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Evolution of the Ligurian Tethys: inference from petrology and geochemistry of 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 dominantly fertile, clinopyroxene(*cpx*)-rich lherzolites, while depleted, *cpx*-poor peridotites are subordinate; 2) gabbroic intrusives and basaltic volcanites have a MORB affinity; 3) gabbroic rocks were intruded into mantle peridotites. The Jurassic Ligurian Tethys was floored by a peridotite-gabbro basement, subsequently covered by extrusion of discontinuous basaltic flows and by sedimentation of radiolarian cherts, i.e. the oldest oceanic sediments. In the whole Ligurian Tethys the inception of the oceanic stage, that followed rifting and continental breakup, occurred during Late Jurassic.

The Ligurian ophiolites (Voltri Massif of the Ligurian Alps (LA) and Liguride Units of the NA) are a representative sampling of the diversity of the oceanic lithosphere which floored the Jurassic Ligurian Tethys.

In the WA-NA ophiolites the gabbroic rocks occur as km-scale bodies intruded in mantle peridotites. REE composition of computed liquids in equilibrium with their clinopyroxenes indicates a clear MORB affinity. Geochronological data on NA ophiolitic gabbros yield ages of intrusion in the range 185-160 Ma: Triassic ages of intrusion are documented for gabbroic rocks from the Montgenevre ophiolites (Western Alps) (212-192 or 185 Ma). The intrusion ages of the ophiolitic gabbroic rocks are significantly older than the Late Jurassic (160-150 Ma) opening of the Ligurian Tethys and the basaltic extrusion.

Basaltic volcanites are widespread in the WA-NA ophiolites: petrological and geochemical studies have provided clear evidence of their overall tholeiitic composition and MORB affinity. Zircon U/Pb dating on acidic differentiates yield ages in the range 160-150 Ma for the basaltic extrusion: these ages are consistent with the palaeontological ages of the radiolarian cherts (160-150 Ma).

The External Liguride (EL) mantle peridotites are fertile spinel lherzolites and display a complete recrystallization under spinel-facies conditions, that is interpreted as the stage of annealing recrystallization at the conditions of the regional geotherm, after accretion of the EL mantle section to the conductive lithosphere (i.e. isolation from the convective asthenospheric mantle). Nd model ages indicate Proterozoic times for the lithospheric accretion. The Internal Liguride (IL) mantle ultramafics are depleted peridotites, i.e. refractory residua after low-degree fractional melting on a MORB-type asthenospheric mantle source,

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producing MORB-type melts. The IL peridotites display a complete equilibrium recrystallization that is related to accretion of the IL residual mantle to the conductive lithosphere, after partial melting. Nd model ages indicate Permian times (275 Ma) for the depletion event. The Erro-Tobbio (ET) mantle peridotites of the Voltri Massif (LA) are spinel lherzolites, and represent refractory residua after variable degrees of incremental partial melting starting from a MORB-type asthenospheric mantle source: they show granular to tectonite-mylonite fabrics, these latter occur in km-scale shear zones where plagioclase- and amphibole-facies assemblages were developed during deformation.

The Ligurian peridotites show records of a tectonic-metamorphic evolution, after the accretion to the conductive subcontinental lithosphere, i.e. 1) development of km-scale shear zones, 2) partial reequilibration at plagioclase-facies and amphibole-facies conditions, and 3) later sea-water interaction and partial serpentinization, which indicates their progressive upwelling from subcontinental lithospheric depths to the ocean floor. Plagioclase-facies reequilibration developed at 273-313 Ma in the ET peridotites and 165 Ma in the EL peridotites (Sm-Nd systematics). These data indicate that the decompressional evolution of the lithospheric mantle of the Europe-Adria system was already active since Late Carboniferous - Permian times and continued till the Late Jurassic opening of the Ligurian Tethys. Further evidence of the extensional decompressional evolution of the Europe-Adria lithosphere in the Ligurian sector is given by the continental crust material (the gabbro-derived granulites): their gabbroic protoliths were intruded during Lower Carboniferous – Upper Permian times (about 290 Ma, Sr-Nd systematics), and underwent decompressional retrogression from granulite to amphibolite facies between Permian and Middle Triassic times.

Geological-structural knowledge on the Western Alps indicates that the Europa-Adria system, following Variscan convergence, underwent Late Palaeozoic onset of lithosphere extension through simple shear mechanisms along deep low-angle detachment zones, evolving to asymmetric continental rift and Late Jurassic oceanic opening. This may account for the partial melting under decompression of the asthenospheric mantle and the gabbroic intrusions. This post-Variscan evolution is evidenced by: 1) the Late Carboniferous to Jurassic subsolidus decompressional evolution (spinel- to plagioclase- to amphibole-facies transition to late oceanic serpentinization) recorded by the subcontinental lithospheric mantle sections of the EL and ET peridotites; 2) the Permian decompressional partial melting of asthenospheric mantle sources recorded by the IL residual peridotites; 3) the post-Variscan Permian MORB-derived gabbroic bodies, which were intruded into the extending lithosphere of the Adria margin (Austroalpine Units of the Western Alps); 4) the Triassic-Jurassic ophiolitic MORB-type gabbros, intruded into the subcontinental mantle, which were exposed at the sea-floor during Late Jurassic opening of the Ligurian Tethys.

The Ligurian ophiolites represent, therefore, the spatial association of:

- Proterozoic and Permian subcontinental lithospheric mantle peridotites, which are locally (as in the EL Units) linked to continental crust granitoids and granulites;
- Triassic to Jurassic gabbroic rocks, intruded in the peridotites;
- Late Jurassic MORB volcanites, interlayered with radiolarian cherts.

This peculiar association cannot be reconciled with present-day mature oceanic lithosphere, where the mantle peridotites and the associated gabbroic-basaltic crust are linked by a direct cogenetic relationship and are almost coeval. In addition, the large exposure of mantle peridotites to the sea-floor, and the long history of extensional upwelling recorded by peridotites agree with a geodynamic evolution driven by the passive extension of the Europe-Adria continental lithosphere. 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. Structural, metamorphic and magmatic features recorded by the Austroalpine (Sesia-Lanzo) and Southalpine (Ivrea-Verbano) units (the marginal units of the future Adria plate) suggest that the lithosphere extension was asymmetric, with eastward dipping of the detachment zones.

The subduction history of mafic-ultramafic associations of the Western NA and WA ophiolites was accompanied by prograde reactions, culminating in one main high pressure event. It caused eclogitization (i.e. development of metamorphic assemblages characterized by the association of sodic clinopyroxene and almandine-rich garnet, in the absence of plagioclase) of mafic rocks and partial recrystallization and dewatering (i.e. formation of metamorphic olivine in equilibrium with antigorite, diopside, Ti-clinohumite and fluids) of ultramafites, previously variably hydrated (serpentinized) during the oceanic evolution. The high pressure ultramafic rocks still

preserve oxygen isotope signatures of the oceanic settings, indicating that the fluid recycled at the eclogitic stage was the one incorporated during exposure close to the oceanic floor.

RIASSUNTO. — Le ofioliti che affiorano lungo la catena orogenica delle Alpi Occidentali (WA), delle Alpi Liguri (LA) e dell'Appennino Settentrionale (NA) rappresentano la litosfera oceanica della Tetide Ligure, un bacino oceanico che separò, durante il Giurassico Superiore e il Cretaceo, le placche Europa e Adria. Le ofioliti WA-NA mostrano peculiari caratteristiche composizionali, strutturali e stratigrafiche: 1) le peridotiti di mantello sono prevalentemente lherzoliti fertili, ricche in clinopirosseno (*cpx*), mentre le peridotiti impoverite sono subordinate; 2) le rocce gabbriche intrusive e le vulcaniti basaltiche hanno affinità MORB; 3) i gabbri sono intrusi nelle peridotiti di mantello. Il bacino della Tetide Ligure Giurassica fu pavimentato da un basamento gabbro-peridotitico, successivamente ricoperto dall'effusione di colate basaltiche discontinue e dalla sedimentazione dei diaspri, cioè i primi sedimenti oceanici. In tutta la Tetide Ligure, l'inizio dell'apertura del bacino oceanico, che seguì stadi di *rifting* e di rottura continentale, avvenne durante il Giurassico Superiore.

Le ofioliti liguri (Massiccio di Voltri delle LA e Unità Liguridi del NA) sono un campionamento rappresentativo delle variabilità della litosfera di tipo oceanico del bacino della Tetide Ligure.

Nelle ofioliti WA-NA le rocce gabbriche affiorano come corpi di dimensioni chilometriche intrusi nelle peridotiti di mantello. La composizione in REE dei fusi calcolati all'equilibrio con i loro clinopirosseni indicano una chiara affinità MORB per i fusi capostipiti. Dati geocronologici sui gabbri ofiolitici NA danno età di intrusione nell'intervallo 185-160 Ma: età Triassiche di intrusione sono documentate nei gabbri delle ofioliti WA di Monginevro (212-192 o 185 Ma). Le età di intrusione dei gabbri ofiolitici sono significativamente piu' vecchie rispetto all'apertura al Giurassico Superiore (160-150 Ma) della Tetide Ligure ed alle effusioni basaltiche.

Le vulcaniti basaltiche sono diffuse nelle ofioliti WA-NA: le attuali conoscenze petrologiche e geochimiche indicano composizioni tholeiitiche ed affinità MORB. Datazioni U/Pb su zirconi di differenziati acidi hanno fornito età nell'intervallo 160-150 Ma per le effusioni basaltiche: queste età sono in buon accordo con le età paleontologiche dei diaspri.

Le peridotiti di mantello delle Liguridi Esterne (EL) sono lherzoliti fertili a spinello e mostrano una completa ricristallizzazione in facies a spinello, che è interpretata come lo stadio di equilibratura alle condizioni del locale gradiente geotermico, dopo l'accrezione del mantello delle EL alla litosfera conduttiva (cioè l'isolamento dal mantello astenosferico convettivo). Età modello del Nd indicano tempi Proterozoici per l'accrezione alla litosfera. Le peridotiti delle Liguri Interne (IL) sono impoverite, e rappresentano residui refrattari da ricollegare ad una fusione frazionata di basso grado su una sorgente di mantello astenosferico di tipo MORB, che ha prodotto fusi MORB. Le peridotiti IL mostrano una ricristallizzazione completa che è riferita all'accrezione del mantello residuale IL alla litosfera conduttiva, dopo la fusione parziale. Età modello del Nd indicano tempi Permiani (275 Ma) per l'evento di fusione. Le peridotiti ET (Erro-Tobbio) del Massiccio di Voltri (LA) sono lherzoliti a spinello, e rappresentano residui refrattari da ricollegare a variabili gradi di fusione parziale incrementale, a partire da un sorgente di mantello astenosferico di tipo MORB: esse mostrano strutture e tessiture sia granulari che tettonitiche-milonitiche, queste ultime sono sviluppate lungo zone di shear di dimensioni chilometriche in cui si sviluppano paragenesi a plagioclasio e ad anfibolo durante la deformazione.

Le peridotiti Liguri mostrano chiare evidenze di una evoluzione tettonico-metamorfica, dopo la loro accrezione alla litosfera conduttiva sottocontinentale, cioè: 1) lo sviluppo di zone di shear di dimensioni chilometriche; 2) la parziale ricristallizzazione in facies a plagioclasio e ad anfibolo; 3) la tardiva interazione con acqua di mare e la parziale serpentinizzazione; questi processi indicano la loro progressiva risalita da profondità di mantello litosferico sottocontinentale fino al fondo oceanico della Tetide Ligure. La ricristallizzazione a plagioclasio si sviluppò a 273-313 Ma nelle peridotiti ET e a 165 Ma nelle peridotiti EL (sistematica Sm-Nd). Questi dati indicano che l'evoluzione decompressionale del mantello litosferico del sistema Europa-Adria era già attiva da tempi Tardo Carboniferi – Permiani e proseguì fino all'apertura della Tetide Ligure (Giurassico Superiore). Ulteriori evidenze dell'evoluzione estensionale decompressionale della litosfera del sistema Europa-Adria nel settore Ligure sono fornite dal materiale di crosta continentale (le granuliti di derivazione gabbrica): i loro protoliti gabbrici furono intrusi durante il Carbonifero-Permiano (circa 290 Ma, sistematiche Sr e Nd), e subirono, dopo una ricristallizzazione in facies granulitica, una retrogressione decompressionale da facies granulitica a facies anfibolitica fra il Permiano e il Triassico Medio.

Le conoscenze geologico-strutturali sulle Alpi

Occidentali indicano che il sistema Europa-Adria, dopo la convergenza Varisica, iniziò a subire, dal Tardo Paleozoico, un processo di estensione della litosfera attraverso meccanismi di shear semplice lungo zone profonde di faglie a basso angolo, che evolvette in un *rifting* continentale asimmetrico ed infine nell'apertura Tardo Giurassica del bacino oceanico. Questo processo rende anche conto della fusione parziale sotto decompressione della sottostante astenosfera, della produzione di fusi MORB e della loro intrusione nella soprastante litosfera in estensione sotto forma di corpi gabbrici. Questa evoluzione post-Varisica è messa in evidenza da: 1) l'evoluzione decompressionale di subsolidus (transizione da facies a spinello a facies a plagioclasio e ad anfibolo, fino alla tardiva serpentinizzazione oceanica), dal Carbonifero Superiore al Giurassico, registrata dal mantello litosferico sottocontinentale rappresentato dalle peridotiti EL e ET; 2) la fusione parziale decompressionale Permiana di sorgenti di mantello astenosferico, che è registrata dalla peridotiti delle IL; 3) le intrusioni gabbriche post-Varisiche Permiane derivanti da fusi astenosferici ad affinità MORB, che furono intruse nella litosfera in estensione del margine Adria (le Unità Austroalpine delle Alpi Occidentali); 4) le intrusioni gabbriche, ad affinità MORB che intrusero, dal Triassico al Giurassico, il mantello litosferico sottocontinentale successivamente denudato ed esposto sul fondo marino durante l'apertura Giurassico Superiore della Tetide Ligure.

Le ofioliti liguri rappresentano, quindi, l'associazione spaziale di:

1) peridotiti di mantello litosferico sottocontinentale, accrete alla litosfera nel Proterozoico e nel Permiano, che sono ancora associate (come nelle Unità EL) a materiale di crosta continentale, granitoidi e granuliti derivanti da gabbri Permiani;

2) gabbri intrusi nelle peridotiti da tempi Triassici a Giurassici;

3) vulcaniti basaltiche ad affinità MORB, interstratificate con i primi sedimenti (diaspri a radiolari) del bacino oceanico.

Questa associazione peculiare non può essere confrontata con l'attuale litosfera oceanica di oceani maturi, dove le peridotiti di mantello e l'associata crosta oceanica, gabbrica e basaltica, sono legate da dirette relazioni cogenetiche e sono coeve. Inoltre, la grande esposizione di peridotiti di mantello sul fondo del bacino, e la lunga storia di risalita in regime estensionale registrata dalle peridotiti, bene si inquadrano in un modello di evoluzione geodinamica guidata dall'estensione passiva della litosfera continentale del sistema Europa-Adria. L'estensione passiva della litosfera è il processo geodinamico piu' idoneo per giustificare il denudamento tettonico sul fondo oceanico di larghi settori di mantello sottocontinentale, come è stato dedotto anche da modelli geofisici analogici per l'esumazione del mantello lungo i limiti oceano-continente. Le caratteristiche geologico-strutturali, metamorfiche e magmatiche registrate dalle Unità Austroalpine (Sesia-Lanzo) e Sudalpine (Ivrea-Verbano) (cioè le unità marginali della futura placca Adria) suggeriscono che l'estensione della litosfera fu asimmetrica, con l'approfondimento verso est della zona di faglie a basso angolo.

La storia di subduzione delle rocce femiche ed ultrafemiche delle ofioliti WA e LA fu accompagnata da reazioni prograde, che culminarono in un principale evento di alta pressione. Esso produsse la eclogitizzazione della rocce femiche (sviluppo di paragenesi caratterizzate dall'associazione di pirosseno sodico e granato almandinico, in assenza di plagioclasio) e ricristallizzazione, con parziale disidratazione (sviluppo di paragenesi caratterizzate da olivina, antigorite, diopside, Ti-clinohumite e fluidi), delle peridotiti di mantello, che erano state variamente idratate (serpentinizzate) durante l'evoluzione oceanica. Queste rocce ultrafemiche di alta pressione ancora conservano nell'impronta isotopica dell'Ossigeno il segno dell'evoluzione oceanica, ad indicare che i fluidi riciclati durante lo stadio eclogitico sono quelli incorporati durante l'esposizione sul fondo oceanico.

