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32nd INTERNATIONAL
GEOLOGICAL CONGRESS

THE OCEANIC LITHOSPHERE OF THE JURASSIC LIGURIAN TETHYS: FORMATION AND SUBDUCTION

Leader: G.B. Piccardo

Associate Leaders: E. Rampone, A. Romairone, M. Scambelluri, P. Elter, N. Malaspina, G. Molli, R. Tribuzio, R.L.M. Vissers

Post-Congress **P12**

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Front Cover:
Monte Maggiore peridotite (Northern Corsica).

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Introduction

The field trip aims to show the main petrological and structural features related to the formation and consumption of the oceanic lithosphere in the Ligurian sector of the Mesozoic Tethys. This oceanic lithosphere consisted of a peridotite basement locally intruded by gabbroic rocks and discontinuously covered by basaltic volcanites and radiolarian cherts.
Present knowledge indicates that the Ligurian Tethys oceanic basin: 1) was originated by passive extension of the Adria-Europe lithosphere causing tectonic denudation and sea-floor exposure of large sectors of the subcontinental mantle, 2) was consumed by subduction during convergence between the European and Adria plates, leading to formation of the Alpine orogenic belt.
The field trip will visit two classic sections of the Ligurian ophiolites: 1) the obducted ophiolites from the Internal and External Liguride Units of the Northern Apennines (Eastern Liguria –NW Italy), and 2) the subducted high-pressure ophiolites from the Erro-Tobbio and Beigua Units of the Voltri Massif (Ligurian Alps, Western Liguria – NW Italy).
The excursion to the Northern Apennine ophiolites will focus on the up-to-date structural, petrologic and geochronologic knowledge about mantle peridotites and their associated crustal rocks (gabbros and basalts), aiming to highlight the petrologic/geodynamic processes which governed the formation of this peculiar oceanic lithosphere.
The excursion to the Voltri Massif will be devoted to the tectonic and metamorphic evolution of mafic and ultramafic rocks representing sections of subducted oceanic lithosphere which diffusely preserve remnants of the pre-Alpine protoliths, of their exhumation evolution during lithosphere extension and their low-grade alteration during sea-floor exposure. Major emphasis will be given to the structural and petrologic evidence of the tectonic-metamorphic subsolidus evolution of mantle lithosphere, HP recrystallization at eclogite-facies conditions of both ultramafic and mafic oceanic rocks, fluid production in hydrated oceanic mantle during subduction, and high pressure metamorphism.

Regional geologic setting
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 (or Ligurian-Piemontese basin), which separated, during Late Jurassic - Cretaceous times, the European and Adria continental blocks.
In recent decades, numerous contributions concerning the WA-NA ophiolites have shown that: i) rather fertile, cpx-rich lherzolites are dominant (Bezzi and Piccardo, 1971; Nicolas and Jackson, 1972), while depleted, cpx-poor peridotites are subordinated; 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 and accretion to the subcontinental lithosphere;
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 dike complexes are lacking and comagmatic relations did not exist between the gabbro bodies and the basaltic dikes 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), and then subsequently covered by extrusion of a discontinuous layer of younger pillowed basaltic flows and by radiolarian cherts, i.e. the first oceanic sediments.
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) throughout the whole Ligurian Tethys: accordingly, the inception of the oceanic stage, following the continental breakup, is considered not older than Late Jurassic.

Palaeogeography of the ligurian ophiolites

The Ligurian Tethys is believed to have developed due to the progressive divergence of the European and Adria blocks, in connection with the pre-Jurassic rifting and Late Jurassic opening of the Northern Atlantic (Lemoine et al., 1987; Dewey et al., 1973), (Fig. 1).
Palinspastic reconstructions suggest that this basin was limited in size, and that it never reached the

dimensions of present-day oceans. In addition, age data indicate a narrow time span between the end 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 the oceanic crust started during the Early Cretaceous, about 25 Ma after

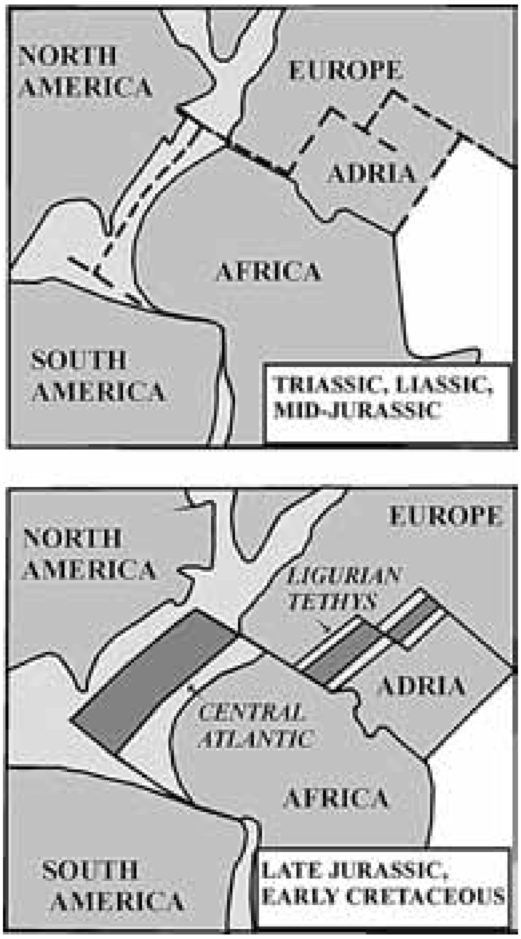


Figure 1 - Mesozoic evolution of Central Atlantic and Ligurian Tethys oceans, from rifting to ocean formation (redrawn and modified after Lemoine** et al., **1987).

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 northen sector of the Western Alps, and progressively intra-oceanic towards the Ligurian sector.

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 Apennines.

Depending on their stratigraphic, structural and metamorphic characteristics, the different ophiolitic sequences of the Ligurian sector have been ascribed to different palaeogeographic settings in the Jurassic-Cretaceous Ligurian Tethys. The Voltri Massif ophiolites, which 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 Northern Apennine ophiolites, 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 Western Alps 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 mainly composed of ophiolitic materials, associated with slices of continental crystalline rocks from the European margin (Chiesa et al., 1975; Messiga et al., 1992). To the east it is separated from the Ligurian Apennines by t Sestri-Voltaggio zone, a composite terrain consisting of Triassic-Liassic carbonates and of dismembered

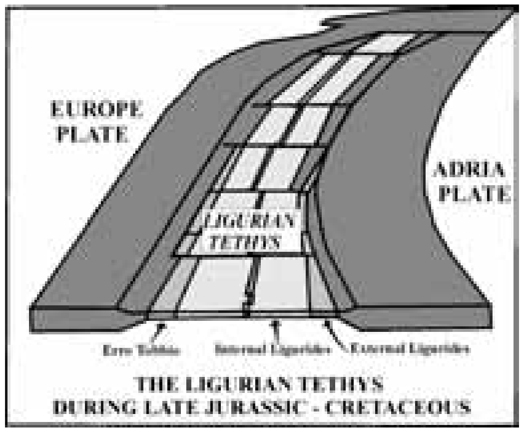


Figure 2 - Generalized paleogeographic reconstruction of the Upper Jurassic Ligurian Tethys, with location of the different Ligurian domains (redrawn and modified after Dal Piaz, 1995).

Mesozoic ophiolites, showing peak blueschist 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, made up of Hercynian gneisses (granitoids with associated amphibolites), which show greenschist- to blueschist-facies Alpine metamorphism. Towards the north the Voltri Massif is bounded by Tertiary sediments of the Piemontese Basin, whose basal breccias include clasts of high-pressure metaophiolites (metagabbros and metaperidotites), and give a 35-38 Ma age for the exhumation and erosion of the high-pressure terrains of the Voltri Massif.

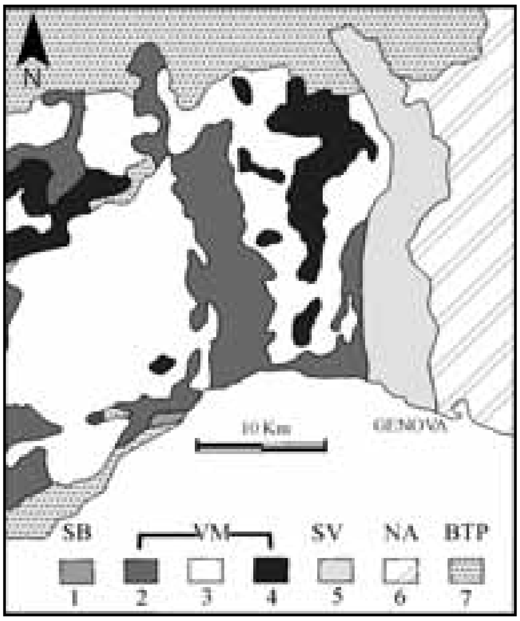


Figure 3 - Geological sketch map of the Voltri Massif showing location of the Erro-Tobbio peridotite (after Chiesa et al., 1975). Major units as follows: 1 = Arenzano Crystalline Massif (SB = Gran San Bernardo Nappe); VM = Voltri Massif: 2 = Alpicella, Voltri-Rossiglione and Ortiglieto Units: metavolcanics and paraschists with relic 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).

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

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

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

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

(3) the Erro-Tobbio Unit, consisting of partly recrystallized antigorite-bearing metaperidotites, preserving km-scale volumes of their mantle protoliths, and associated rodingitic and eclogitic mafic rocks (mostly deriving from MORB Mg-Al-rich gabbros and subordinate basaltic dikes with MORB affinity).

Eclogitic metagabbros and HP serpentinites and metaperidotites of the Beigua Unit

The Beigua unit mostly consists of serpentinites enclosing lenses of eclogites and minor bodies of metarodingite and Ti-clinohumite dikelets. Intrusive relations between eclogitized mafic rocks and host ultramafites are locally preserved. Petrological studies have shown that the eclogites formed by recrystallization (at 1.3 GPa and 450-500°C) of original gabbros, represented by dominant Fe-Ti-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).

On the basis of 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. The different intrusive types have flat REE patterns with a negative LREE fractionation. REE concentrations are 2-3xC1 in Mg-Al rich rocks, and rise up to > 100xC1 in the most differentiated Fe-Ti-rich types (Ernst et al., 1982; Piccardo, 1984).

The intrusion of gabbroic rocks was followed by the emplacement of shallow, level basaltic dikes. This stage was likely coeval with effusion of MORB basaltic lava flows that are presently associated with metasediments in 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. These metasomatic rocks consist of: (1) metarodingite boudins containing garnet + diopside + zoisite/clinozoisite + chlorite + magnetite ± apatite; (2) brownish dikelets containing Ti-clinohumite + diopside + magnetite + chlorite + apatite. These rocks have been interpreted as the result of HP metamorphism of gabbros which underwent pre-subduction, oceanic Ca- and Mg-metasomatism (Piccardo et al., 1980; Cimmino et al., 1981; Scambelluri and Rampone, 1999).

The classical garnet + Na-pyroxene + rutile eclogites of the Beigua Unit (Ernst, 1976; Messiga, 1987; Messiga and Scambelluri, 1988; 1991; Messiga et al., 1995a) mostly derive from original Fe-Ti-oxide-bearing gabbros (the "superferrian eclogites" of Mottana and Bocchio, 1975): the Beigua eclogites show both coronitic and mylonitic structures. Relics of igneous minerals (mostly clinopyroxene) are locally preserved in coronitic eclogites: igneous augite is topotactically replaced by omphacite ± fine-grained garnet and rutile; plagioclase is pseudomorphed by fine-grained omphacite + garnet ± paragonite and epidote; igneous ilmenite is replaced by rutile.

Mylonitic and tectonitic eclogites consist of omphacite porphyroclasts (after magmatic clinopyroxene) in a fine-grained matrix of omphacite, garnet and rutile. Garnet cores locally contain inclusions of sodic clinopyroxene (Tribuzio, 1992), crossite, paragonite, which represent relics of a prograde blueschists facies assemblage.

The trace element compositions of the eclogite minerals (Messiga et al., 1995a; Tribuzio et al., 1996) show that omphacite has a negligible contribution to the whole-rock REE inventory: almost all the LREE and HREE in the rock are incorporated in the coexisting garnet and accessory allanite. The gabbro/eclogite transformation was not accompanied by significant REE mobilization, and REE were redistributed among the new eclogite-facies minerals (Tribuzio et al., 1996).

The post eclogitic evolution of the Beigua eclogites consists of the superposition of a composite series of metamorphic events driven by interaction with fluids at decreasing pressure conditions. An early study by Ernst (1976) showed that the eclogitic minerals were first overgrown by glaucophanic amphiboles, followed by barroisite–bearing and finally by actinolite + albite + chlorite greenschist parageneses: this evolution pointed to an adiabatic uplift of the deeply buried eclogites. A later study by Messiga and Scambelluri (1991) evidenced 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 the 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).

Serpentinites forming a great part of the Beigua Unit: they display an antigorite + chlorite + magnetite assemblage overgrown by olivine + antigorite, which derive from incomplete deserpentinization of the previous assemblages (Cimmino et al., 1979).

The Erro-Tobbio mantle peridotites

The Erro-Tobbio mantle peridotite were involved in the Alpine orogenesis, but the extreme localization of alpine deformation along mylonite shear zones preserves km-scale volumes of coherent unaltered peridotites which retain mantle textures and assemblages. This has allowed detailed structural and petrological investigations of their composite (magmatic, tectonic and metamorphic) upper mantle evolution, which predated their sea-floor emplacement during the opening of the Ligurian Tethys (Bezzi and Piccardo, 1971; 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 Erro-Tobbio mantle peridotites consist of partly-serpentinized, cpx-poor lherzolites and harzburgites, 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 features preserved are represented by the granular texture and the spinel-facies assemblage. These latter ones became overprinted by spinel-, to plagioclase-, to hornblende-bearing peridotite tectonites and mylonites forming composite km-scale shear zones (Vissers et al., 1991).

Bulk rock and mineral chemistry data on the Erro-Tobbio peridotites point to an overall depleted signature. The most important features are: i) the depletion in fusible components (i.e. low Ca, Al, Ti, LREE contents in both bulk rocks and constituent clinopyroxene) (Figs. 4 and 5), ii) the Nd-isotopic compositions of clinopyroxenes (Fig. 6). In principle, these features could be simply interpreted as resulting from partial melting processes. However, the comparison between bulk-rock and mineral compositions indicates that the Erro-Tobbio spinel peridotite protoliths most likely record a composite history of partial melting and melt migration by reactive porous flow (Rampone et al., 2003a). Major (and trace) element compositions of minerals in all the spinel peridotites (both granular and tectonite types) are remarkably similar. In spite of this, the bulk-rock compositions define striking correlations, i.e. increasing FeO_{tot}, Ni, Co, and decreasing Al_2O_3, SiO_2, CaO, Sc, Cr, Yb_N, with increasing MgO, similar to those recently recognized in the abyssal peridotites (Niu et al., 1997; Asimow, 1999) (see Fig. 4). The bulk-rock chemical variations are coupled to systematic modal changes, namely a progressive cpx, opx decrease and olivine increase, at increasing bulk MgO. These bulk-rock/mineral compositional contrasts suggest that the Erro-Tobbio spinel peridotites cannot be simply interpreted as mantle residues after variable partial melting degrees. Instead, they may be explained as resulting from combined histories of partial melting and subsequent melt migration, involving pyroxene dissolution and olivine precipitation reactions (Rampone et al., 2003a). In contrast with the situation at Ronda, where the observed geochemical variability is correlated with the structural facies (Van der Wal & Bodinier, 1996), the melt extraction and interaction processes in the Erro-Tobbio region were fully annealed, and clearly preceded the subsequent tectono-metamorphic evolution, including the recrystallization in the plagioclase stability field.

