Geological Field Trips

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The Ligurian Ophiolites: a journey through the building and evolution of slow spreading oceanic lithosphere

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The Ligurian Ophiolites: a journey through the building and evolution of slow spreading oceanic lithosphere

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Riassunto

Le ofioliti liguri rappresentano una finestra geologica unica e accessibile per ricostruire le prime fasi di formazione ed evoluzione della litosfera oceanica a bassa velocità di espansione. Le ofioliti delle unità liguri interne sono formate da corpi gabbrici di dimensioni chilometriche all'interno di peridotiti di mantello impoverite e presentano chiare analogie con la litosfera oceanica delle dorsali oceaniche a bassa e ultra-bassa velocità di espansione. Le ofioliti delle unità liguri esterne sono associate a rocce di crosta continentale e includono sequenze di mantello di origine litosferica sottocontinentale. Questa escursione geologica consente l'osservazione di alcuni siti più rappresentativi su due associazioni gabbro-peridotitiche delle ofioliti delle unità liguri interne: **i)** l'ofiolite Bracco-Levanto, che contiene un corpo chilometrico di gabbro simile ai "core complexes" dei settori oceanici estensionali moderni (es. Atlantis Massif, Oceano Atlantico); **ii)** l'ofiolite Scogna-Rocchetta Vara, che è caratterizzata dalla mancanza di basalti, come le sezioni non-vulcaniche degli oceani Atlantico e Indiano. Le peridotiti e i gabbri di entrambe queste ofioliti registrano una storia composita di deformazione e alterazione associata all'esumazione verso il fondale oceanico. L'escursione include inoltre alcuni corpi peridotitici delle ofioliti delle liguridi esterne, che rappresentano un eccellente esempio di mantello tipo MORB con diffuse pirosseniti.

Parole chiave: *ofioliti liguri, gabbri, troctoliti, peridotiti di mantello, pirosseniti, deformazione di alta temperatura, idrotermalismo, oficalciti.*

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Abstract

The ligurian ophiolites constitute an accessible and unique window to track the opening and evolution of slow-spreading oceanic lithosphere. The internal ligurian ophiolites consist of km-scale gabbroic bodies intruded into depleted mantle peridotites and bear remarkable structural and compositional similarities to oceanic lithosphere from slow and ultra-slow spreading ridges. The external ligurian ophiolites are associated with continental crust material and include mantle sequences retaining a subcontinental lithospheric origin. This field trip explores two gabbro-peridotite associations from the internal ligurian ophiolites: **i)** the Bracco-Levanto ophiolite, which includes a km-scale gabbroic body recalling the oceanic core complexes from modern spreading centres (e.g. the Atlantis Massif, Atlantic Ocean); **ii)** the Scogna-Rocchetta Vara ophiolite, which lacks the basalt layer similar to the nonvolcanic sections from Atlantic and Indian oceans. The peridotites and the gabbros from both these ophiolites record a composite history involving deformation and alteration from high temperature to seafloor conditions. The field excursion also explores peridotite bodies from the external ligurian ophiolites, representing a nice example of MORB-type pyroxenite-bearing mantle.

Keywords: *ligurian ophiolites, gabbros, troctolites, mantle peridotites, pyroxenites, high-temperature deformation, hydrothermal alteration, ophicalcites.*

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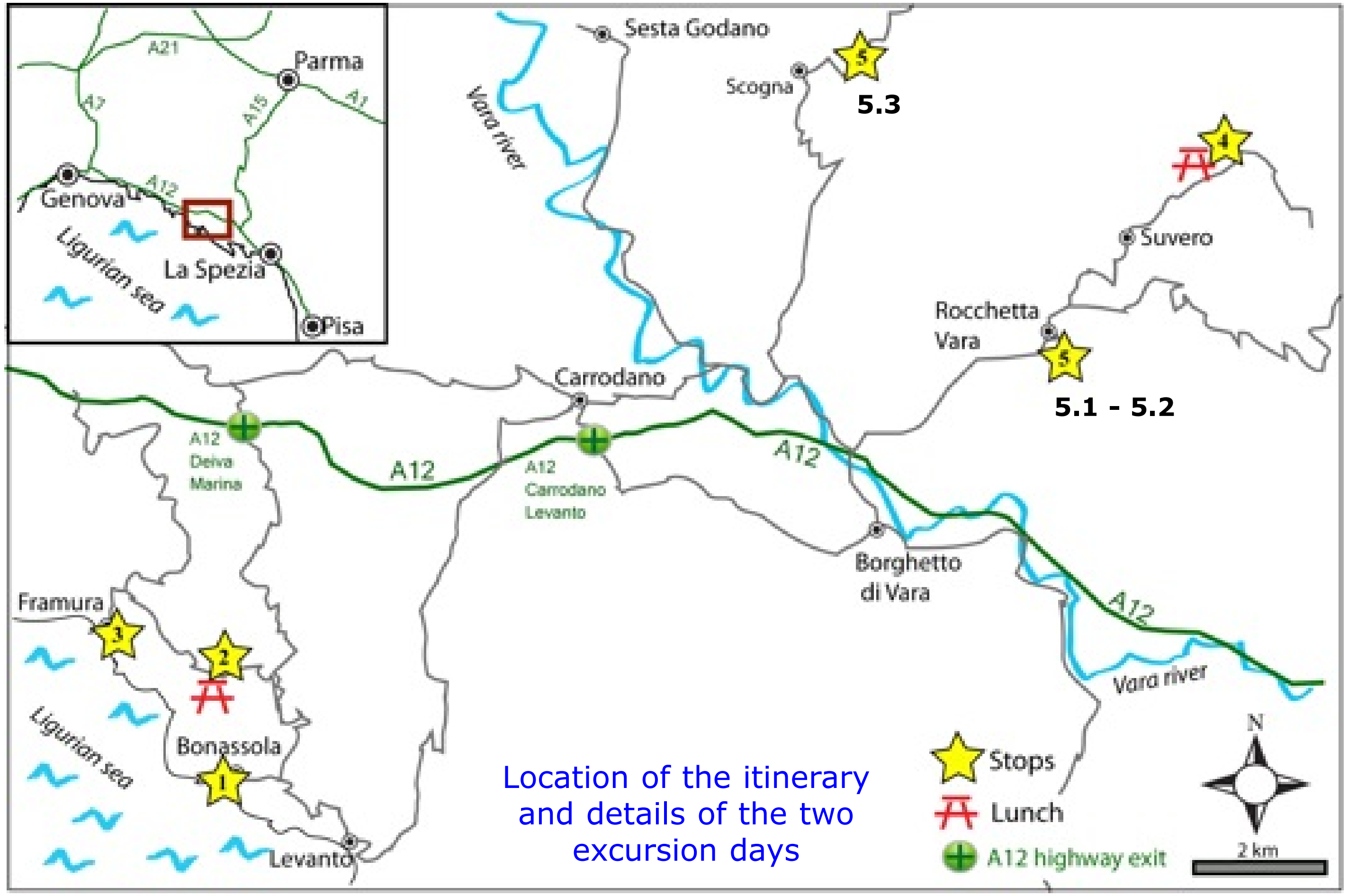
Program

The area covered by the field trip crops out in eastern Liguria, north of La Spezia. The area is located between Vara Valley and the coast north of the wonderful Cinque Terre touristic locality. The area can be easily reached by the A12 highway (Genova-Livorno), at the exit Carrodano-Levanto and Borghetto di Vara. The area can also be reached by train, stopping at the stations of Bonassola or Levanto, on the line Milano-Genova-La Spezia. The excursion starts on the seashore of the Bonassola village, where a gabbro and mantle peridotites can be seen on the two promontories north and south of the beach. After lunch the field trip moves inland, to the "Rosso di Levanto" active quarries of the Reggimonti locality (Stop 2). The day 1 ends at the small Framura village, where pillow lavas are exposed at the cliff, close to a characteristic port. Day 2 explores the Suvero and the Rocchetta Vara localities, in the Vara Valley. At Suvero (Stop 4) exceptionally fresh mantle peridotites from external ligurian units are exposed. At Rocchetta Vara the field trip investigates the relationships between mantle peridotites, a gabbro intrusion and overlying sediments,



Location of the itinerary and details of the two excursion days wonderfully exposed along the road between Rocchetta Vara and Borghetto di Vara and in a inactive quarry (Stop 5.1 and 5.2). The field trip ends at the Scogna locality (Stop 5.3), in a quarry where olivine-rich troctolites and chromitites can be seen. From this Stop it is possible to reach the A12 highway in about 30 minutes.

DAY 1

Altitude: 0-250 m a.s.l. Elevation gain (on foot): ca. 50 m on an steep path along the coast.

Stop 1 - The gabbroic body of Bonassola and its relationships with adjacent serpentinised peridotites.
Stop 2 - Mantle exposure at the seafloor at the active "Rosso di Levanto" quarries.
Stop 3 - MORB-type pillow basalts at the Framura port.

DAY 2

Altitude: 200-900 m a.s.l. Elevation gain (on foot): ca. 50 on a easy path into a pine wood

Stop 4 - Mantle peridotites from external ligurian units.
Stop 5 - The non volcanic ophiolitic sequence of Scogna-Rocchetta Vara.

Safety

Hat, sunglasses and sunscreen are strongly recommended. Depending on weather conditions the path along the coast at Bonassola could be slippery, hiking boots are suggested.

Hospital

Ospedale di Sestri Levante, Via Arnaldo Terzi, 43, 16039 Sestri Levante (Genova).
Tel: +39 0185 4881 (switchboard)

Accomodation

A list of hotels north of La Spezia is available at the following website: www.webliguria.com

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Introduction

The ophiolite bodies of the Alpine-Apennine belt are lithospheric remnants of the Ligurian-Piedmontese (or western Tethys) basin. This basin developed in the Middle to Upper Jurassic in conjunction with the opening of the Central Atlantic Ocean and separated the Europe-Iberia plate to the northwest from the Africa-Adria plate to the southeast (Schettino & Turco, 2011; Vissers et al., 2013). Frequently, the ophiolites from the Alpine-Apennine belt are associated with tectonic slices of continental crust (Marroni et al., 1998; Manatschal & Müntener, 2009; Masini et al., 2013) and/or include mantle sequences retaining a subcontinental lithospheric origin (Rampone et al., 1995; Müntener et al., 2004; Montanini et al., 2006; 2012). These remnants of embryonic oceanic lithosphere are commonly interpreted to have formed at magma-poor ocean-continent transitions similar to the Iberia-Newfoundlands margins. In addition, some of the ophiolites from the Alpine-Apennine belt bear remarkable structural and compositional similarities to oceanic lithosphere from slow and ultra-slow spreading ridges (Lagabrielle & Cannat, 1990; Tribuzio et al., 1995; 1999; Sanfilippo & Tribuzio, 2011). These successions show no relationship with continental material and include mantle sequences mostly consisting of depleted mantle peridotites (Rampone et al., 1996; 1997; 2008; 2009; 2012) intruded by large-scale MOR-type gabbroic sequences (Principi et al., 2004; Menna, 2009; Sanfilippo & Tribuzio, 2013a). These gabbro-peridotite associations were correlated with paleomorphological highs similar to the oceanic core complexes from slow and ultraslow spreading ridges (see also Alt et al., 2012; Schwarzenbach et al., 2012).

Remnants of both embryonic and slow-spreading type oceanic lithosphere are exposed in the tectonic units of eastern Liguria (Northern Apennine, Fig. 1). These ophiolites are found within the ligurian tectonic units, which represent the uppermost nappes of the northern Apennine stack and are subdivided into two main groups (e.g. Marroni et al., 1998). In the external ligurian units, the ophiolites are associated with rocks of continental origin and were attributed to a marginal ocean domain. The ophiolites from the internal ligurian units show no relationship with continental material and were ascribed to an oceanward portion of the Ligurian-Piedmontese basin (Fig. 2). Both the external and internal ligurian units bear evidence of polyphase deformation during the orogenesis that led to their emplacement in the late Oligocene-Miocene (e.g. Marroni et al., 2004). Peak orogenic metamorphism of both the internal and external ligurian ophiolites occurred under prehnite-pumpellyite facies conditions (Lucchetti et al., 1990; Marroni et al., 2002).