KEY WORDS: *Ligurian Tethys, rifting, oceanization, subduction, Ligurian ophiolites, mantle peridotites, serpentinites, eclogites.*

INTRODUCTION

Ophiolites exposed along the Western Alpine-Northern Apennine (and Corsica) (WA-NA) orogenic system are thought to represent the oceanic lithosphere of the Ligurian Tethys, which separated, during Late Jurassic-Cretaceous times, the Europe and Adria continental blocks.

In the last decades, numerous contributions concerning the WA-NA ophiolites evidenced that:

i) rather fertile, *cpx*-rich lherzolites are dominant, while depleted, *cpx*-poor peridotites are scarce (Bezzi and Piccardo, 1971a; Nicolas and Jackson, 1972);

ii) both gabbroic intrusives and basaltic volcanites have MORB affinity (Serri, 1980; Beccaluva *et al.*, 1980).

WA-NA ophiolites show peculiar structural-petrographic features, which indicate that:

i) mantle rocks underwent a composite subsolidus evolution after depletion by partial melting;

ii) gabbroic rocks were intruded into mantle peridotites;

iii) peridotites and gabbroic intrusions were exposed at the sea-floor prior to extrusion of pillowed basalts and deposition of radiolarian cherts.

Moreover, sheeted dyke complexes are lacking and comagmatic relations did not exist between the gabbro bodies and the basaltic dykes and flows.

Accordingly, a general consensus exists on the idea that the Jurassic Ligurian Tethys was floored by an older peridotite-gabbro basement (Decandia and Elter, 1969; Piccardo, 1983; Lemoine *et al.*, 1987), subsequently covered by extrusion of a discontinuous layer of younger pillowed basaltic flows and by deposition of radiolarian cherts, i.e. the first oceanic sedimentation.

The radiolarian cherts, which are coeval to the basaltic extrusions, are not older than Late Jurassic (160-150 Ma) (De Wever and Caby, 1981; Marcucci and Passerini, 1991) in the whole Ligurian Tethys: accordingly, the inception of the oceanic stage, following the continental breakup, is considered not older than Late Jurassic.

The time gap between most of the gabbro intrusions (Triassic to Middle Jurassic) (Bigazzi *et al.*, 1973; Carpena and Caby, 1984) and the basalt extrusion / chert deposition (Late Jurassic) (see also the following discussion) reinforces the structural evidence of the decoupling between the early pre-oceanic intrusion (i.e. the gabbroic bodies) and the late oceanic extrusion (i.e. the pillowed basalts) of MORB-type magmas.

PALAEOGEOGRAPHY OF THE 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 Late Jurassic opening of the Northern Atlantic (Dewey *et al.*, 1973; Lemoine *et al.*, 1987), (fig. 1).

Plate tectonic and palinspastic reconstructions suggest that this basin was limited in size and that it never reached the

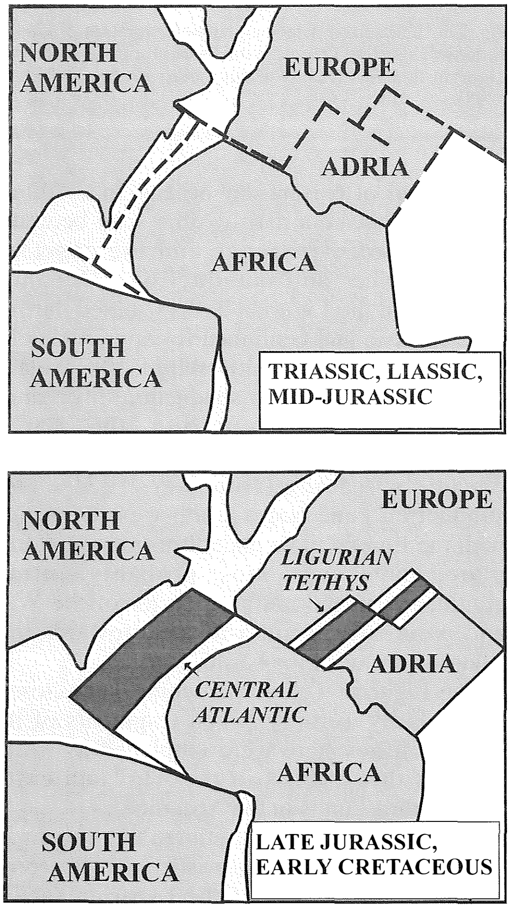

Fig. 1 – Mesozoic evolution of Central Atlantic and Ligurian Tethys oceans, from rifting to ocean formation (redrawn and modified after Lemoine *et al.*, 1987).

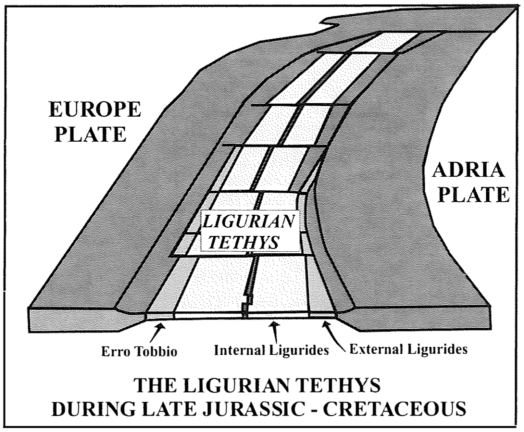

Fig. 2 – Generalized paleogeographic restoration of Upper Jurassic Ligurian Tethys, with location of the different Ligurian domains (redrawn and modified after Dal Piaz, 1995).

dimensions of present-day oceans. In addition, age data indicate a narrow time span between cessation of divergence and the onset of convergence and subduction. Oceanic accretion in the Ligurian Tethys started during Late Jurassic and continued for approximately 25 Ma (cf. Winterer and Bosellini, 1981). Plate convergence leading to subduction of oceanic lithosphere started during the Early Cretaceous, about 25 Ma after cessation of the oceanic spreading (Hunziker, 1974). The subduction zone had a south-west trending, with the Europe plate underthrusting the Adria plate, and it was, most probably, intra-continental in the northern sector of the WA and progressively intra-oceanic towards the Ligurian sector of the basin.

The Ligurian Tethys was completely closed 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 (Erro-Tobbio in fig. 2), which underwent deep evolution in the subduction zone and recrystallized at eclogite facies conditions, were located west of the subduction zone, close to the European margin; the NA ophiolites (Internal and External Ligurides in fig. 2), which underwent solely low-grade oceanic and orogenic metamorphism, were located east of the subduction zone, closer to the Adria margin (fig. 2).

THE VOLTRI MASSIF

Introduction to the geology of the Voltri Massif

The Voltri Massif (fig. 3) occupies the southeastern end of the WA and is structurally ascribed to the Internal Pennidic Units of the Alps. Its tectonic units record a widespread recrystallization at eclogite-facies conditions as the result of subduction zone metamorphism. The Voltri Massif is prevalently composed of ophiolitic materials, associated with slices of continental crystalline rocks of the European margin (Chiesa *et al.*, 1975; Messiga *et al.*, 1992). To the east it is separated from the Ligurian Apennines by the Sestri-Voltaggio zone, a composite terrain consisting of Triassic-Liassic carbonatic rocks and of dismembered Mesozoic ophiolites showing peak blueschists metamorphic assemblages related to the alpine subduction. Klippen of analogous blueschist terrains (Cravasco-Voltaggio-Montenotte units) also overlie the eclogitic terrains of the Voltri Massif. To the west the Voltri Massif overlies the Savona continental basement of Hercynian gneisses (granitoids with associated amphibolites, showing a greenschist to blueschist facies Alpine metamorphism). Towards the north it is bounded by Tertiary sediments of the Piemonte Basin, whose basal breccias include clasts of high-pressure metaophiolites (metagabbros and metaperidotites) and thereby give a 35-38 Ma age for the exhumation and erosion of the high-pressure terrains of the Voltri Massif.

Several studies (Chiesa *et al.*, 1975; Messiga

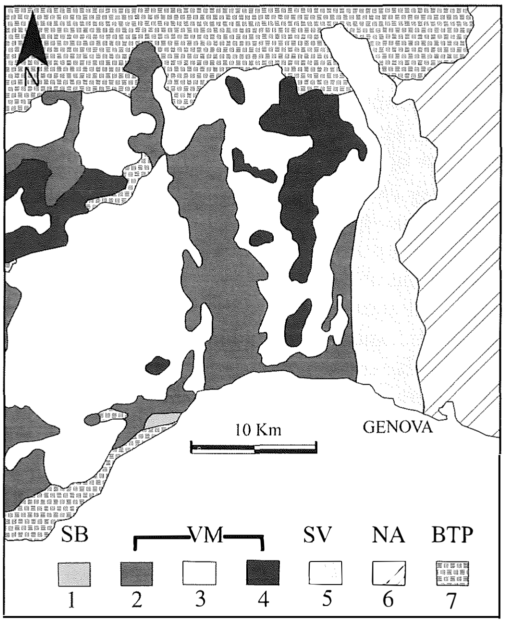

Fig. 3 – Geological sketch map of the Voltri Massif showing location of the Erro-Tobbio peridotite (after Chiesa *et al.*, 1975). Major units as follows: 1 = Arenzano Crystalline Massif (SB = Gran San Bernardo Nappe); VM = Voltri Massif: 2 = Alpicella, Voltri-Rossiglione and Ortiglieto Units: metavolcanics and paraschists with relict eclogitic assemblages; 3 = Beigua Unit: antigoritic serpentinites with eclogitic metagabbros; 4 = Erro-Tobbio Unit: mantle peridotites; 5 = Sestri Voltaggio Zone (SV); 6 = Northern Apennine Unit (NA); 7 = Tertiary molasses (BTP).

and Piccardo, 1974; Piccardo, 1977) have shown that in the Voltri Massif slices from different lithospheric levels (subcontinental mantle, Mesozoic oceanic lithosphere and sediments, continental margin units) are tectonically coupled.

The present-day geometric relationships among the different tectonic units of the Voltri Massif are the result of the collisional tectonic under greenschist-facies conditions, which caused late-stage folding of the high-pressure nappes (post-nappe folding) and enhanced formation of shallow thrusts that masked the original nappe setting. In spite of such grenschist overprint, the relics of previous tectonic-metamorphic evolutions are preserved in the lithologies of the Voltri Massif, and are related to lithospheric-scale tectonic processes: 1) pre-oceanic rifting; 2) oceanic evolution; 3) Cretaceous subduction and pre-Oligocene exhumation.

The Voltri Massif includes the following lithologic and tectonic units (fig. 3):

1) the Beigua Unit consists of antigorite-serpentinites and eclogitic metagabbros, which derived from previous mantle peridotites and MORB-type gabbroic intrusions (dominant Fe-Ti-rich gabbros);

2) the Voltri-Rossiglione, Ortiglieto and Alpicella Units consists of metavolcanics and calcschists, which derived from oceanic MORB-type basalts and their sedimentary cover: they locally preserve primary stratigraphic relationships with the ultramafic and mafic rocks of the Beigua Unit;

3) the Erro-Tobbio Unit (ET) consists of partly recrystallized antigorite-bearing metaperidotites, preserving km-scale volumes of the lherzolite mantle protolith, and associated rodingitic and eclogitic mafic rocks (mostly after Mg-Al-rich olivine gabbros and subordinate basaltic dykes with MORB-type affinity).

As a whole, the ET peridotites are less intensely serpentinized than the ultramafic rock of the Beigua Unit. The latter displays about 90% serpentinization. The most important difference between the Beigua and Erro-Tobbio tectonic units is the survival of composite mantle, oceanic and prograde, subduction-related structures inside the Erro-Tobbio peridotites. These structures are no longer preserved in the Beigua mafic-ultramafic association: it mostly records an eclogite-facies metamorphism, that affected the precursor oceanic rocks, overprinted by retrograde metamorphism and tectonics during exhumation of the high pressure rocks towards the surface.

Preservation of such a long geological memory inside the ET peridotites is likely the results of less intense hydration and hydrothermal alteration during exposure close to the floor of the Mesozoic Ligurian Tethys ocean.

Eclogitic metagabbros and high pressure serpentinites of the Beigua Unit

The Beigua unit mostly consists of serpentinites enclosing lenses of eclogites and minor bodies of metasomatic rocks consisting of metarodingite and Ti-clinohumite dykelets. Intrusive relations between eclogitized mafic rocks and host ultramafites are still locally preserved within the Beigua Unit. Generally, the eclogites form lenses several tens of meters long and boudins of smaller dimensions. Previous petrological studies have shown that the eclogites formed by metamorphism (at 13 kbar pressure and 450-500°C) of original gabbroic material, represented by dominant iron- and titanium-rich varieties, subordinated Mg-Al-rich gabbros and basalts, and rare diorites and plagiogranites (Mottana and Bocchio, 1975; Ernst *et al.*, 1982; Piccardo *et al.*, 1979; Piccardo, 1984; Messiga and Scambelluri, 1991).

Based on major and trace element data metavolcanites have been interpreted as tholeiitic basalts with N-MORB affinity (Ernst *et al.*, 1982; Piccardo, 1984). Mafic intrusives correspond to crystal cumulates at different fractionation steps from a common primary tholeiitic N-MORB magma. On the whole, the different types of intrusives (Mg-Al to Fe-Ti metagabbros) show flat REE patterns fractionated in LREE. Absolute REE concentrations are 2-3 times × chondrite in Mg-Al rich rocks, and rise to > 100 times × chondrite in the most differentiated Fe-Ti-rich types (Ernst *et al.*, 1982; Morten *et al.*, 1979; Piccardo, 1984). The intrusive relations and the compositional variability discussed above, indicate that upper mantle peridotites were intruded by MORB melts. Low pressure crystallization and differentiation firstly produced olivine-plagioclase cumulates and Mg-Al rich gabbros; presence of Fe-Ti gabbros, rare diorites and plagiogranites, indicate further emplacement of more differentiated melts.

Such intrusion episodes were followed by the emplacement of basaltic dikes at shallow depths. This stage was likely coeval with effusion of MORB basaltic lava flows that are presently associated with metasediments of the Voltri-Rossiglione, Ortiglieto and Alpicella Units. Exposure of the Beigua gabbro-peridotite association at the ocean floor was accompanied by local metasomatic exchanges between ultramafic and mafic rocks. Metasomatic rocks of the Beigua Unit are represented by: 1) metarodingite boudins containing garnet+diopside+zoisite/clinozoisite+chlorite+ magnetite±apatite; 2) brownish dykelets containing Ti-clinohumite+diopside+ magnetite+chlorite+apatite. These rocks have been described by Piccardo *et al.* (1980), Cimmino *et al.* (1981), Scambelluri and Rampone (1999), and interpreted as the result of high-pressure metamorphism of gabbros which underwent pre-subduction Ca- and Mg-metasomatism.

The classic garnet, pyroxene, rutile eclogites of the Beigua Unit mostly derive from original Fe-Ti gabbros (superferrian eclogites; Mottana and Bocchio, 1975), these rocks have been thoroughly described and analyzed by a number of papers (Ernst, 1976; Messiga, 1987; Messiga and Scambelluri, 1988; 1991; Messiga *et al.*, 1995a). Since subduction deformation was localized within ductile shear zones, the Beigua eclogites can be subdivided in coronitic and mylonitic types. Relics of igneous minerals (mostly clinopyroxene) are locally preserved in coronitic eclogites, where the high pressure assemblages develop either as pseudomorphic replacements of the igneous minerals, or as reaction coronas among the various igneous mineral sites. The igneous augite is topotactically replaced by omphacite±fine-grained garnet and rutile. Plagioclase is pseudomorphed by fine-grained omphacite + garnet ± paragonite and epidote. The igneous ilmenite is replaced by rutile locally associated with pyroxene. Coronas of almandine-rich garnet develop along interfaces separating the igneous minerals sites. The eclogitic minerals of coronitic metagabbros display heterogeneous major and trace element compositions, which reflect the compositional variability of the precursor igneous mineral, thereby reflecting global chemical disequilibrium at hand sample scale.

Mylonitic and tectonitic eclogites consist of omphacite porphyroclasts in a finegrained matrix of omphacite, garnet and rutile. Mylonitic omphacite is compositionally different from porphyroclastic one, being richer in jadeite end member (Messiga and Scambelluri, 1991; Messiga *et al.*, 1995a). Rutile is strongly elongated parallel to the foliation and garnet displays inclusion-rich core and neoblastic rims. Transition from the garnet cores to their rims is accompanied by an increase in pyrope and almandine components and decrease in grossular and spessartine. The cores of garnet crystals from tectonitic and mylonitic eclogites, locally still enclose inclusions of sodic clinopyroxene (Tribuzio, 1992), crossite, paragonite representing relics of a prograde blueschists facies matrix present in these rocks. The above textural and compositional features were intepreted to result from blueschist to eclogite facies transition and from increasing pressure-temperature conditions during eclogite-facies recrystallization.