The isotopic composition of the Erro-Tobbio mantle protolith is similar to other peridotites such as Lanzo, and it is indistinguishable from modern-depleted to slightly-enriched MORB-source reservoirs (Fig. 6). Such compositions are also common in the subcontinental lithosphere, and they cannot be used to distinguish between particular environments such as oceanic versus subcontinental mantle or plume sources (Bodinier et al., 1991).

In terms of bulk rock compositions, the plagioclase peridotites plot at the “more fertile” end of all trends discussed above (higher Ca, Al, Sc, V, HREE, modal cpx contents) (see Figs. 4 and 5). Thus, it could be argued that these peridotites were refertilized by impregnating melts which caused plagioclase crystallization. However, field and microtextural evidence (Hoogerduijn Strating et al., 1993, Rampone et al., 2003b) indicates that plagioclase in the studied peridotites results from a subsolidus reaction rather than from melt crystallization. According to Rampone et al. (2003b), the evidence that plagioclase-facies recrystallization is mostly recorded by more fertile peridotites is most likely due to the fact that Ca- and Al-richer bulk compositions enhanced crystallization of the plagioclase-bearing assemblage.

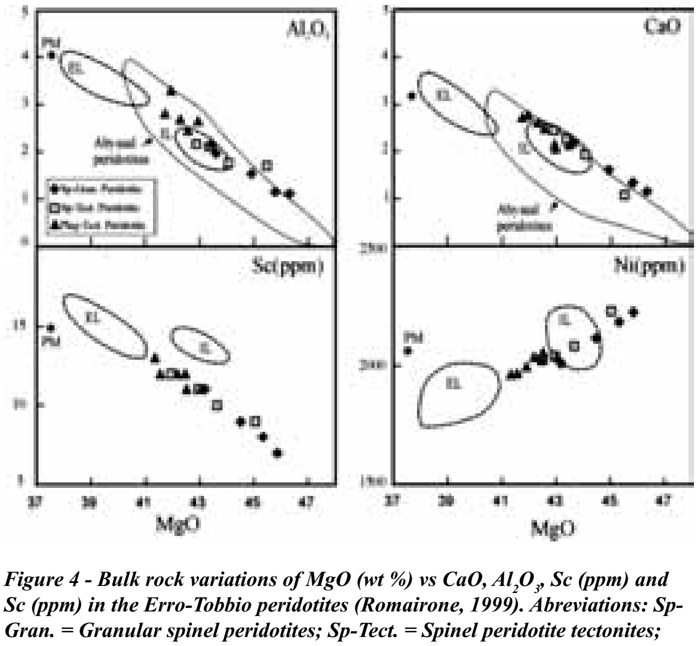


Figure 4 - Bulk rock variations of MgO (wt %) vs CaO, Al_2O_3, Sc (ppm) and Sc (ppm) in the Erro-Tobbio peridotites (Romairone, 1999). Abreviations: Sp-Gran. = Granular spinel peridotites; Sp-Tect. = Spinel peridotite tectonites; Plg-Tect. = Plagioclase peridotite tectonites. Primordial mantle estimates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

The early spinel-facies equilibration

Thermobarometry of the spinel-facies recrystallization yields a rough pressure estimate of about 20 Kb, with corresponding maximum temperatures below 1100 °C (Hoo-

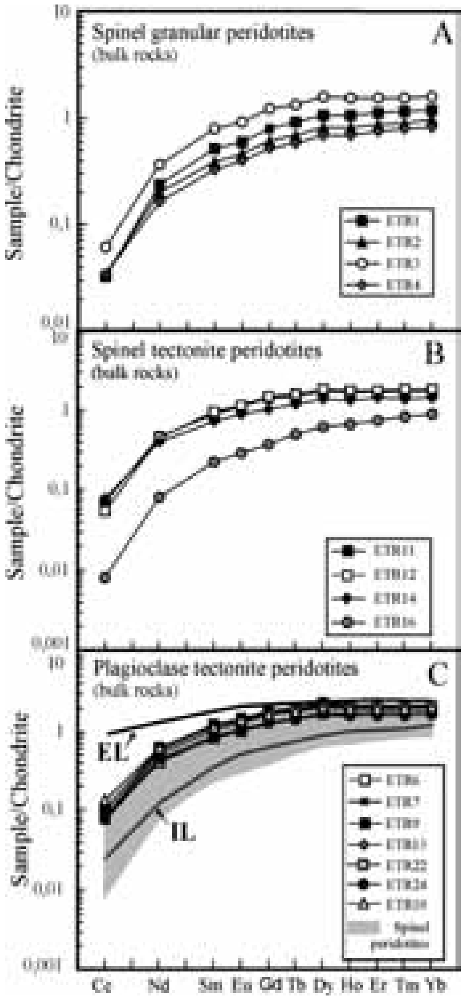


Figure 5 - REE patterns (normalization to Anders and Ebihara, 1982) of the Erro-Tobbio peridotites (Romairone, 1999).

gerduijn Strating et al., 1993). Such P-T estimates are consistent with equilibration along an intermediate (neither cratonic nor mid-oceanic) lithospheric geothermal gradient.

In conclusion, the earliest events recorded by the Erro-Tobbio mantle peridotite have been related to the early upwelling of asthenospheric mantle, which was accreted to the Europe-Adria subcontinental lithosphere and cooled to the regional geotherm during thermal equilibration within the conductive lithosphere (Piccardo et al., 1990; Hoogerduijn Strating et al., 1993).

The decompressional evolution

The spinel-facies granular textures are overprinted by tectonite and mylonite fabrics that mostly develop within km-scale shear zones and are related to a complex tectonic-metamorphic history. The shear horizons were active during a polyphase metamorphic evolution marked by recrystallization of the peridotite to spinel-, plagioclase-, hornblende- and chlorite-bearing parageneses.

Detailed structural studies (Drury et al., 1990; Vissers et al., 1991) reveal several generations of shear-zone structures, and the intensity of the deformation associated with these structures varies considerably. Progressive deformation and concomitant recrystallization led to the development of tectonite-to- mylonite fabrics and spinel- to plagioclase- to amphibole-bearing assemblages.

Mineral chemistry data (Hoogerduijn Strating et al., 1993; Romairone, 1999; 2000; Rampone et al., 2003), performed on peridotite samples with similar bulk rock chemistry, point to systematic variations of the clinopyroxene compositions, from the oldest (spinel-facies) to the youngest (amphibole-facies) assemblages. The highest Al_2O_3 and Na_2O contents (average 7.1 and 0.6 wt%, respectively) pertain to

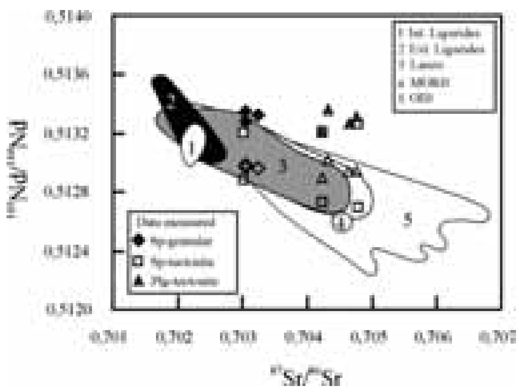


Figure 6 - Present-day $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram for clinopyroxenes separates from the Erro-Tobbio peridotites (Romairone, 1999; Rampone et al., 2003b). We reported both: i) the measured values (filled symbols), and ii) the age-corrected (300 Ma) values. Fields refer to clinopyroxene data for peridotites from: (1) IL Units (N.Apennines, Rampone et al., 1996; 1998), (2) EL Units (N. Apennines, Rampone et al., 1995), (3) Lanzo (Western Alps, Bodinier et al., 1991). For the IL and Lanzo peridotites, a radiogenic growth correction has been applied, to make the data comparable with present-day MORB mantle and with the Erro-Tobbio peridotites. Also shown are the fields for MORBs (4) and OIBs (5) (from Hofmann, 1997).

clinopyroxenes from the granular spinel peridotites or from spinel-facies porphyroclasts within tectonite-mylonite peridotites. These elements strongly decrease in clinopyroxenes coexisting with plagioclase, and reach the lowest clinopyroxene values in the hornblende-bearing assemblages.

Spinel in granular and tectonite-mylonite peridotites has the highest Al and Mg contents (Al_2O_3 up to 59 wt%, MgO up to 20 wt%). The most Cr-Fe-rich spinel relics occur in the plagioclase- and horneblende-bearing mylonites. Plagioclase has 80-90% anorthite endmember. Amphibole has edenitic-pargasitic hornblende composition (Hoogerduijn Strating et al., 1993). Thermometric estimates (Hoogerduijn Strating et al., 1993) indicate that the Erro-Tobbio peridotites underwent a progressive temperature decrease from 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 tectonic-metamorphic history indicates a subsolidus, non-adiabatic evolution during exhumation from lithospheric mantle depths (Hoogerduijn Strating et al., 1993), (Fig. 7).

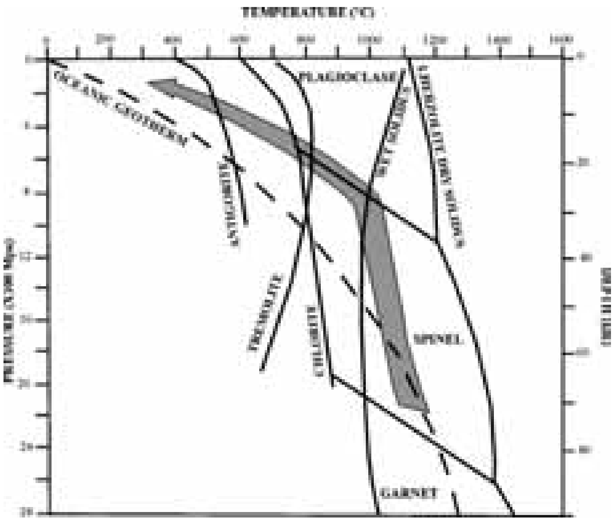


Figure 7 - Pressure – Temperature path showing the mantle evolution of the Erro-Tobbio peridotite (after Hoogerduijn Strating et al., 1993).

The sequence of tectonic and metamorphic events, and the variation in the mineral compositions, indicate that the Erro-Tobbio peridotites, after equilibration within the conductive subcontinental lithosphere, underwent a decompressional evolution towards shallow crustal levels. 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. 8): these data indicate that the lithospheric extension and the mantle decompressional evolution were already active in late Carboniferous-Permian times (Romairone, 1999; Rampone et al., 2003).

The decompressional path of the Erro-Tobbio 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 of subcontinental mantle during passive lithosphere extension (Hoogerduijn Strating et al., 1990,1993; Vissers et al., 1991; Piccardo et al., 1992; Rampone et al., 2003).

The melt impregnation

Ongoing field and petrologic-geochemical studies (Piccardo et al., in preparation) evidence the presence in the Erro-Tobbio Massif of large areas showing plagioclase enrichment and anastomosing networks of channels and dm-scale bodies of spinel dunites.

Field and petrologic-geochemical studies evidenced that the plagioclase enrichment in some ophiolitic Alpine-Apennine peridotites (Lanzo, Internal Ligurides, Corsica) is due to impregnation (reactive porous flow migration and interstitial crystallization) of a percolating exotic melt (Rampone et al., 1997; Piccardo et al., 2002; Piccardo, 2003; Müntener and Piccardo, 2003), whereas the spinel dunite dikes have been interpreted as replacive dunites, formed by a melt migrating via reactive, focused porous flow through the spinel/plagioclase peridotites along preferential conduits, where mantle pyroxenes were completely dissolved by melt/peridotite reaction (Boudier and Nicolas, 1972, Boudier, 1978; Piccardo, 2003; Müntener and Piccardo, 2003).

Melt impregnation in the Erro-Tobbio spinel peridotites is evidenced by peculiar microstructures, i.e. presence of: i) plagioclase blebs or veins along grain boundaries or crosscutting mantle minerals; ii) partial dissolution of exsolved mantle clinopyroxene and replacement by unstrained orthopyroxene rims and orthopyroxene + plagioclase symplectites; iii) corrosion of deformed mantle olivine and partial replacement by undeformed orthopyroxene crystals; iv) undeformed, granular plagioclase+orthopyroxene microdomains along the contacts and frequently cros-

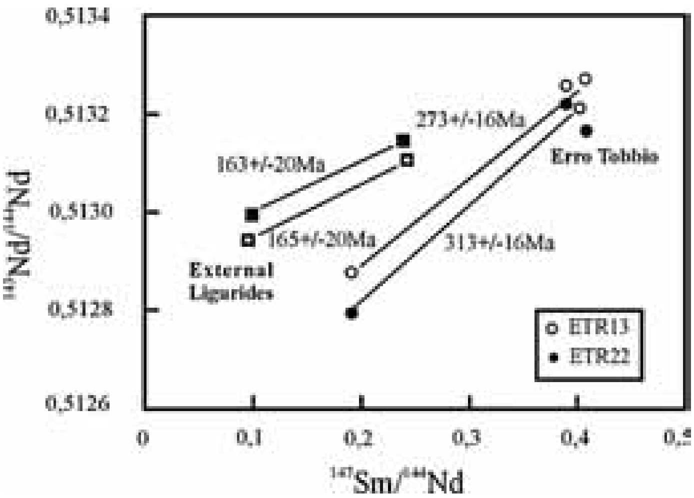


Figure 8 - $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ diagram for clinopyroxene- and plagioclase-separates and whole rock from two samples (ETR13 and ETR22) of the Erro-Tobbio plagioclase tectonites (Romairone, 1999; Rampone et al., 2003b). Also shown are data for plag-cpx pairs from two External Liguride plagioclase peridotites (Rampone et al., 1995)

scutting deformed mantle minerals.

Early crystallization and abundance of magmatic orthopyroxene, together with plagioclase, in the interstitial magmatic aggregates and replacing mantle olivine and clinopyroxene, indicates that the impregnating melts were othopyroxene(-silica)-saturated. The silica saturation of the impregnating melts supports the idea that their primary liquids migrated upwards in the mantle column from deeper levels by reactive porous flow (Rampone et al., 1997; Piccardo et al., 2002) and reacted with the country peridotite, dissolving pyroxenes and crystallizing olivine (Kelemen et al., 1995).

The intrusion of gabbroic bodies and dikes

The Erro-Tobbio peridotites are intruded by discrete bodies (up to 1 km wide) and dikes of gabbroic rocks, which are locally recrystallized to rodingitic and eclogitic assemblages, but frequently preserve magmatic textures and assemblages. The gabbroic bodies mostly consist of ultramafic cumulates and olivine gabbros; the dikes are constituted by troctolites, and olivine gabbros. Basaltic dikes are also found. The REE composition of magmatic clinopyroxene and whole rocks in all the above intrusives indicate a clear MORB affinity for the parental magmas.

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

The oceanic evolution

The sea-floor hydration led to widespread serpentinization of peridotites and to rodingitization of the mafic dikes (Cimmino et al., 1979; Piccardo et al., 1988). Hydrous assemblages, including several generations of serpentine minerals (mostly chrysotile and lizardite), 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).

Oceanic chrysotile and lizardite can contain slight amounts of Cl, which is absent in the high-pressure antigorite. This stage is also marked by development of mixed-layer phyllosilicates at the expense of mantle spinel, which can contain up to 5 wt% K_2O and 0.35 wt% Cl; they are overgrown by high-pressure chlorite lacking chlorine and alkalies.

