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Mantle dynamics during Permo-Mesozoic extension of the Europe-Adria lithosphere: insights from the Ligurian ophiolites

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ABSTRACT. — Petrologic and isotope investigations on the Ligurian ophiolites have provided evidence that they do not resemble oceanic lithosphere formed at a mid-ocean ridge setting, rather, they represent peculiar and atypical sectors of oceanic lithosphere composed by older lithospheric mantle peridotites (Proterozoic and Permian) intruded by younger MORB-type magmas (Jurassic and late-Jurassic). The Ligurian ophiolites thus reflect a lithologic association which develops in response to passive lithosphere extension and slow-spreading oceanization, and which characterizes embryonic stages of evolution of an oceanic basin. Mantle peridotites from the External Liguride (EL, Northern Apennines) and the Erro-Tobbio (ET, Ligurian Alps) ophiolitic units both record a tectono-metamorphic subsolidus evolution characterized by progressive recrystallization from spinel- to plagioclase- to amphibole-bearing assemblages and deformation from granular to tectonite- to mylonite-types. Sr, Nd and Os isotope investigations have indicated that the EL lherzolites were accreted to the subcontinental lithospheric mantle since Proterozoic times. Sm-Nd dating on the plagioclase-facies recrystallization stage have yielded 273-313 Ma in the ET peridotites and 165 Ma in the EL lherzolites. The ET and EL peridotites thus represent different pieces of subcontinental lithospheric mantle which experienced tectonic exhumation during distinct stages of extension of the Europe-Adria continental lithosphere, leading to the formation of the Jurassic Ligurian Tethys ocean. Results on the ET peridotites point that the decompressional evolution of lithospheric mantle was already active since Late-Carboniferous-Permian times. A striking feature of oceanic basins developed by passive lithosphere extension is therefore the tectonic sea-floor exposure of large sectors of subcontinental lithospheric mantle. This is consistent with the results of petrologic and structural investigations on mantle peridotites from modern oceanic analogues (embryonic oceans and passive continental margins). Another peculiar feature of the Ligurian ophiolites is the predominant lack of a mantle-crust cogenetic link, as it would be expected in mid-ocean ridge type oceanic lithosphere. Both the EL and ET peridotites represent subcontinental lithospheric mantle whose tectonic exhumation was even completely unrelated to mantle melting and melt production. Sm/Nd isotope studies on the depleted mantle peridotites from the Internal Liguride (Northern Apennine) ophiolitic units provided Permian (275 Ma) DM model age of depletion. Associated gabbroic rocks have been dated to 164 ± 14 Ma. Thus, even in the IL ophiolitic sequences, residual mantle and associated crustal rocks are not cogenetic and coheval. Sm/Nd isotope data on the depleted ophiolitic peridotites from Mt.Maggiore (Corsica) have furnished Jurassic (165 Ma) DM model age of

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depletion. Associated gabbroic rocks have been dated to 162 ± 10 Ma. The Mt. Maggiore gabbro-peridotite association thus constitutes the first record of the attainment of a mature oceanic stage of the Ligurian Tethys ocean, where residual peridotites and associated magmatic rocks are in isotopic equilibrium.

Riassunto. — Indagini petrologiche ed isotopiche sulle ofioliti Liguri hanno evidenziato che esse non sono riconducibili a litosfera oceanica formatasi in un ambiente di dorsale medio-oceanica, ma piuttosto rappresentano settori di litosfera oceanica costituita da mantello litosferico di eta Permiana o Proterozoica, intruso da magmatismo MORB di età Giurassica. Le ofioliti Liguri quindi riflettono la peculiare associazione litologica che si sviluppa a seguito di processi di estensione passiva della litosfera, e che caratterizza gli stadi embrionali di evoluzione di un bacino oceanico. Le peridotiti di mantello delle unità ofiolitiche delle Liguridi Esterne (EL, Appennino Settentrionale) e dell'Erro-Tobbio (ET, Alpi Liguri) registrano una evoluzione tettonico-metamorfica caratterizzata da progressiva ricristallizzazione (da condizioni di facies a spinello, a condizioni di facies a plagioclasio e ad anfibolo) e deformazione (sviluppo di strutture tettonitiche e milonitiche, a spese di preesistenti peridotiti granulari). Investigazioni isotopiche Rb/Sr, Sm/Nd e Re/Os, hanno indicato che le peridotiti EL rappresentano mantello litosferico sottocontinentale di età Proterozoica. Datazioni Sm/Nd sullo stadio di ricristallizzazione metamorfica a plagioclasio hanno fornito età di 273-313 Ma nelle peridotiti ET, e di 165 Ma nelle peridotiti EL. Le peridotiti EL ed ET quindi rappresentano differenti settori di mantello litosferico riesumati tettonicamente durante differenti stadi del processo di estensione della litosfera continentale Europa-Adria, che ha portato alla formazione dell'oceano Giurassico della Tetide Ligure. I risultati delle indagini isotopiche sulle peridotiti ET indicano che processi di riesumazione del mantello litosferico erano già attivi sin da tempi tardo Carboniferi – Permiani. Una caratteristica peculiare dei bacini oceanici sviluppati mediante processi di estensione passiva della litosfera è perciò l'esposizione sul fondo oceanico di vasti settori di mantello litosferico sottocontinentale. Ciò è consistente con i risultati di studi petrologici e strutturali sulle peridotiti di mantello da contesti oceanici attuali (oceani embrionali e margini continentali passivi). Un'altra caratteristica peculiare delle ofioliti Liguri è la predominante mancanza di un legame cogenetico crosta-mantello, come dovrebbe verificarsi in un settore di litosfera formatasi in una zona di dorsale oceanica. Le peridotiti EL ed ET rappresentano entrambe mantello litosferico sottocontinentale la cui esumazione tettonica è avvenuta in condizioni di subsolidus, e non ha comportato fusione parziale e produzione di fusi. Studi isotopici Sm/Nd sulle peridotiti di mantello impoverite delle unità ofiolitiche delle Liguridi Interne (Appennino Settentrionale), hanno fornito età Permiane (275 Ma) per l'evento di fusione parziale (età modello DM). Le rocce gabbriche associate sono state datate a 164 ± 14 Ma. Quindi, anche nelle sequenze ofiolitiche IL, il mantello residuale e le rocce crostali associate non sono cogenetiche e coeve. I dati isotopici Sm/Nd sulle peridotiti ofiolitiche impoverite di Mt.Maggiore (Corsica), hanno indicato età modello (DM) Giurassiche, di fusione parziale. Le rocce gabbriche associate sono state datate a 162 ± 10 Ma. L'associazione gabbro-peridotite di Mt. Maggiore rappresenta pertanto la prima testimonianza di uno stadio oceanico maturo dell'oceano della Tetide Ligure, dove le peridotiti residuali e le rocce magmatiche associate sono in equilibrio isotopico.