Trace element analyses of minerals from the eclogites were carried out by Messiga *et al.* (1995a) and Tribuzio *et al.* (1996). These data show that the omphacite contribution to the whole-rock REE inventory is negligible. In particular, the omphacites have a bell-shaped REE pattern, which was related to the coexistence with garnet and accessory allanite, respectively incorporating almost all the LREE and HREE of the rock (Tribuzio *et al.*, 1996). The transformation of original gabbroic protoliths into eclogites was not accompanied by significant REE mobilization, and REE were redistributed among newly formed minerals. This implies that the subduction of mafic oceanic crust to 65 km depths did not release significant amounts of LREE (Tribuzio *et al.*, 1996).

The post eclogitic evolution of the Beigua eclogites consists of the complex superposition of metamorphic events driven by interaction with fluids at decreasing pressure conditions. An early study by Ernst (1976) showed that the eclogitic minerals were firstly overgrown by glaucophanic amphiboles, followed by barroisite–bearing assemblages and finally by actinolite+albite+chlorite greenschist parageneses. This superposition of metamorphic assemblages pointed to an adiabatic uplift of the deeply subducted eclogites. A later study by Messiga and Scambelluri (1991) pointed out the early development of amphibole+plagioclase± diopside symplectites that predated glaucophane formation. This stage was interpreted as due to an initial post-peak increase in temperature, followed by rock cooling and glaucophane formation as the result of deep underthrusting of cold nappes during exhumation of the Beigua eclogites. Development of amphibole + plagioclase + diopside symplectite was accompanied by reequilibration and internal cycling of eclogitic fluid inclusions that catalized mineral reactions and kynetics (Vallis and Scambelluri, 1996). This process of internal redistribution of eclogitic fluids within these eclogite facies rocks continued at lower grades to produce greenschist facies parageneses (Scambelluri, 1992).

The serpentinites forming large part of the Beigua Unit display an antigorite+chlorite+ magnetite assemblage overgrown by olivine+antigorite due to partial deserpentinization of the previous paragenesis (Cimmino *et al.*, 1979). They also contain few mineralogical relics of oceanic serpentine (mostly chrysotile) and rare mantle clinopyroxene (Piccardo *et al.*, 1980). The olivine+antigorite-bearing assemblage has been shown to develop at eclogite-facies conditions and represents the highest metamorphic grade achieved in the area (Cimmino *et al.*, 1981).

The Erro-Tobbio mantle peridotites

The ET mantle peridotite were involved in the Alpine orogenesis, due to convergence of

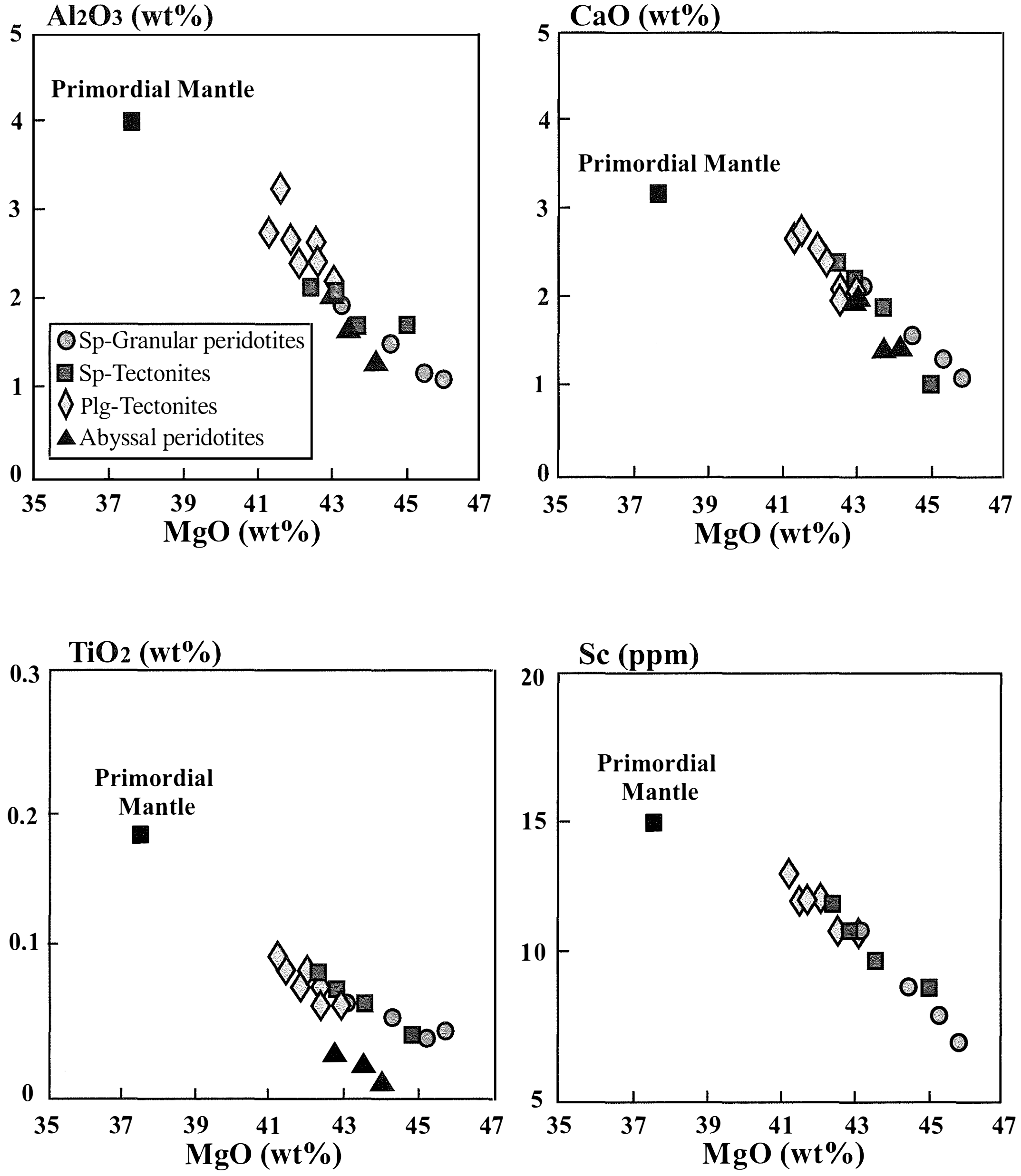

Fig. 4 – Bulk rock variations of MgO (wt%) *vs* CaO, Al_2O_3, TiO_2 (wt%) and Sc (ppm) in the Erro-Tobbio peridotites (Romairone, 1999). Abbreviations: Sp-Granular peridotites = Granular spinel peridotites; Sp-Tectonites = Spinel peridotite tectonites; Plg-Tectonites = Plagioclase peridotite tectonites. Primordial mantle estimates are from Hofmann (1988). The representative compositions of abyssal peridotites are from Dick (1989).

the European and Adriatic plates, but the extreme localization of alpine deformation along mylonite shear zones preserves km-scale volumes of coherent unaltered lherzolites which almost completely retain mantle textures and assemblages. This fact has allowed detailed structural and petrological investigations of the magmatic, tectonic and metamorphic upper mantle evolution which predated their sea-floor emplacement during the opening of the Ligurian Tethys (Bezzi and Piccardo, 1971a; Ernst and Piccardo, 1979; Ottonello *et al.*, 1979; Piccardo *et al.*, 1990,1992; Hoogerduijn Strating *et al.*, 1990,1993; Vissers *et al.*, 1991).

The mantle protolith

The ET mantle peridotites consist of partly serpentinized lherzolites, with variable clinopyroxene contents, which commonly show spinel-bearing assemblage. Texturally, they vary from granular types to highly deformed peridotite mylonites. Detailed field mapping (Hoogerduijn Strating, 1991) has documented that the oldest structures preserved are represented by the spinel-facies assemblages granular textures. These latter are overprinted by spinel-, to plagioclase-, to hornblende-bearing peridotite tectonites and mylonites forming composite km-scale shear zones (Vissers *et al.*, 1991).

The ET peridotites exhibit heterogeneous bulk-rock chemistry, varying from moderately to significantly depleted compositions (Ernst and Piccardo, 1979; Ottonello *et al.*, 1979; Romairone, 1999; 2000; Romairone *et al.*, 2001). Decrease in modal clinopyroxene (from 10 to 3 vol%) and increase in MgO (from 41.3 to 45.9 wt%) are accompanied by decrease in Al_2O_3 (from 3.3 to 1.1 wt%) and CaO (from 2.7 to 1.1 wt%), (fig. 4). Similarly, the Sc content decreases at decreasing modal clinopyroxene and increasing MgO abundances. Bulk rock C1-normalized REE patterns for granular and tectonite-mylonite peridotites (Romairone, 1999; 2000; Romairone *et al.*, 2001) are rather flat (at less than 2×C1) for the HREE, and significantly fractionated in the LREE (Ce_N/Sm_N=0.05-0.11) (fig. 5). Particularly, the granular spinel-facies peridotites, according to their major element chemistry, show bulk REE absolute concentrations covering a significant range (M- to H-REE from 0.5 to 1.5×C1); bulk REE composition of the deformed rocks generally falls within the above compositional range. Spinel-facies clinopyroxenes show, accordingly, low concentration of fusible elements (Al, Ti, Sr, Zr, Y) and significant depletion in LREE: their REE patterns are almost flat from HREE to MREE (at 7-11×C1) and strongly fractionated in LREE (Ce_N/Sm_N =0.06-0.09). Moreover, the peridotites show increasing forsterite contents in olivine with increasing $Mg^* = Mg/(Mg+Fe_{tot})$ in the bulk rock.

All the above features indicate that the different samples represent refractory residua after variable degrees of partial melting starting from a compositionally homogeneous mantle source: this event most probably predated the complete equilibrium recrystallization under spinel-facies conditions.

The ET peridotites show rather homogeneous Nd isotopic compositions ($^{143}Nd/^{144}Nd$=0.513183-0.513385), while the Sr isotopic ratios are more variable ($^{87}Sr/^{86}Sr$=0.703019-0.704769) (Romairone, 1999; 2000; Romairone *et al.*, 2001) (fig.6). Both $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ (0.38-0.45) ratios are higher than those typical of a MORB upper mantle, confirming the residual nature of the peridotites (fig. 7). The rather high $^{87}Sr/^{86}Sr$ ratios most likely resulted from oceanic alteration, as commonly recognized for oceanic and ophiolitic rocks.

Based on REE geochemical modelling (using both bulk rock and clinopyroxene data) it has been stressed that the compositional features of the Erro-Tobbio peridotites are consistent with refractory residua after variable degrees (5-14%) of incremental melting, most likely occurred at spinel-facies conditions (Romairone, 1999; 2000; Romairone *et al.*, 2001).

The spinel-lherzolites commonly show

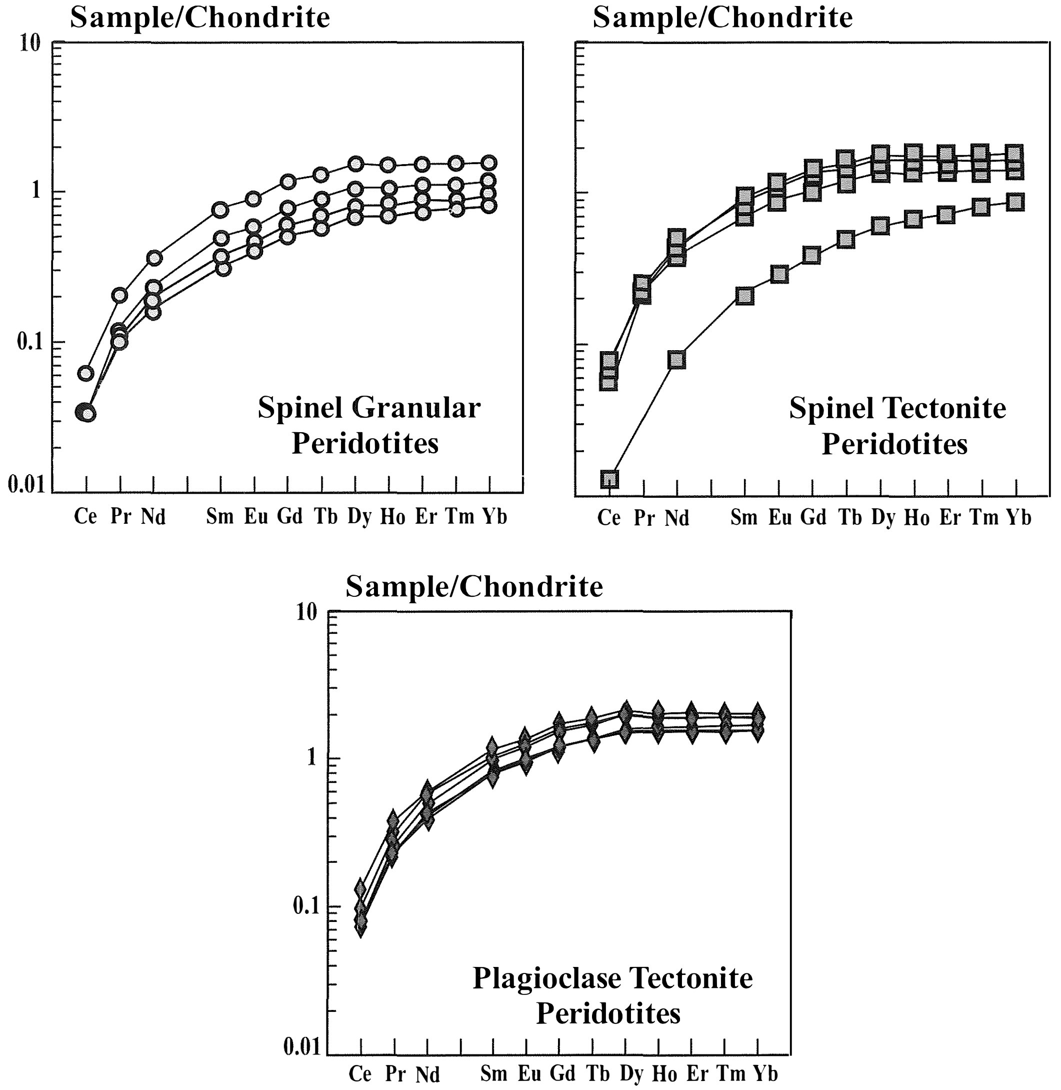

Fig. 5 – REE patterns (normalization to C1 of Anders and Ebihara, 1982) of the Erro-Tobbio peridotites (Romairone, 1999).

pyroxenite bands bounded by strongly depleted peridotite walls. The dominant rock types are spinel-bearing Al-augite clinopyroxenites and Cr-diopside websterites. They have been interpreted as the result of magmatic events (melt intrusion and crystallization) deep-seated in the upper mantle, similarly to the mafic layers in orogenic peridotite massifs and pyroxenite xenoliths in alkaline basalts (Morten and Obata, 1983; Bodinier *et al.*, 1987, Menzies and Hawkesworth, 1987; Fabries *et al.*, 1991).