The above features point to an early stage of peridotite interaction with sea-water-derived Cl-alkali-bearing solutions (Scambelluri et al., 1997).

The alpine evolution

The Erro-Tobbio peridotites and mafic dikes underwent subduction and eclogite-facies recrystallization (Piccardo et al., 1988; Hoogerduijn Strating et al., 1990; Scambelluri et al., 1991). Peak HP metamorphic assemblages consist of omphacite + garnet + Mg-chloritoid + zoisite + talc + chlorite in the metagabbros (Messiga et al., 1995b), and olivine + titanian clinohumite + antigorite + diopside in the peridotite. P-T estimates suggest that the eclogitic parageneses in metagabbros formed at 18-25 Kbar and 500-650 °C (Messiga et al., 1995b).

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. Oceanic serpentine is 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 leads to stability of olivine + antigorite + diopside + Ti-clinohumite + chlorite and metamorphic fluid release. The most obvious evidence of fluid release is the development of widespread vein systems containing olivine, titanian clinohumite, diopside and chlorite (Scambelluri et al., 1991; 1995). During subduction and eclogitization, deformation was channelled within intensely serpentinized domains (serpentinite mylonites), whereas large volumes of ultramafic rocks did not undergo significant plastic deformation and developed a static olivine + antigorite - bearing assemblage.

A major implication of antigorite stability in HP ultramafic rocks is that they represent the 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 Erro-Tobbio peridotite had relevant consequences on deep transport of water during subsequent subduction, and on element cycling into the mantle via production of deep eclogitic deserpentinization fluids. Stable isotope studies of the Erro-Tobbio ultramafic rocks have revealed the fluid-rock interactions during shallow hydration and subsequent subduction dewatering of these rocks, and the scales of fluid migration at depth (Vallis, 1997; Frueh Green et al., 2001).

As a whole, the ultramafic rocks have heterogeneous ^{18}O values, ranging from ^{18}O-enriched to ^{18}O-depleted compositions compared 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 ^{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 ^{18}O values pertain to high pressure veins (3.5 to 5.7‰) and to eclogitized metagabbros (3.1 to 5.3‰). The ^{18}O variability of clinopyroxene and serpentine reflects the same general variations as the bulk-rock compositions. The ^{18}O compositions of mantle clinopyroxene (5 to 7‰) and of serpentine (chrysotile and lizardite, 5.8 to 7.6‰) preserved in the serpentinized mantle peridotites, are closely comparable with those of the 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‰) in respect to the pre-eclogitic ones.

These variations are comparable to the ones measured in mafic and ultramafic rocks from modern oceanic environments and ophiolites, which record both low temperature and high temperature alterations 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 ^{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 the 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. The recognition that pre-subduction water, chlorine, alkalis and strontium were carried by the vein fluid, indicate closed system behaviour during eclogitization, and internal cycling of exogenic components at a depth of 80 km . 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 Schliesedt, 1984; Nadeau et al., 1993; Barnicoat and Cartwright, 1997; Philippot et al., 1998; Putlitz et al., 2000). Preservation of pre-eclogitic -^{18}O signatures of the Erro-Tobbio 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, absence of large-scale fluid flushing causing resetting of pre-subduction isotopic signatures.

The trace element compositions of ET- serpentinized mantle peridotites and high-pressure ultramafites are shown in Fig. 11. Main features of the shallow serpentinization are the immobility of REE, considerable water increase, a local CaO decrease and uptake of trace amounts of Sr (Scambelluri et al., 2001). Comparable REE behaviour and Sr-enrichment were observed by Menzies et al. (1993) in peridotite-seawater interaction experiments at 300 °C, and were reported for abyssal serpentinites by Bonatti et al. (1970). The alkalies and Cl earlier stored in oceanic hydrous phases are no longer present in the HP parageneses, as they likely partitioned in the synmetamorphic fluid drained in the veins.

Fluid inclusions studies (Scambelluri et al., 1997) have pointed to the presence of hypersaline fluids containing NaCl, KCl and $MgCl_2$ in the vein filling minerals. Trace element analyses of mantle clinopyroxenes and high-pressure diopsides (in country ultramafites and veins), highlight the close similarity of the various clinopyroxenes in the REE compositions (Fig. 12), again indicating rock control on the vein fluids and lack of exotic components.

Presence of appreciable Sr contents in vein-forming diopside indicate cycling of oceanic Sr in the high-pressure fluid. The aqueous fluid equilibrated with this clinopyroxene lacks HFSE, has Sr contents of about 1.5 x chondrite (i.e. in the range of normal mantle values) and is Cl- and alkalis- rich.

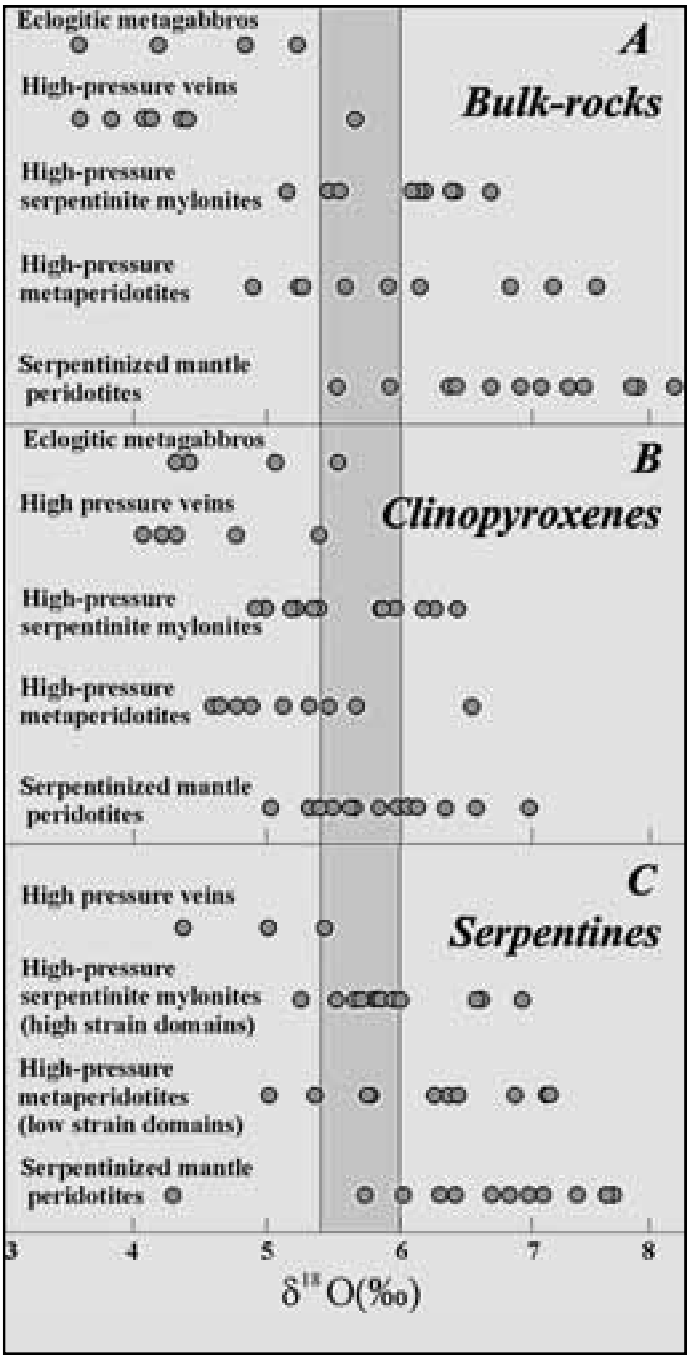


Figure 9 - Oxygen isotope variability of bulk rocks (A), clinopyroxene (B) and serpentine separates (C) from the Erro-Tobbio metaperidotite and eclogitized metagabbro. The shaded vertical fields represent the primary isotopic ratios in unaltered mantle rocks and in mantle clinopyroxenes (Chazot et al., 1993).

The Northern Apennines

Introduction to the geology of the Northern Apennines

The Northern Apennine region is formed by the Late Oligocene-Miocene stacking of tectonic units belon-

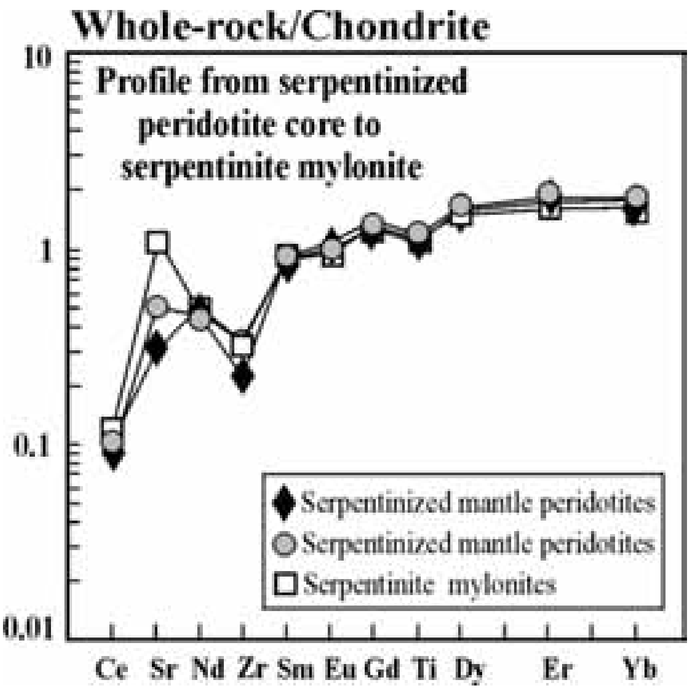


Figure 10 - Bulk trace-element compositions of samples in profiles from serpentinized mantle peridotite to serpentinite mylonite.

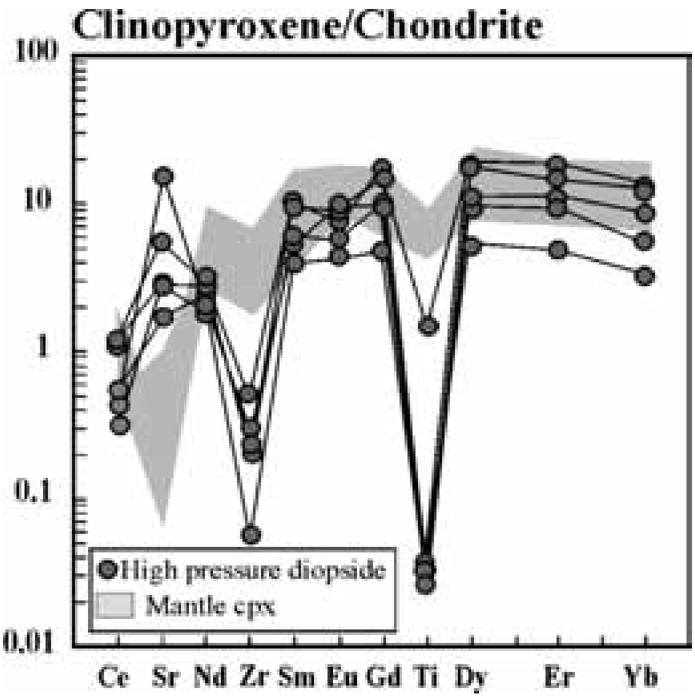


Figure 11 - Trace element compositions of clinopyroxenenes from the Erro-Tobbio peridotite. Grey dots: high-pressure diopside from host rocks and veins. Shaded field: reference mantle clinopyroxenes.

ging to two main systems:
- the lowermost Tuscan units, derived from continental domains and formed by sedimentary and meta-sedimentary 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 its 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 (IL) and the External (EL) 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

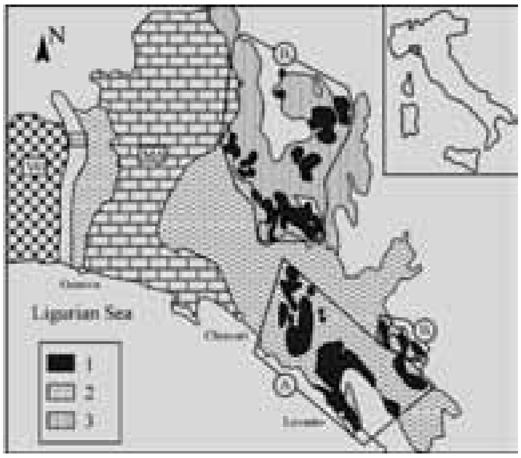


Figure 12 - Geologic sketch map of the Northern Apennines (Eastern Liguria) with indication of the main ophiolitic bodies. VG: the Voltri Group. SV: the Sestri-Voltaggio Units. MA: the Mt.Antola Formation and Mt. Caio flysch (calcareous sandy turbidites with interbedded shales). (1) Ophiolites (peridotites, gabbros and basalts); field A: Internal Liguride ophiolites; fields 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.

(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 (Marroni et al., 1998 and references therein).:

1) the Western External Liguride Domain, characterized by units containing ophiolites (MORB-type basalts and mantle peridotites occurring as olistoliths, slide blocks and tectonic slices in the basal complex) and ophiolite-derived debris, which are associated with continental mafic and felsic granulites, and granitoids.

2) the Eastern External Liguride Domain, characterized by units containing fragments of mesozoic sedimentary sequences and conglomerates with Austro-Sudalpine or Insubrian affinity, without ophiolites. This evidence indicates the presence of a thinned continental crust representing the westernmost 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 EL Domains and the ubiquitous presence of the Late Cretaceous-Paleocene Helminthoid Flysch, suggest the transition between a thinned continental crust (Eastern EL 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 the slicing and inversion of the EL Domain. The Mesoalpine deformation in the Liguride Units involved early west-verging, large scale folding and thrusting. The Mesoalpine deformation wasfollowed by large-scale backthrusting, gravitational spreading and extensional tectonics associated with east-directed tectonic transport. The subsequent large scale deformational history of the Apennines 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 due to the underthrusting of the External Tuscan Domain.

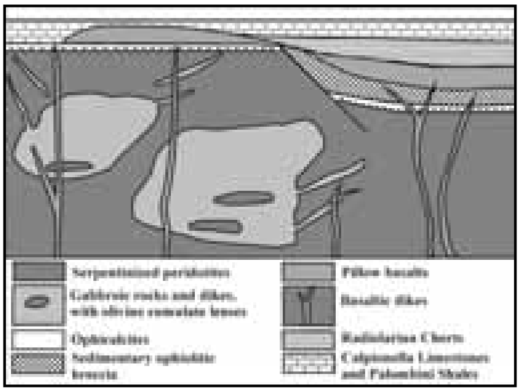


Figure 13 - Stratigraphy and internal structure of the Northern Apennine Ophiolites. Hypothetical cross section showing the main stratigraphic and structural features of a typical Internal Liguride ophiolite section: it shows the sea-floor exposure of mantle paridotites, with an uppermost level of ophicalcite3s, which have been intruded by small gabbroic bodies. The mafic-ultramafic basament is discontinuously covered by ophiolitic breccias, pillowed basalts and oceanic sedimentary cover (i.e. Radiolarian Cherts, Calpionella Limestones and Palombini Shales).

The Northern Apennine Ophiolites

A representative sampling of the diversity of the oceanic lithosphere which floored the Jurassic Ligurian Tethys is shown by the Northern Apennine ophiolites (Fig.13). In the IL Units, ophiolites 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 evidence indicate that mantle peridotites were intruded by gabbroic bodies at depth. Subsequently, the peridotite-gabbro association experienced a tectonic-metamorphic decompressional evolution, as testified by deformation and recrystallization along shear zones: this 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.

In the EL Units, ophiolites consist of mantle peridotites and MORB-type pillowed basalts, and are associated with continental crust material (Marroni et al., 1998, and quoted references). Thus, 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 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).