Key Words: *Mantle peridotites, ophiolites, Sm-Nd isotopes, mantle exhumation*

INTRODUCTION

The Alpine-Apennine ophiolites represent lithosphere remnants of a small ocean, the Ligurian Tethys, which was generated by passive rifting, thinning and breakup of the Europe-Adria continental lithosphere, connected to the Triassic-Jurassic opening of the Central Atlantic.

Some peculiar features of the Alpine-Apennine ophiolites, i.e. the abundance of fertile mantle peridotites, the scarceness of gabbroic rocks, the lack of a sheeted dyke complex, and the direct exposure to the sea-floor of the peridotite-gabbro basement (testified by peridotite serpentinization, basaltic dyke intrusion and rodingitization), were pointed out in a series of pioneering papers (Piccardo, 1976; Pognante *et al.*, 1985), and were interpreted to reflect the peculiar origin of the Ligurian Tethys ocean, generated by passive lithosphere extension and continental mantle tectonic denudation.

Last decade petrologic and isotope

investigations on the Ligurian ophiolites, particularly on mantle peridotites, have provided evidence that none of these ophiolites represent mature oceanic lithosphere formed at a mid-ocean ridge setting, in which residual mantle peridotites and associated magmatic crust are linked by a cogenetic relationship (Rampone *et al.*, 1993; 1995; 1996; 1998; Piccardo *et al.*, 1994; Romairone, 1999; Rampone *et al.*, 2004a). Rather, they represent peculiar and atypical sectors of «oceanic lithosphere» composed by older lithospheric mantle peridotites (Proterozoic and Permian) intruded by younger (Jurassic and late-Jurassic) MORB-type magmas. Thus, it has been definitely stated that the Ligurian ophiolites do not represent mid-ocean ridge – type oceanic lithosphere, rather, they reflect the peculiar lithologic association which develops in response to passive lithosphere extension and slow-spreading oceanization, and which characterizes embryonic stages of evolution of an oceanic basin (Rampone & Piccardo, 2000, and quoted references). Aim of this work is thus to provide, by reviewing knowledge on the Ligurian and Corsica (France) ophiolites, a synthetic picture of some major geodynamic and petrologic processes which governed the evolution of the asthenospheric-lithospheric mantle during the Permo-Mesozoic extension of the Europe-Adria lithosphere, leading to the opening of the Jurassic Ligurian Tethys ocean. On a more general geodynamic context, the paper aims to highlight the key features of the unique lithosphere which is formed during passive rifting and slow-spreading ocean formation. Two major geodynamic-petrologic features which characterize the birth and evolution of an ocean by passive rifting and slow-spreading oceanization, are here addressed:

1) the tectonic denudation of km-scale sectors of subcontinental lithospheric mantle, which evolve towards shallow levels by entirely subsolidus P-T trajectories;

2) the predominant lack of a cogenetic relationship between the exposed lithospheric mantle and the associated MORB-type gabbros and basalts, i.e. the possibility that gabbroic and basaltic magmas, produced by underlying asthenospheric mantle levels intrude already exhumed lithospheric mantle peridotites which either did not experience melting during exhumation, and/or they melted in older times relative to the age of the associated crust. This particular feature in principle disappears when the oceanic basin reaches a mature oceanic stage, in which residual mantle and associated magmatic crust are roughly coeval (Snow *et al.*, 1994).

THE LIGURIAN AND CORSICAN OPHIOLITES

In the Western Alpine – Northern Apennine belt various ophiolitic units outcrop (Fig. 1). Although most of these units are volumetrically dominated by mantle peridotites (e.g. the Lanzo, Erro-Tobbio and External Liguride massifs) they are considered «ophiolitic», because mantle peridotites are invariably associated to gabbroic intrusions and, in places, to basaltic volcanics, with MORB-type affinity.

The Ligurian ophiolites, particularly, constitute a representative sampling of the peculiar «oceanic lithosphere» which floored the Jurassic Ligurian Tethys ocean. Palinspastic reconstructions suggest that this basin was limited in size and that it never reached the dimensions of present-day oceans (Dal Piaz, 1999).

In the Ligurian Alps, high-pressure meta-ophiolites occur in the Voltri Massif Units, in association with slices of continental crystalline rocks of the European margin (Chiesa *et al.*, 1975; Messiga *et al.*, 1992). These rocks have long been thought to be the Alpine equivalents to the Northern Apennine ophiolites, except that they were caught up and partly metamorphosed by the Alpine orogeny (Bezzi & Piccardo, 1971; Piccardo *et al.*, 1992; Hoogerduijn Strating *et al.*, 1990, 1993; Scambelluri *et al.*, 1991).

The Erro-Tobbio (ET) Unit pertains to the Voltri Massif, and mostly consists of recrystallized antigorite-bearing metaperidotites,