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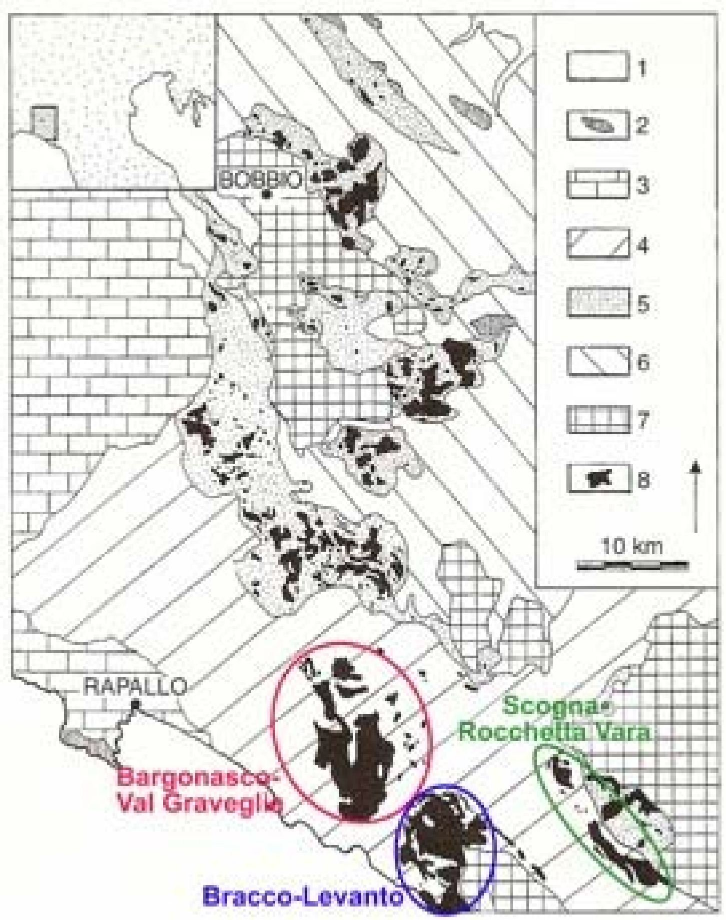

Fig. 1 - Sketch map of the eastern Ligurian Apennine (slightly modified after Marroni & Tribuzio, 1996). **1)** Plio-Quaternary deposits; **2)** Ranzano sequence (late Eocene-early Miocene); **3)** Antola Helminthoid flysch unit (Campanian-Paleocene); **4)** Other internal ligurian units (Middle Jurassic-Paleocene); **5)** sedimentary mélanges of the external ligurian units; **6)** Helminthoid flysch and associated sedimentary sequences of the external ligurian units; **7)** Tuscan and Canetolo units; **8)** main ophiolitic bodies from internal and external ligurian units. Green, red and purple circles indicate the internal ligurian ophiolites.

In the external ligurian units, ophiolite bodies occur as slide blocks (up to km-scale, Marroni et al., 1998), together with slide blocks of continental origin, within Upper Cretaceous sedimentary mélanges. These ophiolites are mostly represented by mantle and basalt flow sequences, with minor gabbros and Middle Jurassic-Upper Cretaceous pelagic sediments. The rocks of the continental crust are essentially peraluminous granitoids, gabbro-derived granulites and lower-crust pyroxenites (Marroni et al., 1998; Montanini & Tribuzio 2001) of late Paleozoic age (Meli et al., 1996; Renna & Tribuzio, 2009). The peraluminous granitoids are locally in primary contact relationships with the ophiolitic basalts and the pelagic sediments (Molli, 1996). Gabbros and basalts from the external ligurian ophiolites show a MOR-type geochemical signature (Tribuzio et al., 2004; Montanini et al., 2008), whereas associated mantle bodies retain a subcontinental lithospheric signature (Rampone et al., 1995). In particular, the external ligurian mantle sequences mainly consist of spinel-plagioclase amphibole-bearing lherzolites, which show a fertile geochemical fingerprint and include abundant pyroxenite layers. These pyroxenites in places preserve relics of garnet facies assemblages, thereby providing evidence that the external ligurian mantle section was once equilibrated at deep lithospheric environments (Montanini et al., 2006, 2012; Borghini et al., 2013). The subcontinental mantle bodies and associated rocks of the continental crust record decompression and retrograde tectono-metamorphic evolutions

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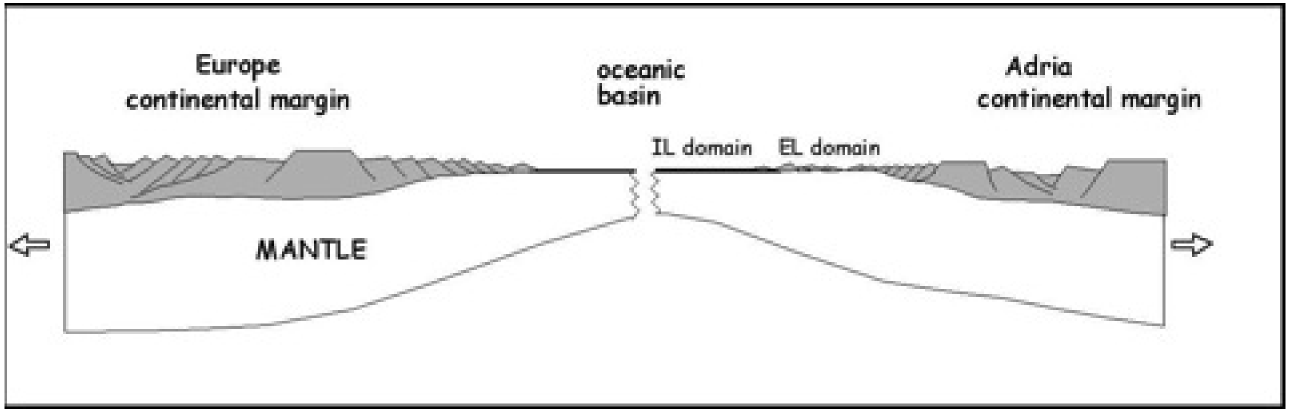

Fig. 2 - Schematic transect of the Ligurian-Piedmontese basin in the Upper Jurassic indicating the position of the Ligurian ophiolites. The ophiolites from external (EL) and internal ligurian (IL) units are attributed to marginal and distal domains, respectively (slightly modified after Marroni et al., 2002).

linked to the rifting process that led to their exhumation in the Middle Jurassic (Rampone et al., 1993, 1995; Renna & Tribuzio 2009; Borghini et al., 2011). The association of ophiolites and continental crust material from the external ligurian units (Fig. 3) is considered a fossil analogue of the Western Iberia ocean-continent transition, in which mantle sequences of subcontinental origin are associated with embryonic oceanic crust and minor tectonic slices of the continental crust (e.g. Péron-Pinvidic & Manatschal, 2008).

In the internal ligurian units, the ophiolite successions crop out as up to 1 km-thick bodies exhibiting a gabbro-peridotite basement covered by a Middle Jurassic to Upper Cretaceous basalt-sedimentary sequence (Principi et al., 2004). The basement consists of up to kilometer-scale gabbroic intrusions into depleted mantle peridotites. The basalt-sedimentary cover commonly exhibits interlayering among MORB-type lava flows, polymittic ophiolitic breccias

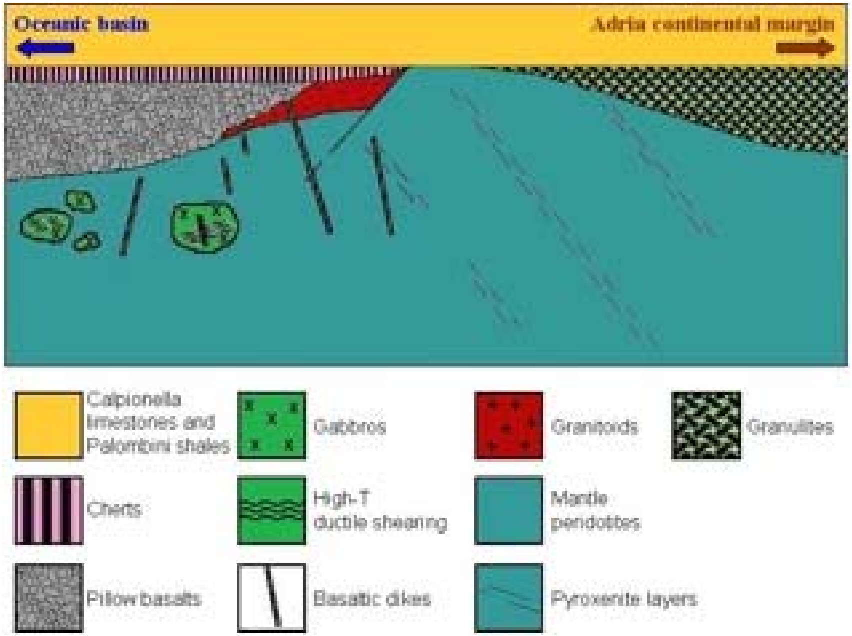

Fig. 3 - Schematic reconstruction of the external ligurian domain of the Ligurian-Piedmontese basin in the Upper Jurassic-Lower Cretaceous (modified after Marroni et al., 1998).

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and Middle to Upper Jurassic radiolarian cherts. The gabbroic intrusions are mostly made up of clinopyroxene-rich gabbros to troctolites, locally interlayered with lenses of olivine-rich troctolites, and show a MORB-type geochemical signature (Tribuzio et al., 1995, 2000a; Tiepolo et al., 1997; Rampone et al., 1998; Renna & Tribuzio, 2011; Sanfilippo & Tribuzio, 2011). The mantle sequences mainly consist of depleted spinel lherzolites showing incipient re-equilibration under plagioclase-facies conditions (Rampone et al., 1996). These mantle sequences represent either asthenospheric material that ascended in response to oceanic spreading, or exhumed subcontinental mantle that experienced thermochemical erosion by the upwelling asthenosphere during rifting (see also Sanfilippo & Tribuzio, 2011; Rampone & Hofmann, 2012).

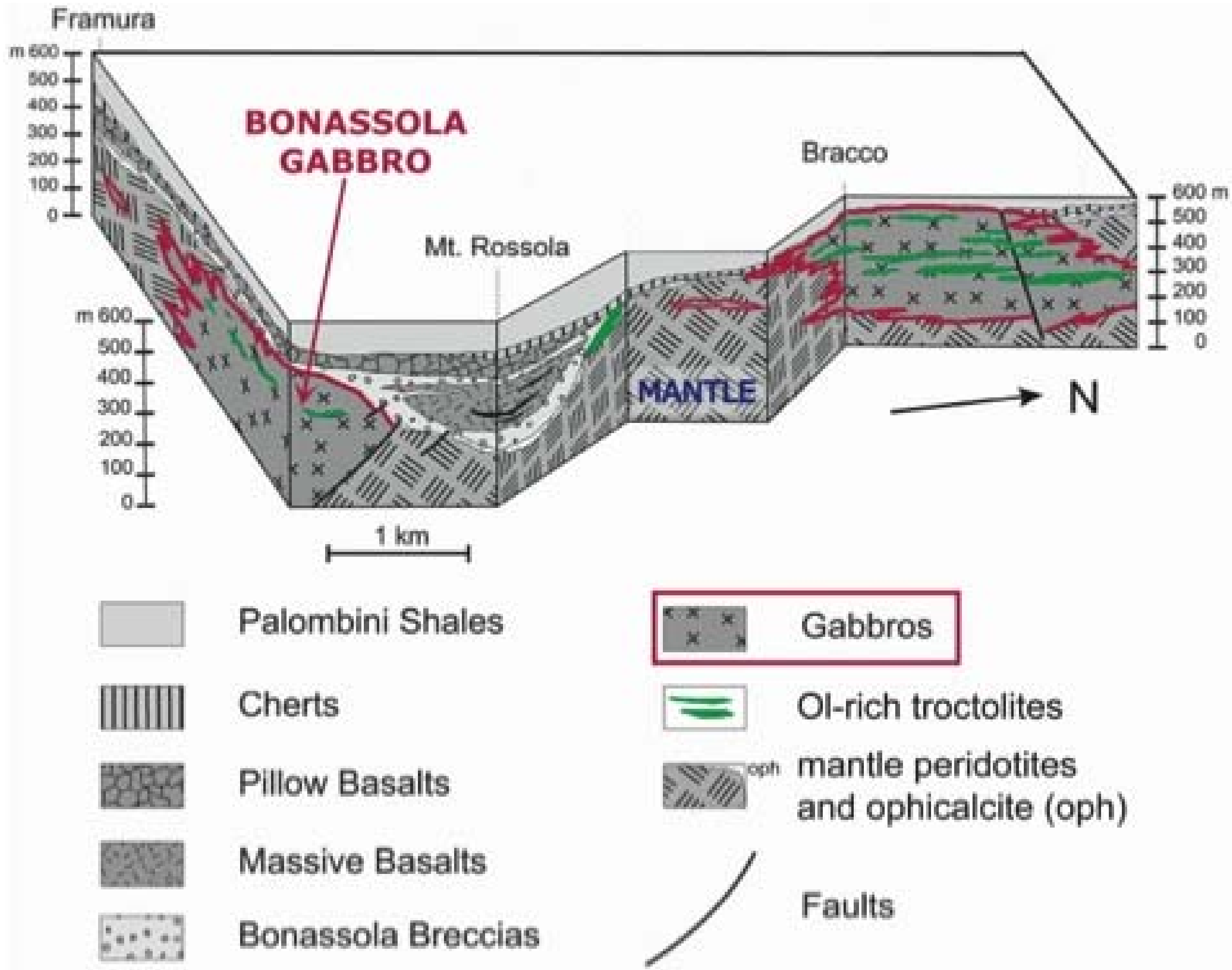

Fig. 4 - Schematic reconstruction of the Bracco-Levanto ophiolite (internal ligurian units) in the Upper Jurassic-Lower Cretaceous. Slightly modified after Principi et al., 2004.