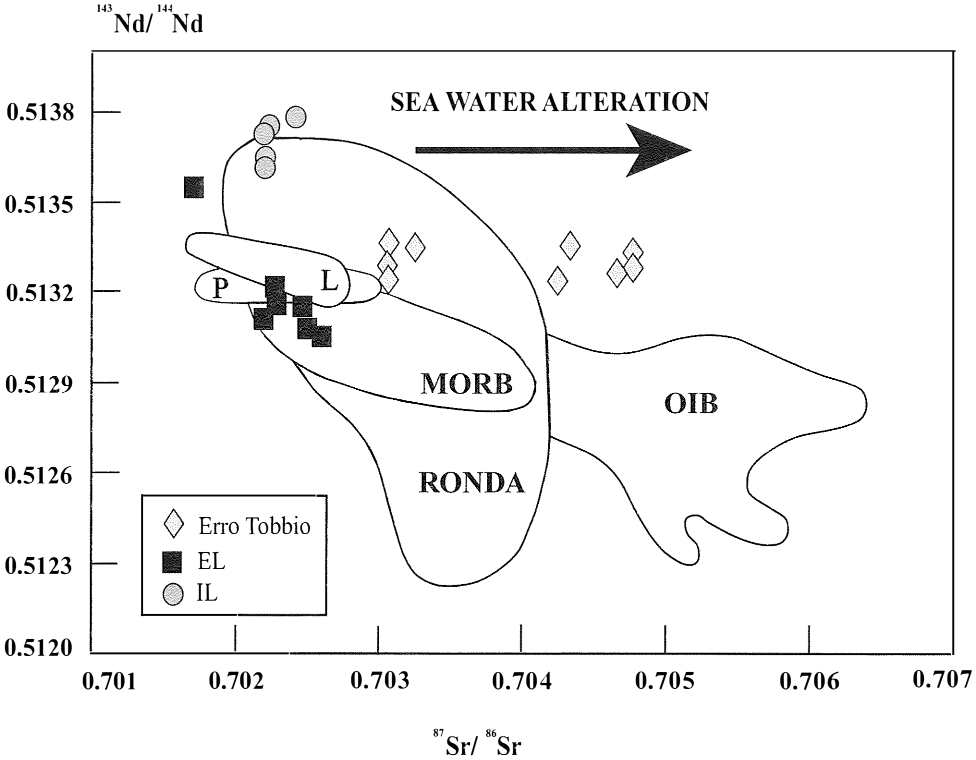

Fig. 6 – Present-day ^{143}Nd/^{144}Nd *vs* ^{87}Sr/^{86}Sr diagram for the Erro-Tobbio clinopyroxenes (Romairone, 1999). Also reported, for comparison: *i)* the data of IL and EL peridotites (Rampone *et al.*, 1995, 1996); *ii)* the fields for MORB and OIB (Zindler and Hart, 1986) and for Ronda peridotites (Reisberg and Zindler, 1986; Reisberg *et al.*, 1989); *iii)* field L refers to the Lanzo (Western Alps) peridotites (Bodinier *et al.*, 1991); *iv)* field P refers to the Pyrenean peridotites (Downes *et al.*, 1991).

The early spinel-facies equilibration

The granular spinel-facies recrystallization commonly overprints both peridotites and pyroxenite layers. Locally, the pyroxenite layers exhibit isoclinal folds lacking of any axial-plane foliation and showing hinge structures completely recovered by granular spinel-bearing equilibrium textures (Hoogerduijn Strating *et al.*, 1990, 1993; Vissers *et al.*, 1991). This evidence points out that the peridotites have been plastically deformed after the pyroxenite formation, and prior to the static, spinel-facies equilibrium recrystallization.

Thermobarometry of the spinel-facies recrystallization yields a rough pressure estimate of about 20 Kb with corresponding maximum temperatures below 1100°C (Hoogerduijn Strating *et al.*, 1993), i.e. at much lower temperatures than the dry solidus for fertile upper mantle compositions. Such P-T estimates are consistent with equilibration along an intermediate (neither cratonic, nor mid-oceanic) lithospheric geothermal gradient.

The early stability of a hydrous phase (most probably a Ti-rich pargasitic amphibole) in the spinel-bearing granular assemblage is testified by widespread pseudomorphs and rare reddish, deeply chloritized, amphibole relics. It is noteworthy that stability of pargasitic amphibole in mantle peridotites implies temperature below 1100°C (Jenkins, 1983). This temperature limit is consistent with the T estimates made for the spinel-facies

facies porphyroclasts within tectonite-mylonite peridotites has the highest Al and Mg contents (Al_2O_3 up to 59 wt%, MgO up to 20 wt%); relict spinels in tectonites and mylonites are progressively enriched in Cr and Fe. The most Cr-Fe-rich spinel relics occur in the plagioclase- and hornblende-bearing mylonites. Plagioclase has 80-90% anorthite end-member. Amphibole in the amphibole-bearing mylonites is edenitic to pargasitic hornblende (Hoogerduijn Strating *et al.*, 1993).

Thermobarometry made on the various assemblages recognized (Hoogerduijn Strating *et al.*, 1993) indicate that, starting from the P-T conditions of the early spinel-facies complete equilibration, the ET peridotites underwent a progressive temperature decrease through spinel-facies (T ranging 1000-1100°C) to plagioclase-facies (T ranging 900-1000°C), to hornblende-facies (T lower than 900°C) conditions. The composite tectono-metamorphic history indicates a subsolidus, non-adiabatic evolution during exhumation from lithospheric mantle depths (Hoogerduijn Strating *et al.*, 1993), (fig. 8).

The sequence of tectonic and metamorphic events and the variation in the mineral compositions indicate that the ET peridotites, after equilibration within the conductive subcontinental lithosphere, underwent a decompressional evolution towards shallow crustal levels. So far, no precise informations are available about the timing of the tectono-metamorphic evolution.

Sm-Nd isotope data, performed on two samples of plagioclase–bearing tectonites, have yielded two essentially parallel isochrons giving ages of 273 and 313 Ma (± 16 Ma) for the plagioclase-bearing recrystallization (fig. 9): these data indicate that the lithospheric extension and the mantle decompressional evolution were already active since Late Carboniferous-Permian times (Romairone, 1999; 2000; Romairone *et al.*, 2001; Piccardo *et al.*, 2001).

The decompressional path of the ET subcontinental lithospheric peridotites has been related to the early pre-oceanic rifting stage in the Ligurian Tethys. It is, moreover, consistent with mechanisms of tectonic unroofing following the passive and asymmetric extension of the lithosphere (Hoogerduijn Strating *et al.*, 1990,1993; Vissers *et al.*, 1991; Piccardo *et al.*, 1992, 2001; Romairone *et al.*, 2001).

The intrusion of basic dykes

The ET peridotites are intruded by mafic dykes: they frequently retain textural, mineralogical and geochemical characteristics which allow recognition of troctolites, olivine-bearing clinopyroxene-gabbros and basalts as the magmatic protoliths.

Major element compositions and metamorphic mineral assemblages of the mafic dykes indicate that slight to significant chemical changes occurred after their magmatic crystallization and prior to the Alpine recrystallization. REE absolute concentrations and spectra of both rodingitic and eclogitic meta-basaltic dykes in the ET peridotites indicate a clear MORB affinity for the parental magmas (Cazzante, 1991). They closely resemble REE compositions of basaltic rocks from the ophiolites of the EL Units of the NA.

These evidence are suggestive of the shallow emplacement of the ET peridotites close to the ocean floor, where they were intruded by MORB-type magmas deriving from deeper asthenospheric mantle sources.

The oceanic evolution

The seafloor hydration led to widespread serpentinization of peridotites and to partial rodingitization of the mafic dykes (Cimmino *et al.*, 1979; Piccardo *et al.*, 1988). Hydrous assemblages including several generations of serpentine minerals, chlorite, brucite and mixed-layer phyllosilicates statically replace the mantle assemblages and are in turn overgrown by subduction-related antigorite-bearing assemblages (Scambelluri *et al.*, 1991; 1995). Several generations of serpentine are present: chrysotile, lizardite and antigorite, which show variable Al_2O_3 content (max 0.7

wt% in chrysotile; 2.5 to 7 wt% in lizardite; 0.5 to 3.2 wt% in antigorite).

The oceanic serpentine minerals are mostly chrysotile and lizardite whereas antigorite is the serpentine phase stable at high-pressure. Chrysotile and lizardite, in association with magnetite and locally brucite, replace the mantle olivine and pyroxenes: they can contain slight amounts of Cl, which is absent in the high-pressure antigorite.

The oceanic stage is also marked by development of mixed-layer phyllosilicates mainly at the expence of mantle spinel both as coronitic layers and as pseudomorphic replacements. These phyllosilicates can contain up to 5 wt% K_2O, 0.5 wt% Na_2O and 0.35 wt% Cl; they are overgrown by high-pressure chlorite lacking chlorine and alkalies.

The low-grade nature of such a metamorphic essamblage and the mineral compositios, point to an early stage of peridotite interaction with Cl- and alkali-bearing solutions, presumably sea-water-derived (Scambelluri *et al.*, 1997). Compositional data on oceanic mantle sampled during DSDP and ODP reveal the occurrence of oceanic serpentine minerals and mixed layer phyllosilicates whose compositions are comparable to the one described here for the ET peridotite (Agrinier *et al.*, 1988; Bassias and Triboulet, 1982).

The alpine evolution

Studies on the alpine history of the ET Unit demonstrate that peridotites and mafic dykes underwent common subduction and eclogite-facies recrystallization (Piccardo *et al.*, 1988; Hoogerduijn Strating *et al.*, 1990; Scambelluri *et a*l., 1991). Peak metamorphic assemblages consist of omphacite+garnet+Mg-chloritoid+zoisite+talc+chlorite in the metagabbros (Messiga *et al.*, 1995b), of olivine+titanian clinohumite+antigorite+diopside in the peridotite.

Eclogitic minerals in the metagabbros develop both as static assemblages in massive coronitic rocks, and in tectonitic and mylonitic structures. In massive coronitic metagabbros, the igneous clinopyroxene is overgrown by omphacite with minor garnet and talc, and plagioclase is replaced by finegrained aggregates of jadeite, zoisite and garnet, whereas olivine is pseudomorphed by tremolite and talc. Coronas between pseudomorphs after olivine and plagioclase consist of early layered coronas of orthopyroxene+chlorite+garnet, which appear progressively overgrown by talc+chloritoid+garnet. Coronas between pyroxene and plagioclase pseudomorphs mostly consist of garnet and omphacite. Tectonitic and mylonitic eclogitized metagabbros display an equilibrium assemblage of omphacite+zoisite+garnet+chloritoid+talc. The pressure and temperature estimates suggest that the eclogitic parageneses in metagabbros formed at 18-25 Kbar and 500-650 °C (Messiga *et al.*, 1995b).

Several structural studies (Scambelluri *et al.*, 1991; 1995) have shown that eclogitization of metagabbros is coeval with formation of metamorphic olivine in the associated ultramafic rocks as the result of their partial deserpentinization. Oceanic serpentine is infact cut by prograde antigorite veins and foliations, which are in turn cut by olivine structures. Formation of peak metamorphic olivine is caused by the reaction antigorite+brucite = olivine+fluid, which brings to stability of olivine+antigorite+diopside+Ti-clinohumite+chlorite and to liberation of a metamorphic fluid phase. The most obvious evidence of fluid release is the development of widespread vein systems containing olivine, Ti-clinohumite, diopside and chlorite (Scambelluri *et al.*, 1991; 1995). During subduction and eclogitization, deformation was extremely channelled within intensely serpentinized domains (serpentinite mylonites), whereas large volumes of ultramafic rocks did not undergo significant plastic deformation and recrystallized statically into the new olivine+antigorite - bearing assemblage (metaperidotites).

One main implication of antigorite serpentine stability in the ultramafites at eclogite facies is that these rocks represent the

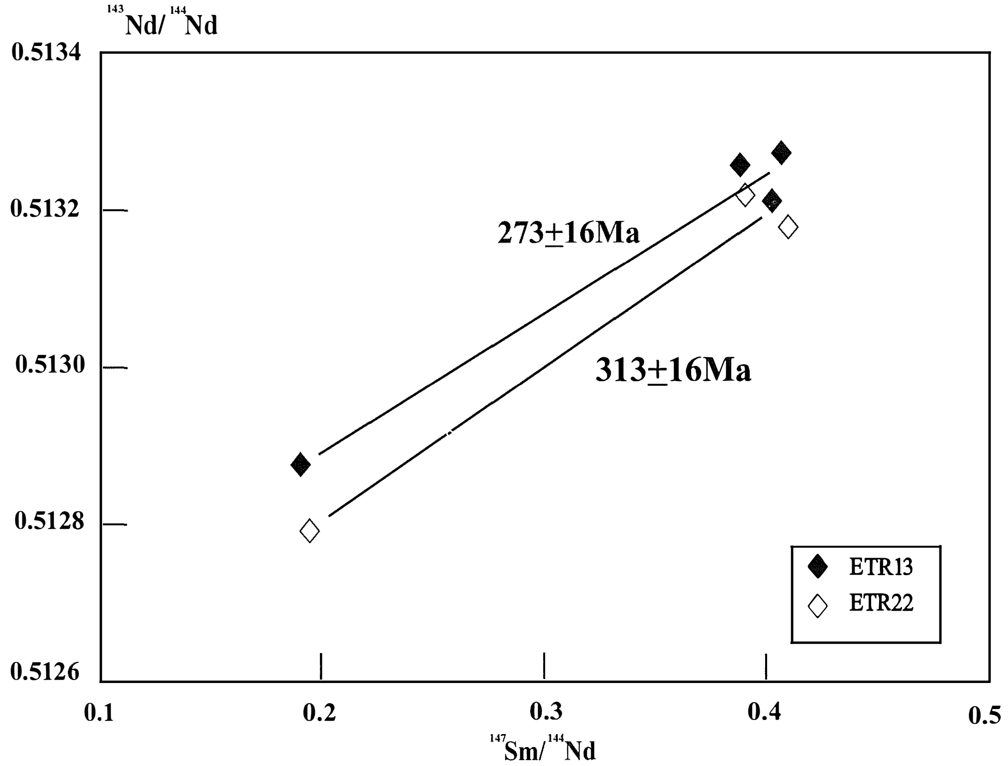

Fig. 9 – ^{143}Nd/^{144}Nd *vs* ^{147}Sm/^{144}Nd diagram for clinopyroxene and plagioclase separates and whole rock from two samples (ETR13 and ETR22) of the Erro-Tobbio plagioclase tectonites (Romairone, 1999).

most effective carriers of water into deep levels of subduction zones and that they maintain extremely low densities at mantle depths (Scambelluri *et al.*, 1995; Hermann *et al.*, 2001).

Geochemical inference on fluid and element cycling during subduction of the Erro-Tobbio peridotite

The shallow hydration of the ET peridotite had relevant consequences on deep transport of water and element during subsequent subduction, and on element cycling into the mantle via production of deep eclogitic deserpentinization fluids. Stable isotope studies of the ET ultramafic rocks have clarified the fluid-rock interactions during shallow hydration and subsequent subduction dewatering of these rocks, as well as the scales of fluid migration at depth (Vallis, 1997; Frueh Green *et al.*, 2001).

As a whole, the ultramafites have heterogeneous δ^{18}O values, ranging from ^{18}O-enriched to ^{18}O-depleted compositions with respect to unaltered reference mantle values (fig. 10). Serpentinized mantle peridotites are generally enriched in bulk ^{18}O (5.7 to 8.1‰), high pressure metaperidotites and serpentinite mylonites cover the same range of bulk-rock δ^{18}O values (4.4 to 7.6‰) and show a slight ^{18}O depletion compared with the serpentinized mantle (fig. 10A). The lowest bulk rock δ^{18}O values pertain to high pressure veins (3.5 to 5.7‰) and to eclogitized metagabbros (3.1 to 5.3‰). The δ^{18}O variability of clinopyroxene and serpentine reflects the same general

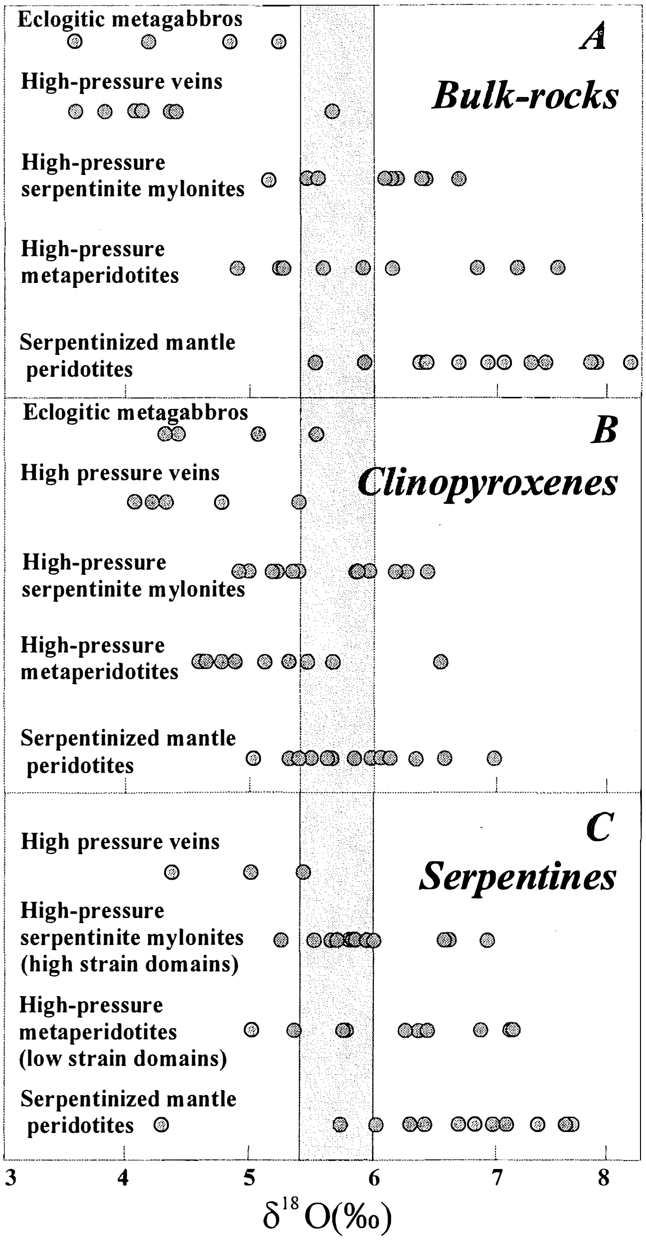

Fig. 10 – Oxygen isotope variability of bulk rocks (A), clinopyroxene (B) and serpentine separates (C) from the Erro-Tobbio metaperidotite and eclogitized metagabbro. The shaded vertical fields represent the primary isotopic ratios in unaltered mantle rocks and in mantle clinopyroxenes (Chazot *et al.*, 1993) (redrawn and modified after Frueh-Green *et al.* 2001).

variations as the bulk-rock compositions. The ^{18}O compositions of mantle clinopyroxene (5 to 7‰) and of serpentine (chrysotile and lizardite, 4.2 to 7.6‰) preserved in the serpentinized mantle peridotites, are closely comparable with the ones of metamorphic diopside (4.1 to 6.5‰) and antigorite (5.0 to 7.1‰) of the high pressure ultramafic rocks (fig. 10B, C). In general the oxygen isotope composition of high pressure phases are slightly depleted in ^{18}O (less than 1‰) with respect to the pre-eclogitic ones.