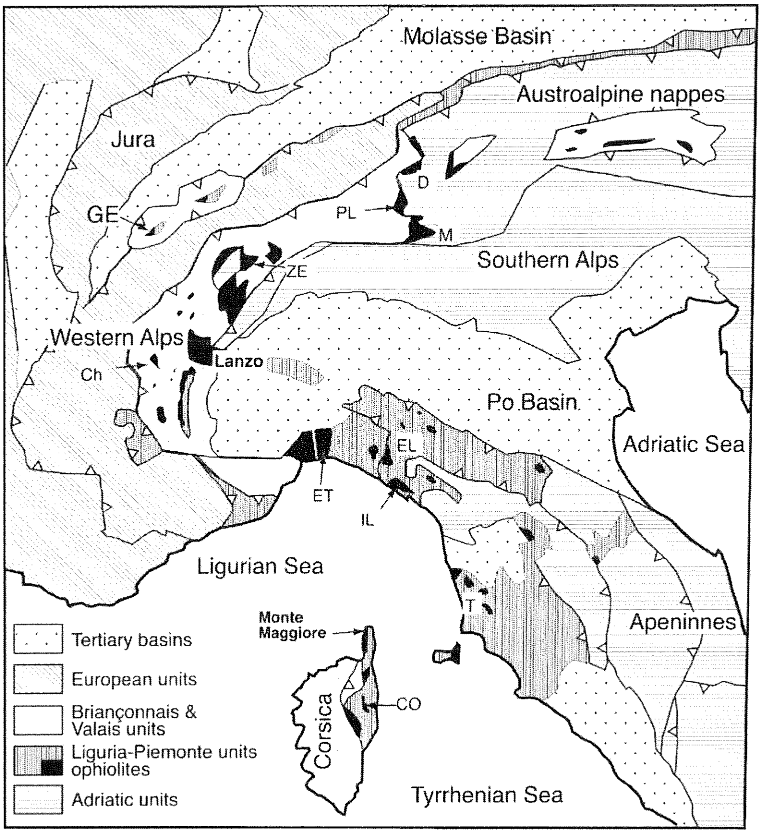

Fig. 1 – Schematic tectonic map of the Alpine – Northern Apennine ophiolites (redrawn after Schaltegger *et al.*, 2002; Münter and Piccardo, 2003). Abbreviations are: D = Totalp periodotite; Pl = Platta ophiolite; M = Malenco peridotite; Ze = Saas Zermat ophiolite; Ch = Chernaillet ophiolite; ET = Erro-Tobbio peridotite; EL = External Ligurides ophiolite; IL = Internal Ligurides ophiolites; T = Tuscan ophiolite; CO = Corsica ophiolite.

and associated rodingitic and eclogitic mafic rocks (mostly deriving from MORB-type gabbros and subordinate basaltic dykes). In spite of the alpine overprint, the Erro-Tobbio Unit preserves kilometer-scale volumes of unaltered peridotites which retain mantle textures and mineral assemblages, thus allowing the study of the pre-alpine mantle evolution (Ernst and Piccardo, 1979; Ottonello *et al.*, 1979; Piccardo *et al.*, 1990, 1992; Hoogerdujin Strating *et al.*, 1990, 1993; Vissers *et al.*, 1991). The Erro-Tobbio mantle peridotites consist of partly serpentinized cpx-poor lherzolites and harzburgites, which commonly show spinel-bearing assemblage. Bulk rock and mineral chemistry data on the ET peridotite protoliths have pointed to an overall depleted signature. The most important features are: i) the depletion in fusible components (i.e. low Ca, Al, Ti, LREE contents in both bulk rocks and constituent clinopyroxene) (Fig. 2, 3), ii) the MORB-type Nd isotopic compositions of clinopyroxenes (Fig. 4). However, on the basis of combined bulk-rock and mineral chemistry investigations, it has been inferred that the Erro-Tobbio spinel peridotite protoliths most likely record a composite history of partial melting and melt migration by reactive porous flow (Rampone *et al.*, 2004b). After this event, the peridotites were annealed at lithospheric conditions and subsequently experienced tectonic exhumation along km-scale shear zones, testified by subsolidus reequilibration from spinel- to plagioclase- to amphibole- facies conditions, and progressive deformation from granular to tectonite to mylonite fabrics (Hoogerdujin Strating *et al.*, 1990, 1993; Vissers *et al.*, 1991;

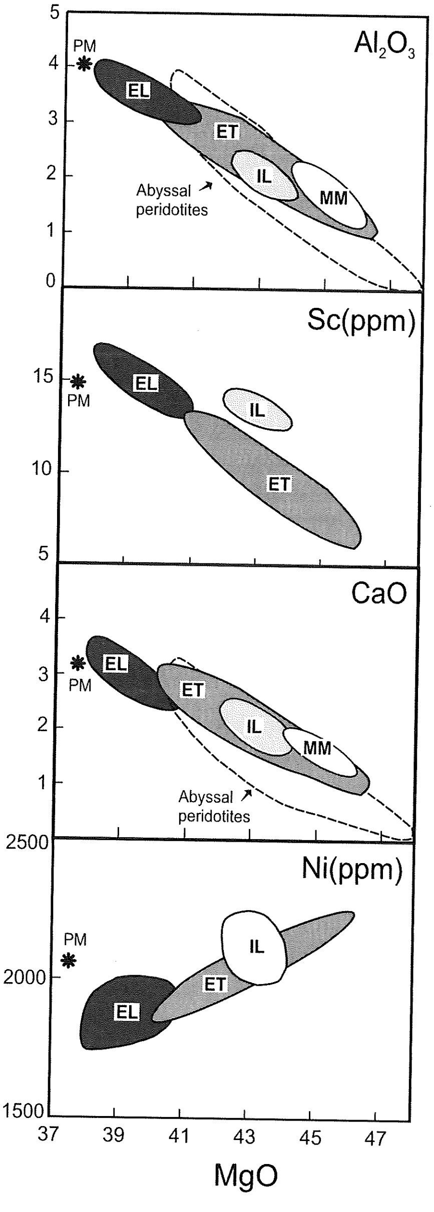

Fig. 2 – Whole rock abundances of CaO, Al_2O_3, Sc and Ni versus MgO (data on anhydrous basis) for: i) Internal (IL) and External (EL) Liguride, ii) Erro-Tobbio (ET) peridotites (data from Rampone *et al.*, 2004a), iii) Mt.Maggiore (Corsica) peridotites (MM) (unpublished data, Rampone *et al.*, in preparation). Primordial mantle estimate from Hofmann (1988). Also reported is the compositional field for abyssal peridotites (data from Niu *et al.*, 1997 and Baker & Beckett, 1999).