Three major ophiolite bodies are present in the internal ligurian units, namely the Bracco-Levanto, Scogna-Rocchetta Vara and Val Graveglia-Bargonasco ophiolites (Fig. 1). The Bracco-Levanto ophiolite provides evidence for the occurrence of a morphological high in the Ligurian-Piedmontese basin (Fig. 4) represented by a sequence in which the Jurassic basalt-sedimentary cover is lacking and the basement is overlain by Cretaceous

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shaly pelagites (Principi et al., 2004). This paleo-morphological high consists of a gabbroic sequence bearing close compositional and structural resemblances to the sequences from modern oceanic core complexes such as the Atlantis Massif at the Central Atlantic (e.g. Blackman et al., 2006, 2011). The Scogna-Rocchetta Vara ophiolite is characterized by the lack of basalt lava flows (Sanfilippo & Tribuzio, 2011), like the nonvolcanic sections from Mid Atlantic and Southwest Indian ridges (e.g. Dick et al., 2003; Kelemen et al., 2007; Zhou & Dick, 2013). Conversely, the basalt flows in the Val Graveglia-Bargonasco ophiolite form an overall continuous layer within the basalt-sedimentary cover overlying the gabbro-peridotite basement.

The two-day excursion will mainly focus on the relationships between mantle peridotites, gabbros, basalts and sedimentary material in the internal ligurian ophiolites. Specifically, the first day of the excursion will be devoted to the Bracco-Levanto ophiolite. On the second day, will be visited the outcrops of i) the Scogna-Rocchetta Vara ophiolite and ii) of pyroxenite-bearing mantle bodies from the external ligurian ophiolites.

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DAY 1

STOP 1

Stop 1.1 - Bonassola, Punta della Madonnina: clinopyroxene-rich gabbros with pegmatoid lenses and microgabbros.
Stop 1.2 - Bonassola village, near the coast: gabbros with high temperature ductile shear zones crosscut by hornblende veins and albitites.
Stop 1.3 (optional) - Bonassola, "Villaggio la Francesca": serpentinised peridotites of mantle origin with replacive dunites, gabbroic bodies and hornblendite veins.

STOP 2

Reggimonti locality: "Rosso di Levanto" (mantle ophicalcites) active quarries. Mantle exposure at the seafloor (Bracco-Levanto ophiolite).

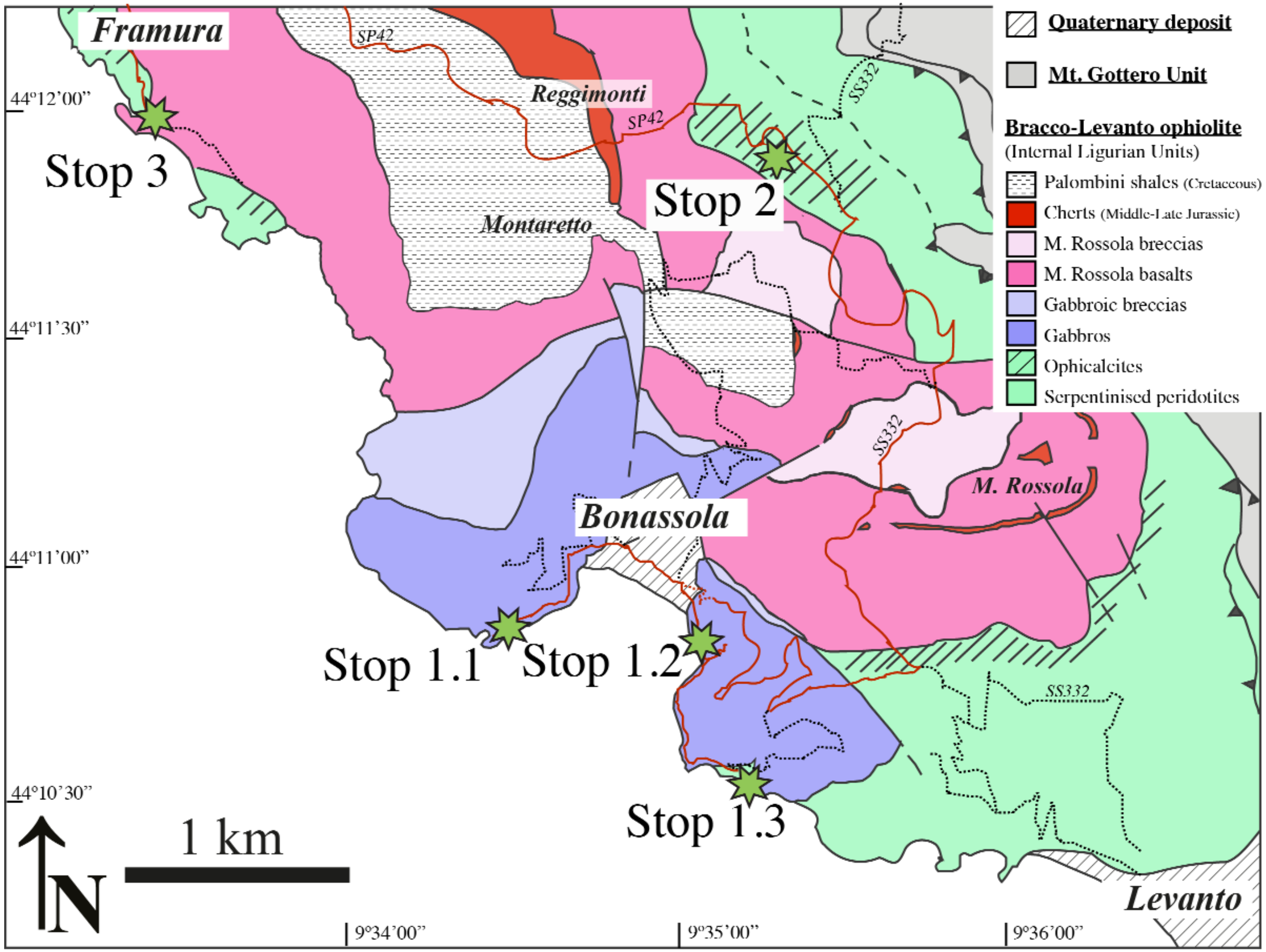

Fig. 5 - Geological map of the Bonassola area (Bracco-Levanto ophiolite, internal ligurian units; redrawn after Molli, 1995). Red lines indicate the itinerary.

STOP 3

Framura village, near the seaside: MORB-type pillow basalts (Bracco-Levanto ophiolite).

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STOP 1: The gabbroic body of Bonassola and its relationships with adjacent serpentinised peridotites (Bracco-Levanto ophiolite)

Along the western and eastern shorelines of Bonassola village a km-scale gabbroic body is exposed (Fig. 5). The gabbro body was variably affected by the polyphase tectono-metamorphic processes associated with its exhumation to sub-seafloor conditions. To the southeast (near Levanto), the Bonassola gabbro is in contact with a km-scale body of serpentinised mantle peridotites (see also Fig. 4). The intrusive relationships of the gabbros within the serpentinised peridotites are locally preserved, although contacts are commonly reworked by late tectonic deformation.

Stop 1.1: Bonassola - Punta della Madonnina, clinopyroxene-rich gabbros with pegmatoid lenses and microgabbros

This outcrop allows us to observe the primary features of the Bonassola gabbro. The gabbroic body essentially consists of coarse-grained clinopyroxene-rich gabbros with a subophitic structure displaying a weakly defined modal and/or grain size layering. These gabbros locally contain minor plagioclase-rich (up to 80 vol%) pegmatoid lenses up to 2 m long (Fig. 6) and elongated microgabbro bodies (up to a few tens of

Fig. 6 - Stop 1.1, pegmatoid gabbro lens within coarse-grained clinopyroxene-rich gabbros.

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meters long and <0.5 m thick) forming low angles with respect to the igneous layering and showing diffuse contacts with the host gabbro (Fig. 7). The microgabbros locally display a magmatic foliation defined by the preferred orientation of plagioclase and clinopyroxene.

The whole-rock chemical compositions of the gabbros do not represent frozen melts. For instance, these rocks have chondrite-normalised REE patterns characterised by a positive Eu anomaly, which reflects a process of plagioclase accumulation. The chemical compositions of the clinopyroxene cores indicate formation by MORB-type melts. The pegmatoid gabbros display the lowest Mg-values, thereby suggesting that they originated from the localized concentration of residual melts. The microgabbros most likely formed from residual melts expelled from the crystal mush as a result of compaction and/or deformation.

Scattered hornblende-bearing (plagioclase) veins crosscut the igneous layering of the gabbroic sequence at high angles. Although most of these veins are thin (commonly <1 mm) and nearly planar, there are also irregular dykelets characterized by a coarse grain size and a high modal proportion of plagioclase. Late cataclastic fault zones characterized by prehnite, calcite, albite and actinolite are present locally; they crosscut the layering of the host gabbro at low angles. These deformation bands are likely linked to the ocean-floor setting.

Fig. 7 - Stop 1.1, diffuse contacts between microgabbro and host coarse-grained clinopyroxene-rich gabbro.

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Stop 1.2: Bonassola village, gabbros with high temperature ductile shear zones crosscut by hornblende veins and albitites

The Bonassola gabbro is here characterized by a pervasive shear foliation forming a low angle with respect to the igneous layering and produces porphyroclastic mylonites to rare ultramylonites (Fig. 8). Ductile shear zones are diffuse in the gabbroic plutons from the internal ligurian ophiolites and commonly have a width from a few decimeters to several meters (Molli, 1996; Sanfilippo & Tribuzio, 2011). The ductile shear zones locally occur in groups, where they form anastomosing patterns characterized by foliated domains around lenses of undeformed or less-deformed host rocks. At the microscopic scale, the foliation is defined by recrystallized clinopyroxene and plagioclase grains, locally associated with accessory titanian pargasite and ilmenite (Fig. 9). Major and trace element mineral compositions indicate that the recrystallization occurred at ~850 °C and in the presence of a volatile-rich phase of igneous origin (Tribuzio et al., 1995; Sanfilippo & Tribuzio, 2011). A second generation of shear zones is locally present in the gabbroic plutons from the internal ligurian ophiolites and is associated with crystallization of horneblende + plagioclase).

Fig. 8 - Stop 1.2, mylonitic fold in a high strain domain of the gabbro body.

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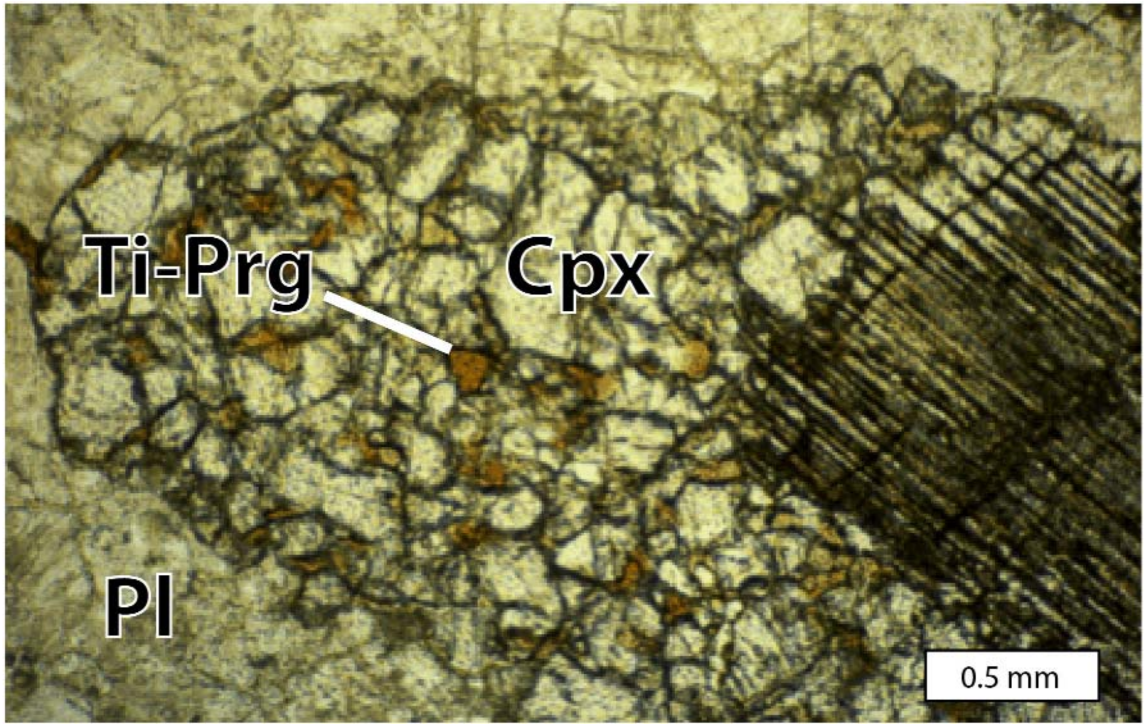

Fig. 9 - Stop 1.2, parallel nicols image of a sheared gabbro. Accessory Ti-Prg is locally present within the recrystallized clinopyroxene.