These variations are comparable to the ones measured in mafic and ultramafic rocks from modern oceanic environments and from ophiolites, which record both low temperature and high temperature alteration and varying fluid fluxes (e.g. Wenner and Taylor 1973; Gregory and Taylor 1981; Agrinier *et al.*, 1988; Früh-Green *et al.*, 1996; Agrinier *et al.*, 1995). In particular, a large number of oxygen isotope ratios of clinopyroxene in serpentinized mantle peridotites, high pressure metaperidotites, serpentinite mylonites, high pressure veins and omphacite of metagabbros, have d^{18}O depleted compositions (< 5‰), thereby suggesting exchange with seawater at T >300°C. In contrast, most of the serpentine oxygen isotope compositions are greater than 5‰: these values are similar to serpentine compositions of the Iberian passive margin (5 to 13‰, Agrinier *et al.*, 1988; Agrinier *et al.*, 1995; Plas, 1997) and the Tyrrhenian Sea (3 to 8‰, Plas, 1997), reflecting lower temperature fluid/rock interaction at crustal levels.

Similarities in the oxygen isotope signatures of oceanic and eclogite-facies rocks have been pointed out in a number of stable isotope studies, and have been interpreted as an indication of the preservation of oceanic signatures and thus a lack of isotopic overprinting during eclogitization (e.g. Matthews and Schliestedt, 1984; Nadeau *et al.*, 1993; Barnicoat and Cartwright, 1997; Philippot *et al.*, 1998; Putlitz *et al.*, 2000). Preservation of pre-eclogitic d^{18}O signatures of the ET ultramafic rocks and metagabbros implies local-scale fluid flow at low water/rock ratios, closed system behaviour during high-pressure metamorphism, local-scale exchange with compositionally heterogeneous eclogitic fluids and absence of large-scale fluid flushing causing resetting of pre-subduction isotopic signatures. Frueh Green *et al.* (2001) have thus interpreted the heterogeneity of oxygen isotope signatures as evidence for centimeter-scale recycling of internally-derived fluids during eclogitization of the ET Unit. Fluid uptake in these rocks most likely occurred during shallow (crustal) interaction processes; inflow of externally-derived fluids along shear zones at high pressure conditions seems to be unlikely.

Based on the hydrogen isotope signature of the various serpentine minerals in the serpentinized mantle peridotites (chrysotile and lizardite) and in the high pressure ultramafites (antigorite), Frueh Green *et al.* (2001) have concluded that fluid uptake in the ET peridotite occurred at oceanic conditions and during the early (shallow) stages of subduction.

The trace element compositions of serpentinized mantle peridotites and of high pressure ultramafites of the ET peridotites are

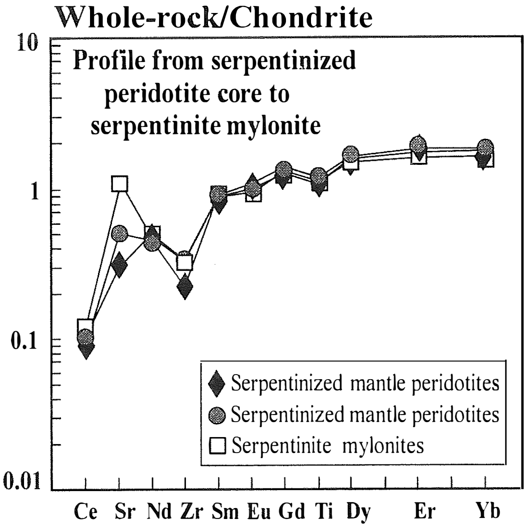

Fig. 11 – Bulk trace-element compositions of samples in profiles from serpentinized mantle peridotite to serpentinite mylonite from the Erro-Tobbio peridotite (redrawn and modified after Scambelluri *et al.*, 2001).

shown in fig. 11. Main features of the shallow serpentinization are immobility of rare earth elements, considerable water increase, local CaO decrease and uptake of trace amounts of Sr, probably as a function of intensity of the shallow alteration (Scambelluri *et al.*, 2001). Comparable rare earth element behaviour and Sr enrichment were observed by Menzies *et al.* (1993) after experimental peridotite-seawater interactions at 300°C, and were reported for abyssal serpentinites by Bonatti *et al.* (1970). The alkalies and chlorine early stored in oceanic hydrous phases are no longer present in the high pressure parageneses, as they likely partitioned in the synmetamorphic fluid drained in the veins.

A fluid inclusions study (Scambelluri *et al.*, 1997) has pointed to the presence of hypersaline fluids containing NaCl, KCl and $MgCl_2$ in the vein filling minerals. The fluid inclusion compositions strongly suggest that the fluid incorporated at the seafloor, was released at high pressure and its composition was mostly controlled by the host peridotite (Scambelluri *et al.*, 1997). Trace element analyses of mantle clinopyroxenes and high-pressure diopsides (in country ultramafites and veins), highlight the close similarity in the REE compositions of the various clinopyroxenes (fig. 12), again indicating rock control on the vein fluids and lack of exotic components carried by externally-derived fluids. Presence of appreciable Sr contents in vein-forming diopside indicate cycling of oceanic Sr in the high-pressure fluid. The aqueous fluid equilibrated with such a clinopyroxene lacks HFSE, has Sr contents of about 1.5 × chondrite (i.e. in the range of normal mantle values) and is Cl- and alkalies-rich. The recognition that pre-subduction water, chlorine, alkalies and strontium were carried by the vein fluid, indicate closed system behaviour during eclogitization and internal cycling at 80 km depth of exogenic components.

Geodynamic inference

The ET peridotite is presently interpreted as upper mantle which underwent an early partial melting event, responsible of its variable depletion, and melt intrusion (pyroxenite dykes).

The diffuse and complete reequilibration under spinel-facies conditions, at temperature not higher than 1100°C, evidences that the ET peridotite, after an early upwelling and partial melting (asthenosphere evolution) was accreted to the subcontinental conductive lithosphere and reequilibrated to the regional geotherm.

The subsequent composite retrograde evolution from lithospheric mantle depth towards shallow levels is well constrained on the basis of structural and petrological data. Sm/Nd isotopic data indicate that the lithospheric extension and the decompressional evolution were already active since Late Carboniferous-Permian times.

During upwelling, the ET peridotite was intruded by masses and dykes of gabbroic and later basaltic dykes showing clear MORB affinity. It is indicative that the peridotite reached shallow levels during the opening of the Jurassic Ligurian Tethys.

Sea-floor exposure is, moreover, testified by

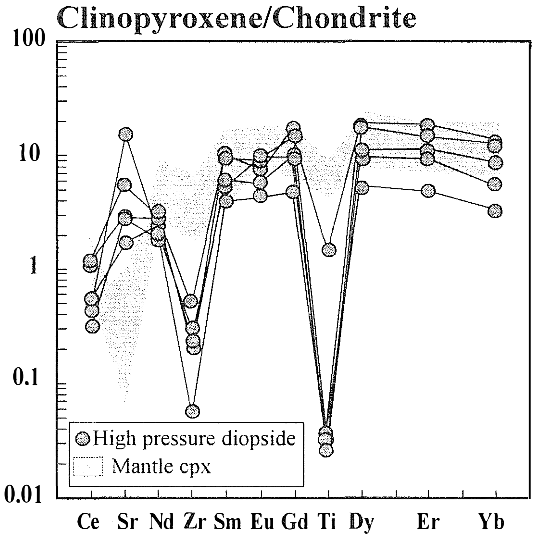

Fig. 12 – Trace element compositions of clinopyroxenenes from the Erro-Tobbio peridotite. Grey dots: high-pressure diopside from host rocks and veins. Shaded field: reference mantle clinopyroxenes (redrawn and modified after Scambelluri *et al.*, 2001).

the diffuse serpentinization of the peridotite and rodingitization of the mafic dykes. The oceanic origin of the intervening fluids is indicated by the chlorine contents of early serpentine minerals and the formation of potassium-bearing phyllosilicates consisting of mixed chlorite-biotite layers. At the ocean-floor, heterogeneity of fluid infiltration and peridotites alteration caused the spatial association of extremely serpentinized volumes close to less altered peridotites domains. This variability in water distribution inside the oceanic lithosphere strongly controlled strain localization during later subduction. The intensely serpentinized domains worked as soft horizons during convergence and closure of the oceanic basin, and became the main shear zones and detachment horizons which accomplished deformation during subduction.

During alpine subduction and collision, the ET peridotites recrystallized to antigorite serpentinites and antigorite-bearing metaperidotites. The peak metamorphic assemblage in the peridotite consists of the antigorite+olivine+diopside+Ti-clinohumite association which is coeval with the omphacite+garnet - bearing assemblage in the mafic dykes, which indicates peak metamorphic conditions in the range 18-25 kb and 500-650°C.

Survival at eclogite-facies conditions of coerent tectonic units containing dominant low-density antigorite serpentinites, provides a low-density buoyant medium driving the exhumation of deeply subducted rocks and of eclogite bodies present inside alpine tectonic units with dominant serpentinite (Hermann *et al.*, 2001).

In conclusion, structural and petrologic studies on the ET peridotite indicate an early asthenosphere upwelling and lithosphere accretion, followed by progressive uprise of this subcontinental lithosphere starting from Late Carboniferous-Permian time and sea-floor exposure during the Jurassic opening of the Ligurian Tethys: these peridotites were later subducted during closure of the oceanic basin and exhumed during alpine collision.

THE NORTHERN APENNINE

Introduction to the geology of the Northern Apennine

The NA is formed by the Late Oligocene-Miocene stacking of tectonic units belonging to two main systems:

– the lowermost Tuscan units, derived from continental domains and formed by sedimentary and metasedimentary sequences originally deposited on a Paleozoic basement;

– the uppermost Liguride units, derived from oceanic and ocean-continent transitional domains. The Liguride units occupy the highest position in the nappe pile.

The stratigraphic and structural features of the Tuscan Domain allowed the reconstruction of the evolution of the Adriatic continental margin from the Hercynian orogen, to the Late Paleozoic trans-extensional setting. During the Middle Triassic, evidence of further crustal attenuation was provided by the Anisian-Ladinian extensional basins (Punta Bianca sequence) in which marine platform sediments are associated with alkaline basaltic flows and breccias.

Early to Middle Jurassic block faulting and progressive subsidence of the continental margin led to the dismembering of the carbonate platforms and the formation of the ocean basin of the Ligurian Tethys (Malm).

The Liguride Units have been subdivided into two main groups of units on the basis of stratigraphic and structural features, i.e. the Internal and the External Liguride Units.

The IL Units consist of serpentinized mantle peridotites, generally covered by ophicarbonate breccias (ophicalcite), and gabbroic bodies. Ultramafic and gabbroic rocks are locally covered by ophiolitic sedimentary breccias interlayered with MORB-type basaltic flows. Their sedimentary cover consists of Radiolarian Cherts (Callovian-Oxfordian), Calpionella Limestone (Berriasian) and Palombini Shales (Berriasian-Aptian).

The EL Units are characterized by the presence of «basal complexes» (pre-flysch formations) overlain by the typical Helminthoid Flysch (Cretaceous-Paleocene calcareous-dominant sequences). According to their internal stratigraphy, two main groups of units have been recognized and referred to different domains: *i*) the Western External Liguride Domain, characterized by units containing ophiolites and ophiolite-derived debris and *ii*) the Eastern External Liguride Domain, characterized by units containing fragments of mesozoic sedimentary sequences and conglomerates with Austro-Sudalpine or Insubrian affinity, without ophiolites.

In Western External Liguride Domain ophiolite rocks are mainly represented by MORB-type basalts and mantle peridotites occurring as olistoliths, slide blocks and tectonic slices in the basal complex (i.e. the Casanova complex, a Santonian-Early Campanian sedimentary melange). MORB-type basalts and mantle peridotites are associated with continental mafic and felsic granulites, and granitoids. The basal complex (sedimentary melange) grades upward to the Late Cretaceous-Paleocene Helminthoid Flysch (Marroni *et al.*, 1998 and references therein).

In the Eastern External Liguride Domain the basal complex is locally characterized by slices of Middle Triassic to Early Cretaceous carbonate sequences which represent the pre-Early Cretaceous base (Vercesi and Cobianchi, 1998) of the basal complex. This evidence indicates the presence of a thinned continental crust representing the westermost domain of the Adria continental margin (Sturani, 1973; Zanzucchi, 1988; Elter and Marroni, 1991; Molli, 1996). The differences between the basal complexes in the two External Liguride Domains and the ubiquitous presence of the Late Cretaceous-Paleocene Helminthoid Flysch, suggest the presence of a transition between a thinned continental crust (Eastern External Liguride Domain) and an ocean-continent transition area (Western External Liguride Domain).

The Liguride Units bear evidence of Eoalpine (Cretaceous) and Mesoalpine (Eocene) deformation predating their involvement in the overthrusting (Late Oligocene-Miocene) onto the easternmost continental margin (i.e. the Tuscan Domain).

The Cretaceous evolution produced the formation of the basal complexes, resulting in slicing and inversion of the External Ligurian Domain. The Mesoalpine deformation in the Liguride Units involved early west-verging large scale folding and thrusting. This tectonic processes were associated with metamorphic recrystallizations ranging from very low- to low blueschists grade (Van Wamel, 1987; Hoogerdujing Strating, 1994; Marroni and Pandolfi, 1996) in the IL Units and very low- to anchimetamorphic grade in the EL Units. The Mesoalpine deformation was followed by large scale backthrusting, gravitational spreading and extensional tectonics associated with east-directed tectonic transport. The subsequent large scale deformational history of the Apennine involved northeastward nappe transport and progressive deformation of the westernmost sector of the Adriatic continental margin, when the Liguride Units became parts of the Apenninic accretionary wedge in relationship with the underthrusting of the External Tuscan Domain.

The Northern Apennine Ophiolites

A representative sampling of the diversity of the oceanic lithosphere which floored the Jurassic Ligurian Tethys is shown by the NA ophiolites, which crop out in two distinct geological units, the IL and EL Units (fig. 13).