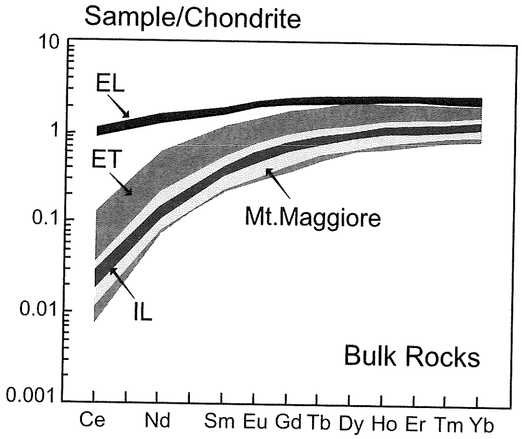

Fig. 3 – Bulk-rock REE abundances (normalized to chondrite C1 after Anders & Ebihara, 1982) for: i) Internal (IL) and External (EL) Liguride peridotites (Northern Apennines, data from Rampone *et al.*, 1995, 1996), ii) Erro-Tobbio peridotites (data from Rampone *et al.*, 2004a), iii) Mt.Maggiore (Corsica) peridotites (unpublished data, Rampone *et al.*, in preparation).

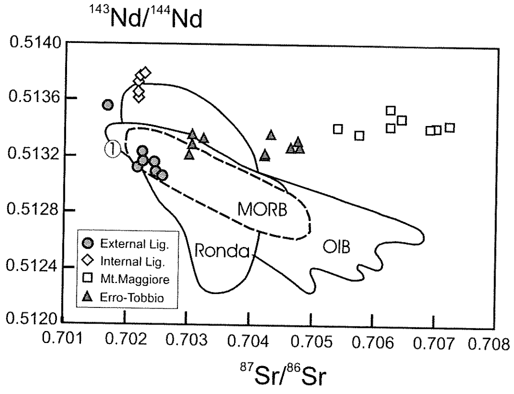

Fig. 4 – Present-day $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram for the Ligurian and Corsica peridotites (clinopyroxene separates; data from Rampone *et al.*, 1995, 1996; 2004b; data on the Mt.Maggiore peridotites are unpublished). Also shown are the fields for MORB and OIB (Hofmann, 1997), as well as for the Ronda peridotites (Reisberg *et al.*, 1989, and references therein). Field (1) refers to the Lanzo (Western Alps) peridotites (data from Bodinier *et al.*, 1991).

Romairone, 1999; Rampone *et al.*, 2004b). During exhumation, the peridotites were impregnated by percolating melts, as testified by the occurrence of plagioclase-enriched peridotites, and networks of replacive dunites and gabbroic dykelets, crosscutting the tectonite-mylonite foliation (Piccardo *et al.*, 2004; Borghini *et al.*, 2004). The peridotites were later intruded by discrete gabbroic bodies (mostly troctolites and olivine gabbros) and gabbroic dikes; all these magmatic intrusives display MORB-type affinity (Borghini *et al.*, 2004; De Ferrari *et al.*, 2004). The final seafloor exposure of the peridotites is testified by diffuse serpentinization, and by the intrusion of MORB-type basaltic dykes, which crosscut the above mantle structures.

In the Northern Apennines, ophiolites outcrop in two distinct geological units, the so-called Internal (IL) and External (EL) Ligurides (Fig. 1). The terms «External» and «Internal» refer to the inferred paleogeographic position (i.e., pericontinental versus intraoceanic settings) in the Jurassic Ligurian Tethys. Ophiolites of the External Liguride Units are spatially associated with continental crust (Marroni *et al.*, 1998, and references therein). In these units, ophiolites mostly consist of fertile mantle lherzolites (Fig. 2, 3) and pillowed basaltic lavas which occur as large slide blocks (olistoliths) within the Cretaceous-Eocene flysch sequences. Due to the association with continental crust, the source area for the EL lherzolites and basalts has been located close to the Adria continental margin (Piccardo *et al.*, 1990, and references therein). Accordingly, the External Liguride units have been regarded as a fossil example of the ocean to continent transition (Marroni *et al.*, 1998). Peridotites record a composite tectonic-metamorphic evolution, which indicates progressive upwelling of the upper mantle rocks toward the sea-floor prior to widespread serpentinization (Piccardo *et al.*, 1990; Rampone *et al.*, 1995). Chilled basaltic dikes intruding peridotites and crosscutting all mantle structures are abundant. The continental crust consists of late Hercynian granitoids, mafic and felsic granulites, and paragneisses (Eberhardt *et al.*, 1962; Marroni *et al.*, 1998, Montanini & Tribuzio, 2003). In some larger olistoliths, the primary relationships between granitoids, ophiolitic basalts, and radiolarian cherts are preserved, and, in places, granite remnants are interposed between overlying pillowed basalts and mantle peridotites.

The Internal Liguride (IL) ophiolitic units consist of a peridotite-gabbro basement stratigraphically covered by ophiolitic breccias, pillowed basaltic lava flows, and marine sediments (Abbate *et al.*, 1994, and quoted references). The peridotites mostly consists of clinopyroxene-poor (5-10 vol%) spinel lherzolites, and show depleted compositions (Fig. 2, 3), consistent with mantle residua left after low degrees (< 10%) of fractional melting (Rampone *et al.*, 1996). Given their compositional similarity to present-day oceanic mantle, it was previously inferred that the IL peridotites represented the «true» oceanic mantle of the Jurassic Ligurian Tethys (Beccaluva *et al.*, 1984); however, isotope work provided unexpected results about the age of depletion recorded by these peridotites (Rampone *et al.*, 1996) (see later discussion). After melting and incorporation at lithospheric mantle levels, the peridotites were impregnated by non-aggregated depleted melt increments (Rampone *et al.*, 1997). Extensional tectonics led to progressive exhumation of the IL peridotites, and shallow (P< 6 Kbar) intrusion by discrete gabbroic bodies (ranging from ultramafic cumulates to plagiogranites), representing the cumulate products of low-pressure fractionation of MORB-type parental melts (Serri, 1980; Rampone *et al.*, 1998; Tribuzio *et al.*, 2000). Subsequently, the peridotite-gabbro association experienced a tectonic-metamorphic retrograde evolution as testified by deformation and recrystallization fabrics (from upper amphibolite to greenschist-facies conditions) along shear zones: this indicates progressive uplift and final exposure at the sea-floor, where the peridotites were extensively serpentinized. The uppermost serpentinites suffered intensive fracturing with development of tectonic breccias (ophicalcites), which were partially covered by sedimentary ophiolitic breccias. Ophicalcites and sedimentary breccias were discontinuously covered by MORB-type basaltic pillow lava flows (Beccaluva *et al.*, 1984; Vannucci *et al.*, 1993) and by Oxfordian-Callovian radiolarian cherts, i.e. the oldest pelagic sediments (Marcucci and Passerini, 1991). Discrete basaltic dikes, temporally related to the basaltic extrusions, commonly crosscut serpentinized peridotites and foliated gabbros, as well as the overlying tectonic and sedimentary breccias.