The gabbroic body frequently contains veins filled with hornblende (plagioclase), which are up to 15 m in length (Fig. 10). These hornblende veins form in places sub-parallel swarms with a spacing among veins commonly ranging from few mm to few tens of mm. These veins are nearly planar, not associated with displacement and crosscut at a high angle the magmatic layering and/or the high-temperature foliation of the host gabbro. The hornblende veins are commonly <1 mm thick; some of the veins are up to 20 mm in thickness. When crosscut by the hornblende veins, the clinopyroxene of the host gabbro is partially to completely replaced by hornblende (Fig. 11). The veins are filled with hornblende and hornblende + plagioclase when the fracture crosscuts the clinopyroxene and the plagioclase of the host gabbro, respectively (Tribuzio et al., 2014). In the host gabbros, hornblende is also commonly found as coronas around clinopyroxene; in the porphyroclastic sheared rocks, hornblende envelopes the lens-shaped structures containing deformed clinopyroxene relics. The geochemical signature of the coronitic hornblendes (e.g. high Cl contents, low ^{18}O values and low concentrations of incompatible trace elements) indicates an origin by reaction between migrating seawater-derived fluids and the host gabbros. This implies that gabbro intrusion and ductile shearing was followed by infiltration of seawater-derived fluids through a downward-propagating fracture front.

The Bonassola gabbro also includes scattered felsic dykelets to dykes made up of coarse grained, hornblende-bearing albitite (see Fig. 12 in next stop), which are elongated nearly parallel to the orientation of the hornblende veins. The albitite dykelets are up to few tens of mm in thickness and show diffuse sinuous contacts against the host gabbro. These contacts are commonly characterized by a high concentration of coarse-grained

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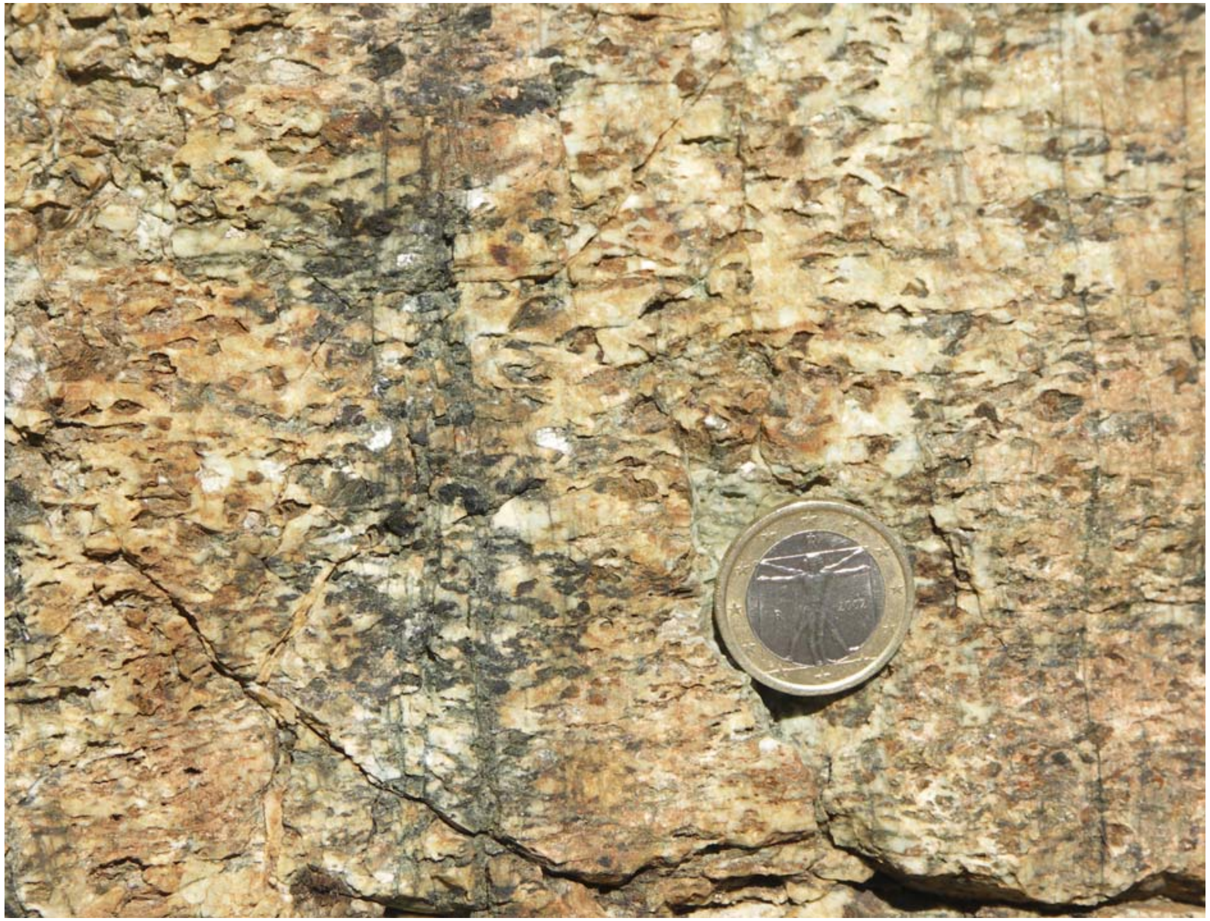

Fig. 10 - Stop 1.2, parallel fractures filled with hornblende, crosscutting at high angle the shearing foliation of the host gabbro. Hornblende is also found as coronas around (sheared) clinopyroxenes in the gabbro.

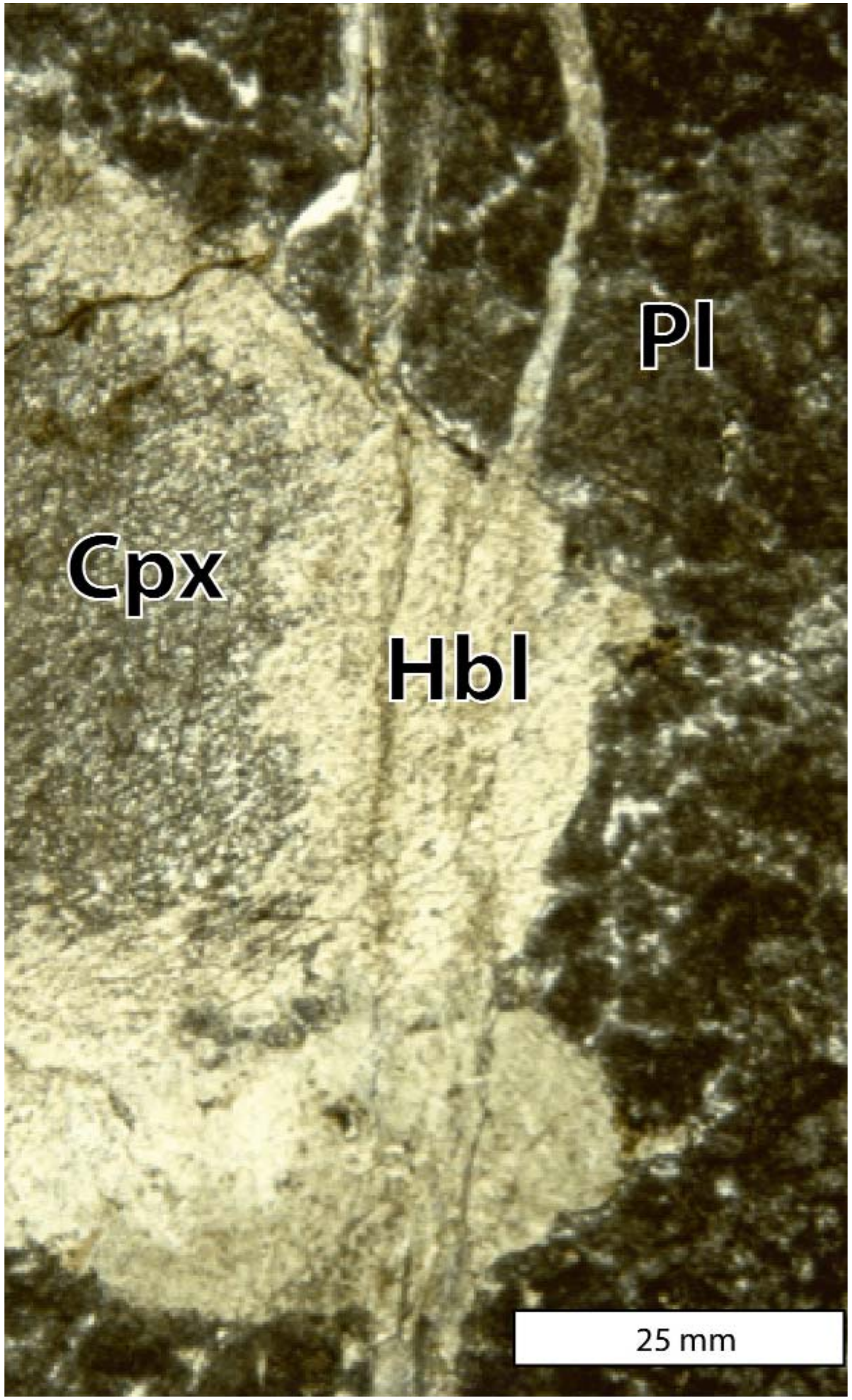

Fig. 11 - Stop 1.2, hornblende vein crosscutting a pegmatoid gabbro. Clinopyroxene of the host gabbro is replaced by hornblende and altered plagioclase is replaced by a new-plagioclase + hornblende assemblage.

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hornblende; these hornblende-rich domains are up to 20 mm thick. The albitite dykes are up to few meters in length and few hundreds of millimeters in thickness, and display sharp planar contacts against the host gabbro. In addition, the albitite dykes contain in places lens-shaped fractures (up to 0.1 m thick and 1 m long) filled with coarse-grained hornblende displaying euhedral to subhedral habitus. These massive veins are orientated approximately parallel to the strike of the host albitite dyke. Trace elements and Nd-O isotopic compositions document that albitites formed by SiO_2-rich silicate melts derived from high degree fractional crystallization of MOB-type basalts. The hornblendes from the veins have relatively high concentrations of LREE and Na and variable $\delta^{18}O$, thereby indicating a formation constrained by both magmatic and seawater components.

The hornblende veins and albitite bodies are locally crosscut by fractures filled with quartz Fe-sulphides. These quartz veins in places rework the hornblende veins and are presumably related to low temperature interaction of the gabbro with seawater-derived fluids. Cataclastic bands associated with the growth of prehnite, calcite, albite and actinolite occur sporadically and crosscut both the hornblende and quartz veins.

Fig. 12 - Stop 1.3, elongated albitite body showing sharp planar boundaries with the host gabbro.

Stop 1.3 (optional): Bonassola - "Villaggio la Francesca", serpentinised peridotites of mantle origin with replacive dunites, gabbroic bodies and hornblendite veins

East of Stop 1.2, a mantle-derived serpentinite sliver within the Bonassola gabbro is exposed along the path to "Villaggio La Francesca" (Fig. 5). The serpentinite retains a weak mantle tectonite

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fabric defined by oriented prismatic serpentine pseudomorphs after orthopyroxene, and only rarely preserves relics of the mantle mineral assemblages (Tribuzio et al., 1997). Two meter-scale bodies of replacive dunite crop out (Fig. 13). These dunites have spinel-rich layers oriented parallel to the contact with the host rock, which is characterized by a gradual outward increase in modal proportions of orthopyroxene (Fig. 14). Spinel in this dunite body have anomalously low Cr/(Cr+Al) and TiO_2 (~26 and ~0.2 wt%, respectively), which

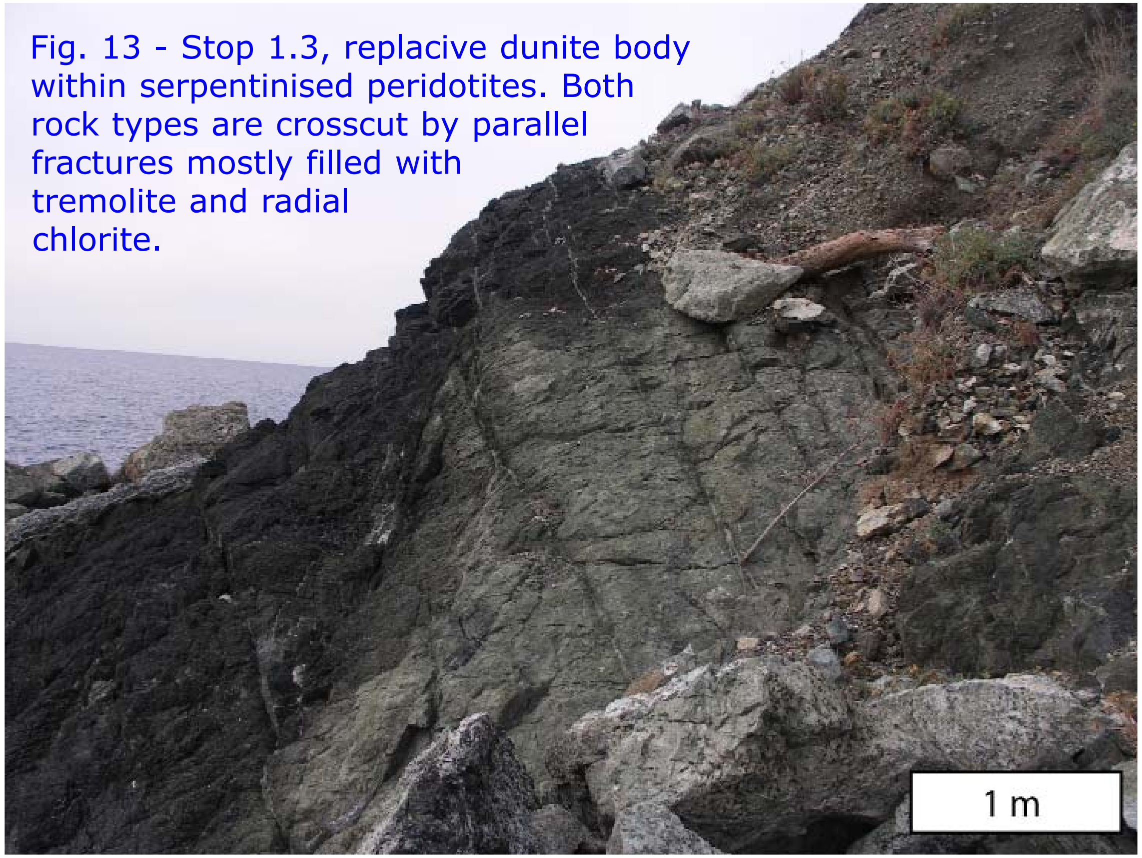

Fig. 13 - Stop 1.3, replacive dunite body within serpentinised peridotites. Both rock types are crosscut by parallel fractures mostly filled with tremolite and radial chlorite.

were attributed to equilibration with melts depleted with respect to N-MORB (see Sanfilippo & Tribuzio, 2011). In addition, the serpentinised peridotite contains various gabbroic bodies of varied thickness (up to 1 m), orientation and composition.