In the IL Units, ophiolitic rocks show 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 (Abbate *et al.*, 1994, and quoted references). Field and structural evidences indicate that mantle peridotites were intruded by gabbroic bodies at depth. Subsequently, the peridotite-gabbro association experienced a tectono-metamorphic decompressional evolution as testified by deformation and recrystallization along shear zones: this

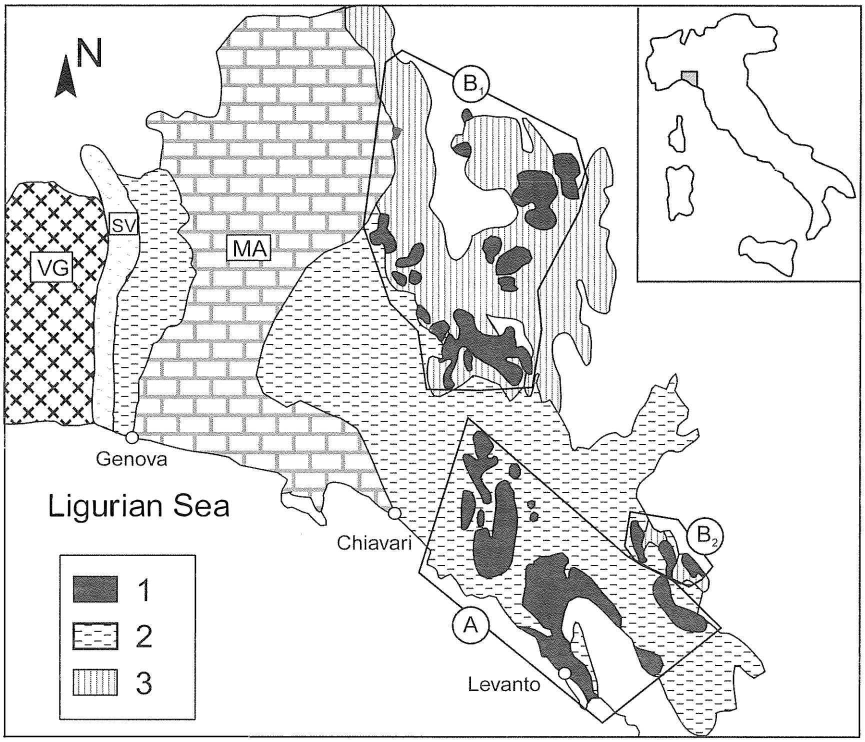

Fig. 13 – Geologic sketch map of the Northern Apennines (Eastern Liguria) with indication of the main ophiolitic bodies. VG: Voltri Group. SV: Sestri-Voltaggio Units. MA: Mt.Antola Formation and Mt. Caio flysch (calcareous sandy turbidites with interbedded shales). 1) Ophiolites (peridotites, gabbros and basalts); field A: Internal Liguride ophiolites; field B1 and B2: External Liguride (Mt.Ragola-Mt.Aiona and Suvero, respectively) ophiolites. 2) Internal Liguride sedimentary sequences: Radiolarian Cherts, Calpionella Limestones, Palombini Shales, Lavagna and Giaiette Shales, Gottero Sandstones. 3) External Liguride flyschoid sequences: Sopralacroce Shales and Casanova Complex, (redrawn and modified after Rampone and Piccardo, 2001).

indicates progressive uplift and final exposure at the sea-floor, where the peridotites were extensively serpentinized. The uppermost part of the 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 pillowed basaltic lava flows and Oxfordian-Callovian radiolarian cherts, i.e. the oldest pelagic sediments (Marcucci and Passerini, 1991). Discrete basaltic dikes, related to the basaltic extrusions, commonly cut serpentinized peridotites and foliated gabbros, as well as the overlying tectonic and sedimentary breccias.

The NA ophiolites also crop out in the EL Units, where they are associated with continental crust material (Marroni *et al.*, 1998, and quoted references). In these units, ophiolites mostly consist of mantle lherzolites and pillowed basaltic lavas which occur as huge slide blocks (olistoliths) within the basal complexes of 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 quoted references). Accordingly, the

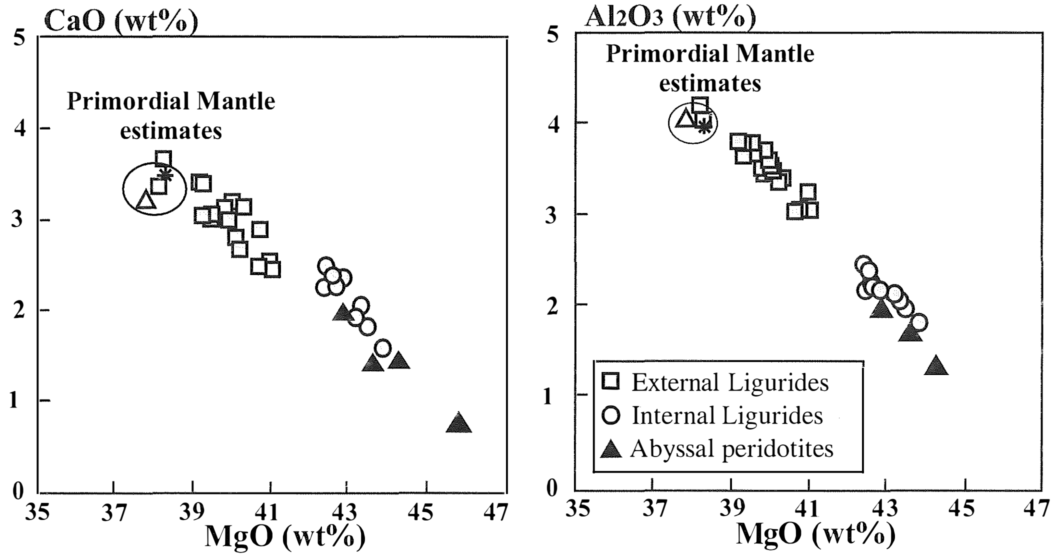

Fig. 14 – Whole rock abundances of CaO and Al_2O_3 *vs* MgO for the Internal and External Liguride peridotites (data from Rampone *et al.*, 1995, 1996; all data on anhydrous basis in wt%). Primordial mantle estimates (open triangle and asterisk) are from Hofmann (1988) and Jagoutz *et al.* (1979), respectively). The representative compositions of abyssal peridotites are from Dick (1989), (redrawn after Rampone and Piccardo, 2001).

EL 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, developed prior to widespread serpentinization, which indicates progressive upwelling toward the sea-floor (Piccardo *et al.*, 1990; Rampone *et al.*, 1995). Chilled basaltic dikes intruding peridotites and crosscutting all mantle structures are abundant. The continental crust consist of late Hercynian granitoids, granulites and paragneisses (e.g., Eberhardt *et al.*, 1962; Marroni *et al.*, 1998). The primary relationships between granitoids, ophiolitic basalts and radiolarian cherts are locally preserved.

The mantle peridotites

As outlined above, the dominant lithotype in the NA ophiolites is mantle peridotite. Quite distinct petrologic and isotope features characterize peridotites belonging to the EL and IL Units, as recently summarized by Piccardo *et al.* (1994) and Rampone and Piccardo (2001).

The mantle protoliths

The EL peridotites are dominantly fertile spinel lherzolites which crop out as km-scale bodies largely preserving mantle textures and assemblages, despite widespread serpentinization. Pyroxenite bands (spinel-bearing Al-augite clinopyroxenites and Cr-diopside websterites) are common within the peridotites, and represent high-pressure cumulates from basaltic melts (Rampone *et al.*, 1995, and quoted references).

The EL peridotites exhibit rather fertile composition, with only slight depletion in fusible components. This is indicated by: 1) the lherzolitic modal compositions, 2) the relatively high bulk rock Al_2O_3 (2.86-4.00%) and CaO (2.33-3.39%) contents (fig. 14), 3) the clinopyroxene REE patterns, showing only moderate LREE depletion (Ce_N/Sm_N=0.6-0.8) and absolute concentrations at 10-16×C1 (fig.

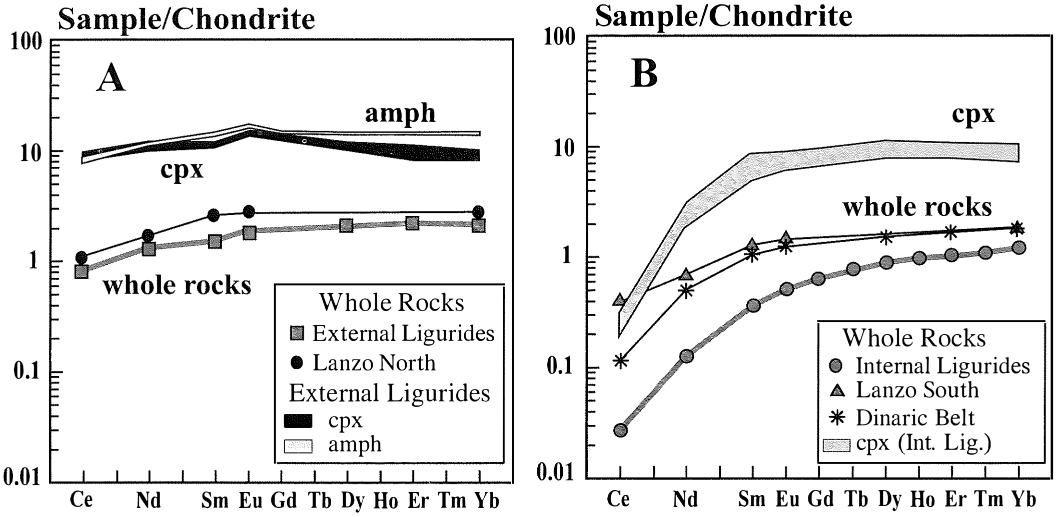

Fig. 15 – Representative chondrite-normalized REE compositions for: (A) whole rock, clinopyroxenes (*cpx*) and pargasitic amphiboles (*amph*) from the External Liguride peridotites (data from Rampone *et al.*, 1995); also reported, for comparison, a representative whole rock composition for the Lanzo North (Western Alps) (Bodinier, 1988) peridotites; (B) whole rock and clinopyroxenes from the Internal Liguride (IL) peridotites; the IL data are compared with those of the Lanzo South (Bodinier, 1988) and Central Dinaric Ophiolite Belt (Yugoslavia) (Lugovic *et al.*,1991) peridotites. Normalizing values are from Anders and Ebihara (1982), (redrawn after Rampone and Piccardo, 2001).

15A) (Ernst and Piccardo, 1979; Beccaluva *et al.*, 1984; Ottonello *et al.*, 1984; Rampone *et al.*, 1993; 1995).

The EL lherzolites are characterized by a complete static equilibrium recrystallization under spinel-facies conditions. Disseminated kaersutite/Ti-pargasite amphiboles, in equilibrium with the spinel-bearing assemblage, show LREE-depleted REE spectra (fig. 15A) and very low Sr, Zr and Ba contents. The stability of pargasitic amphibole constrains the spinel-facies equilibration to temperatures lower than 1100°C (e.g. Jenkins, 1983), in agreement with thermometric estimates on the spinel-facies assemblage (T = 1000-1100°C). The spinel-facies reequilibration in a rather «cold» (T<1100°C) thermal regime has been interpreted as a stage of annealing recrystallization after accretion of the EL mantle to the conductive lithosphere (Piccardo *et al.*, 1994; Rampone *et al.*, 1995). Information about the timing of lithospheric accretion has been derived from Rb-Sr and Sm-Nd isotope studies (Rampone *et al.*, 1995).

Present-day Sr and Nd isotope ratios of the EL peridotites (fig. 16) plot within the depleted end of the MORB field; this feature is common to many subcontinental orogenic spinel-lherzolites from the western Mediterranean area (e.g. the Pyrenees and Lanzo North peridotites). Most EL peridotites display Nd model ages (assuming a CHUR mantle source) in the range 1.9-1.7 Ga (fig. 17), and consistent results are obtained with Rb-Sr systematics (Rampone *et al.*, 1995). In particular, one single sample with extremely depleted isotopic composition ($^{87}Sr/^{86}Sr=0.701736$; $^{143}Nd/^{144}Nd=0.513543$) yields Sr and Nd model ages of 2.1 and 2.4 Ga (assuming a DM and a CHUR mantle source respectively) (fig. 17): these can be considered as minimum ages of differentiation form the asthenospheric mantle.

The IL peridotites consist of clinopyroxene-poor (5-10 vol%) spinel-lherzolites showing depleted compositions: their bulk rock MgO, CaO and Al_2O_3 contents are comparable to those of abyssal peridotites (see fig.14). The

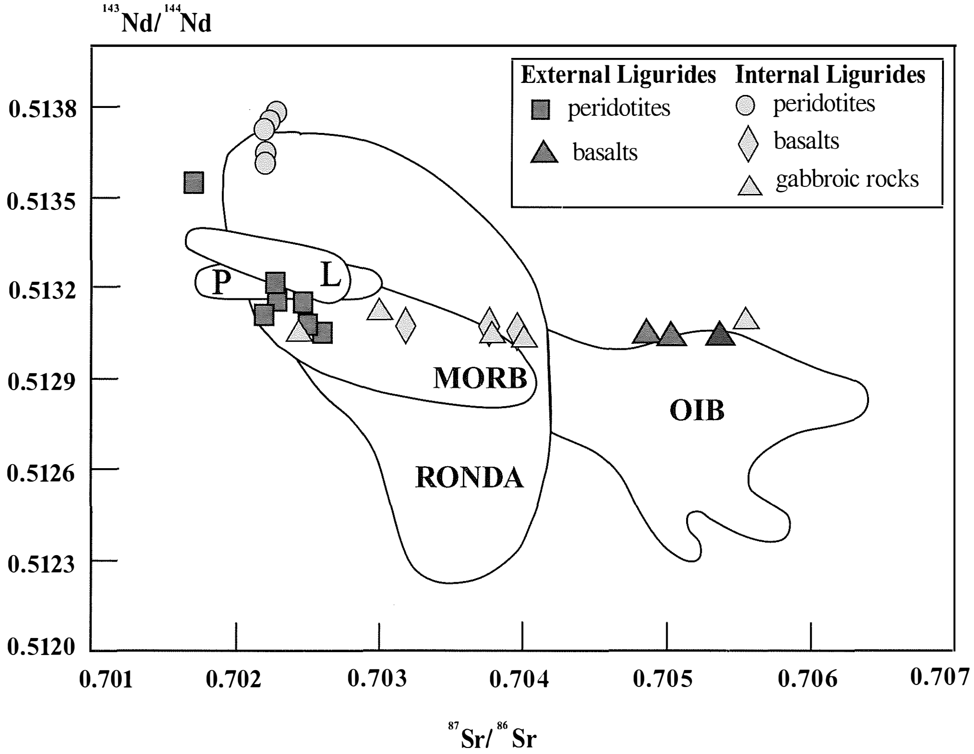

Fig. 16 – Present-day $^{143}Nd/^{144}Nd$ *vs* $^{87}Sr/^{86}Sr$ diagram for the Northern Apennines (IL and EL) peridotites and basalts, and for the IL gabbroic rocks (data from Rampone et al., 1995, 1996, 1998). Also shown are the fields for MORB and OIB (Hofmann, 1997), as well as for the Ronda peridotites (Reisberg *et al.*, 1989, and quoted references). Field L refers to the Lanzo (Western Alps) peridotites (data from Bodinier *et al.*, 1991). Field P refers to the Pyrenean peridotites (data from Downes *et al.*, 1991) (redrawn after Rampone and Piccardo, 2001).

REE spectra are characterized by strong fractionation (Ce_N/Yb_N=0.015-0.028), and very low LREE absolute concentrations. These compositions are among the most depleted of ophiolitic peridotites from the Western Mediterranean area (see fig. 15B). Geochemical modeling indicates that the IL peridotite compositions are consistent with mantle residua left after low-degree (<10%) fractional melting, presumably initiated in the garnet-facies stability field (Rampone *et al.*, 1996).

The IL peridotites exhibit strong chemical similarity to present-day oceanic mantle, and could therefore represent depleted oceanic mantle which produced the Jurassic MORB-type gabbros and basalts of the Ligurian Tethys. A Middle- to Late-Jurassic age of shallow emplacement and sea-floor exposure for the IL peridotites is indicated by the Oxfordian-Callovian age of the overlying radiolarian cherts (Marcucci and Passerini, 1991). However, isotope investigations have provided unexpected results about the age of the partial melting event.