Mantle peridotites
The mantle protoliths

The EL peridotites crop out as km-scale bodies which largely preserve mantle textures and assemblages, despite widespread serpentinization. They are dominantly fertile spinel lherzolites with granular to tectonite-mylonite textures. Pyroxenite bands, mainly consisting of spinel-bearing Al-augite clinopyroxenites and Cr-diopside websterites, are common within the peridotites. The EL peridotites display rather fertile compositions. This is indicated by: (1) lherzolitic modal compositions (clinopyroxene up to 10-15 % by volume), (2) relatively high bulk rock Al_2O_3 (2.86-4.00%) and CaO (2.33-3.39%) contents (Fig. 14), (3) clinopyroxene REE spectra, showing only moderate LREE depletion and absolute concentrations at 10-16 x C1 (Fig. 15A), (4) the high Na, Ti,

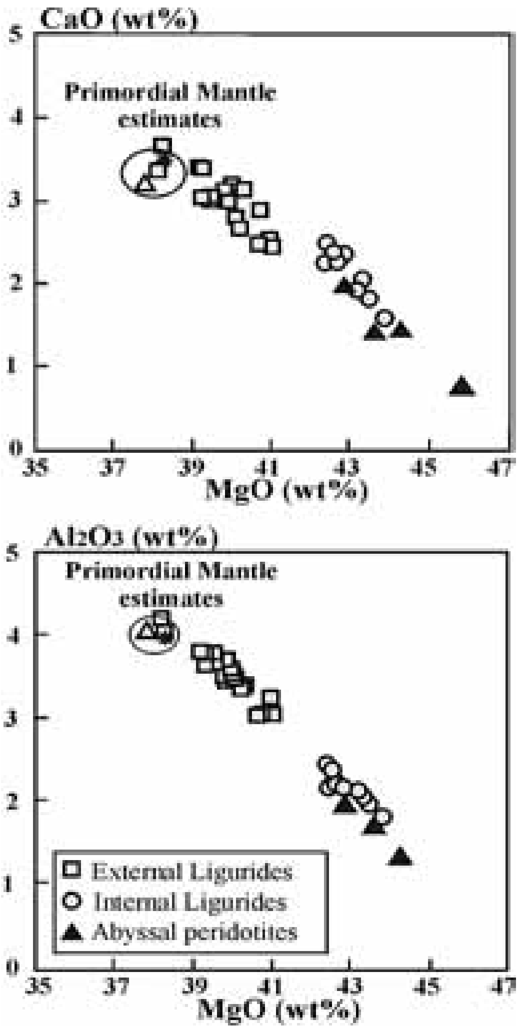


Figure 14 - Whole rock abundances of CaO and Al2O3 versus MgO for the Internal and External Liguride peridotites (data from Rampone et al., 1995, 1996; all data on anhydrous basis in wt.%). Primordial mantle estimates are from Hofmann (1988) and Jagoutz et al. (1979). The representative compositions of abyssal peridotites are from Dick (1989).

Sr and Zr contents in clinopyroxenes and whole rocks (Ernst and Piccardo, 1979; Beccaluva et al., 1984; Ottonello et al., 1984; Rampone et al., 1993; 1995).

The EL lherzolites display a complete static equilibrium recrystallization under spinel-facies conditions. Disseminated kaersutite/Ti-pargasite amphiboles occur in equilibrium with the spinel-bearing assemblage: they 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 fair agreement with thermometric estimates (T in the range of 1000-1100 °C). The presence of LREE-depleted, Ti-rich amphibole is an ubiquitous feature of many subcontinental lithospheric peridotites (Piccardo et al., 1991b; Vannucci et al., 1995; Ionov et al., 1997; and quoted references).

The spinel-facies recrystallization in a rather "cold" (T<1100°C) thermal regime represent the annealing recrystallization after accretion of the 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 for the EL peridotites are shown in Fig. 16. As a whole, they plot within the depleted end of the MORB field, similar to many subcontinental orogenic spinel-lherzolites from the western Mediterranean area (e.g. the Pyrenees and Lanzo North peridotites). One sample, in particular, displays an extremely depleted isotopic composition ($^{87}Sr/^{86}Sr = 0.701736$; $^{143}Nd/^{144}Nd = 0.513543$).

Similar, exceptionally low, Sr ratios have been also measured in the Lanzo North and Pyrenean peridotite massifs (see Fig. 16), and have been considered to reflect a very long time of isolation from the convective mantle and incorporation into the subcontinental lithophere. This is supported by model age calculations (Fig. 17). Most EL peridotites display Nd model ages (assuming a CHUR mantle source) in the range of 1.9-1.7 Ga (Fig. 17), and consistent results are obtained with Rb-Sr systematics (Rampone et al., 1995). Moreover, the single sample with extremely depleted isotopic composition yields Sr and Nd model ages of 2.1 and 2.4 Ga (assuming a DM and a CHUR mantle source respectively) (Fig. 17A): these can be considered as minimum ages of differentiation form the asthenospheric mantle. The coupling of high $^{143}Nd/^{144}Nd$ (>0.51310) and rather low $^{147}Sm/^{144}Nd$ (0.22-0.30) ratios is a peculiar feature of many subcontinental peridotites (see the data for Lanzo N, Ronda, and Pyrenees in Fig. 17A), and it bears witness of ancient

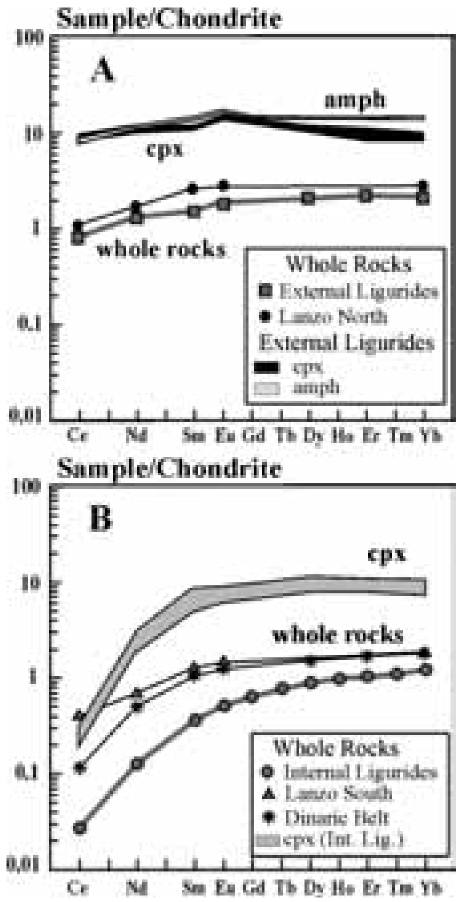


Figure 15 - Representative chondrite-normalized REE compositions for: (A) whole rock, clinopyroxenes (cpx) and pargasitic amphiboles (amph) from the External Liguride peridotites (data from Rampone et al., 1995); we have also reported, for comparison, a representative whole rock composition for the Lanzo 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).

(usually Proterozoic) depletion events. Proterozoic ages of lithospheric accretion of the EL mantle have been also indicated by Re/Os isotopic investigations (Snow et al., 1999).

The IL peridotites consist of clinopyroxene-poor (5-10 vol%) spinel-lherzolites. IL peridotites display depleted compositions: their bulk rock MgO, CaO and Al_2O_3 contents are comparable to those of abyssal peridotites (see Fig.14). The REE spectra are strongly fractionated and display extremely low LREE absolute concentrations. Geochemical modeling indicates that their compositions are consistent with mantle residua after low-degree (<10%) fractional melting (Rampone et al., 1996).

The present-day Sr and Nd isotope ratios of the IL peridotites are shown in Fig. 16. Their $^{87}Sr/^{86}Sr$ ratios (0.702203-0.702285) 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. Their high Nd ratios are coupled to very high $^{147}Sm/^{144}Nd$ ratios (0.54-0.56): this is shown in the $^{147}Sm/^{144}Nd$ versus $^{143}Nd/^{144}Nd$ diagram of Fig. 18A, where the IL ultramafics are compared with other depleted peridotites of the Western Alpine belt (e.g. the Lanzo South, Bodinier et al., 1991, and Balmuccia, Ivrea Zone, Voshage et al., 1988). It is noteworthy that the IL samples display the most "extreme" Nd isotope compositions.

As discussed in Rampone et al., (1996) (1998), such compositions are not consistent 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 also been inferred for the Balmuccia peridotites (Voshage et al., 1988) (see Fig. 18A).

Asthenospheric mantle upwelling and melting during

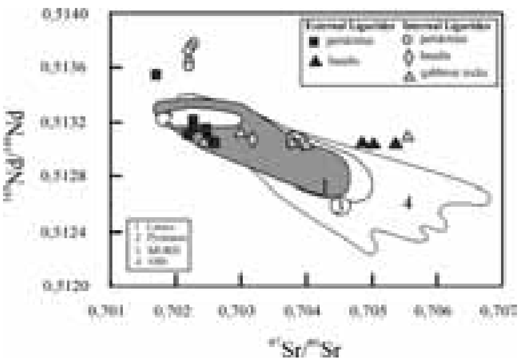


Figure 16 - Present-day $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram for the Northern Apennine (IL and EL) peridotites and basalts, and for the IL gabbroic rocks (data from Rampone et al., 1995, 1996, 1998. Fields refer to clinopyroxene data for peridotites from: (1) Lanzo (Western Alps, Bodinier et al., 1991), (2) Pyrenees (Downes et al., 1991). Also shown are the fields for MORBs (3) and OIBs (4) (from Hofmann, 1997).

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 (Piccardo et al., 1994; Rampone et al., 1996, 1998; 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 framework 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 of 1150-1250 °C (Beccaluva et al., 1984; Rampone et al., 1996).

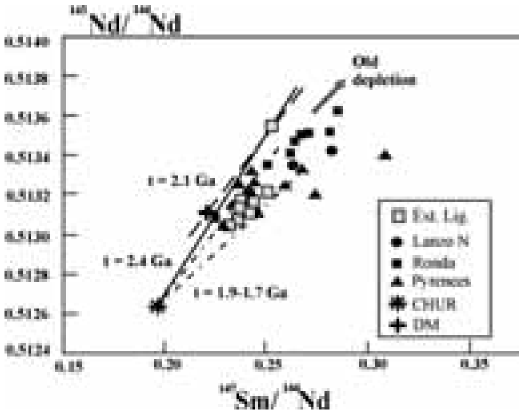


Figure 17 - (A) $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ diagram for the External Liguride (Ext. Lig.) peridotites (data from Rampone et al., 1995), compared with data from other subcontinental orogenic peridotites (Ronda, Reisberg et al., 1989; Pyrenees, Downes et al., 1991, Mukasa et al., 1991; 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). (B) $^{187}Os/^{188}Os$ versus Al_2O_3 diagram for the External Liguride peridotites (whole rock data; from Snow et al., 1999). We have also reported the fields relative to the compositions of the Ronda (Reisberg and Lorand, 1995) and Pyrenee (Reisberg and Lorand, 1995; Burnham et al., 1998) peridotites, as they both define strong positive correlations which yield ages of 1.9 ± 0.3 Ga (Pyrenees) and 1.3 Ga (Ronda) for the isolation of these peridotites from the convective mantle and incorporation into the subcontinental lithosphere.

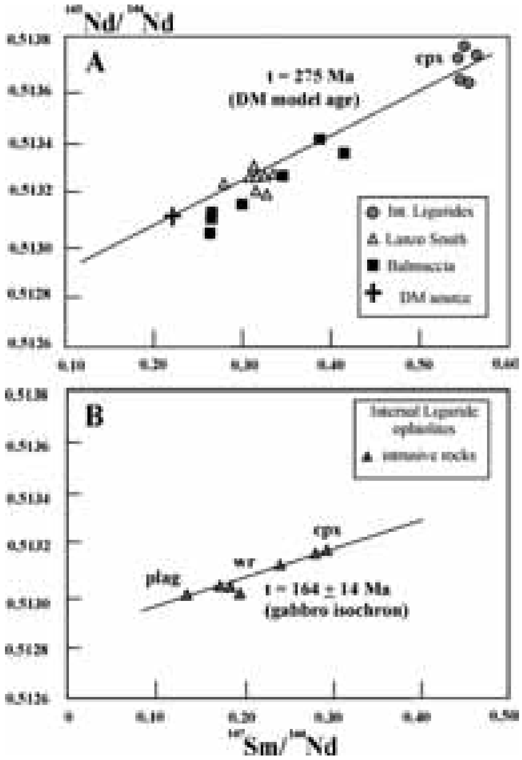


Figure 18 - $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ diagram for: (A) the Internal Liguride peridotites (data from Rampone et al., 1996), compared with data from the Balmuccia (Ivrea Zone, Voshage et al., 1988) and Lanzo South (Bodinier et al., 1991) peridotites. All data refer to clinopyroxene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

The early decompressional evolution

The EL peridotites show the effects of subsequent tectonic and metamorphic evolution, i.e. widespread partial recrystallization from spinel- to plagioclase-bearing assemblages, and progressive deformation leading to the development of porphyroclastic textures and tectonite to mylonite fabrics, in kilometer-wide shear zones (Beccaluva et al., 1984, Piccardo et al., 1990; Rampone et al., 1993, 1995). The spinel- to plagioclase-facies transition is reflected by peculiar microstructures: i) large exsolution lamellae of orthopyroxene and plagioclase within spinel-facies clinopyroxene, ii) plagioclase rims around spinel and plagioclase + olivine coronas between spinel and pyroxenes, and, iii) granoblastic domains consisting of olivine + plagioclase + neoblastic pyroxenes. This recrystallization is accompanied by significant mineral compositional variations, i.e. a decrease in Al, Na, Sr, Eu/Eu* and an increase in V, Y, Sc, Cr, Zr and Ti in clinopyroxene, a decrease in Al and an increase in Cr, Ti in spinel, a decrease in Eu/Eu*, Sr and Ba and an increase in Zr and V in amphibole. According to mass-balance calculations, within-mineral major and trace element redistribution occurred in a closed system, due to the spinel- to plagioclase- subsolidus transition (Rampone et al., 1993). This is consistent with relatively low temperatures (T=900-950°C) obtained for the plagioclase-facies metamorphic recrystallization (Beccaluva et al., 1984; Rampone et al., 1995). Sm/Nd data on plagioclase-clinopyroxene pairs from the plagioclase-facies assemblage yield ages of about 165 Ma for this metamorphic recrystallization (Rampone et al., 1995).

The melt impregnation

Recent field studies evidence the presence in the EL peridotite bodies of large areas showing plagioclase enrichment and anastomosing networks of channels and dm-scale bodies of spinel dunites. Ongoing petrologic-structural and geochemical investigations (Piccardo et al., 2004) evidence that the plagioclase enrichment is due to impregnation (reactive porous flow migration and interstitial crystallization) of a percolating exotic melt, showing MORB affinity and pyroxene saturation, whereas the spinel dunite channels are replacive in origin, and were formed by melt/peridotite interaction (pyroxenes dissolution and olivine crystallisation) along preferential conduits through the peridotites.