Fig. 14 - Stop 1.3, spinel-rich levels in replacive dunite oriented parallel to the contact with the host serpentinised peridotite. The contact region is characterised by a gradual outward increase in modal proportion of orthopyroxene.

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One sill of a coarse-grained clinopyroxene-rich gabbro is well exposed (Fig. 15). It is ~0.5 m thick and shows a sharp planar contact with the serpentinised host peridotite. This gabbro body is characterized by modal and grain size layering parallel to the contact with the enclosing rock. The primary mineralogy of the gabbro is pervasively replaced by chlorite, pumpellyite and Ca-rich clinopyroxene. At the contacts with the gabbroic dykes, the serpentinised peridotite is overgrown by tremolite and minor andradite.

A few mafic bodies cropping out along the cliff are characterized by a high modal proportion of hornblende, which commonly preserves relics of clinopyroxene (Tribuzio et al., 1997). Some of these mafic bodies are associated with an irregular vein network that permeates the enclosing rock for a few tens of centimeters. In both mafic bodies and veins, hornblende is associated with relatively high quantities of ilmenite, apatite and zircon. The geochemical signature of hornblende (e.g. low Cl contents, high ^{18}O values and high concentrations of incompatible trace elements) shows an origin from highly differentiated MORB-type melts (Tribuzio et al., 2014).

The serpentinised peridotite contains three generations of serpentine-bearing veins. The earliest veins (cm-scale thickness) are filled with tremolite and radial chlorite, plus minor serpentine and Fe-sulphides. At the contact with these veins, the host rock shows tremolite/chlorite alteration zones (up to centimeter-wide) that postdate the prismatic serpentine pseudomorphs after orthopyroxene. The tremolite/chlorite veins are crosscut by thin (commonly <1 mm), diffuse parallel veins filled with serpentine. These veins are in turn crosscut

Fig. 15 - Stop 1.3, gabbro sill showing sharp planar contacts with the serpentinised host peridotite. The gabbro body is characterised by modal and grain size layering parallel to the contact with the enclosing rock.

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by scattered fractures filled with calcite plus minor Fe-sulphides and serpentine. Near the serpentinised peridotite body, the Bonassola gabbro contains a chilled basaltic dyke that locally crosscuts at a high angle the high temperature shearing foliation (Fig. 16). In addition, there are large gabbro blocks with albitite bodies displaying either irregular hornblende-rich reaction zones or sharp planar boundaries.

Fig. 16 - Stop 1.3, chilled basaltic dyke.

STOP 2: Mantle exposure at the seafloor (Bracco-Levanto ophiolite)

Reggimonti locality: "Rosso di Levanto" (mantle ophicalcites) active quarries

The "Rosso di Levanto" (mantle ophicalcites) quarries will be visited. Here, structures associated with the brittle deformation that led to exhumation of mantle peridotites to the seafloor may be observed. These carbonate-veined serpentinised peridotites occur at the stratigraphic top of the mantle sequences; they are commonly a few tens of meters thick and are covered by basalt flows, sedimentary breccias and radiolarian

cherts. Seafloor exposure of the mantle was therefore achieved through “amagmatic” tectonic extension prior to the deposition of sedimentary material and the outpouring of basalt flows.
The ophicalcites (locally known as Levanto breccia, but also under the commercial name of “Rosso di Levanto”) broadly consist of serpentinites disrupted by a polyphase network of calcite veins. The serpentinite retains structural relics of the mantle peridotite protolith and becomes progressively more faulted upwards. The polyphase tectonic evolution recorded by the ophicalcites, which show evidence for ductile to brittle deformation under progressively lower temperature conditions, was attributed to the detachment faulting that led to mantle uplift at the ocean floor (Treves & Harper, 1994; Molli, 1995). These fault rocks structurally and chemically resemble the basement underlying the Lost City hydrothermal vent field at Mid-Atlantic Ridge (Alt et al., 2012; Schwarzenbach et al., 2012).

The mantle tectonite foliation produced by the orientation of orthopyroxene porphyroclasts is locally crosscut by up to meter-scale gabbroic dykes/sills. High temperature shearing may be observed in the gabbroic bodies and, in places, it also affects the host mantle peridotites. This deformation event is most likely correlated with the ductile shearing event identified in the gabbroic bodies (see Stop 1.2). Subsequent serpentinization of the peridotite was likely associated with brittle fracturing, as indicated by the local occurrence of serpentine veins, and the growth of rodingitic mineral assemblages in the gabbroic dykes.
Several generations of brittle deformation structures characterized by the precipitation of calcite are identified in the mantle serpentinite on the basis of crosscutting relationships, type of filling and structural style. The reddish color of the ophicalcite developed in response to oxidation and carbonatation of serpentinite (i.e. development of hematite + calcite) (Fig. 17). The most recent fractures are filled with calcite and talc (Fig. 18).

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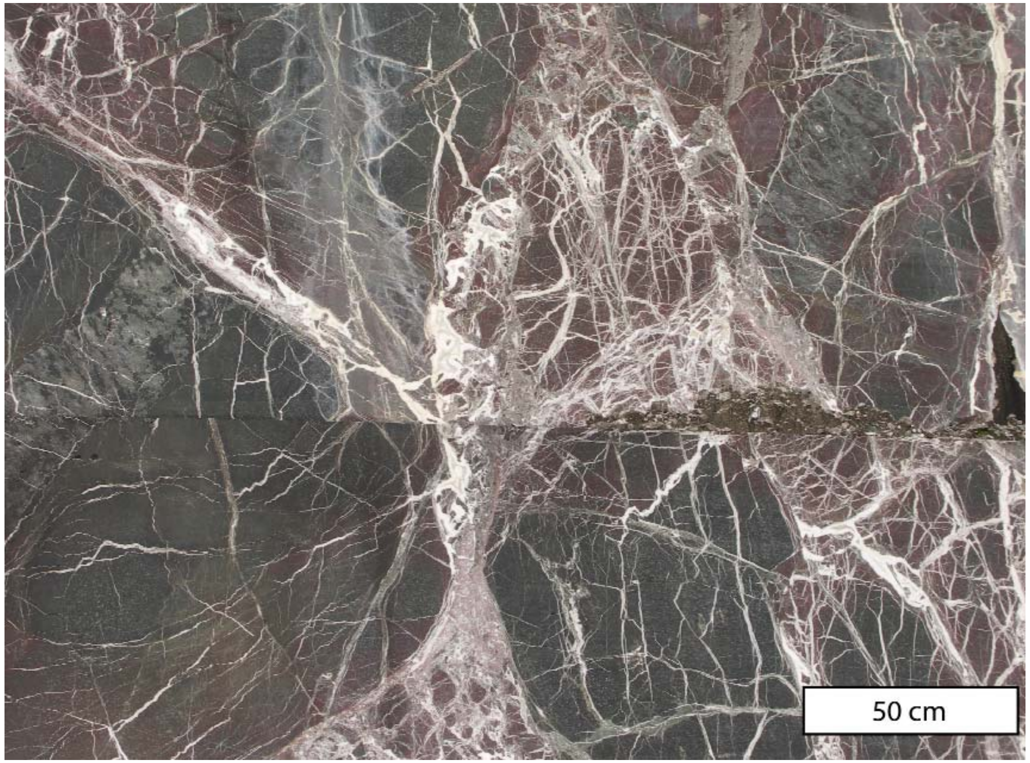

Fig. 17 - Stop 2, typical brittle deformation structures of mantle ophicalcites (total width of the photo is ~4 m).

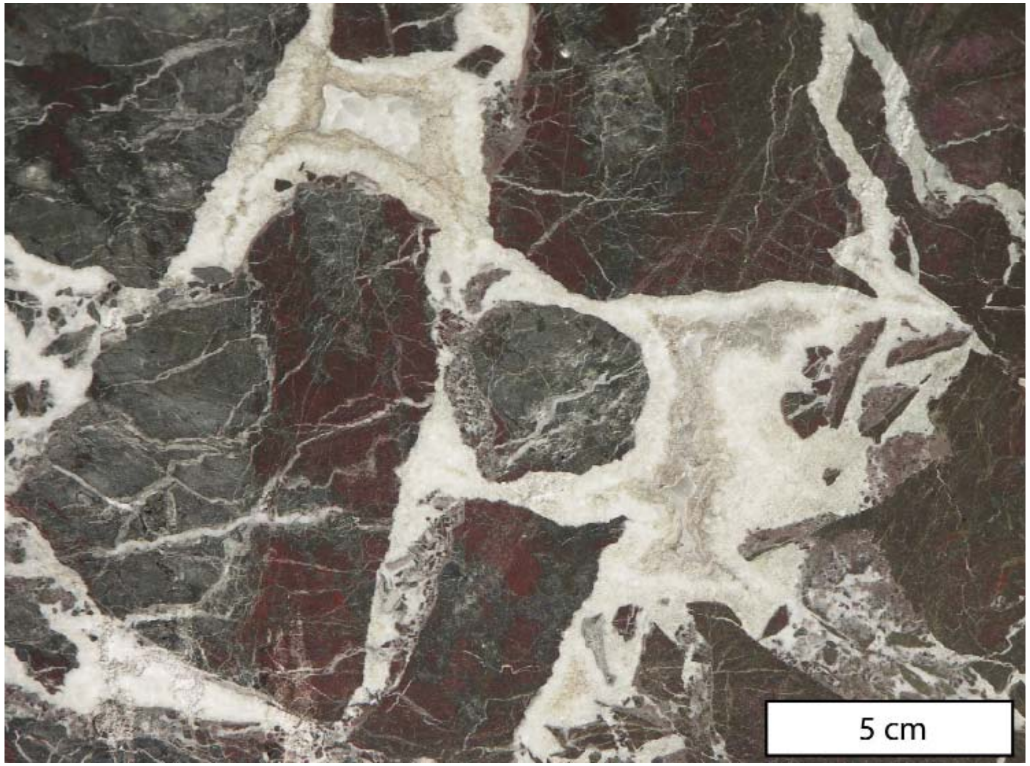

Fig. 18 - Stop 2, latest fractures filled with calcite and talc (total width of the photo is ~0.2 m).

STOP 3: MORB-type pillow basalts (Bracco-Levanto ophiolite)

Framura village, near the seaside

The Bonassola gabbro is overlain by sedimentary breccia/fault rocks and pillowed basalt flows (Fig. 19). The pillow sequence locally includes basalt dykes and massive lava flows. The pillows and the dykes are fine-grained with some plagioclase phenocrysts. The massive lava flows show variable grain-size and ophitic structure. Trace elements and Nd isotopic compositions indicate a MORB-type signature (Rampone et al., 1998).
The whole rock compositions of basalts from the alpine Jurassic ophiolites are slightly LREE- and Zr-enriched with respect to typical N-MORB (see also Desmurs et al., 2002; Montanini et al., 2008). This incompatible

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element signature is also locally reported for basalts erupted along asymmetrical segments of Mid-Atlantic Ridge and attributed to low degree melting of asthenospheric sources (Kempton & Casey, 1997; Escartin et al., 2008). Some of the alpine Jurassic ophiolites could represent slow-spreading centres characterized by a low magma supply and an elevated lithospheric thickness (see also Sanfilippo & Tribuzio, 2011; 2013b).

Fig. 19 - Stop 3, pillow lava flows in the Framura village.

