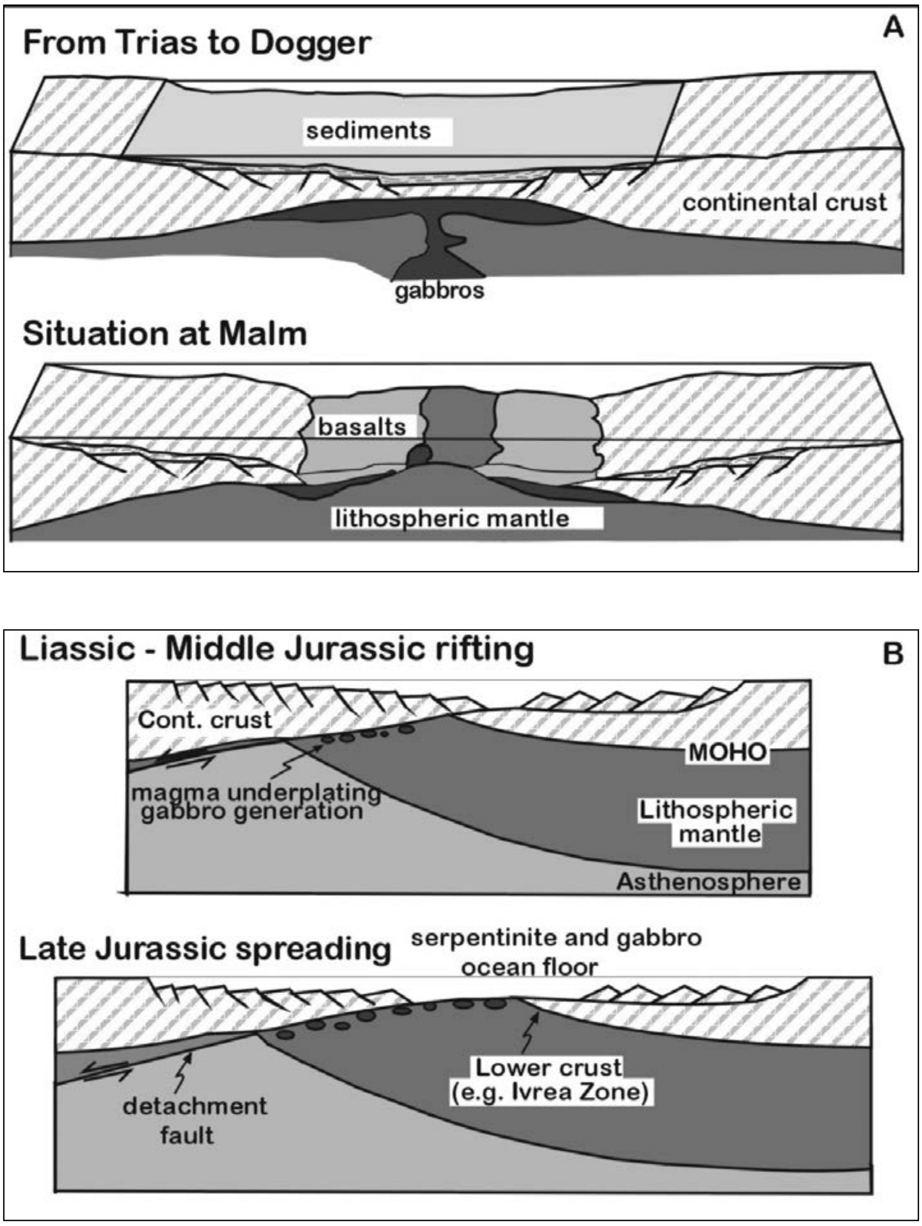

Fig. 14 - Models of mantle denudation and oceanic inception of the Ligurian Tethys by means of passive extension of the continental lithosphere.
(A) Symmetric extension according to Elter (1972). Upper section: Triassic-Dogger interval (note the underplating of the gabbroic bodies prior to continental crust break-up). Lower section: configuration at Malm, with sea-floor exposure of lithospheric mantle and extrusion of basalts (redrawn and modified after Elter, 1972).
(B) Asymmetric extension according to Lemoine et al. (1987). Upper section: Liassic - Middle Jurassic rifting (note the underplating of the gabbroic bodies prior to continental crust break-up). Lower section: upper Middle Jurassic spreading and sea-floor exposure of the subcontinental lithospheric mantle (redrawn and modified after Lemoine et al., 1987).

sociation of rifted subcontinental mantle and discontinuous MORB magmatism can be related to processes of lithosphere stretching combined with reduced magma generation, which characterizes the onset of the oceanic opening in a slow spreading system. The ocean-continent transition in the magma-poor rifted margin of Galicia (Western Iberia) (see: Manatschal and Bernoulli, 1999, and quoted references) represents, therefore, a suitable modern analogue of the early evolution of the Jurassic Ligurian Tethys (Piccardo, 1995; Marroni et al., 1998; Rampone and Piccardo, 2000; Tribuzio et al., 2002).

The available petrological and structural data, the setting of Ligurian ophiolites at regional scale (Internal and External Ligurian domain) and the frame of paleotectonic reconstruction of the Ligurian Tethys suggest that the ocean was not larger than 400-500 km (Stampfli, 1993, and quoted references). As early envisaged (Decandia and Elter, 1969; Piccardo, 1976), the Northern Apennine ophiolites can be therefore inserted in a geodynamic scenario of passive rifting to incipient oceanization of the Ligurian sector of the Jurassic Tethys (Vissers et al., 1991; Piccardo et al., 1994; Molli, 1996; Marroni et al. 1998; Tribuzio et al., 2000; Rampone and Piccardo, 2000). A similar interpretation has been recently proposed for the segments of the Jurassic Tethyan marging exposed in the Malenco and Platta-Err nappes of the Central Alps (Trommsdorff et al., 1993; Muentener and Hermann, 2001; Manatschal and Nievergelt, 1997; Manatschal and Bernoulli, 1999; Schaltegger et al., 2002).