Melt impregnation in the EL peridotites is evidenced by (Piccardo et al., 2004):

1) peculiar microtextures, i.e. presence of: i) unstrained olivine rims surrounding exsolved mantle pyroxenes; ii) plagioclase, clino- and orthopyroxene blebs or veins along grain boundaries or crosscutting strained mantle minerals; iii) corrosion of deformed mantle olivine and partial replacement by undeformed orthopyroxene crystals; iv) undeformed, granular gabbroic microdomains and veinlets, mainly made of plagioclase+orthopyroxene+clinopyroxene;

2) significant enrichment of mantle and magmatic pyroxenes in many trace elements (i.e M-HREE,Ti,Sc,V,Zr,Y), with respect to porphyroclastic pyroxenes in the spinel lherzolites and to clinopyroxenes in equilibrium with MORB melts. Enriched clinopyroxenes show convex-upward REE patterns with a significant REE enrichment (MREE up to 30xC1),

and both ortho- and clinopyroxenes frequently show a negative Eu_N anomaly. Mantle and magmatic orthopyroxenes show similar trace element enrichment as clinopyroxenes.

The IL peridotites too show clear microtextural and chemical records which indicate melt impregnation and interaction of the peridotite matrix with percolating melts (Rampone et al., 1997; Piccardo et el., 2004):

1) peculiar microtextures, i.e. i) unstrained plagioclase and orthopyroxene blebs along grain boundaries or crosscutting deformed mantle minerals; ii) orthopyro xene+plagioclase intergrowths which partially replace deformed and exsolved mantle clinopyroxenes;

2) chemical modification in mantle clinopyroxenes (i.e. Ti, M-HREE,Zr,Y,Sc enrichment, coupled to Al depletion) when reacting with the impregnating melts.

Microtextural and chemical features suggest a deeper melt/peridotite interaction, leading to pyroxene dissolution and olivine precipitation [peridotite depletion and melt orthopyroxene(-silica)- saturation], followed by a shallower interstitial crystallization of the upward migrating melts, leading to peridotite impregnation [peridotite refertilization] (Piccardo, 2003; Piccardo and Müntener, 2003; Piccardo et al., 2004).

Rampone et al. (1997) inferred that melts entrapped in the IL and Corsica peridotites most likely consisted of depleted single melt fractions produced by fractional melting on an asthenospheric mantle source. Melt impregnation can be related, as in the case of the Corsica and Lanzo ophiolitic peridotites (Rampone et al., 1997; Piccardo, 2003; Müntener and Piccardo, 2003) to the partial melting of the rising asthenosphere, which occurred during the lithosphere extension (i.e. exhumation of the mantle lithosphere), and to the upward migration through the lithospheric mantle column of the asthenospheric melts.

The late decompressional evolution and sea-floor exposure

The subsequent retrograde evolution of the EL peridotites, which ended with the sea-floor emplacement, is documented by the development of amphibole-bearing assemblages and later widespread serpentinization, and by the intrusion of chilled basaltic dikes crosscutting the mantle tectonite and mylonite fabrics (Piccardo et al., 1990). The IL peridotites, after the early Permian partial melting and subsequent spinel-facies annealing recrystallization during accretion to the lithosphere, underwent progressive exhumation and melt impregnation, and were later intruded by gabbroic bodies. Peridotites and gabbros experienced tectonic-metamorphic retrograde evolution, from upper amphibolite to greenschist-facies conditions (Beccaluva et al., 1984; Rampone et al., 1996), and sea-floor exposure, which is documented by the widespread serpentinization and rodingitization.

The gabbroic rocks

Gabbroic rocks mostly occur as intrusive bodies and dikes in the peridotites, and are more frequently found in the Internal Liguride sequences (Serri, 1980; Hebert et al., 1989; Piccardo, 1995; Tiepolo et al., 1997; Tribuzio et al., 2000a). The gabbroic rocks are volumetrically dominated by olivine-bearing (5-15 %) gabbros, which are commonly coarse-grained, nearly isotropic with a subophitic texture. The olivine-bearing gabbros contain lenticular bodies (tens of meters in size) of troctolites to spinel-bearing melatroctolites (Bezzi and Piccardo, 1971; Cortesogno et al., 1987; Molli, 1995). Fe-Ti-rich rocks are also present and mostly represented by Fe-Ti-oxide-bearing (up to 15 %) gabbors and diorites. Intermediate gabbroic rocks (gabbronorites) and highly evolved hornblende-bearing diorites to albitites occur locally.

Northern Apennine ophiolitic intrusives represent the cumulate products at different stages of low-pressure fractionation of tholeiitic MORB parental magmas (Beccaluva and Piccardo, 1978; Serri, 1980; Hebert et al., 1989; Piccardo, 1995; Tiepolo et al., 1997; Tribuzio et al., 1999; 2000a) (Fig. 19A). $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of whole rocks and mineral separates from IL ophiolitic gabbros (Rampone et al., 1998) are consistent with typical MORB compositions; Sm/Nd data on an olivine gabbro define an internal isochron, giving an age of 164 $\pm$ 14 Ma and an initial ε_{Nd} = 8.6 (see Fig. 18B). As a whole, the lithostratigraphic and petrological features of the gabbroic rocks from the Northern Apennine ophiolites are closely similar to those of the gabbroic rocks recovered from modern slow-spreading ridges, such as the Southwest Indian Ridge (ODP Hole 735B; Ozawa et al., 1991, and Hebert et al., 1991), the Mid Atlantic Ridge (MARK area; Ross and Elthon, 1997), and the Mid-Cayman Rise (Elthon, 1987). In particular, clinopyroxenes from the gabbroic rocksof the Northern Apennine ophiolites show marked trace element zonings that are most likely related to the entrapment of interstitial liquid, similarly to what was observed for the gabbroic rocks from ODP Leg 153 in the MARK area (Ross and Elthon, 1997). However, as clearly documented in Figure 18B, the Internal Liguride gabbroic

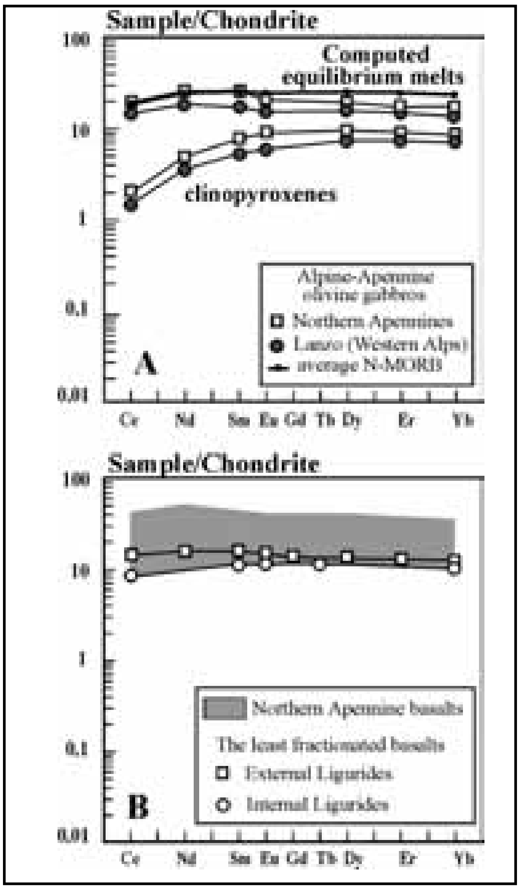


Figure 19 - Chondrite-normalized REE abundances for: (A) representative clinopyroxenes in ophiolitic olivine gabbros from Lanzo, Western Alps (Bodinier et al., 1991) and the Northern Apennines (Rampone et al., 1997; Tribuzio et al., 1999). Also shown are the compositions of computed equilibrium melts (calculated using $D_{cpx/melt}$ partition coefficients from Hart and Dunn, 1993), and an average composition for the N-MORB (from Hofmann, 1988); (B) representative whole rock data for the least fractionated IL and EL basalts (data from Ottonello et al., 1984 and Vannucci et al., 1993a, respectively). The field represents the entire range of compositions defined by the Northern Apennine basalts (in both External and Internal Units) (data from Ottonello et al., 1984; Venturelli et al., 1981; Vannucci et al., 1993a; Marroni et al., 1998; Rampone et al., 1998).

rocks and peridotites do not fall on the same linear array, thus indicating that peridotites and associated gabbroic rocks are not linked by a simple residua-melt relationship, as is expected in a mature oceanic lithosphere (Rampone et al., 1998). As already outlined for the peridotites, the gabbroic rocks record a low-pressure tectono-metamorphic evolution, characterized by a 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 an 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 exhumation 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 are abundant in both the EL and IL ophiolites; they mostly occur as pillow or massive lava flows, and as discrete dikes intruding deformed gabbros and mantle peridotites. Petrologic and geochemical studies devoted to the Alpine-Apennine ophiolitic basalts have provided clear evidence of their 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). As a whole, the IL and EL basaltic rocks display a large degree of differentiation; this is demonstrated by their REE compositions, which range from about 10xC1 to more than 40xC1 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 and HREE abundances at about 10xC1, whereas even the least differentiated EL basalts display almost flat or slightly LREE-enriched REE spectra (Fig. 19B). Whole-rock and clinopyroxene-trace-element chemistry indicate that the compositions of the most primitive EL and IL basalts are consistent with melts generated by varying degrees of fractional melting (totalling no more than 10%) of a MORB-type asthenospheric spinel-facies mantle source (Vannucci et al., 1993a). The MORB affinity of the Northern Apennine ophiolitic basalts has been confirmed by their fairly homogeneous $^{143}Nd/^{144}Nd$ ratios, ranging 0.513046-0.513098 (Rampone et al., 1998).

U/Pb dating of zircons in acidic differentiates (plagiogranites and albitites), which occur as veins or dikes and are considered, on the basis of structural evidence, to be almost contemporaneous with the basaltic volcanism, have yielded ages in the range of 150-160 Ma (Bortolotti et al., 1991, 1995; Borsi et al., 1996; Ohnenstetter et al., 1981; Costa and Caby, 1997). This age is consistent 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.

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 peculiar stratigraphy of the Alpine-Apennine ophiolites led researchers to propose various genetic models: 1) the transform fault model (Gianelli and Principi 1977, Lemoine, 1980; Weissert and Bernoulli 1985), 2) the slow-spreading ridge model (Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990, Lagabrielle and Lemoine, 1997), and 3) the low-angle detachment fault model (Lemoine et al. 1987, Froitzheim & Eberli 1990, Piccardo et al. 1990,1994, Froitzheim & Manatschal 1996). The subcontinental origin of the mantle peridotites from the Ligurian ophiolites, stressed by some authors (Decandia and Elter, 1969, 1972; Piccardo, 1976), outlined the diversity of the Alpine-Apennine ophiolites compared with mature oceanic lithosphere formed at mid-ocean ridges of modern oceans. Based on the atypical association of MORB magmatism and fertile subcontinental mantle, it was suggested (Piccardo, 1977; Beccaluva and Piccardo, 1978) that the Ligurian ophiolites were formed during early stages of the opening of the oceanic basin, following rifting, thinning, and break-up of the continental crust, and were therefore located in a marginal, peri-continental position of the Jurassic oceanic basin.

Recent petrologic and isotope investigations on the mantle ultramafics 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 (Rampone et al., 1998). It has been definitively 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 Northern Apennine ophiolites therefore represent the spatial association of older (Proterozoic and Permian) subcontinental mantle peridotites, 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 Northern Apennine ophiolites most likely represent lithological associations which are expected to develop after the breakup 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.

Formation and evolution of the ligurian oceanic lithosphere

Ophiolites exposed along the Western Alpine - Northern Apennine orogenic belt represent the oceanic lithosphere of the Ligurian Tethys ocean which separated, during Late Jurassic - Cretaceous times, the European and Adria continental blocks. These ophiolites are characterized by: i) dominant fertile, cpx-rich, mantle lherzolites, while more depleted peridotites are subordinate; ii) gabbroic intrusives and basaltic volcanites with MORB affinity. Stratigraphic-structural evidence points to the Ligurian Tethys being floored by a peridotite-gabbro basement, subsequently covered by a discontinuous layer of pillowed basaltic flows and radiolarian cherts. Palaeontological ages of the radiolarian cherts and isotopic

(U/Pb) zircon ages of acidic differentiates, linked to the basaltic volcanites, concordantly indicate a Late Jurassic (160-150 Ma) age for the inception of the oceanic stage. The EL fertile mantle peridotites show Sr/Nd model ages indicating a minimum Proterozoic ages of differentiation and accretion to the Europe-Adria subcontinental lithosphere, where the ultramafics underwent complete equilibration at a temperature below 1100°C, under spinel-facies conditions. The IL residual mantle peridotites are interpreted as refractory residua formed by partial melting of an asthenospheric MORB-type mantle source sand show Permian (290 Ma) Sr/Nd model ages for this melting event. The intrusives rocks (ultramafic cumulates, Mg-Al-gabbros, Fe-Ti-gabbroids and plagiogranites) show clear MORB affinity: available geochronological data indicate variable intrusion ages, ranging from about 185 Ma (some EL gabbros) to about 160 Ma (some IL gabbros). 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 exhumation of the ET and EL peridotites indicate that lithospheric extension of the Europe-Adria continental lithosphere and asthenospheric upwelling were already active in late Palaeozoic times.

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 breakup 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. Oceanic serpentinization was heterogeneous, and led 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 part in controlling its behaviour during later Alpine convergence and subduction. Serpentinization did not produce significant changes in the major and REE compositions of the primary ultramafic rocks, but was accompanied by an uptake of trace amounts of marine Sr, Cl and alkalis. Serpentinization enacted 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 the HP event (i.e. formation of olivine+antigorite+ diopside+Ti-clinohumite assemblages), accompanied by partial dewatering, which led to fluid production.

Mafic rocks at this stage developed different peak assemblages depending on their bulk rock compositions and on their pre-subduction evolutions:
- garnet+rutile+omphacite (Fe-Ti-rich metagabbros);
- garnet+chloritoid+omphacite+zoisite+talc (Mg-rich metagabbros);
-grossular+zoisite+chlorite+diopside (rodingites);
-Ti-clinohumite+ diopside+chlorite+magnetite (Mg-enriched metagabbros).

The pressures and temperatures of eclogitic recrystallization range from P>13 Kbar and T in the range of 450-500°C in the Beigua Unit, to P 20-25 Kbar and T 550-650°C in the Erro-Tobbio Unit.

Antigorite survived HP 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 hypersaline fluid inclusions inside these minerals, indicate that besides water, the eclogitic fluid contained oceanic Sr, chlorine and alkalies. This has significant implications on the global cycling of exogenic fluid and elements via serpentinites at mantle depths.