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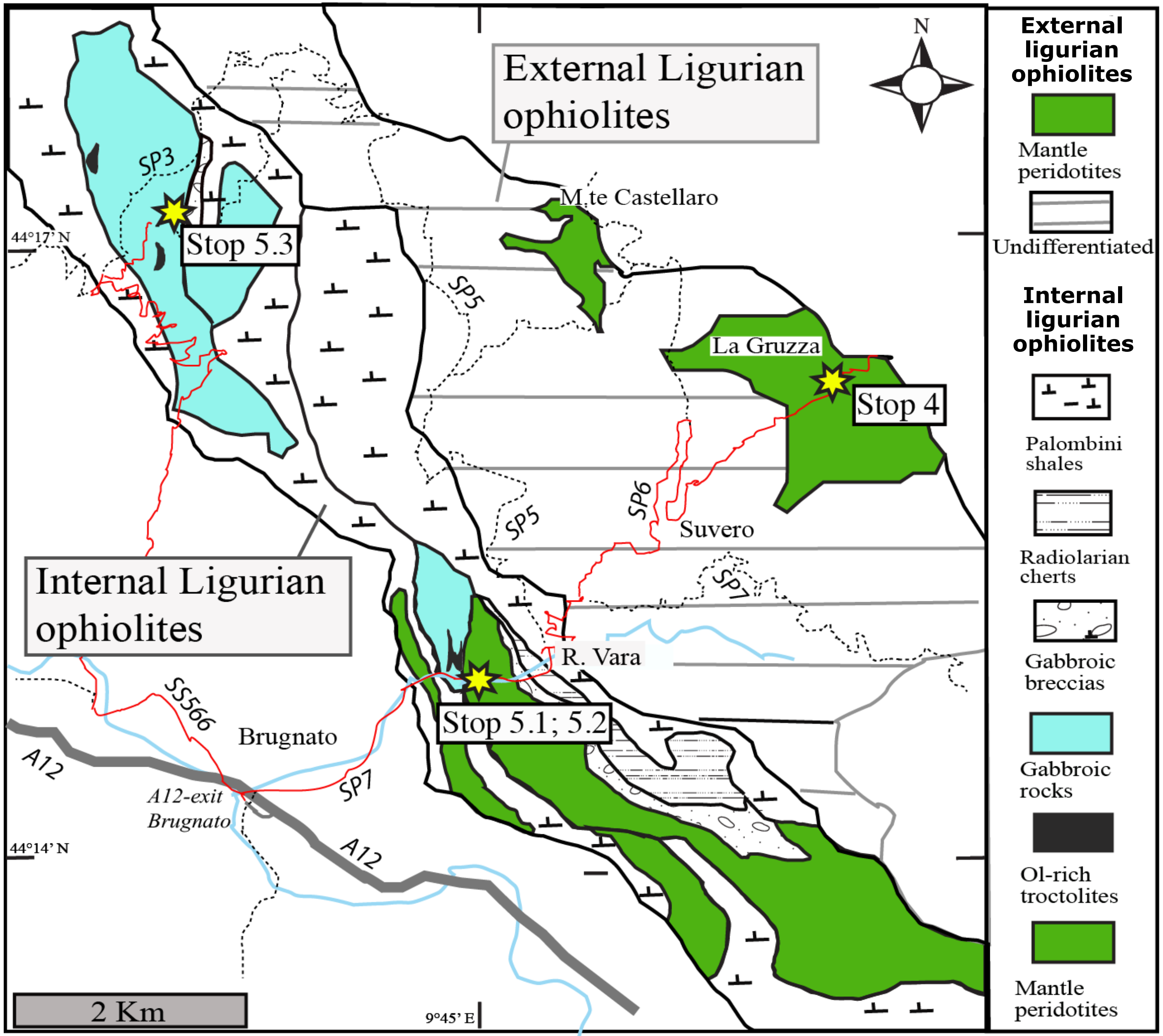
DAY 2



STOP 4

La Gruzza and M.te Castellaro outcrops the external liguride pyroxenite-bearing mantle.

STOP 5

Stop 5.1 - Rocchetta Vara: relationships between mantle peridotites and overlying sediments.

Stop 5.2 – A mantle sequence overlying Ol-rich troctolites and Cpx-rich gabbros.

Stop 5.3 - Olivine-rich troctolites within the gabbroic sequence of Scogna.

Fig. 20 - Geological sketch map of the Scogna-Rocchetta Vara ophiolite. Internal ligurian units containing the ophiolite of Scogna-Rocchetta Vara (Middle-Upper Jurassic); EL-external ligurian units (Upper Cretaceous turbidites and breccias containing ophiolitic blocks). Red lines indicate the itinerary.

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STOP 4: La Gruzza and M.te Castellaro outcrops, the external liguride pyroxenite-bearing mantle

In the Suvero area mantle peridotites of the external ligurian units outcrop as slide blocks within the basal section of the M.te Caio flysch sequence. They consist of two main ultramafic bodies, about 1 to 3 km^2 sized, dominated by spinel-plagioclase lherzolites showing pervasive tectonite foliation (Fig. 21). Mantle peridotites show the diffuse occurrence of pyroxenite layers mostly ranging in thickness from < 1 up to about 15 cm (Fig. 21), and in rare cases up to 40 cm. Pyroxenite layers are subparallel to mantle tectonite foliation, and show sharp contacts with the host peridotites (Fig. 22). They are

Fig. 21 - Stop 4, tectonite foliation in spinel-plagioclase lherzolite from La Gruzza.

Fig. 22 - Stop 4, centimeter-thick pyroxenite layer within mantle peridotite.

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irregularly distributed in the peridotites, and may locally constitute up to 50% of an outcrop. Pyroxenites range from spinel-bearing websterite to clinopyroxenite and usually show thin irregular orthopyroxene-rich borders along the pyroxenite-peridotite contact: this feature, together with large blebs of orthopyroxene in the adjacent (~4 cm) peridotites, indicates interaction between pyroxenite-derived melts and the host mantle rock.

In place, peridotites are characterized by lithological variations made by alternation of lherzolite, harzburgite and dunite centimeter-width portions forming a compositional layering parallel to the tectonite foliation and the pyroxenite layers (this is well shown in the Mt. Castellaro peridotite outcrop, Fig. 23). In the lherzolite and pyroxenite lithotypes, the tectonite foliation is coupled to a fine-grained plagioclase-bearing granoblastic assemblage partially replacing the early spinel-facies porphyroclastic

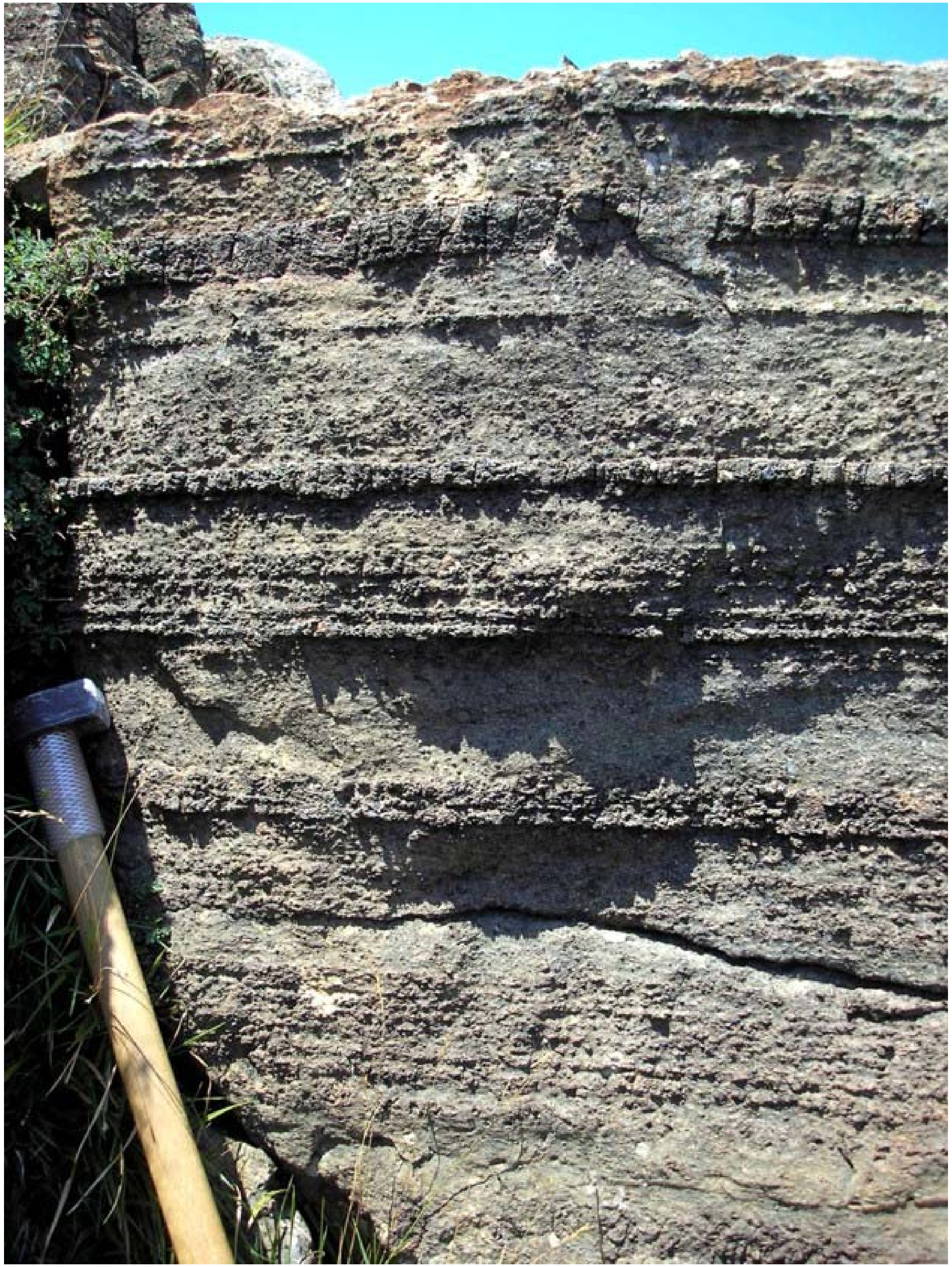

Fig. 23 - Stop 4, lithologic heterogenity made by alternation of centimeter-scale layers of pyroxenite, lherzolite, harzburgite and dunite in the outcrop of M.te Castellaro.

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minerals (Rampone et al., 1993; 1995; Borghini et al., 2011; 2013). Peculiar microstructures indicating the low-P plagioclase-facies recrystallization are: **i)** plagioclase plus olivine coronas between spinel and pyroxene (Fig. 24), and **ii)** plagioclase + olivine + new pyroxene fine-grained granoblastic aggregates partly substituting sp-facies pyroxene porphyroclasts (Fig. 25). Differently, in the harzburgite and dunite portions, the tectonite foliation is associated with medium- to fine-grained spinel-facies neoblastic crystallization around coarse spinel and orthopyroxene porphyroclasts. A Ti-pargasitic amphibole is widespread in both peridotites and pyroxenites, generally associated with the

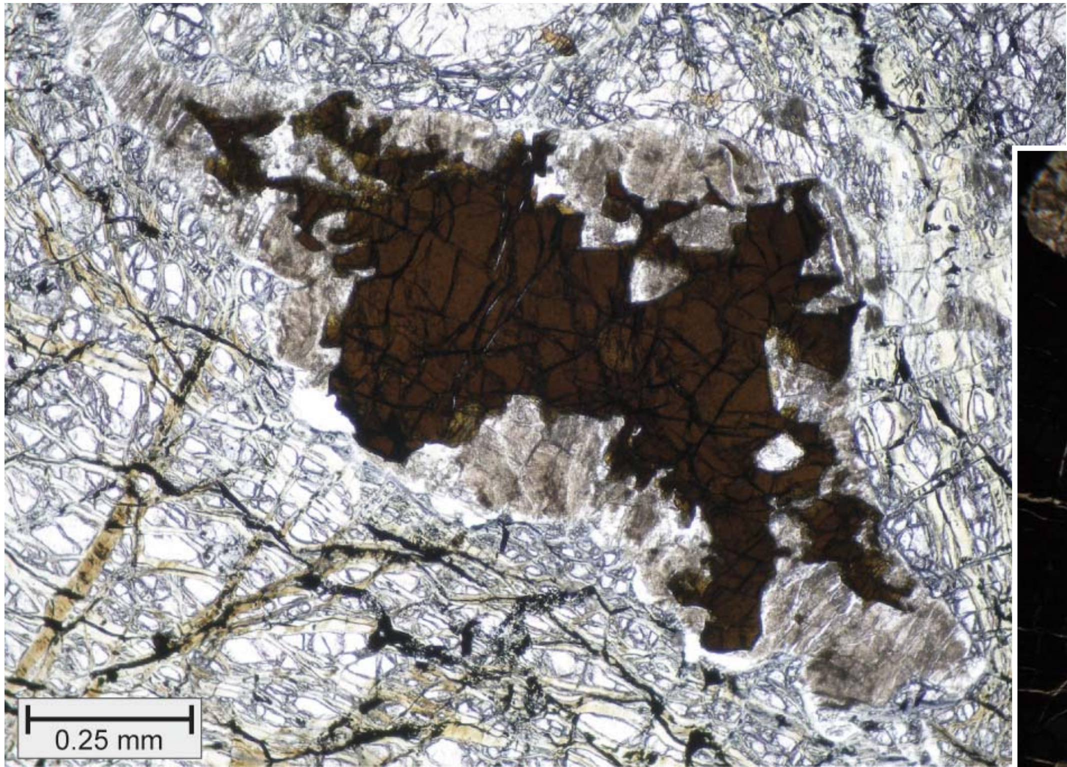

Fig. 24 - Stop 4, relict of spinel porphyroclast rimmed by plagioclase and olivine in La Gruzza lherzolite, nicols parallel.