In the Europe-Adria system, during the late stages of lithosphere extension, most probably during Jurassic and prior to complete oceanization, the conductive lithospheric mantle of the extensional system, represented by the Western Alps - Northern Apennine ophiolitic peridotites, was percolated and impregnated by depleted melts, mostly representing single fractional melt increments, and later on it was intruded by aggregated MORB melts.

Melt accumulation, entrapment and impregnation occurred when the mantle sections were cooling by conductive

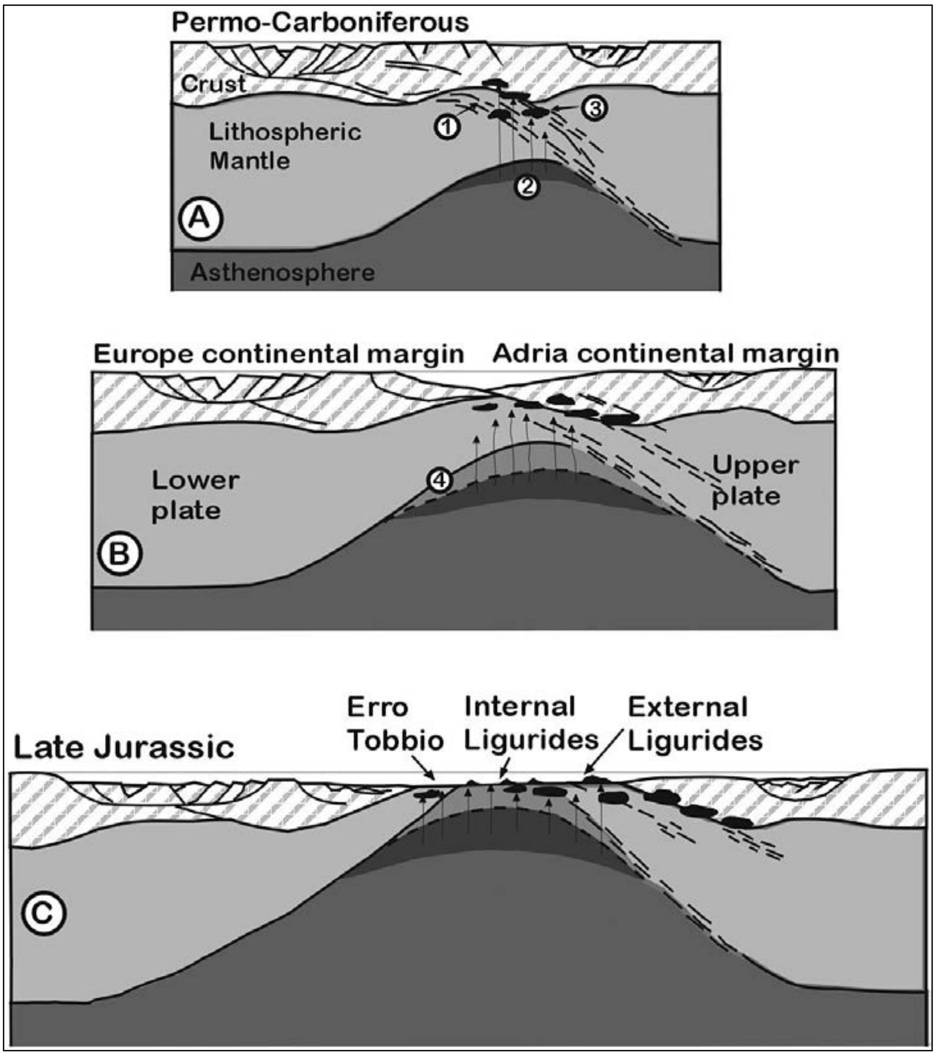

Fig. 15 - Model for the evolution of the Ligurian Tethys from upper Palaeozoic extension to Jurassic continental break-up and ocean opening. The model only considers the Permian asthenospheric partial melting and the intrusion of the manle-derived melts (in black) into the Adria lithosphere; Late Variscan crustal magmatism and Permian calcalkaline magmatism are not considered. (A) Inception of the asymmetric passive extension of the continental lithosphere and of the decompressional evolution of the lithospheric mantle (Erro-Tobbio peridotites): (1) Upwelling and subsolidus reequilibration to plagioclase-facies of the subcontinental lithospheric uppermost mantle (i.e. the Erro-Tobbio peridotites); (2) Upwelling and partial melting of the asthenospheric mantle (the mantle protoliths for the Internal Liguride peridotites); (3) Permian gabbroic intrusions from mantle-derived basaltic melts into the marginal units of the Adria plate. (B) Accretion of Permian residual mantle (4) (the Internal Liguride peridotites) to the subcontinental lithosphere, after partial melting of the asthenosphere mantle protolith; (C) Upper Jurassic opening of the Ligurian Tethys and sea-floor exposure of the subcontinental lithospheric mantle (redrawn and updated after Piccardo et al., 1994).

heat loss, but were still permeable for melt migration by diffuse and chanellized porous flow. Dyke intrusion occurred when this lithospheric mantle was fragile and rigid, at shallower levels in the conductive lithosphere.

This evolution indicates that the Western Alps - Northern Apennine ophiolitic mantle peridotites were continuously upwelling during lithospheric extension and underwent progressive cooling by conductive heat loss.

Acknowledgements

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