The Corsican ophiolites are also considered to represent fragments of the oceanic lithosphere of the Jurassic Ligurian Tethys ocean (Dal Piaz, 1974). In particular, peridotites and associated gabbroic rocks of the Mt. Maggiore massif represent the deepest part of a reconstructed ophiolitic sequence outcropping in eastern Alpine Corsica. Within the ophiolite, differently evolved gabbroic intrusives (from troctolites to Fe-rich gabbros, Fe-rich diorite and albitites) constitute disrupted members of low-pressure magma chambers. Associated extrusive liquids are represented by massive dolerites and pillow lavas (Jackson & Ohnenstetter, 1981; and references therein). In the Mt. Maggiore massif, peridotites mostly consist of cpx-poor spinel lherzolites, which show major and trace element compositions quite similar to those of the IL peridotites (Fig. 2, 3) (Rampone *et al.*, 1997), and have thus been considered to represent depleted mantle material, after MORB-type partial melting. Field and petrologic evidence indicates that the peridotites, after melting, were cooled and incorporated at lithospheric mantle levels, they were then impregnated by melts percolating through the peridotites by reactive porous flow (Rampone *et al.*, 1997; Rampone *et al.*, 2003), and later intruded by gabbroic bodies and dykes (ranging from olivine gabbros to Fe-rich gabbros and diorites) showing MORB-type affinity (Piccardo *et al.*, 2002; Rampone *et al.*, 2003).

THE TECTONIC DENUDATION OF SUBCONTINENTAL LITHOSPHERIC MANTLE

Mantle peridotites from the External Liguride (EL, Northern Apennines) and the Erro-Tobbio (ET, Ligurian Alps) ophiolitic units record a similar petrologic and structural evolution, although occurred in different times, characterized by the progressive subsolidus recrystallization from spinel- to plagioclase- to amphibole-bearing assemblages and deformation from granular to tectonite- to mylonite- types (Fig. 5).

Thermometric estimates on the oldest equilibration stage (i.e. the granular, spinel-facies recrystallization) have yielded temperatures in the range of 1000-1100 °C (Rampone *et al.*, 1995; Hoogerduijn Strating *et al.*, 1993; Romairone, 1999; Rampone *et al.*, 2004b). Disseminated LREE-depleted kaersutite/Ti-pargasite amphiboles occur in equilibrium with the spinel-bearing granular assemblage: this is an ubiquitous feature of many subcontinental lithospheric peridotites (Vannucci *et al.*, 1995; Niida & Green, 1999),

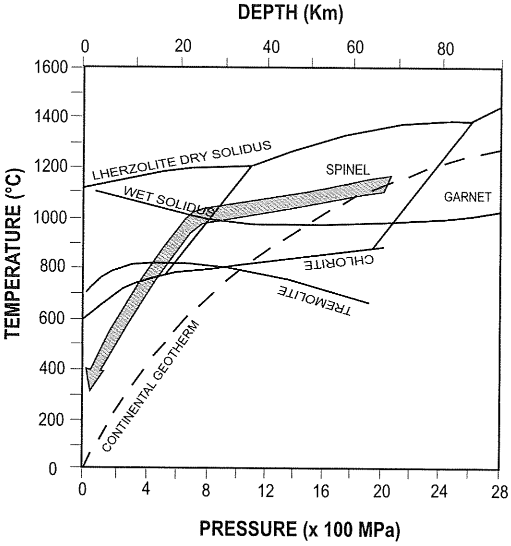

Fig. 5 – P-T evolution inferred for the Erro-Tobbio peridotites (redrawn after Hoogerduijn Strating *et al.*, 1993).

and constrains the spinel-facies equilibration to temperatures lower than 1100 °C. Thus, both the ET and EL peridotites record a complete annealing recrystallization at low T (< 1100 °C), which has been interpreted as a stage of cooling and accretion of the EL and ET mantle to the conductive lithosphere (Piccardo *et al.*, 1994; Rampone *et al.*, 1995; Rampone *et al.*, 2004b; Rampone & Piccardo, 2000). In the EL peridotites, model ages of lithospheric accretion have been derived from Rb-Sr, Sm-Nd and Re-Os isotope studies (Rampone *et al.*, 1995; Snow *et al.*, 2000).

Most EL peridotites display Nd model ages (assuming a CHUR mantle source) in the range 1.9-1.7 Ga (Fig. 6a), and consistent results are obtained with Rb-Sr systematics (Rampone *et al.*, 1995). For these peridotites, DM model ages cannot be calculated, because their Nd isotope ratios are too similar to the Depleted Mantle source. Noteworthy, one single sample with extremely depleted isotopic composition (^{87}Sr/^{86}Sr = 0.701736; ^{143}Nd/^{144}Nd = 0.513543) (see Fig. 4) yields Sr and Nd DM model ages of 1.2 and 2.1 Ga respectively (a Nd model age of 780 Ma is obtained if an extremely depleted mantle source is assumed; see Rampone *et al.*, 1995 for more details): these can be considered as minimum ages of differentiation from the asthenospheric mantle. The coupling of high ^{143}Nd/^{144}Nd (> 0.51310) and rather low ^{147}Sm/^{144}Nd (0.22-0.30) ratios is characteristic of many subcontinental peridotites (see the data and references for Lanzo N, Ronda, and Pyrenees in Figure 6a), recording ancient (usually Proterozoic) depletion events. Furthermore, the EL peridotites display a correlation between the Al_2O_3 contents and the ^{187}Os/^{188}Os ratios, which is consistent with the trends defined by the Ronda and Pyrenean peridotites, interpreted to reflect Proterozoic times of isolation of the peridotites from the convective mantle (Reisberg & Lorand, 1995). This provides further evidence for a Proterozoic accretion of the EL mantle, although the EL compositional range is too limited to constrain a robust Os model age (Snow *et al.*, 2000).