Fig. 25 - Stop 4, plagioclase + olivine + new pyroxene fine-grained granoblastic aggregates partly substituting sp-facies pyroxene and spinel porphyroclasts in La Gruzza pyroxenite, nicols parallel.

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plagioclase-bearing granoblastic assemblage; in the peridotites, amphibole is more abundant in the wall rock near to the pyroxenite layers (Fig. 26). Pargasitic amphiboles in equilibrium with the sp-facies assemblage are only preserved in the harzburgite and dunite lithotypes (Fig. 27).

In terms of bulk-rock chemistry pyroxenites exhibit high Al (Al_2O_3 = 9.94-16.46 wt%) and Ca (CaO = 6.77-19.52 wt%) contents and rather low Mg-number (Mg# = 0.74-0.88). Bulk rock REEs spectra display overall LREE depletion and MREE/HREE ratio varying from almost flat (Sm_N/Yb_N=0.64-1.04) to HREE-enriched

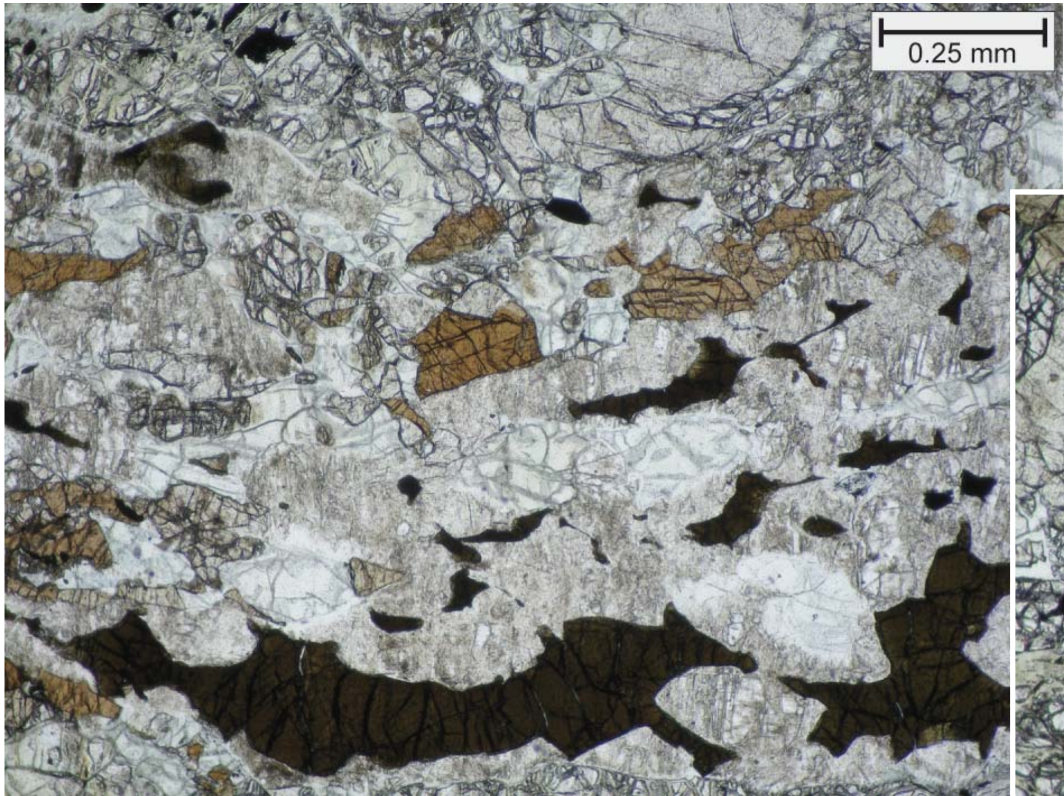

Fig. 26 - Stop 4, Ti-pargasitic amphibole associated to plagioclase-facies assemblage in wall-rock peridotite (M.te Castellaro), nicols parallel.

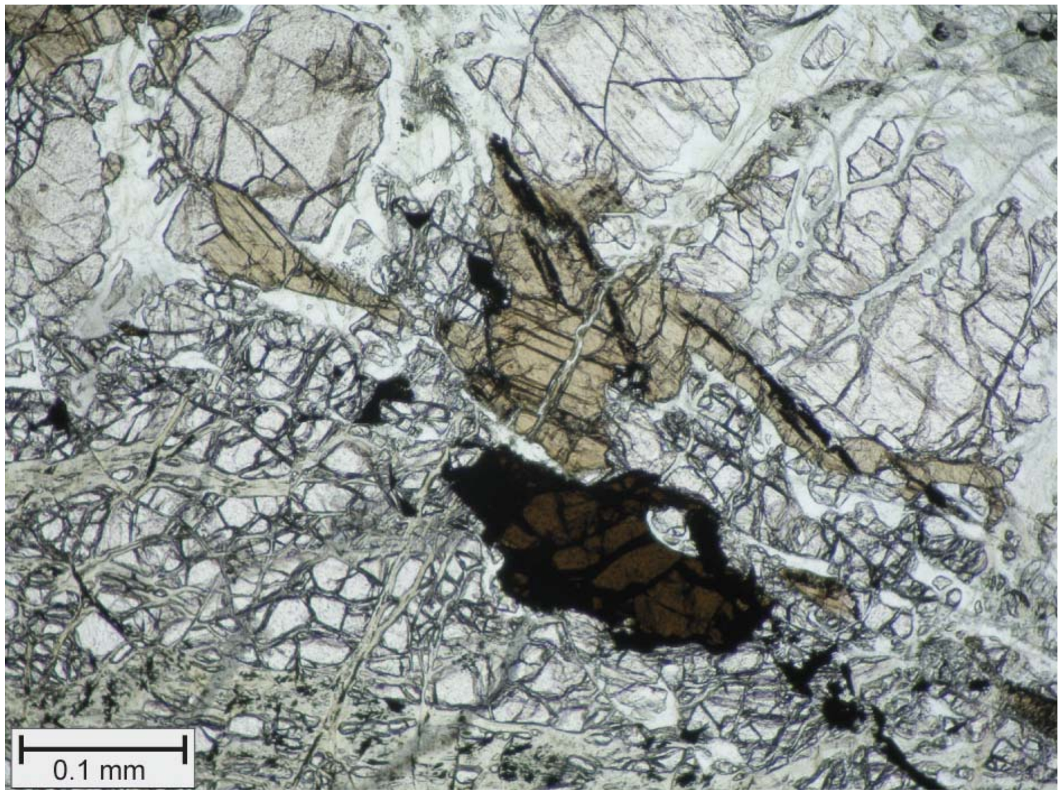

Fig. 27 - Stop 4, Ti-pargasitic amphibole in equilibrium with the spinel-facies assemblage in La Gruzza harzburgite-dunite layers, nicols parallel.

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(Sm_N/Yb_N=0.30-0.52; Borghini, unpublished data). Spinel-facies porphyroclasts are constituted by Al-rich green-spinel (Al_2O_3 = 58-64 wt%) and Al-rich pyroxenes (cpx: Al_2O_3 = 7.06-9.29 wt%), thus resembling Al-Di types pyroxenites (Frey & Prinz, 1978). Bulk-rock and mineral trace element compositions of pyroxenites suggest that they have been originated by crystal accumulation from enriched tholeiitic melts at pressures compatible with the presence of garnet in the primary mineral assemblage (1.3-1.8 GPa; Borghini et al., 2013). Sr and Nd isotopic compositions point to their MORB magmatic affinity and Sm-Nd isotope investigations yielded ages of 424–452 Ma for the pyroxenite emplacement (Borghini et al., 2013).

Chemical and isotopic profiles through the pyroxenite-peridotite boundaries have revealed that pyroxenite intrusion significantly modified the composition of the surrounding peridotites; local melt infiltration from the pyroxenite veins caused significant chemical variations in minerals (e.g. clinopyroxene) and large isotopic heterogeneity in the host peridotite at >0.1 m scale, with the $^{143}Nd/^{144}Nd$ variation of a single mantle outcrop covering most of the global Nd isotopic variability documented in abyssal peridotites (Borghini et al., 2013). However, extremely depleted Sr and Nd isotope ratio still recorded by few pyroxenite-free peridotites ($^{87}Sr/^{86}Sr$ = 0.701736; $^{143}Nd/^{144}Nd$ = 0.513543), indicated that the pristine mantle, prior to pyroxenite intrusion, experienced more ancient depletion event(s), (Rampone et al., 1995). Such extremely depleted Sr isotopic compositions have never been observed in oceanic basalts and modern oceanic peridotites (Rampone & Hofmann, 2012). Such isotopic signature, together with the early-Paleozoic ages derived for pyroxenite emplacement (see above), reinforces the geologic evidence that the external ligurian peridotites represent MORB-type subcontinental lithospheric mantle, likely accreted at lithospheric environments since Proterozoic times (Rampone et al., 1995).
Preliminary chemical profiles through lherzolite-harzburgite-dunite domains have shown that the Mg-value of minerals remains almost constant (Mg# in cpx around 0.90) in the different lithotypes, and the trace element composition of the rare clinopyroxenes preserved in the harzburgitic/dunitic portions is only slightly LREE depleted (La_N/Sm_N = 0.40-0.50, H-M-REE at about 10 x CI). This indicates that the observed modal heterogeneity in the peridotites was likely caused by melt-rock reaction processes. When pyroxenite layers are present (Fig. 23) the wall-rock peridotites, in spite of their variable modal composition, are always modified by interaction with pyroxenite-derived melts, indicating that reactive percolation causing the modal variability in mantle rocks presumably preceded pyroxenite emplacement.

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After pyroxenite emplacement, this mantle sequence was tectonically exhumed, as indicated by development of a tectonite fabric associated to the metamorphic recrystallization from spinel- to plagioclase-facies conditions. The transition from spinel- to plagioclase-facies is accompanied by major and trace element chemical changes in minerals, e.g. Al decrease and REE increase in clinopyroxene, Cr# [Cr# = Cr/(Cr+Al)] and Ti content increase in spinel (Rampone et al., 1993; Borghini et al., 2011). Thermometric investigations have provided T ranging 940-1000°C for the spinel-facies recrystallization. Detailed microstructural analysis and chemical profiles on minerals pertaining to the plagioclase-bearing granoblastic assemblage in the peridotites have revealed core-rim An-reverse zoning in plagioclase (ranging An_{58}-An_{80}), coupled to Al, Na, Ca zoning in pyroxenes (Borghini et al., 2011). Thermometric estimates on plagioclase-facies pyroxene neoblasts have yielded T ranging 850-950°C, with the lowest T recorded by the rims of pyroxene neoblasts. Parallel experimental investigations carried on lherzolite composition similar to the Suvero lherzolite (Borghini et al., 2010) revealed that Ca-Na partitioning between plagioclase and clinopyroxene is a powerful geobarometer for low-P peridotites (Borghini et al., 2011). Accordingly, geobarometric estimates in the Suvero lherzolites have provided equilibrium pressure from 0.7 to 0.3 GPa, indicative of exhumation from about 22 to 9 km depth of this lithospheric mantle sector. This relatively cold decompressional evolution occurred in response to the extensional processes leading to the opening of the Jurassic ligurian Tethys (Schettino & Turco, 2011; Vissers et al., 2013), as also supported by Lower-Jurassic ages provided by internal Sm-Nd isochrones on plagioclase-clinopyroxene pairs of pyroxenites (Borghini et al., unpublished data).

STOP 5: The non-volcanic ophiolite of Scogna-Rocchetta Vara

The Scogna-Rocchetta Vara ophiolite (internal ligurian unit) crops out below the overlying Gottero unit in the eastern limb of a regional-scale synform structure crosscut by the Vara Valley. It consists of two tectonically juxtaposed sequences, the Scogna and the Rocchetta Vara successions (Fig. 20). The Scogna succession may be interpreted as a paleomorphological high and mainly consists of a ~400 m-thick gabbroic body intruded into mantle peridotites and overlain by a thin cover of breccias and pelagic sediments. The Rocchetta Vara succession is composed of mantle peridotites intruded by different gabbroic bodies and topped by a thick sedimentary cover. This latter is continuous above the gabbro-peridotite basement and consists of gabbroic breccias overlain by radiolarian cherts. Both sequences are therefore characterized by the lack of basalt lava flows. A reconstruction of this sequence in Upper Jurassic time is shown in Fig. 28.