The present-day $^{87}Sr/^{86}Sr$ ratios (0.702203-0.702285) of the IL peridotites are consistent with a MORB-type mantle, but the $^{143}Nd/^{144}Nd$ ratios (0.513619-0.513775) are very high and plot significantly above the MORB field (fig. 16). The high Nd isotope ratios are coupled to very high $^{147}Sm/^{144}Nd$ ratios (0.54-0.56) (fig. 18A). As discussed in Rampone *et al.*, (1996) (1998), such compositions are not consistent

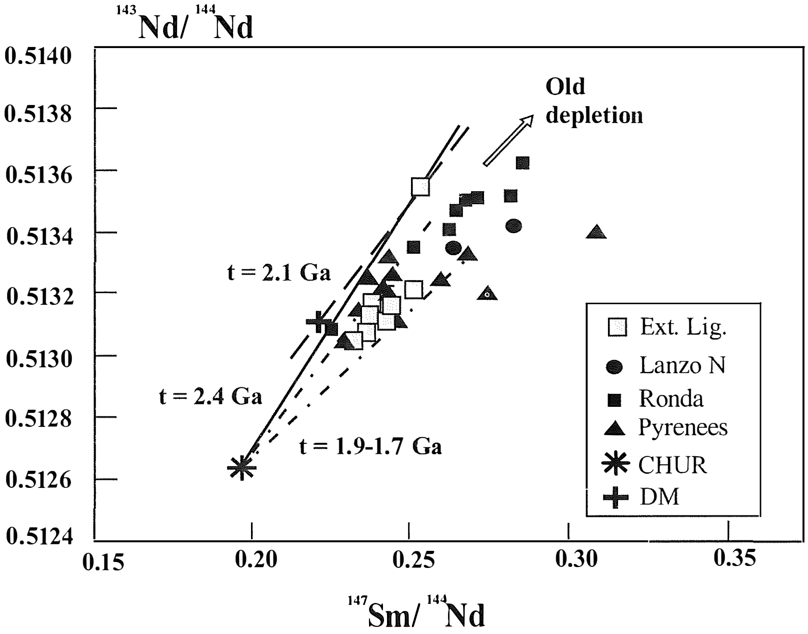

Fig. 17 – ^{143}Nd/^{144}Nd *vs* ^{147}Sm/^{144}Nd diagram for the External Liguride (Ext. Lig.) peridotites (data from Rampone *et al.*, 1995), compared with data from other subcontinental orogenic peridotites (Ronda, Reisberg *et al.*, 1989; Pyrenees, Downes *et al.*, 1991, Mukasa *et al.*, 1991; Lanzo 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 (see text and Rampone *et al.*, 1995 for more explanation) (redrawn after Rampone and Piccardo, 2001).

with a Jurassic partial melting event of a MORB-type asthenosphere: Nd model ages calculated for an average IL peridotite composition and assuming a depleted mantle (DM) source (see fig. 18A) yield a Permian time of depletion (*t*=275 Ma). A Permian age (about 270 Ma) of partial melting has been also inferred for the Balmuccia peridotites (Voshage *et al.*, 1988) (see fig. 18A). Asthenospheric mantle upwelling and melting during the Permian is well documented by the widespread occurrence, in the Alpine belt, of Permian gabbroic bodies intruded beneath or within the Adria thinned continental crust (see discussions in Piccardo *et al.*, 1994; Rampone *et al.*, 1996, 1998; Rampone and Piccardo 2001, and quoted references). Thus, the Permian age of depletion recorded by the IL ultramafics is surprising as they represent the upper mantle of the Jurassic oceanic lithosphere, but it is reasonable in the frame of the Permian extension-related mantle partial melting and magma production in the Alpine realm (Dal Piaz, 1993; and quoted bibliography).

The IL peridotites, after the melting event, were completely recrystallized under spinel-facies conditions; the spinel-facies assemblages record equilibration temperatures in the range 1150-1250°C (Beccaluva *et al.*, 1984; Rampone *et al.*, 1996).

The decompressional rift evolution

The EL peridotites and associated pyroxenites show a composite tectono-metamorphic evolution, i.e. partial recrystallization from spinel- to plagioclase-bearing assemblages, and progressive deformation leading to the development of porphyroclastic textures and tectonite to

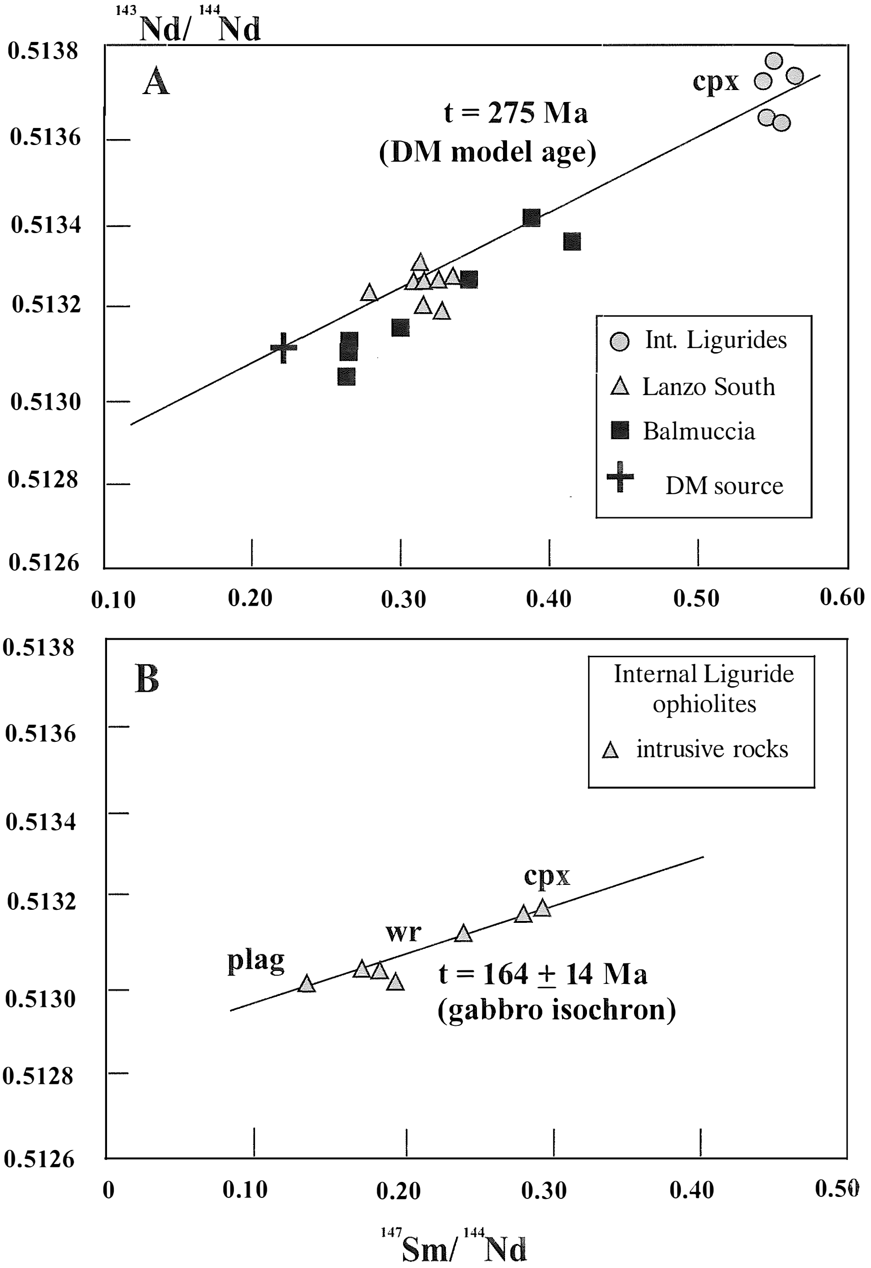

Fig. 18 – $^{143}Nd/^{144}Nd$ *vs* $^{147}Sm/^{144}Nd$ diagram for: (A) the Internal Liguride peridotites (data from Rampone *et al.*, 1996), compared with data from the Balmuccia (Ivrea Zone, Voshage *et al.*, 1988) and Lanzo South (Bodinier *et al.*, 1991) peridotites. All data refer to clinopyroxene separates (see fig. 5 for definition of the DM source, and text for explanation on the model age calculation); (B) the gabbroic rocks (whole rocks [*wr*], clinopyroxene [*cpx*] and plagioclase *[plag]* separates) of the Internal Liguride ophiolites (data from Rampone *et al.*, 1998) (redrawn after Rampone and Piccardo, 2001).

Available geochronologic data on the NA ophiolitic gabbroids commonly yield ages of intrusion older than the age of basaltic extrusion and chert deposition, i.e. older than the opening of the Ligurian Tethys (Piccardo *et al.*, 1994). Moreover, relatively younger ages are recorded by the IL intrusives (160-167 Ma; Bigazzi *et al.*, 1972, 1973; Rampone *et al.*, 1998), with respect to gabbroic rocks from the EL (185 Ma; Bigazzi *et al.*, 1973). Triassic ages of magmatic emplacement are also documented for gabbroic rocks from the Montgenevre ophiolites (Western Alps) (192-212 Ma, Carpena and Caby, 1984; about 185 Ma, Costa and Caby, 1997). Thus, the gabbroic rocks were mostly intruded in a pre-oceanic subcontinental environment, prior to the Late Jurassic oceanic break-up (Dal Piaz and Lombardo, 1985; Piccardo *et al.*, 1994).

The gabbroic rocks, like the peridotites, record a low-pressure tectono-metamorphic evolution, characterized by progressive temperature decrease (Cortesogno *et al.*, 1975). The early high-temperature (T about 900°C) metamorphic recrystallization is localized along ductile shear zones (Molli, 1994; 1995) and develops an assemblage of clinopyroxene, plagioclase, titanian pargasite and ilmenite. Trace element mineral compositions indicate that such a metamorphic event occurred in the absence of seawater-derived fluids (Tribuzio *et al.*, 1995). The high temperature ductile shear zones are commonly postdated by a retrograde metamorphic event, from amphibolite- to subgreenschist-facies conditions (Messiga and Tribuzio, 1991; Tribuzio *et al.*, 1997). This event was most likely related to interaction with seawater-derived fluids and was frequently accompanied by the development of brittle deformations. In the IL ophiolites, in particular, parallel swarms of hornblende-bearing veins are locally widespread, thus indicating the development of active, high temperature hydrothermal system (Cortesogno *et al.*, 1975; Tribuzio *et al.*, 1995; 1997). Similar metamorphic histories are documented for many Alpine ophiolitic gabbros, and have been related to the exumation of these rocks, in response to the Triassic-Jurassic rifting of the Ligurian Tethys (Lemoine *et al.*, 1987, and quoted references).

The basaltic rocks

Basaltic rocks mostly occur as pillow or massive lava flows, and as discrete dikes intruding deformed gabbros and mantle peridotites. Petrologic and geochemical studies highlighted that the Alpine-Apennine ophiolitic basalts have overall tholeiite composition and MORB affinity (Ferrara *et al.*, 1976; Venturelli *et al.*, 1981; Beccaluva *et al.*, 1984; Ottonello *et al.*, 1984; Vannucci *et al.*, 1993a; Rampone *et al.*, 1998). The IL and EL basaltic rocks show a large degree of differentiation, as indicated by their REE compositional variation (from about 10×C1 to more than 40×C1 absolute values) (see the field in fig. 19B; data from Venturelli *et al.*, 1981, Beccaluva *et al.*, 1984, Ottonello *et al.*, 1984, Marroni *et al.*, 1998). The most primitive IL basalts show moderate LREE fractionation ($Ce_N/Sm_N=0.6$) and HREE abundances at about 10×C1, the least differentiated EL basalts display almost flat or slightly LREE-enriched REE spectra ($Ce_N/Sm_N=0.9-1$) (fig. 19B). Vannucci *et al.* (1993) have shown that the compositions of EL and IL basalts could be derived by varying degrees of fractional melting (totalling less than 10%) of a MORB-type asthenospheric spinel-facies mantle source. Sr-Nd isotope study stresses out the MORB affinity of the NA ophiolitic basalts, which show, in spite of a large $^{87}Sr/^{86}Sr$ variability caused by seawater alteration, a fairly homogeneous $^{143}Nd/^{144}Nd$ ratios ranging 0.513046-0.513098 (Rampone *et al.*, 1998).

Information concerning the age of basaltic activity in the Ligurian Tethys has been mostly derived by U/Pb dating of zircons from acidic differentiates which are considered, on the basis of their field occurrence and structural relationships, to be almost contemporaneous with the basaltic volcanism. These U/Pb data have yielded ages in the range 150-160 Ma, which are interpreted as the age of the basaltic volcanism (Bortolotti *et al.*, 1991, 1995; Borsi *et al.*, 1996; Ohnenstetter *et al.*, 1981; Costa and Caby, 1997), consistently with palaeontological data on the coeval radiolarian cherts (not older than 150-160 Ma: De Wever and Caby, 1981; Lemoine, 1983; Marcucci and Passerini, 1991) which are frequently interlayered with the basaltic volcanites.

The continental crust material

Ophiolitic rocks cropping out in the EL Units are associated with materials from the lower (mafic and felsic granulite) and upper (granitoids) continental crust (Marroni *et al.*, 1998, and quoted references). Marroni and Tribuzio (1996), based on petrologic and geochronologic studies, have inferred that the mafic granulites derived from gabbroic protoliths which were emplaced at low crustal levels (P about 8 kb) during Lower Carboniferous-Upper Permian times (about 290 Ma; Meli *et al.*, 1996). The gabbroic protoliths of the granulites were most likely formed by fractional crystallization of tholeiite primary melts and concomitant assimilation of continental crust material (Montanini *et al.*, 1998; Montanini and Tribuzio, 2001). The felsic granulites are mainly represented by quartz-feldspathic anatectic rocks (Balestrieri *et al.*, 1997), which probably resulted from multi-stage melting of lower crustal basement gneisses (Montanini and Tribuzio, 2001).

The mafic granulites experienced a retrograde metamorphic evolution from granulite- to subgreenschist-facies conditions. Radiometric data (Ar-Ar amphibole age of 228 Ma; Meli *et al.*, 1996) indicate that the granulite- to amphibolite-facies recrystallization occurred between Permian and Middle Triassic times. A similar retrograde evolution has been also inferred for the felsic granulites that are primarily associated with mafic granulites (Marroni *et al.*, 1998). In both mafic and felsic granulites, retrogression is commonly accompanied by deformations progressively changing from ductile to brittle.

The granitoids are mostly represented by two-mica granodiorites to leucogranites with pertithic alkali feldspars (Ebherardt *et al.*, 1962; Marroni *et al.*, 1998). These rocks show peraluminous chemical character, which is consistent with the local occurrence of Mn-rich garnet. Mineral and whole-rock compositions point to orogenic affinity and shallow level emplacement (Marroni *et al.*, 1998). Radiometric data indicate that the granitoids were emplaced during late Hercynian times (280-310 Ma; Ferrara and Tonarini, 1985). After the Middle Triassic, the granitoids experienced cataclastic deformation and were finally exposed at shallow levels during Jurassic, as testified by the intrusion of basaltic dikes, and by the occurrence of primary stratigraphic contacts between granitoids and Oxfordian-Callovian radiolarian cherts (Marroni *et al.*, 1998, and quoted references).

Geodynamic inference

The NA ophiolites represent the spatial association of late Jurassic MOR basalts with Proterozoic and Permian mantle peridotites and Jurassic gabbros with MORB affinity:

1) mantle peridotites derived from the sub-continental mantle of the Europe-Adria plate;

2) gabbros were formed by intrusion of asthenospheric MORB melts into the sub-continental mantle during lithospheric extension, prior to the Jurassic oceanic stage of the Ligurian Tethys;

3) basalts were produced by late Jurassic partial melting of the upwelling asthenospheric mantle during the oceanic opening.

Structural and petrological evidence does not support relating the formation of this peculiar ophiolitic association to active asthenospheric upwelling and mid-ocean ridge – transform fault systems, as common at divergent plate margins of mature oceanic basins.

More properly, these ophiolitic sequences represent the lithological associations which are expected to develop after the break up of the continental crust, driven by the passive extension of the continental lithosphere.

Most probably the NA ophiolites were formed when the passive, extensional mechanisms were still dominant, prior to the inception of the sea-floor spreading driven by active asthenospheric mantle upwelling. This, more mature, oceanic stage is not recorded by to known ophiolite sequences from the NA as well as the whole Alpine-Apennine system.

ORIGINAL TECTONIC SETTING OF THE NORTHERN APENNINE OPHIOLITES

In the past, different interpretations of the main structural and/or petrological features of the Alpine-Apennine Jurassic ophiolites have led to the development of different models for their original tectonic setting. Besides the common interpretation as sections of a MORB-type oceanic lithosphere, mainly based on the MORB affinity of the magmatic rocks, the widespread occurrence of peridotites exposed on the sea-floor has 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).

Investigations on the structure of present-day oceanic lithosphere have provided increasing evidence that slow-spreading ridges are frequently characterized by the direct exposure of serpentinized mantle peridotites on the sea-floor. These latter are intruded by discrete gabbroic bodies and only partially covered by basaltic lava flows. Based on these features, it has been argued by some authors 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).

Other contributions, however, stressed the probable subcontinental origin of many mantle rocks flooring the Ligurian ocean (Decandia and Elter, 1969, 1972; Piccardo, 1976), and opened the discussion on the diversity of the Alpine-Apennine ophiolites compared with mature oceanic lithosphere. Based on the atypical association of fertile subcontinental-type lherzolitic mantle and MORB magmatism (as recognized in the EL units), it was argued that these 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 oceanic basin (Beccaluva and Piccardo, 1978). Further petrologic investigations on the NA ophiolitic ultramafics, demonstrated the depleted compositions of the IL peridotites, and inferred the existence of a residua-melt relationship between the peridotites and associated MORB magmatism (Ottonello *et al.*, 1984). It was therefore asserted that the IL ophiolites represent oceanic lithosphere produced during a more evolved stage of evolution of the Ligurian Tethys (Beccaluva *et al.*, 1984). The comparison with peridotites from different settings in modern oceanic basins emphasized close similarities between the EL peridotites and the marginal and pre-rift lherzolites, and between the IL ultramafics and mid-ocean ridge peridotites (Piccardo *et al.*, 1990).