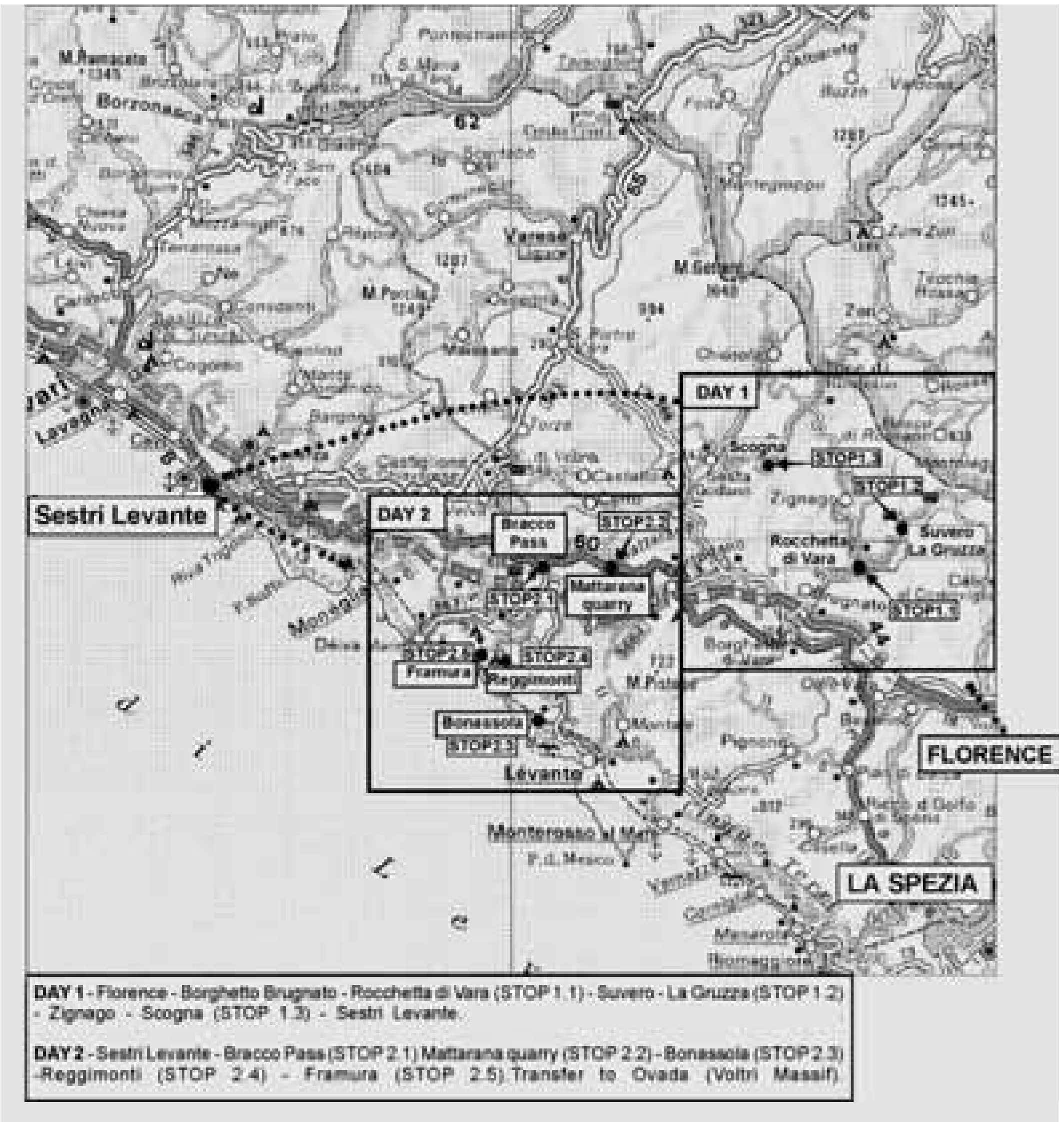
Field Trip Itinerary

DAY 1

Itinerary: Florence – Borghetto Brugnato – Rocchetta di Vara (STOP 1.1) – Suvero – La Gruzza (STOP 1.2) – Zignago – Scogna (STOP 1.3) – Sestri Levante.

Stop 1.1

- Rocchetta di Vara.



"Reduced" Internal Liguride sequence: radiolarian cherts and gabbroic breccia.

This site shows an overturned sequence formed by serpentinized mantle peridotites, ophicalcites, ophiolitic breccias (called M. Zenone Breccia), cherts, Calpionella limestones and Palombini shales.

The road cuts across an almost vertical section of reddish radiolarian cherts, which represent the first oceanic sedimentation in the Ligurian Tethys. Along the small brook the radiolarian cherts are in sedimentary contact with originally underlying gabbroic breccias (Mt. Zenone breccia), made of pebbles and boulders of variable size (from centimeters to meters) of gabbro. Up on the hill the gabbro breccia stratigraphically overlie a serpentinite unit presenting, at its uppermost part, an ophicalcite level. The interposition of basaltic volcanites between serpentinized mantle peridotites and oceanic sediments is lacking. The cherts are currently quarried for Mn-ores deposits.

This stratgraphic sequence is one of the most typical for the Internal Liguride terrains, where serpentinized mantle peridotites are directly overlain by ophiolitic breccias and oceanic sediments, without the interposition of basaltic volcanites: this indicates the direct exposure of upper mantle rocks at the sea-floor during the Jurassic ocean opening. The gabbroic rocks in the Mt. Zenone breccia are mainly composed of coarse-grained-to-pegmatoid olivine-bearing clinopyroxene gabbro, generally isotropic and rarely foliated. Primary minerals are generally replaced by low-grade minerals, but clinopyoxene is sometimes still preserved. The reddish patches correspond to pre-existing olivine, currently replaced by calcite + hematite. Some of the gabbro clasts show evidence of high temperature shearing.

The sedimentary contact with the overlaying cherts is attested to by the intercalation of arenitic ophiolitic debris within the ribbon cherts, which have revealed a palaeontological age of 150-160 Ma.

Stop 1.2:

La Gruzza (Suvero) (twenty-minute walk in a pine wood). A typical External Liguride lherzolite body.

The La Gruzza ultramafic body covers a surface of about 3 square Km and represents a huge olistolith within the basal section of the Mt. Caio flysch sequence. It mainly consists of banded tectonite spinel (sp)-lherzolites with sp-bearing pyroxenite layers.

These mantle lherzolites are characterized by abundant pyroxenes (opx about 25%, cpx about 15%) and preserve sp-bearing assemblages and equilibrium granular textures. A Ti-pargasitic amphibole is widespread, particularly close to the pyroxenite bands, showing equilibrium texture within the sp-facies minerals. Thermometric data indicate about 1000°C for the spinel-facies recrystallization.

Based on their mineral assemblage and chemistry (i.e. abundant Al-rich sp and cpx), pyroxenite layers (Al-Di type) can be interpreted asdeep-seated crystallization of basaltic melts.

The fertile character of the La Gruzza lherzolite is stressed by the major element composition of the bulk rock,(Al_2O_3 3.55-3.58 wt%, CaO 3.17-3.22 wt%, Na_2O 0.20-0.25 wt%) and the constituent spinel-facies minerals: olivine (Fo 90), clinopyroxene (Al_2O_3 7.50 wt%, Cr_2O_3 0.78 w%, Na_2O 0.94 wt%), orthopyroxene (Al_2O_3 6.45 wt%, Cr_2O_3 0.55 w%) and spinel (Al_2O_3 48.57 wt%, Cr_2O_3 52.64 w%).

Similar to the bulk rocks, the spinel-facies clinopyroxenes have nearly flat REE patterns at about 15xC1, only slightly fractionated for the LREE. The spinel-facies Ti-pargasitic amphibole is characterized by relatively high Ti (TiO_2 3.20 wt%) and REE contents and spectra similar to those of the coexisting clinopyroxenes. As for the Sr and Nd isotopic composition of separated clinopyroxenes, La Gruzza lherzolite is peculiar among the External Liguride peridotites: they show extremely depleted isotopic compositions ($^{87}Sr/^{86}Sr$ = 0.701736; $^{143}Nd/^{144}Nd$ = 0.513543), and plot, on an extension of the oceanic mantle array, towards residual mantle composition. Such low values are unusual for Phanerozoic mantle rocks, and bear some similarities to values of peridotite xenoliths from Proterozoic continental lithosphere: moreover, such extremely-depleted Sr-isotopic compositions have never been observed in oceanic basalts. Model ages have been calculated, assuming either a primitive (CHUR) or a depleted (DM) mantle source, and yield Sr and Nd Proterozoic model ages (2.1 and 2.4 Ga, respectively): these can be considered as minimum ages of differentiation from the asthenospheric mantle and of accretion to the lithospheric mantle. This peridotite body, in particular, provides the strongest evidence that the EL peridotites are actually subcontinental lithospheric mantle.

On the outcrop the peridotite shows a tectonite fabric due to strong plastic deformation effects and incipient recrystallization to plagioclase (pl)-bearing granoblastic assemblages. Plagioclase-facies clinopyroxenes show compositions lower in CaO (21.05 wt%) and Na_2O (0.70 wt%) than spinel-facies ones and plagioclases range in composition from An_{45} to An_{70}.

Accordingly, the La Gruzza ultramafic body underwent:

- an early (Proterozoic) accretion to the subcontinental lithosphere and subsolidus recrystallization at lithospheric mantle conditions (spinel-facies and T=1000°C), consistent with the geotherm of a conductive continental lithosphere;
- a late a not adiabatic exhumation from lithospheric mantle depth to shallow levels, most probably during the lithosphere extension leading to the opening of the Jurassic Ligurian Tethys.

Stop 1.3:

Scogna.

Internal Liguride ophiolitic intrusives: ultramafic olivine cumulates.

The road cuts through a large outcrop of gabbroic rocks pertaining to the Internal Liguride Units. Mg-gabbroic rocks are the dominant lithotypes and are mainly represented by troctolites and olivine-bearing clinopyroxene-gabbros. Sporadically they show poorly developed layered textures and variable grain size. A small body of ultramafic cumulates crops out in a deserted quarry: the cumulate textures are made up by cumulus euhedral olivines and chromites, surrounded by interstitial-to-poikilitic plagioclase and subordinate clinopyroxene. Chromite+olivine cumulates represent the first crystallization products during the low-pressure crystal fractionation of MOR-type tholeiites, which are the parental magmas of the Liguride ophiolitic intrusives.

Bulk rock compositions of the ultramafic cumulates are characterized by relatively high MgO (36.04-36.60 wt%) contents, and low silica (37.27 wt%), Al_2O_3 (4.84-5.35 wt%) and CaO (1.94-2.10 wt%) contents: they, moreover, show very low contents in incompatible elements and high concentrations of Ni (1276-1334 ppm) and Cr (1900-2942 ppm). They display very low REE concentrations (< 1xC1), almost flat LREE patterns and strong positive Eu anomalies (Rampone et al., 1998) . Early minerals in the ultramafic cumulates are highly magnesian: cumulus olivine has Fo contents in the range of 87-89, interstitial clinopyroxene ha Mg number in the range of 89-90, coupled with relatively high Al_2O_3 (3.7-4.4 wt%) and Cr_2O_3 (1.28-1.64 wt%).

Bulk rock and clinopyroxene separates give quite homogeneous $^{143}Nd/^{144}Nd$ ratios (0.513037-0.513171), which are consistent with typical MORB compositions. Moreover, the clinopyroxene from an ultramafic cumulate plot along the internal Sm-Nd isocrhron of 164 +/- 14 Ma defined by whole rock and mineral separates of a olivine-gabbro sample from the Bracco-Massif (IL ophiolites) (Rampone et al., 1998).

DAY 2

Itinerary: Sestri Levante - Bracco Pass (STOP 2.1) - Mattarana quarry (STOP 2.2) - Bonassola (STOP 2.3) - Reggimonti (STOP 2.4) - Framura (STOP 2.5). Move on to Ovada (the Voltri Massif).

The main aim of this day's excursion is to visit outcrops of gabbroic intrusives and basaltic volcanites with MORB affinity to the ophiolites from the Internal Liguride Units of the Northern Apennines. Attention will be also given to the primary relationships between Permian mantle peridotites, Middle Jurassic gabbros and Late Jurassic basalts, in order to distinguish some specific features of the Ligurian ophiolite sequence, i.e. the intrusive relationships of gabbroic rocks into mantle peridotites and the primary stratigraphic relationships between underlying mantle peridotites, strongly brecciated in their uppermost part (ophicalcites), and MORB pillowed lavas flows.

The sea-floor exposure of pre-Triassic subcontinental mantle, and its primary association with younger and genetically-unrelated MORB magmatism, is a typical feature of the Internal Liguride ophiolites. It indicates that subcontinental mantle peridotites were progressively uplifted during the rift stages, preceeding the Late Jurassic oceanic formation, were intruded by basaltic magmas with MORB affinity during the pre-oceanic rifting, and were tectonically denudated and exposed at the sea-floor before extrusion of MORB volcanites.

The presence of subcontinental mantle peridotites at the sea floor during ocean formation has been related to the passive extension of the lithosphere which was responsible for the pre-oceanic continental rifting and the opening of the Ligurian Tethys ocean.

Stop 2.1:

the Bracco Massif.

Internal Liguride Mg-gabbros and basaltic dikes.

Internal Liguride gabbroic rocks crop out as km-scale bodies and discrete dikes intruded into mantle peridotites. The ophiolitic intrusives are products of low-pressure fractional crystallization of parental tholeiites with MORB affinity. The crystallization order is: Cr-Mg spinel + olivine, plagioclase, clinopyroxene $\pm$ orthopyroxene, Fe-Ti oxides. The rock sequence is: ultramafic olivine cumulates, Mg-gabbros (troctolites, olivine-bearing gabbros and minor orthopyroxene-bearing gabbros), Fe-Ti-gabbros (Fe-Ti-oxide-rich gabbros to diorites), and acidic differentiates (amphibole-bearing diorites to albitites).

The road cuts through a large outcrop of gabbroic rocks: Mg-gabbros are the dominant lithotypes and are mainly represented by troctolites and olivine-bearing gabbros. Sporadically they show poorly developed layered textures (from plagioclase-poor to plagioclase-rich layers) and extremely variable grain size. At the Bracco Pass, along the roadcut, layered and isotropic gabbros are exposed. The outcrop is disturbed by some faults which put in contact a layered olivine-rich gabbro-troctolite sequence with an isotropic olivine-bearing gabbro The isotropic olivine-bearing gabbros contain pegmatoid patches and are crosscut by basaltic dikes showing chilled margins. The isotropic olivine-bearing gabbro is relatively fresh and shows a well-evident crystallization order, i.e. euhedral plagioclase (55-60 % by volume) and olivine (about 10%), and subhedral, locally poikilitic, clinopyroxene (30-35 %). Olivine is commonly altered to low-temperature minerals, whereas clinopyroxene and, in places, plagioclase preserve their primary magmatic compositions. Plagioclase is moderately anorthitic (An% = 60.7-62.5), and clinopyroxene di-

splays relatively high Mg numbers (Mg* = 86-88) and moderate Al_2O_3 (3.06-3.88 wt%) and Cr_2O_3 (0.57-1.25 wt%) contents. The bulk rock gabbro composition is characterized by relatively high Ni (198 ppm) and Cr (994 ppm) contents, higher than common basaltic rocks. Its REE concentrations do not exceed 2-3xC1 values, and show sligh LREE depletion and moderate positive Eu anomaly (Rampone et al., 1998).
Bulk rock and separated clinopyroxene and plagioclase give rather homogeneous initial $^{143}Nd/^{144}Nd$ ratios (0.513009-0.51318), which are consistent with typical MORB compositions. Moreover, whole-rock and mineral separates yield an internal Sm-Nd isochron of 164 $\pm$ 14 Ma.
Interestingly, the Sm-Nd compositions of whole rocks and one clinopyroxene separate from some ultramafic cumulate samples (from the Mattarana quarry, next Stop) plot along this linear array. The above data thus indicate that the analyzed Internal Liguride ophiolitic intrusives were generated in Middle Jurassic times from MORB-type parental melts.
The basaltic dikes are almost aphyric, showing a few altered plagioclase phenocrysts. The groundmass is ophitic and still contains relics of clinopyroxene. The almost vertical basaltic dike has been analyzed for bulk-rock major and trace element and Sr-Nd isotopic compositions (Rampone et al., 1998). It shows an olivine-tholeiite composition, a relatively flat REE pattern, at absolute values of about 20xC1, slightly fractionated for the LREE, $^{87}Sr/^{86}Sr$ = 0.703206 and $^{143}Nd/^{144}Nd$ = 0.513098. Isotope compositions confirm a clear MORB-affinity: in the $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram, it plots in the MORB field. The gabbroic rocks locally show an early, incipient reequilibration under high-temperature conditions: metamorphic clinopyroxene, brown horneblende and calcic plagioclase form granoblastic aggregates at the expenses of the igneous minerals. In many places of the Bracco Massif, the high-temperature assemblages are associated with strong plastic deformation generally restricted to narrow shear bands. This deformation-recrystallization event occurred before the intrusion of the basaltic dikes.
Gabbros and basalts later underwent a low-grade metamorphic recrystallization (subgreenschist-facies conditions), ascribed to sea-floor alteration. In particular, dikes and Mg-gabbros are crosscut by veins and fractures filled with prehnite ± chlorite ± albite ± calcite. Prehnite and albite also commonly develop in the gabbroic rocks at the expense of igneous plagioclase, whereas olivine is altered to chlorite and tremolite/actinolite (± serpentine) and clinopyroxene is in places replaced by tremolite/actinolite (Messiga and Tribuzio, 1991).