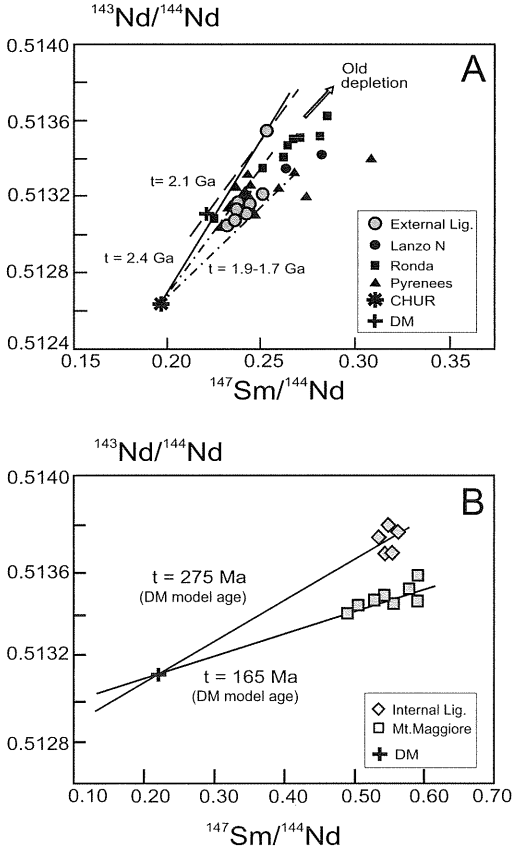

Fig. 6 – [A] ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd diagram for the External Liguride (External Lig.) peridotites (data from Rampone *et al.*, 1995), compared with data from other subcontinental orogenic peridotites (Ronda, Reisberg *et al.*, 1989; Pyrenees, Downes *et al.*, 1991, Mukasa *et al.*, 1991; Lanzo North, Bodinier *et al.*, 1991). All data are from clinopyroxene separates. The Depleted Mantle (DM) 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. The ages reported are DM (t = 2.1 Ga) and CHUR (t = 2.4 Ga, t = 1.7-1.9 Ga) model ages (see Rampone *et al.*, 1995 for details). [B] ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd diagram for the Internal Liguride (Northern Apennines, data from Rampone *et al.*, 1996) and Mt.Maggiore (Corsica, unpublished data, Rampone *et al.*, in preparation) peridotites (clinopyroxene separates). DM source ratios as in Fig. 6A.

As stated above, the EL and ET peridotites show the effects of subsequent tectonic and metamorphic evolution, documented by partial recrystallization from spinel- to plagioclase- to amphibole- bearing assemblages, and progressive deformation leading to the development of porphyroclastic textures and tectonite to mylonite fabrics, in km-wide shear zones (Rampone *et al.*, 1993, 1995; Hoogerduijn Strating *et al.*, 1993; Rampone *et al.*, 2004b). The spinel- to plagioclase-facies transition is reflected by peculiar microstructures: i) exsolution lamellae of orthopyroxene and plagioclase within spinel-facies clinopyroxene, ii) plagioclase rims around spinel and, iii) granoblastic domains consisting of olivine + plagioclase + neoblastic clino- and ortho- pyroxenes. This recrystallization is accompanied by significant within-mineral major and trace element redistribution which, according to mass-balance calculations, occurred in a closed system (Rampone *et al.*, 1993). Thermometric estimates on the plagioclase-facies and amphibole-facies recrystallization stages have yielded, respectively, 900-1000 °C and 850-950°C (Beccaluva *et al.*, 1984; Rampone *et al.*, 1995; Hoogerduijn Strating *et al.*, 1993; Rampone *et al.*, 2004b).This decompressional, entirely subsolidus, P-T path is inconsistent with the evolution of oceanic-type mantle at a mid-ocean ridge setting (i.e. adiabatic upwelling and melting of hot and deep asthenosphere), rather, it is consistent with the thermal history expected for the footwall of a lithospheric-scale extensional shear zone (Piccardo *et al.*, 1994; Hoogerduijn Strating *et al.*, 1993; Rampone & Piccardo, 2000). The EL and ET peridotites thus represent fragments of subcontinental lithospheric mantle which underwent progressive tectonic unroofing during the passive extension of the Europe-Adria continental lithosphere leading to the opening of the Jurassic Ligurian Tethys.

Isotope investigations on the EL and ET peridotites exhumation have provided significant results. Sm-Nd dating on the plagioclase-facies recrystallization stage have yielded 163-165 (± 20) Ma in the EL lherzolites, and significantly older ages of 273-313 (± 16) Ma in the ET peridotites (Rampone *et al.*, 1995; Romairone, 1999; Rampone *et al.*, 2004b) (Fig. 7). Thus, it has been inferred that the EL and ET peridotites represented different lithospheric mantle regions, which were activated at different times during extension of the Europe-Adria lithosphere. Specifically, results on the ET peridotites provide further evidence that the Europe-Adria lithosphere was dominated by an extensional regime during the Late Palaeozoic (Dal Piaz, 1993), and show that extensional mechanisms were also active at deep lithospheric mantle levels.

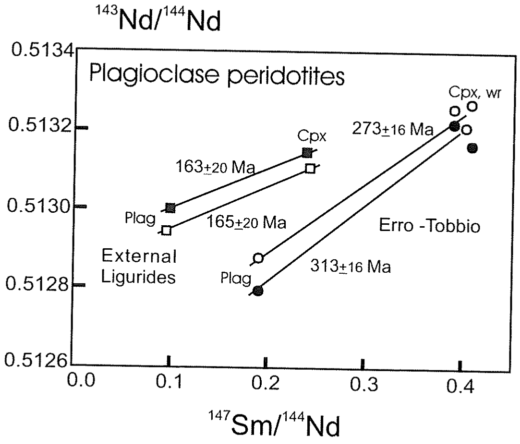

Fig. 7 – ^{143}Nd/^{144}Nd vs. ^{147}Sm/^{144}Nd diagram for clinopyroxene separates (cpx), whole rock powders (wr) and plagioclase separates (plag) from two pairs of plagioclase peridotites from the External Ligurides (Northern Apennine, Rampone *et al.*, 1995) and Erro-Tobbio (Ligurian Alps, Rampone *et al.*, 2004a) peridotites (see text for more explanation).