However, recent petrologic and isotope investigations of the NA ophiolitic mantle ultramafics (as reported in the previous chapters) have shown that none of the Ligurian peridotites can be considered as typical oceanic mantle, and that a simple mantle residua-basaltic melt genetic relationship does not exist in the IL ophiolites.

As recently discussed by Rampone and Piccardo (2001), it has been definitely demonstrated that the EL peridotites consist of fertile subcontinental lithospheric mantle (presumably Proterozoic), whereas the IL mantle ultramafics are depleted peridotites which experienced MORB-type partial melting during the Permian, i.e. well before production of the associated Jurassic basaltic crust. Both the EL and IL peridotites display a composite subsolidus retrograde evolution, which reflect their uplift from lithospheric mantle depths, and emplacement on the ocean floor.

The NA ophiolites therefore represent the spatial association of older (Proterozoic and Permian) subcontinental mantle peridotites,

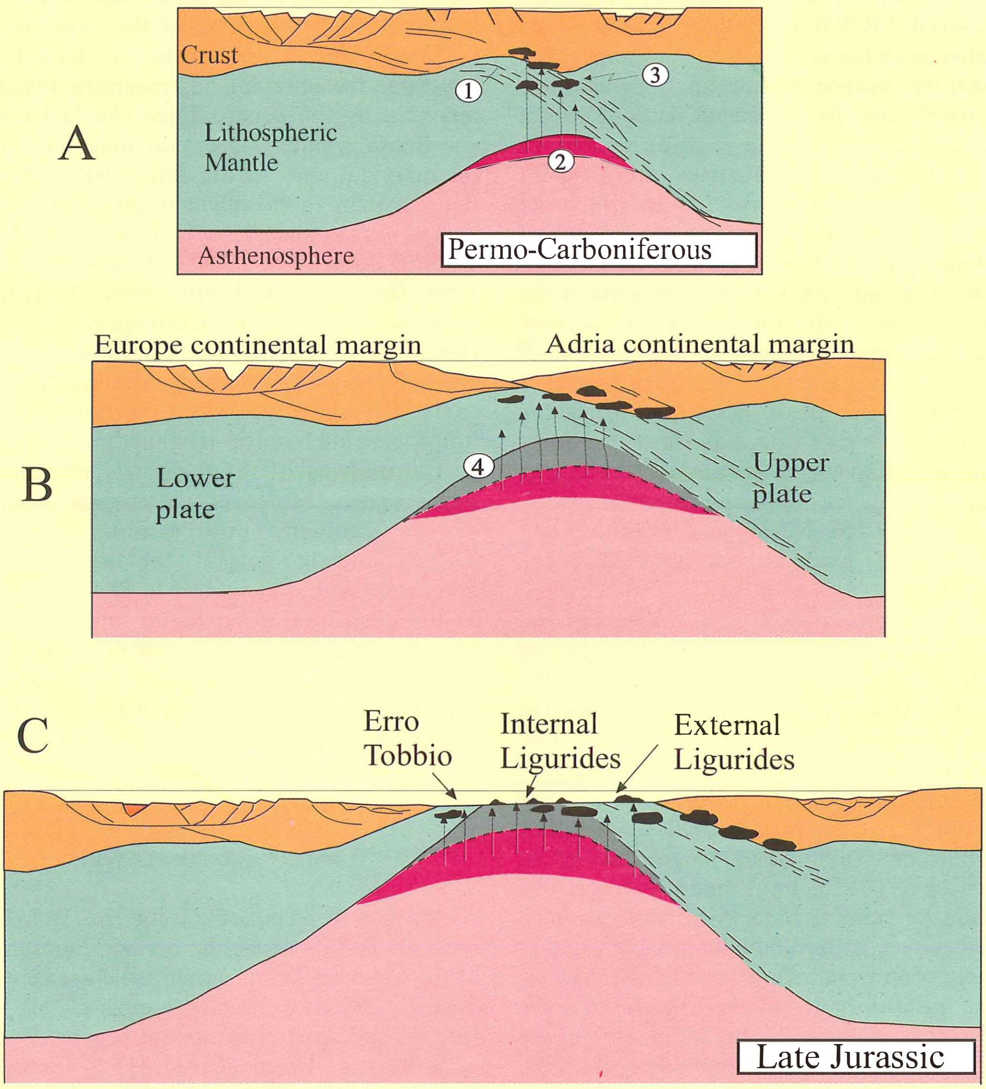

Fig. 20 – Model for the evolution of the Ligurian Tethys from late Palaeozoic extension to Jurassic continental break-up and ocean opening (redrawn and updated after Piccardo *et al*., 1994). The model only considers the Permian asthenospheric partial melting and the intrusion of the manle-derived melts (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 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 (the Internal Liguride peridotites) 4), after asthenospheric partial melting, to the subcontinental lithospheric mantle; C) Late Jurassic opening of the Ligurian Tethys and sea–floor exposure of the subcontinental lithospheric mantle.

which are partly still linked to continental crust material, and younger (mostly Jurassic) unrelated MORB-type magmatism. This peculiar association cannot be reconciled with present-day mature oceanic lithosphere, where the mantle and the associated mafic crust are linked by a direct genetic relationship. In contrast, the NA ophiolites most likely represent lithological associations which are expected to develop after the break-up of continental crust in response to passive extension of the lithosphere. This latter is the most suitable geodynamic process to account for the tectonic denudation of large sectors of subcontinental mantle. The exumation of lithospheric mantle in response to passive lithosphere extension has been recently confirmed by analogue geophysical modelling (Brun and Beslier, 1996) performed to study the modes of passive-margin formation and related mantle exumation at continent-ocean boundary.

Mechanisms of passive extension of the lithosphere were already invoked in pioneering studies on the NA ophiolites, to explain the peculiar structural features of the Ligurian Tethys seafloor (Decandia and Elter, 1969, 1972; Elter, 1972). More recently, models of asymmetric passive extension of the lithosphere by means of normal simple-shear mechanisms (according to the model of Wernicke, 1985), have been proposed to account for some asymmetrical features which have been recognized on both sides of the pre-oceanic continental rift of the Ligurian Tethys. Some authors have inferred the large-scale extensional geometry of the oceanic rift of the Ligurian Tethys by the comparison of the tectono-sedimentary evolution of the conjugate (Europe and Adria) continental margins. Based on the contrast between syn-extensional (Lias-Dogger) subsidence of the Adria margin and uplift of the Briançonnais ridge of the European margin, it has been argued that Adria and Europe were, respectively, the lower and upper plate margin during simple-shear extension (Lemoine *et al.*, 1987; Hoogerduijn *et al.*, 1993; Vissers *et al.*, 1991).

Other contributions have proposed the eastward dipping of the detachment zone, i.e. Adria as the upper plate of the extensional system. This interpretation is based on structural, metamorphic and magmatic features recorded by the Austroalpine (Sesia-Lanzo) and South Alpine (Ivrea-Verbano) units (i.e. the marginal units of the Adria plate), which indicate their involvement in the pre-oceanic extensional regime (Dal Piaz, 1993; Trommsdorff *et al.*, 1993; Piccardo *et al.*, 1994; Dal Piaz and Martin, 1998). According to these authors, the occurrence of post-Hercynian gabbroic bodies in the Austroalpine units of the Western-Central Alps testifies the early intrusion into the extending Adria lithosphere of basaltic magmas produced by partial melting of the passively upwelling asthenosphere. Moreover, the original location of the gabbroic bodies indicates that asthenospheric partial melting started asymmetrically with respect to the future axis of the continental break-up, and that the melting zone shifted progressively towards the location of the future oceanic basin (fig. 20) (Piccardo *et al.*, 1994; Rampone *et al.*, 1998; Rampone and Piccardo, 2001; Piccardo *et al.*, 2001; and quoted references).

SUMMARY AND CONCLUSION

Ophiolites exposed along the WA-NA orogenic belt represent the oceanic lithosphere of the Ligurian Tethys ocean which separated, during Late Jurassic-Cretaceous times, the Europe and Adria continental blocks. These ophiolites are characterized by: *i*) dominant fertile, cpx-rich mantle lherzolites, while more depleted peridotites are scarce; *ii*) gabbroic intrusives and basaltic volcanites with MORB affinity.

WA-NA ophiolites show peculiar structural and petrological characteristics which indicate that: *i*) mantle ultramafics underwent a composite subsolidus evolution from subcontinental lithospheric mantle depths towards the sea-floor; *ii*) the gabbroic rocks were intruded into mantle peridotites during their decompressional evolution; *iii*) mantle peridotites and gabbros were exposed at the sea-floor before basaltic extrusion and radiolarian chert deposition.

Stratigraphic-structural evidence points out that the Ligurian Tethys was floored by a peridotite-gabbro basement, subsequently covered by a discontinuous layer of pillowed basaltic flows and radiolarian cherts, i.e. the first oceanic sediments. Palaeontological ages of the radiolarian cherts and isotopic (U/Pb) zircon ages of acidic differentiates, linked to the basaltic volcanites, concordantly indicate Late Jurassic (160-150 Ma) ages for the inception of the oceanic stage, along the whole Ligurian Tethys.

In the Ligurian ophiolites, primary stratigraphic-structural relationships are preserved in the IL Units, while in the EL Units, which are considered to derive from a paleogeographic realm transitional between the continental (Adria) and oceanic (IL) domains, mantle peridotites and basalts crop out as giant olistholiths within Cretaceous/Eocene flysch sequences, where they are associated to continental crust material (Permian granulites and Hercynian granitoids).

Mantle peridotites from the EL Units are fertile, *cpx*-rich lherzolites: Sr/Nd models ages indicate minimum Proterozoic ages of differentiation. This is interpreted as the accretion age of the EL mantle to the Europe-Adria subcontinental lithosphere, where the ultramafics underwent complete equilibration at temperature below 1100°C, under spinel-facies conditions. Sm/Nd *pl-cpx* isochrons indicate that transition from spinel- to plagioclase-facies conditions during the decompressional evolution of the subcontinental mantle started from Late Palaeozoic (273-313 Ma: ET peridotites of the Voltri Massif) and continued up to Jurassic (165 Ma: EL peridotites). Mantle peridotites from the IL Units are significantly depleted, *cpx*-poor, lherzolites: they are interpreted as refractory residua formed by partial melting of an asthenospheric MORB-type mantle source. Sr/Nd model ages indicate that this melting event occurred during Permian (275 Ma).

Intrusives rocks (ultramafic cumulates, Mg-Al-gabbros, Fe-Ti-gabbroids and plagiogranites) represent the crystallization products, during low pressure fractionation, of tholeiitic MORB-type basaltic magmas, similarly to the whole intrusive rocks of the WA-NA ophiolites. Available geochronological data on the NA gabbroic rocks indicate variable intrusion ages, ranging from about 185 Ma (some EL gabbros) to about 160 Ma (some IL gabbros): it must be mentioned that some WA ophiolitic gabbros (i.e. the Chenaillet body) record Triassic age of intrusion. Accordingly, the gabbroic rocks are significantly younger with respect to the partial melting events recorded by the associated mantle peridotites and, moreover, they are significantly older than the true oceanic magmatism, represented by the Late Jurassic basaltic extrusion.

The continental mafic granulites were derived from gabbroic protoliths which were emplaced at low crustal levels (P about 8 kb) during Lower Carboniferous-Upper Permian times (about 290 Ma). The gabbro-derived mafic granulites experienced a retrograde metamorphic evolution from granulite- to subgreenschist-facies conditions. Radiometric data (Ar-Ar amphibole age of 228 Ma) suggest that the granulite- to amphibolite-facies recrystallization occurred between Permian and Middle Triassic times. The continental granitoids were emplaced at shallow levels during late Hercynian times (about 310 Ma). After the Middle Triassic, the granitoids experienced cataclastic deformation and were finally exposed at shallow levels during Jurassic, as testified by the intrusion of basaltic dikes, and by the occurrence of primary stratigraphic contacts between granitoids and Oxfordian-Callovian radiolarian cherts.

The composite decompressional evolution of the peridotites and the associated continental gabbro-derived granulites and granitoids, deriving from the continental lithosphere (crust and upper mantle) of the Europe-Adria system, is related to the pre-oceanic rifting processes which were active within the Europe-Adria lithosphere prior to the ocean opening.

The Permian age of partial melting of the IL peridotites and the Late Palaeozoic to Jurassic subsolidus decompression of the ET and EL peridotites, and the associated continental rocks, indicate that lithospheric extension of the Europe-Adria continental lithosphere and asthenospheric upwelling were already active since late Palaeozoic times. This interpretation is strongly supported by the presence of huge post-Variscan gabbroic bodies, derived by parental MORB magmas, which are intruded into the extending lithosphere of the Adria continental margin (Austroalpine Units of the Western-Central Alps) and by the presence of residual mantle peridotites (IL peridotites) which underwent partial melting during Permian and were accreted to the subcontinental lithosphere of the Europe-Adria plate.

The peculiar oceanic lithosphere of the Jurassic Ligurian Tethys (i.e. the association of Proterozoic and Permian subcontinental mantle peridotites, Triassic to Jurassic gabbroic intrusives and Late Jurassic MORB volcanites) developed after the Jurassic break-up of the continental crust in response to passive extension of the Europe-Adria continental lithosphere. This is the most suitable geodynamic process to account for the tectonic denudation of large sectors of subcontinental mantle.

One main effect of mantle exposure at superficial oceanic (and suboceanic) settings is the widespread hydration of peridotites, leading to a significant ductility change. The oceanic serpentinization of the ET peridotite was heterogeneous, and brought to the spatial association of extremely serpentinized ultramafites close to mantle peridotites less affected by serpentinization. Such a heterogeneity in water distribution in the oceanic lithosphere played a major control on its behaviour during later Alpine convergence and subduction. Serpentinites worked as soft horizons which accomplished ductile deformation and thus became detachments and shear zones which allowed delamination of the subducting oceanic lithosphere.

Serpentinization did not produce significant changes in the major and rare earth element compositions of the primary ultramafic rocks, but was accompanied by uptake of trace amounts of marine Sr, Cl and alkalis. Mafic rocks at this stage locally underwent metasomatic exchanges with their host ultramafites leading first to a stage of Mg-enrichment and chloritization of the mafic rocks, followed by a stage of Ca-enrichment and rodingitization. Serpentinization played a relevant control on the composition of fluid phases evolved during subduction burial of ultramafic rocks. Subduction of the Ligurian ultramafic rocks was accompanied by prograde reactions, culminating in one main high-pressure event of partial dewatering, which led to fluid production and to formation of metamorphic alpine olivine in equilibrium with antigorite, diopside and Ti-clinohumite. Main evidence of this fact is the widespread formation of olivine-bearing metamorphic vein systems coeval with eclogitization of the associated mafic rocks.

Mafic rocks at this stage developed different peak assemblages depending on their bulk rock compositions and on their pre-subduction evolutions stories: garnet–rutile - omphacite (Fe-Ti metagabbros), garnet–chloritoid–omphacite–zoisite–talc (Mg-metagabbros), grossular–zoisite–chlorite–diopside (metarodingite), Ti-clinohumite–diopside–chlorite–magnetite (Mg-enriched metagabbros). The pressures and temperatures of eclogitic recrystallization range from P > 13 Kbar and T 450-500°C in the Beigua Unit, to P 20-25 Kbar and T 550-650°C in the ET Unit.

Despite subduction led in both Units to partial dewatering of the ultramafic rocks, antigorite serpentine survived high pressure metamorphism as a stable mineral phase in the new high-pressure olivine assemblage. Persistence of large volumes of low-density buoyant serpentinites in the deep roots of the Alpine orogeny provides a mechanism for the exhumation of eclogites and other high to ultrahigh presure rocks from mantle depths.

The eclogitized ultramafic rocks still preserve oxygen isotope signatures acquired at oceanic settings, indicating that the fluid recycled at this stage was the one incorporated during exposure close to the oceanic floor. Presence of appreciable amounts of Sr in the high pressure vein minerals, and finding inside these minerals of hypersaline fluid inclusions, indicate that besides water, the eclogitic fluid contained oceanic Sr, chlorine and alkalies. This has profound implications on the global cycling of exogenic fluid and element by serpentinites at mantle depths.

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