Stop 2.2:
Mattarana Quarry.
Ultramafic olivine cumulates.
A small lens of ultramafic cumulates (clinopyroxene-bearing melatroctolites) within Mg-gabbros crops out in an unused quarry. The cumulate texture is made of cumulus euhedral olivines and chromites, surrounded by interstitial plagioclase and subordinate huge (cm-scale) poikilitic clinopyroxene.
A large block in the quarry preserves cumulus textures and shows igneous layering, made by grain-size variations of the cumulus olivine. Thin levels of chromite grains parallel the layering plane and huge poikilitic clinopyroxene crystals are commonly present.
A large portion of the outcrop is characterized by a pegmatoid texture, in which olivine (5 to 30 cm in size) shows a peculiar skeletal (fish-bone or christmas-tree) habit. Skeletal olivine consists of sets of parallel lamellae derived from one general form that is made up of two series of parallel lamellae symmetric to a central lamella, with an angle of about 50° between the central lamella and the oblique set of lamellae (Bezzi & Piccardo, 1971). The origin of these skeletal olivines could be related to a decreasing diffusion rate and an increasing growth rate, as it is commonly found in rapidly cooling magmas.
Bulk rock compositions of the ultramafic cumulates are characterized by relatively high MgO (36.04-36.60 wt%) contents, and low silica (37.27 wt%), Al_2O_3 (4.84-5.35 wt%) and CaO (1.94-2.10 wt%) contents. Moreover these rocks show very low contents in incompatible elements and high concentrations of Ni (1276-1334 ppm) and Cr (1900-2942 ppm). They display very low REE concentrations (<1xC1 chondrite concentration), almost flat LREE patterns and markedly positive Eu anomalies (Rampone et al., 1998).
Mafic minerals from the ultramafic cumulates are highly magnesian. Cumulus olivine has Fo contents in the range of 87-89, interstitial clinopyroxene has Mg number in the range of 89-90, coupled with relatively high Al_2O_3 (3.7-4.4 wt%) and Cr_2O_3 (1.28-1.64 wt%) contents. Bulk rock and clinopyroxene separates give quite homogeneous $^{143}Nd/^{144}Nd$ ratios (0.513037-0.513171) which are consistent with typical MORB compositions. Moreover, they plot along the internal Sm-Nd isochron of 164 + 14 Ma defined by whole rock and mineral separates from the gabbro of the previous stop (Rampone et al., 1998).
Low-temperature mineral transformations are wide-

spread. In particular, plagioclase is invariably replaced by fine-grained aggregates made of prehnite ± chlorite ± hydrogrossular, whereas olivine is partly substituted by serpentine ± Fe-oxides ± chlorite ± tremolite/actinolite.

Stop 2.3:

Bonassola village, near the seaside.
Gabbros with high-temperature shear zones crosscut by hornblende-bearing veins

Our visit winds along the eastern shoreline of Bonassola village. The Bonassola gabbros display intrusive contacts with serpentinized mantle rocks, which crop out along the coast toward Levanto. Both gabbros and serpentinites are covered by ophiolitic mono- and poligenic breccias, or basalt flows. The outcrop consists of gabbros showing crosscutting relations between igneous textures, plastic and brittle deformations. The gabbroic rocks are volumetrically dominated by olivine bearing (5-15 vol%) gabbros, which are commonly nearly-isotropic and with subophitic texture. Plagioclase-rich (up to 80 vol%) pegmatoid patches and small bodies of microgabbro locally occur. Igneous layering, defined by modal and/or grain size variations, is recognizable in some places.
A pervasive, high-temperature foliation at a lower angle than the igneous layering can be observed. The most widespread rock type in these high temperature shear zones is a porphyroclastic mylonite. Dragging of the foliation in high strain zones, asymmetric porphyroclasts and mylonitic folds can be locally recognized. At the microscopic scale, the foliation is defined by recrystallized pyroxene and plagioclase grains, locally associated with accessory titanian pargasite and ilmenite. Arrays of fractures filled with hornblende (± plagioclase) are widespread throughout the area. In addition, there are scattered elongated bodies of hornblende-bearing albitites. Both hornblende veins and albitite bodies locally crosscut at high angles the high-temperature shear zones. The hornblende-bearing veins strike quite uniformely NW/SE and dip steeply to NE and SW. Most veins are nearly planar and range in length from a few millimetres to several metres, whereas their width generally does not exceed a few millimetres. The hornblende veins are mainly of mode-2 (hybrid-type cracks) with no or small displacement. When crosscut by hornblende veins, the igneous clinopyroxene of the wall gabbro is partially replaced by hornblende, due to fluid diffusion away from the fracture (up to a couple of centimetres). This transformation is particularly evident when the hornblende veins crosscut gabbros with pegmatoid texture.
The bodies of hornblende-bearing albitite are up to 0.5 m thick. The albitites are coarse-grained and consist of albitic plagioclase (An ca. 8 mol%) and minor hornblende (not exceeding 15% by volume), both showing euhedral to subhedral habitus, plus accessory Fe-Ti-oxide phases, apatite and zircon. The albitite bodies contain in places fractures filled with coarse-grained hornblende.
Gabbros later underwent a low-grade metamorphic crystallization (greenschist to subgreenschist-facies conditions) ascribed to sea-floor alteration. Fine-grained aggregates of prehnite and albite commonly develop at the expense of igneous plagioclase. This transformation is most likely associated with i) the olivine alteration into chlorite ± tremolite/actinolite ± serpentine, and ii) the local replacement of clinopyroxene by tremolite/actinolite (Messiga and Tribuzio, 1991). Late brittle deformations are attested to by fractures filled with quartz (± Fe-sulphides), which locally reworks the hornblende veins, and by sporadic fractures filled with prehnite (± calcite) crosscutting both hornblende and quartz veins.

Stop 2.4:

Reggimonti: the quarries of "Rosso di Levanto".
Ophicalcites and pillow basalts in primary contact: the Ligurian Moho.

The unused quarry shows the primary stratigraphic contact between underlying serpentinized peridotites (with an uppermost ophicalcite level) and pillow lavas. This sequence is one of the most typical of the Internal Liguride terrains, where serpentinized mantle peridotites are directly overlain by basaltic volcanites: this indicates the direct exposure of upper mantle rocks at the sea-floor during the Jurassic ocean opening and extrusion of MORB basalts.
The ophicalcites reach some tens of meters in thickness and represent an ubiquitous cover of the serpentinite substratum. Owing to the clear sedimentary character of the upper part of the ophicalcites it is evident that the ultramafic rocks were brecciated and widely exposed at the sea-floor prior to basalt extrusion and chert deposition. Ophicalcites (locally known as Levanto breccias, but also by the commercial names of "Rosso" or "Verde Levanto") generally consist of fractured serpentinites (up to a few tens of metres in thickness) disrupted by a polyphase network of calcite veins and breccia wedges. The serpentinite fragments show frequently textural relics of the pristine mantle peridotites. The massive serpentinite becomes progressively more fractured and faulted upwards, where

an upper sedimentary level (Framura Breccia) made of serpentinite clasts within a micrite matrix commonly develop.

The ophicalcites show a complex polyphase evolution, which is characterized by deformations changing from plastic to brittle during progressively lower temperature and pressure conditions (Cortesogno et al., 1987; Molli, 1994b; Treves and Harper, 1994). The overall evolution of the ophicalcite suggests their genesis as fault rocks during the uprise of the mantle toward the ocean floor, and can be reconstructed as follows:

- Intrusion of gabbroic dikes in peridotite;
- Early shearing (T = 850-900°C): mylonitic foliation (Ol + Cpx + Pl ± Ti-Prg in peridotites, and Pl + Cpx ± Ti-Prg in gabbros);
- Onset of serpentinization and second generation of shearing (T< 550°C): mylonitic serpentinite- structures (Serp + Ta ± Tr ± Chl ± Mag) in peridotites and rodingitic mineral assemblages in gabbros;
- Fractures systems: the older veins are filled with serpentine, whereas the most diffused ones contain calcite with less abundant hematite, talc, chlorite, andradite or tremolite.
- Development of sedimentary breccias, neptunian dikes. Hydrothermal phenomena were still active, together with sedimentary reworking.

Many generations of brittle deformation events, characterized by the precipitation of calcite, have been identified by Treves and Harper (1994) on the basis of crosscutting relations, type of filling and structural style. The development of the early calcite veins is associated with the oxidation of magnetite to hematite in the serpentinite, indicating pervasive flow of oxidizing fluids and giving the red colour to the rock. Oxygen and carbon isotope compositions indicate that the calcite precipitation within serpentinized peridotites occurred at temperatures in the orders of 100°C and in the presence of normal seawater (Barrett and Friedrichsen, 1989). These calcite veins are postdated by in-situ breccias that are locally characterized by the occurrence of micrite sediments

The abandoned quarry front shows the direct superposition of pillow lavas over ophicalcites. In the ophicalcites, there are boudinaged gabbro dikes that are crosscut by different generations of fractures filled with calcite. These fractures are not present in the pillow lavas. Along the contact between ophicalcites and pillow lavas, a fault zone characterized by foliated cataclasites can be seen. Shear sense indicators point to a top-to-the-west shearing. Although a possible reworking during orogenic evolution cannot be excluded, the main features of the fault zone can be related to the ocean-floor environment.

Stop 2. 5:

Framura village, near the seaside.
MORB-type basalts in pillows and lava flows.

Along the coast near Framura, basaltic pillow lavas and massive flows crop out. Basalts are dominantly fine-grained and aphyric, with some plagioclase phenocrysts, while flows show a visible grain size and an ophitic texture, made by hydromorphic plagioclase laths and interstitial clinopyroxenes. Plagioclase is always replaced by low-grade minerals (albite, prehnite, hydrogrossular etc.); clinopyroxene is frequently preserved. The rock composition shows rather high MgO (8.30-11.98 wt%) contents relative to typical, fresh tholeiite basalts: these anomalous MgO abundances are coupled with unusually low CaO concentrations (5.12-6.50 wt%). Such major element chemistry (Ca depletion and Mg enrichment) does not reflect primary features and most likely resulted from interaction with seawater. The basalts have almost flat REE patterns and absolute contents up to 30xC1 (Rampone et al., 1998), and plot in the uppermost part of the compositional field defined by the literature data on IL basalts: these features indicate rather evolved compositions. These pillow basalts display quite heterogeneous Sr isotopic compositions: $^{87}Sr/^{86}Sr$ varies in the range of 0.703905-0.705821. The increase of $^{87}Sr/^{86}Sr$ values in rocks which have experienced significant interaction with sea-water is well established in rock from both ophiolites and present oceanic settings. In spite of the observed Sr isotope variability, the basalts have rather uniform Nd isotope ratios ($^{143}Nd/^{144}Nd$ =0.513077-0.513098), which are consistent with typical MORB compositions.

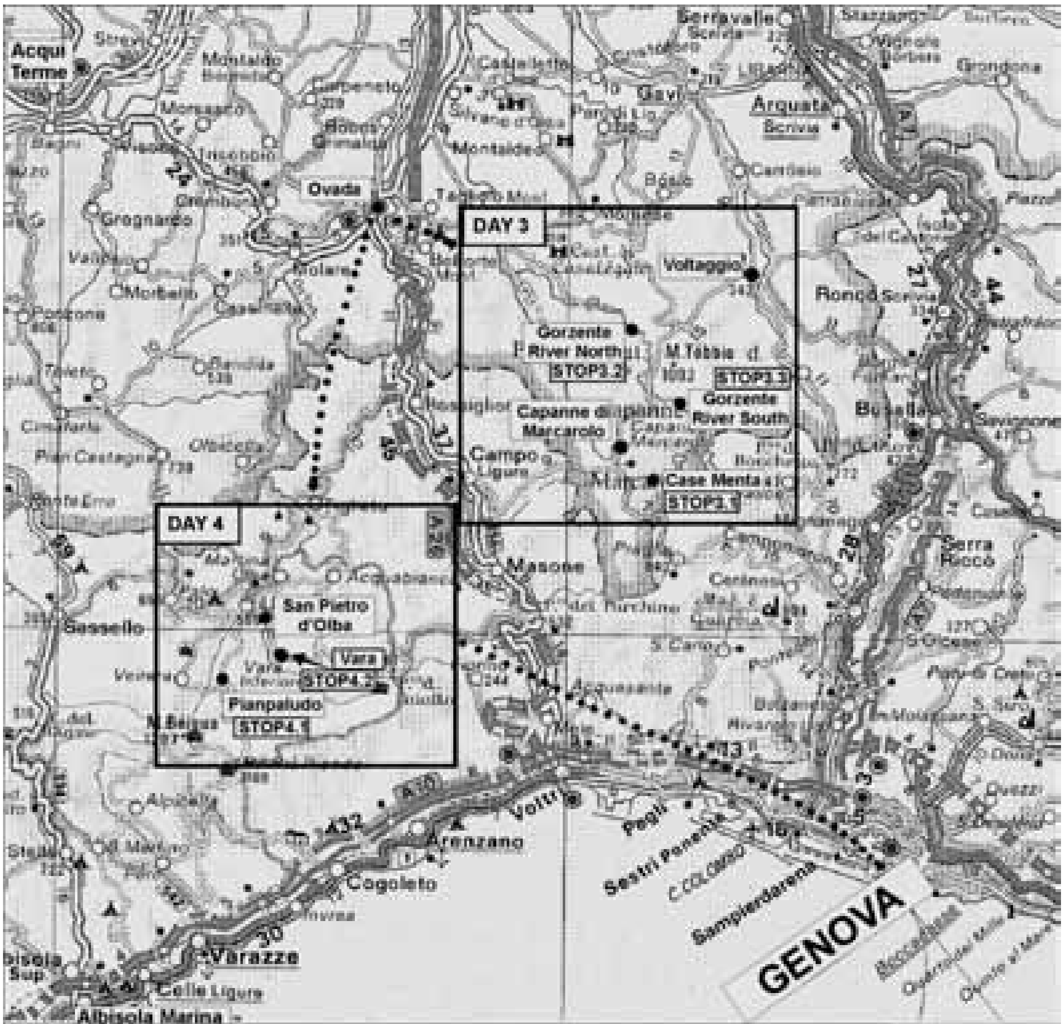
DAY 3

Itinerary: Ovada – Voltaggio – Capanne di Marcarolo – Case Menta (STOP 3.1) – North Gorzente River (STOP 3.2) – South Gorzente River (STOP 3.3) - Ovada.

STOP 3.1 - Case Menta (ten-minute walk down the riverbed south of Costa Lavezzara).

Spinel- and plagioclase-bearing peridotite mylonites.

Detailed mapping of the area of Mt. Tobbio and Mt. Tugello has revealed the presence of km-scale bodies of peridotite preserving spinel-facies assemblage and granular texture, i.e. the oldest paragenetic and textural features of the ET peridotite massif. Granu-



DAY 3 -Ovada - Voltaggio - Capanne di Marcarolo - Case Menta (STOP 3.1) - Gorzente River North (STOP 3.2) - Gorzente River South (STOP 3.3) - Ovada.