In synthesis, a striking feature of oceanic basins developed by passive lithosphere extension is the tectonic sea-floor exposure of large sectors of subcontinental lithospheric mantle. This is consistent with the results of petrologic and structural investigations on mantle peridotites from modern oceanic analogues like embryonic oceans (e.g. the Zabargad peridotites in the Northern Red Sea; Bonatti *et al.*, 1986; Brueckner *et al.*, 1988; Piccardo *et al.*, 1988, 1993) and passive continental margins (e.g. peridotites from the Western Galicia margin, Spain; Boillot *et al.*

1988; Kornprobst and Tabit, 1988; Manatschal & Bernoulli, 1999; Whitmarsh *et al.*, 2001). Also, the exhumation of lithospheric mantle in response to passive lithospheric extension has been predicted by analogue geophysical modeling (Brun and Beslier, 1996) performed to study the modes of passive-margin formation and related mantle exhumation at the continent-ocean boundary.

THE PREDOMINANT LACK OF A MANTLE-CRUST COGENETIC RELATIONSHIP

One of the major consequences of the theory of oceanic lithosphere formation at mid-ocean ridge settings is that the crustal rocks are produced by partial melting of the associated residual peridotites. Thus, in a «mature» oceanic lithosphere, produced at mid-ocean ridges, residual mantle peridotites and associated magmatic crust should be linked by a cogenetic relationship, i.e. the times of asthenospheric mantle melting and magmatic crust production should be roughly coheval. The existence of a cogenetic relationship in turns imply that residual mantle and associated magmatic crust should have the same isotopic composition. In present oceans, this topic has been addressed in a Nd and Sr isotope investigation on clinopyroxenes from a suite of abyssal peridotites (Snow *et al.*, 1994) which confirms the prediction that peridotites and associated MORB are, respectively, residues and melts derived from the same depleted mantle source. By contrast, Salters & Dick (2002) have documented Nd isotope disequilibrium between abyssal peridotites and associated basalts, the peridotites extending towards more depleted compositions, and they have claimed that an enriched pyroxenite component in the melting source could explain the low end of the $^{143}Nd/^{144}Nd$ variation of the basalts.

Isotope investigations on the Ligurian ophiolites have provided striking results on this topic. As stated above, both the EL and ET peridotites represent subcontinental lithospheric mantle whose tectonic, subsolidus, exhumation was even completely unrelated to mantle melting and melt production mechanisms. In this case, it is evident that no genetic link can be inferred between mantle peridotites and the intruded gabbroic rocks. No age information is at present available for the ET gabbroic intrusives. Available geochronologic data on the EL gabbroic rocks have furnished ages of about 180 Ma (Bigazzi *et al.*, 1973; Tribuzio *et al.*, 2001).

Sm/Nd isotope investigations on the Internal Liguride ophiolitic sequences, previously considered to represent the true oceanic lithosphere of the Tethys ocean (Beccaluva *et al.*, 1984), have provided surprising results. In a $^{147}Sm/^{144}Nd$ - $^{143}Nd/^{144}Nd$ diagram, gabbroic rocks (olivine gabbros and troctolites) from the IL ophiolitic unit define a linear array (plag - whole rock – cpx internal isochrone) which have yielded a magmatic crystallization age of 164 ± 14 Ma (Fig. 8a; data from Rampone *et al.*, 1998), with an initial (164 Ma) ε_{Nd} of 8.6. Data from IL basalts also plot on this array (initial [164 Ma] ε_{Nd} ranging 8.4 – 9), as well as the Depleted Mantle source composition. Thus, Sm-Nd data on the «crustal rocks» from the IL terrains point to a MORB-type magmatism of middle Jurassic age, in agreement with previous radiometric data (Bigazzi *et al.*, 1972; 1973; Borsi *et al.*, 1996). As evident in Figure 8a, the IL peridotites do not conform to the Jurassic isochrone defined above. They have extremely depleted Nd isotope compositions ($^{143}Nd/^{144}Nd$ = 0.513619-0.513775, $^{147}Sm/^{144}Nd$ ratios = 0.54-0.56), which are not consistent with a Jurassic partial melting event of a MORB-type asthenosphere (Rampone *et al.*, 1996, 1998); computed initial (165 Ma) ε_{Nd} for the IL peridotites are in the range 11.9-14.8. Nd model ages calculated for an average IL peridotite composition and assuming a depleted mantle (DM) source (see Fig. 6a) have yielded a Permian time (275 Ma) of depletion. Thus, the melting event recorded by the IL mantle is most likely completely unrelated to the generation of the associated oceanic crust; this in turn implies that, even in

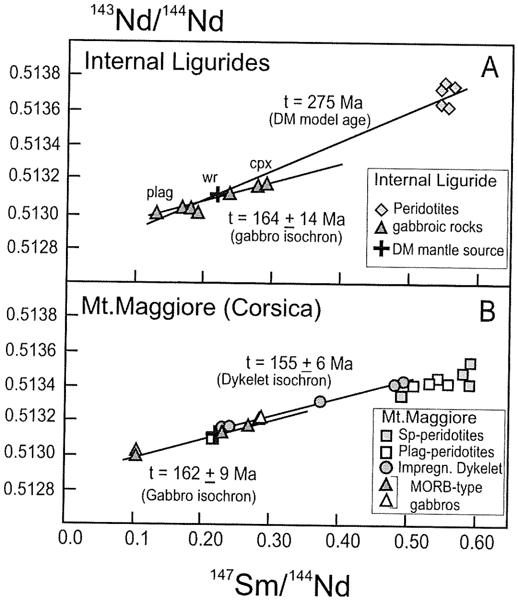

Fig. 8 – [A] ^{143}Nd/^{144}Nd vs. ^{147}Sm/^{144}Nd diagram for the Internal Liguride spinel peridotites and gabbroic rocks. The gabbro isochron (t = 164 ± 14 Ma) is an internal (plagioclase – whole rock – clinopyroxene) isochron defined by an olivine gabbro (data from Rampone *et al.*, 1996; 1998). [B] ^{143}Nd/^{144}Nd vs. ^{147}Sm/^{144}Nd diagram for the Mt. Maggiore (Corsica) spinel and plagioclase (impregnated) peridotites, impregnation-related gabbronoritic dykelets, and MORB-type gabbros (see text for more explanation) (unpublished data, Rampone *et al.*, in preparation). The two isochrons are internal (plagioclase – whole rock – clinopyroxene) isochrons defined by a gabbronoritic dykelet and an olivine gabbro.

the IL ophiolitic sequences, residual mantle and associated crustal rocks are not cogenetic and coeval.