DAY 4 - Ovada - Pianpaludo (STOP 4.1) - San Pietro d'Olba - Vara (STOP 4.2) - Genova.

lar spinel-facies peridotites pass to spinel peridotite tectonites, in which the deformed textures overprint the former granular ones.

The granular peridotites exhibit coarse homogeneous grain size (0.5-1 cm) and display an equilibrium spinel-facies assemblage made of olivine, orthopyroxene, clinopyroxene and spinel. Olivine is partly serpentinized, and the most abundant relics are represented by pyroxenes and spinel. Bulk rock chemistry data indicate that the Mt. Tobbio granular peridotites have an overall depleted signature and define large compositional ranges (see Figs. 4 and 5).

However, the comparison between bulk-rock and mineral compositions indicates that the Erro-Tobbio spinel peridotite protoliths (both granular and tectonite types) most likely record a composite history of partial melting and melt migration by reactive porous flow (Rampone et al., 2003a) which occurred prior to the tectonometamorphic lithospheric evolution.

Major (and trace) element compositions of minerals in all the spinel peridotites (both the Mt.Tobbio granular and the Case Menta tectonite-mylonite peridotites) are remarkably similar. In spite of this,, the bulk-rock compositions define striking correlations, i.e. increasing FeO_{tot}, Ni, Co, and decreasing Al_2O_3, SiO_2, CaO, Sc, Cr, Yb_N, with increasing MgO, (see Fig. 4). The bulk rock chemical variations are coupled to systematic modal changes, i.e. a progressive cpx, opx decrease and olivine increase, at increasing bulk MgO. These bulk-rock/mineral compositional contrasts suggest that the Erro-Tobbio spinel peridotite protoliths cannot be simply interpreted as mantle residues after variable partial melting degrees. Instead, they can be explained as resulting from combined histories of partial melting and subsequent melt migration, involving pyroxene dissolution and olivine precipitation reactions (Rampone et al., 2003a). Thermobarometry on the spinel-bearing granular assemblage (T not exceeding 1100°C and spinel-facies pressure conditions) indicates that, after the partial melting vs. melt/peridotite interaction events described above, the ET peridotite underwent subsolidus equilibration at lithospheric mantle conditions. In the Case Menta area, highly deformed peridotites developed in huge shear zones, and the outcrop visited is part of a hundred-metres-thick peridotite mylonite. Vissers et al., (1991) have shown that the mylonite foliation in this area anastomoses around lenticular domains of less-deformed, coarser tectonite..Two types of peridotite mylonites can be distinguished on the basis of stable mineral assemblages during deformation: spinel- and plagioclase-bearing peridotite mylonites. Peridotite mylonites display flattened and elongated pyroxene augens with pressure shadows and finegrained tails defining a fluidal microstructure. The mylonitic microstructures are characterized by intense grain size reduction of olivine from a 500-1500 micron initial grain size to a 10-150 micron recrystallized grain size (Hoogerduijn Strating et al., 1990). Plagioclase peridotite mylonites display plagioclase in fine-grained stripes parallel to the mylonite foliation. In thin section, mylonites frequently show plagioclase grain aggregates as porphyroclasts in the fine-grained olivine matrix. Plagioclase is locally observed in coronas surrounding strongly-deformed spinel grains in domains with a relict tectonite microstructure. Bulk-rock major and trace element data of the Costa Lavezzara spinel and plagioclase peridotite tectonites and mylonites cover the compositional ranges shown by the granular spinel peridotites. The bulk rock REE contents are similarly characterized by almost flat patterns from HREE to MREE (at less than 2xC1) with a significant LREE fractionation. This indicates that deformation of the pristine granular rocks did not induce significant changes in the bulk rock composition. By contrast, mineral chemistry data indicate that the mineral phases changed their compositions during recrystallization from granular and tectonite spinel peridotites to plagioclase peridotite tectonites and mylonites: the compositional changes are indicative of a progressive decrease of pressure and temperature during the tectonic and metamorphic evolution.

Stop 3.2:

North Gorzente River, east of the Guado
(30-minute walk following the path along river).
The Alpine subduction evolution:
high-pressure serpentinite mylonites.

The most important characteristics of these outcrops are represented by mylonitic antigorite-foliations, shear bands and olivine-veins. The serpentine shear zones envelop undeformed and less serpentinized metre-to-kilometre-scale mantle peridotite bodies.

The first outcrop is represented by a peridotite body preserving tectonitic mantle structures and spinel-to-plagioclase paragenesis. Pyroxenite bands also occur, parallel to the tectonitic mantle foliation. This latter is marked by the orientation of clino- and orthopyroxene porphiroclasts and by small spinel crystals. The olivine forms the matrix of these rocks and it is diffusely overgrown by chrysotile and lizardite: the plagioclase grains are overgrown by chlorite micro-aggregates. Acicular antigorite aggregates, metamorphic olivine and Ti-clinohumite occur within the boundaries of a mantle peridotite body, forming from the break-down of mantle minerals and chrysotile, during the Alpine static crystallization.

There is a gradual transition from partially-serpentinized peridotite tectonites to serpentinite mylonites with an antigorite + magnetite $\pm$ chlorite + diopside foliation. This antigorite foliation is cut by olivine shear bands. In thin section, relics of mantle olivine show the blastesis of antigorite+magnetite (related to the development of the serpentinite mylonite) at the expense of precursor mesh-texture chrysotile veins. This indicate that, prior to the development of the serpentinite mylonite, the peridotite underwent static low-temperature serpentinization. After the antigorite +magnetite formation, peridotites were extensively recrystallized to the static climax olivine + Ti-clinohumite + antigorite assemblage, which marks the temperature increase during Alpine subduction.

The serpentinite mylonite is characterized by a foliation defined by alternating antigorite +magnetite and chlorite+magnetite bands. All these phases have an intense shape preferred orientation, parallel to the foliation. Along the foliation relics of clinopyroxene porphiroclasts are replaced by Alpine diopside neoblasts, stable with the mylonitic foliation minerals. Progressive deformation is accompanied by preferential growth of a very fine-grained assemblage of olivine + Ti-clinohumite + magnetite + antigorite ± chlorite along shear bands cutting the mylonitic fabric. The formation of this latter olivine paragenesis is indicative of the Alpine peak temperature in presence of deformation. The subductive peak temperatures occur at high-pressure conditions, as witnessed by the presence of eclogitic meta-gabbros bodies within the Erro Tobbio Unit.

Stop 3.3:

South Gorzente River, road West of Mt. Tobbio (20-minute walk along a foot path down the Gorzente river).

Static recrystallization zone of high-pressure Alpine paragenesis on peridotites and rodingitized gabbros.

In this outcrop, characterized by alpine metaperidotites, 100-metre-scale masses maintain granular textures and mineralogical relics of the mantle protoliths. Peridotites are intruded by mafic dikes. Alpine recrystallization of peridotites occurred in absence of deformation and is accompanied by brittle-deformation originating vein systems. On the other hand, the mafic dikes are rodingitized and display a pervasive metamorphic foliation. The geometric relationship between veins and foliations in the two rock types suggests that during subduction and HP recrystallization, plastic deformation of the mafic dikes was coeval with brittle deformation of the enclosing peridotite. In thin section, the peridotite mantle minerals appear partly overgrown by neoblastic Alpine assemblages. Spinel shows thin coronas of Mg-chlorite; clinopyroxene is replaced along its rims and cleavages by fine-grained diopside, olivine, Ti-clinohumite and subordinated antigorite; coarse mantle olivine is statically overgrown by radial antigorite in textural equilibrium with fine-grained olivine and Ti-clinohumite neoblasts. The coarse mantle olivine relics locally still record a sequence of overprinting serpentine-bearing assemblages: the oldest one is made of chrysotile+m agnetite±brucite developing mesh-textures, the mesh serpentine is in turn cut by veins and microfractures with antigorite and, finally, these structures are cut by fractures containing olivine.

This sequence of assemblages indicates an increase in metamorphic grade and, therefore, a prograde evolution, from the sea-floor partial serpentinization, that culminates in the HP blastesis of olivine + antigorite + Ti-clinohumite + diopside + chlorite. The same peak metamorphic assemblage develops in the vein systems that diffusely cut the peridotite. These veins represent the most evident feature of the Alpine peak metamorphism: they are arranged in en-enchelon systems oriented at high angles to the dikes and running from within the deformed margins of the dikes to the surrounding peridotite wall rock.

The rodingitized mafic dikes likely derive from the pristine Mg-Al and Fe-Ti-gabbros. They show clinopyroxene porphiroclasts in a foliated matrix made of diopside + chlorite + clinozoisite + magnetite. The margins touching the peridotites are marked by foliated walls with Mg-chlorite and epidote. The above assemblage typically forms at HP conditions during recrystallization of mafic rocks which underwent a pre-subduction, most probably oceanic, rodingitization (Ca-enrichment) stage.

Comparable prograde evolution can be observed in a serpentinite mylonite shear zone within the peridotite on the eastern side of the river. In this case olivine + Ti-clinohumite + antigorite shear bands overprint a previous antigorite (olivine-free) shear foliation and point to extreme channelling of plastic deformation along this mylonite horizon during the prograde alpine subduction history. This mechanism of deformation partitioning allowed preservation of large domains where the mantle structures and assemblages have survived due to static and incomplete recrystallization to alpine metamorphic assemblages.

Concerning the P-T conditions of the climax HP recrystallization of the Erro-Tobbio peridotite, information on the confining temperature can be deduced by the stability of antigorite in equilibrium with olivine and Ti-clinohumite, which indicates temperatures in the range of 600-650°C at a pressure higher than 10 kb. More reliable P and T estimates for the HP climax event have been obtained in mafic systems: ET eclogitic metagabbros, which escaped rodingitization and were recrystallized to omphacite + garnet + chloritoid + talc assemblages during the subductive evolution, give pressure-temperature estimates of 20-25 kb and 500-650°C (Messiga et al., 1995).

DAY 4

Itinerary: Ovada – Piampaludo (STOP 4.1) – San Pietro d'Olba – Vara (STOP 4.2) – Genova.

Stop 4.1:

Near Piampaludo village.

Rock talus with blocks of eclogitized Fe-Ti-gabbros and minor basalts.

Fe-Ti-gabbros and basalts develop a Na-clinopyrox ene+garnet+rutile eclogitic assemblage under static conditions. Therefore, the blocks often preserve their primary igneous textures.

Eclogitized Fe-Ti-gabbros clearly display the intrusive fabric, locally pegmatoid. The low-strain transformation of igneous augite+plagioclase+ Fe-Ti-oxides under eclogite facies conditions originates coronitic eclogites. Reaction coronas, outlined by red brownish garnet, occur around coarse dark-green aegirinaugite after igneous augite, fine-grained aggregates of light green omphacite and garnet idioblasts in pseudomorphs after primary plagioclase and purple rutile aggregates after primary Fe-Ti-oxides.

The transition between coronitic and foliated textures is locally detectable. In deformed eclogites, the fine-grained aggregates after primary plagioclase and the rutile aggregates after igneous ilmenite progressively elongate and recrystallize, whereas coarse aegirine, pseudomorphous after igneous diopside, is frequently preserved as porphyroclast. Due to strain gradients, deformed eclogites range from low-strain flaser eclogites to high-strain mylonitic eclogites.

Both deformed and undeformed eclogites are locally cut by veins filled with garnet ($\pm$ omphacite $\pm$ rutile $\pm$ epidote $\pm$ Fe-sulfides). These veins are, in place, conjugated at right angles and are presumably due to syn-eclogitic fracturing.

The eclogitic minerals are partially replaced by different types of retrograde amphiboles, which preferentially grow within the fine-grained domains. Their compositions vary from sodic, to sodic-calcic and to calcic compositions. Retrogression is also shown by the development of amphibole-bearing or epidote-bearing veins crosscutting the eclogites.

Gabbroic eclogites are in places crosscut by fine-grained dark green eclogites. These eclogitized metabasalts are fine grained and shown by glaucophanic amphibole, probably grown together with small atoll-like garnet.

Stop 4.2:

Near Vara village.

Eclogitized Fe-Ti-gabbroic bodies within relic-bearing serpentinite; metarodingite dikes and Ti-clinohumite-bearing dikelets.

This outcrop shows an ultramafic section enclosing dikes and huge intercalations of primary mafic intrusive. Eclogites display a omphacite, garnet, minor rutile, accessory quartz and apatite assemblage which defines a metamorphic layering. Some geochemical features (i.e. relatively high Fe, Ti and low Mg contents) and textural igneous relics indicate a Fe-gabbroic protolith. These rocks underwent a strong eclogitic ductile deformation which produced the main mylonitic fabric. A widespread, partial, post-eclogitic hydration firstly produced glaucophane- and barroisite-bearing assemblages. A later greenschist-facies equilibration is mainly developed along the boundaries of the larger masses. Along the sheared contacts, fibrous serpentine, chlorite, talc and tremolite recrystallized.

Descending the road and leaving the eclogite bodies, a serpentine mass outcrops, which is cut by parallel mafic dikes: a Fe.gabbroic precursor can be inferred for these dikes on the basis of geochemical data such as relatively high Ti, Fe, Zr, Y and low Mg, Cr, Ni contents, and igneous relics of Ti-augite, Fe-Ti ores and, sometimes, apatite. These mafic intercalations are generally characterized by an early metamorphic assemblage with di-rich clinopyroxene+grs-alm-rich garnet, together with chlorite, vesuvianite, epidote and titanite veins.

Metamorphic mineral assemblages and some geochemical characters (i.e. Ca-enrichment and alkalies-Si-depletion compared to normal Fe-gabbroic compositions) indicate thet the magmatic precursors were rodingitized (metasomatized and recrystallized under low grade conditions) before the Alpine orogenic evolution. Later, they were almost completely recrystallized to metarodingites (anhydrous assemblage) under P-T conditions compatible with the Na-clinopyroxene+garnet eclogitic assemblages of analogous lithologies which escaped metasomatism. Sometimes, an incomplete Na-loss during the ocean floor rodingitization is attested to by the small fractions of jd and acm components in the neoblastic di-rich clinopyroxene and by the presence of barroisitic amphibole. A few thin, brown-coloured dikelets are also visible on the outcrop: they are characterized by abundant red-brownish Ti-clinohumite. In thin section, these intercalations still show relics of the primary Fe-gabbroic assemblages, i.e. Ti-augite, ilmenite and apatite. The dominant metamorphic assemblage is characterized by diopside (replacing primary augite)+Ti-clinohumite (rimming augite and ilmenite)+chlorite+antigorite. Antigorite, magnetite and chlorite partly replace Ti-clinohumite. As previously outlined, these thin Fe-gabbroic intercalations appear to have undergone a complete pre-eclogitic plagioclase chloritization, presumably during the low-grade ocean floor rodingitization. Serpentinite shows schistogenous poliphase deformations. Textural and mineralogical relics of primary Al-Cr-diopside, probably related to the upper mantle assemblage, are locally preserved.

After an early event of partial hydration (ocean-floor serpentinization), these rocks suffered a penetrative antigorite shear foliation, cut by shear bands. These bands, which contain olivine + diopside + antigorite + Ti-clinohumite, develop presumably under HP conditions. The pervasive ductile deformation, which led to formation of the antigorite foliation and of the olivine-bearing shear bands, has determined the transposition and boudinage of eclogitic mafic dikes. The later development of antigorite + magnetite + tremolite ± chlorite, at the expense of diopside and olivine, indicates a decompressional exhumation path.

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