Similar results have been obtained by Tribuzio *et al.* (2001) in the Tuscan ophiolitic sequences. Gabbroic rocks define Sm-Nd mineral isochron ages ranging 170-179 Ma, which are interpreted to date the primary igneous crystallization; their initial ε_{Nd} varies between 8.5 – 8.9, thus confirming their N-MORB affinity. By contrast, Nd isotopic compositions of mantle peridotites (clinopyroxene separates) are respectively higher (ε_{Nd} about 11.0) and lower than those of the associated gabbros. On the basis of this feature, it has been inferred that no genetic residue-melt relation exist in the mantle-gabbro association of Southern Tuscany ophiolites (Tribuzio *et al.*, 2001).

Available data on the Ligurian and Tuscan ophiolites thus indicate that another striking feature of the «immature oceanic lithosphere» formed during early stages of passive continental rifting and slow-spreading oceanization is the predominant lack of a mantle-crust cogenetic relationship, i.e. the association of older (i.e. Proterozoic, Permian) mantle peridotites and younger (Jurassic), genetically unrelated, crustal (gabbroic and basaltic) rocks (Rampone & Piccardo, 2000).

Further constraints on the Ligurian Tethys lithosphere have been obtained by Sm/Nd isotopic investigations on ophiolitic mantle peridotites and intruded gabbroic rocks from the Mt. Maggiore massif (Corsica, France). As already outlined, the Mt. Maggiore peridotites mostly consist of cpx-poor spinel lherzolites which, in places, grade to plagioclase-rich impregnated peridotites. They show major and trace element compositions quite similar to those of the IL peridotites (Rampone *et al.*, 1997; Rampone, 2002; Rampone *et al.*, 2003), thus being consistent with mantle residua after low-degree (<10%) MORB-type fractional melting. However, they show distinct Nd isotope signature (Fig. 6a and 8b).

Clinopyroxene separates from Mt. Maggiore spinel and plagioclase peridotites display high ^{147}Sm/^{144}Nd ratios (0.49-0.59), similar to those of the IL peridotites, but systematically lower ^{143}Nd/^{144}Nd values (0.513367-0.513551) (Fig. 6a, 8b). The associated gabbroic rocks have Nd isotopic compositions typical of MORB (^{143}Nd/^{144}Nd = 0.513122-0.513138). Plagioclase-whole rock-clinopyroxene Sm/Nd data for an olivine gabbro plot on a well defined internal isochron which yields a Jurassic age of 162 ± 10 Ma, and an initial (162 Ma) ε_{Nd} = 8.9 (Fig. 8b); such data are consistent with available radiometric ages on the Corsican ophiolitic albitites (Ohnenstetter *et al.*, 1981). A gabbronoritic dykelet, related to the impregnation event, also defines a consistent internal isochron (plagioclase – whole rock – clinopyroxene), which yields an age of 155 ± 6 Ma, and an initial (155 Ma) ε_{Nd} = 9.7. In a $^{147}Sm/^{144}Nd$ versus $^{143}Nd/^{144}Nd$ diagram, peridotite data conform to the linear array defined by the gabbroic rocks, their initial (160 Ma) ε_{Nd} values varying in the range 7.6-8.9. Sm/Nd isotopic compositions of the Mt.Maggiore peridotites are therefore consistent with a Jurassic age of partial melting, and point to isotopic compositional similarities between depleted peridotites and associated magmatic rocks. The Mt. Maggiore gabbro-peridotite association thus constitutes the first record of the attainment of a mature oceanic stage of the Ligurian Tethys ocean.

CONCLUDING REMARKS

Petrologic and isotope studies on the Ligurian ophiolites have pointed to the diversity (in terms of origin, composition and evolution) of mantle peridotites and peridotite-gabbro associations which constituted the peculiar «oceanic lithosphere» of the Ligurian Tethys ocean, i.e. of an ocean basin developed by passive rifting versus slow-spreading oceanization. Particularly, it has been demonstrated that this lithosphere is quite different from the one which is formed at mid-ocean ridge settings, because it is mostly constituted by the association of older tectonically exhumed lithospheric mantle, and younger, genetically unrelated magmatic crust.

A remarkable feature of the Alpine/Apennine ophiolitic peridotites is the occurrence of preserved records of Permian events, in spite of their later involvement in the Jurassic extension (and association with Jurassic MORB-type crust). Particularly, the Late Carboniferous - Permian age of plagioclase-facies recrystallization in the ET peridotites, and the Permian age of depletion recorded by the Internal Liguride (Rampone *et al.*, 1996) and Platta (Swiss Alps; Müntener *et al.*, in press) peridotites, indicate that extension of the Europe-Adria lithosphere and passive asthenosphere upwelling and melting were already active since Permian times.

The overall geodynamic significance of the Late Carboniferous - Permian extensional stage is a currently debated issue, specifically whether it represented (a) an extensional event resulting from the post-orogenic collapse of the Variscan belt unrelated to the Triassic-Jurassic rifting (Hermann & Müntener, 1996; Manatschal & Bernoulli, 1999; Müntener *et al.*, 2000), or (b) the initiation of the Tethyan rifting (Lardeaux & Spalla, 1991; Diella *et al.*, 1992; Dal Piaz, 1993).

Overall results of isotope studies on the Alpine-Apennine ophiolitic peridotites, although not solving the question whether lithosphere extension acted as a continuous process since Permian to Jurassic, have provided striking evidence that lithospheric versus asthenospheric mantle sectors extending and upwelling during Permian, were later involved in the Triassic-Jurassic extension which led to the oceanization of the Jurassic Ligurian Tethys.

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