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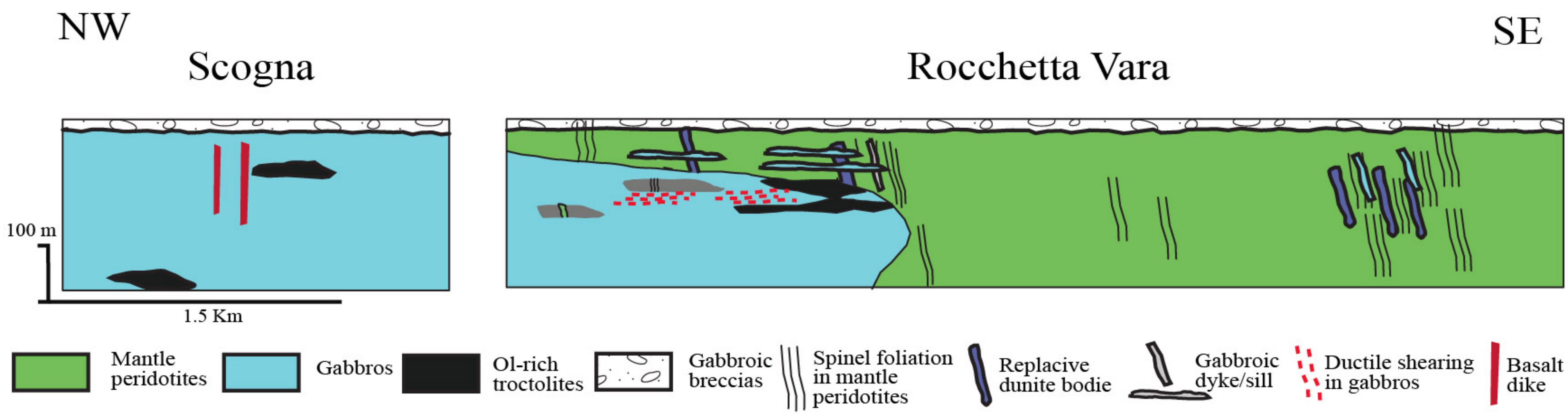

Fig. 28 - Schematic reconstruction of the Scogna-Rocchetta Vara ophiolite (internal ligurian units) during the Upper Jurassic-Lower Cretaceous.

Stop 5.1: Rocchetta Vara, relationships between mantle peridotites and overlying sediments

An overturned sequence consisting of a gabbro-peridotite basement overlain by ophiolitic breccias (Mt. Zenone breccia) and Middle-Upper Jurassic radiolarian cherts is exposed (Fig. 29).
In a disused quarry, the Mt. Zenone breccia overlies a serpentinised mantle sequence, which in turn displays an ophicalcite layer at the top. The contact between the ophicalcites and the Mt. Zenone breccia is tectonically reworked. The Mt. Zenone breccia is ~80 m thick (up to two hundred metres thick to the SE) and is interpreted as a debris flow deposit. The clasts in the Mt. Zenone breccia have variable size (up to meter-scale) and mainly consist of coarse-grained clinopyroxene-rich olivine-bearing gabbros locally showing a high temperature foliation. Primary minerals in the gabbro clasts are commonly replaced by fine-grained low-temperature mineral assemblages. In particular, the reddish patches consist of hematite + calcite (quartz) aggregates that commonly develop as pseudomorphs after olivine.
The road cut exposes a subvertical section (~150 m thick) of the radiolarian cherts, which were quarried for manganiferous deposits (braunite-bearing layers). Note that silicified araucarioid wood fragments were found

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Fig. 29 - Stop 5.1, disused quarry fronts in reddish cherts and blackish serpentinised peridotites of mantle origin, on the left and right side of the photo, respectively. A ~80 m thick layer made up of gabbroic breccia occurs between the cherts and serpentinised peridotites.

Fig. 30 - Stop 5.1, the contact between the cherts and originally underlying gabbroic breccias is characterised by intercalations of cherts, ophiolitic sandstones and breccias (commonly showing size grading). The large gabbro clast in the photo is interpreted as a debris flow deposit.

in the radiolarian cherts (Cortesogno & Galli, 1974). Towards the stratigraphic base, the radiolarian cherts are in contact with the ophiolitic breccias (Fig. 30). Intercalations of ophiolitic sandstones and breccias (up to 20 centimeter-thick and showing graded, inverse grading) within the cherts mark the stratigraphic contact with the originally underlying gabbroic breccia.

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Stop 5.2: Rocchetta Vara, a mantle sequence overlying olivine-rich troctolites and clinopyroxene-rich gabbros

The Stop focuses on the gabbro-peridotite basement of the Rocchetta Vara succession. This basement consists here of a gabbroic pluton (up to 400 m thick) intruded into mantle peridotites (Fig. 31a). In particular, the road intersects the lateral termination of the gabbroic intrusion, which is made up of a close association of olivine-rich troctolites and clinopyroxene-rich gabbros (Fig. 31b).

The mantle peridotites (clinopyroxene ~5 vol%) overlying the gabbroic intrusion locally show a tectonite fabric, which forms a high angle with respect to the stratification of the radiolarian cherts. These peridotites contain high amounts of plagioclase (up to 15 vol%), which commonly develop orthopyroxene-bearing veinlets that are subparallel to the spinel-facies foliation planes. The high amount of plagioclase within the harzburgites, together with the

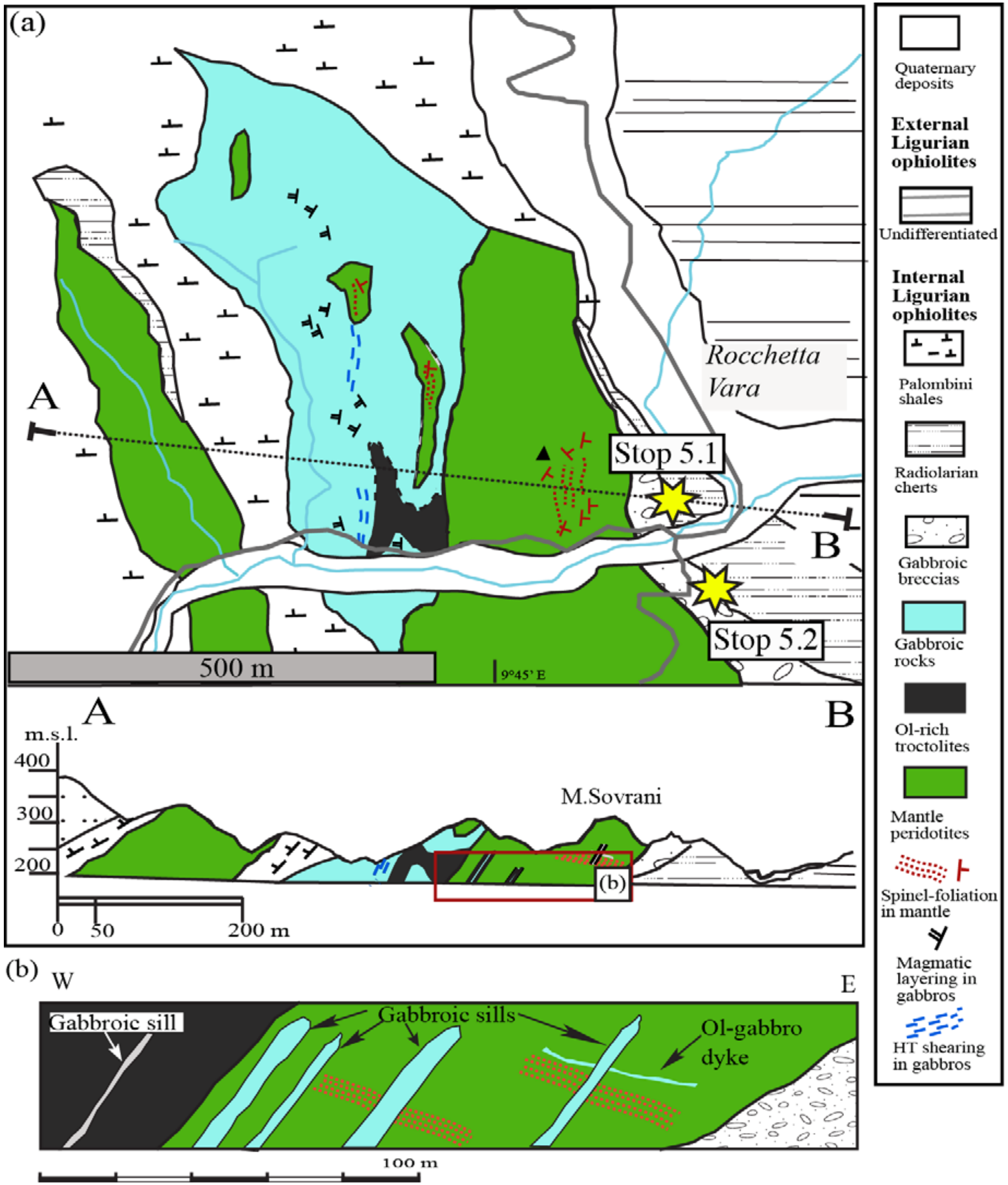

Fig. 31 - **a**) Geological map and cross-section of the Rocchetta Vara ophiolite; **b**) Detail of the cross section in "a" along the road for the Rocchetta Vara village.

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high Cr# and TiO_2 in spinel and a marked Sr depletion of the clinopyroxene, indicate that the peridotites experienced an event of impregnation by melts under plagioclase-facies conditions (Sanfilippo & Tribuzio, 2011). Impregnation of peridotites by orthopyroxene-saturated melts in the plagioclase stability field was also proposed for other mantle sections of the internal ligurian ophiolites (Rampone et al., 1997).

The mantle sequence locally displays meter-scale bodies of replacive dunite (not observed along the road), whose contacts are nearly parallel to the peridotite foliation (Fig. 32). The spinels in these dunites have low Cr# and TiO_2 contents (Fig. 33), and are interpreted to have re-equilibrated with a melt depleted in incompatible elements with respect to N-MORB.

Fig. 32 - Stop 5.2, metre-scale dunite showing gradational contacts and spinel trails oriented nearly parallel to the contact with the host peridotite (and its foliation).

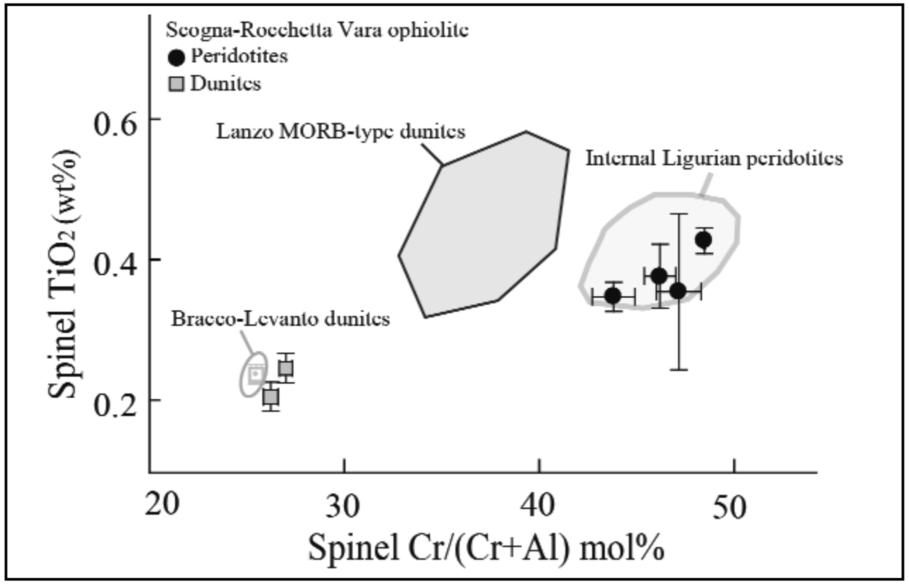

Fig. 33 - Cr/(Cr+Al) versus TiO_2 compositions of the spinels from Scogna-Rocchetta Vara mantle sequence (modified after Sanfilippo & Tribuzio, 2011). Data for internal ligurian peridotites (Rampone et al., 1997; Piccardo et al., 2004), Lanzo dunites (Piccardo et al., 2007; unpublished data) and Bracco Levanto dunites (Sanfilippo & Tribuzio, 2011) are also reported.

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The mantle sequence also contains a few clinopyroxene-rich gabbro sills (up to 3 m thick). These gabbroic bodies form high angles with respect to the foliation of the host peridotites and are elongated nearly parallel to the stratification of the radiolarian cherts (Fig. 20). One of the clinopyroxene-rich gabbro sills crosscuts an olivine-gabbro dyke displaying diffuse contacts with respect to the host peridotites (Fig. 34a). The sills show sharp contacts against the host tectonite peridotites (Fig. 34b), thereby showing a formation within a mantle sequence under relatively low temperature conditions. The contact between the mantle sequence and the underlying gabbroic body is characterized by the occurrence of olivine-rich troctolites. The olivine-rich troctolites are exposed along the road for a thickness of ~75 m and contain sills (cm- to meter-scale in thickness) of clinopyroxene-rich gabbros sub-parallel to the gabbroic sills intruding the associated mantle sequence (Fig. 31b). These olivine-rich troctolites are structurally and chemically similar to those of next stop and will be better described and discussed later. The gabbroic sequence underlying the olivine-rich troctolites mostly consists of coarse-grained clinopyroxene-rich gabbros locally associated with minor, medium grained olivine gabbros to troctolites. The different gabbro types constituting the intrusion do not provide a systematic modal layering. Along the road, these gabbros show in places high temperature recrystallization in ductile shear zones, which produced a foliation that forms a low angle with respect to both the igneous layering and the stratification of the radiolarian cherts (Fig. 35). This shear zones shows a retrograde evolution characterized by early recrystallization of clinopyroxene + plagioclase (± accessory Ti-pargasite, similar to Fig. 9) at ~850°C, followed by a hornblende + plagioclase amphibolite facies event at ~710°C (Fig. 36).

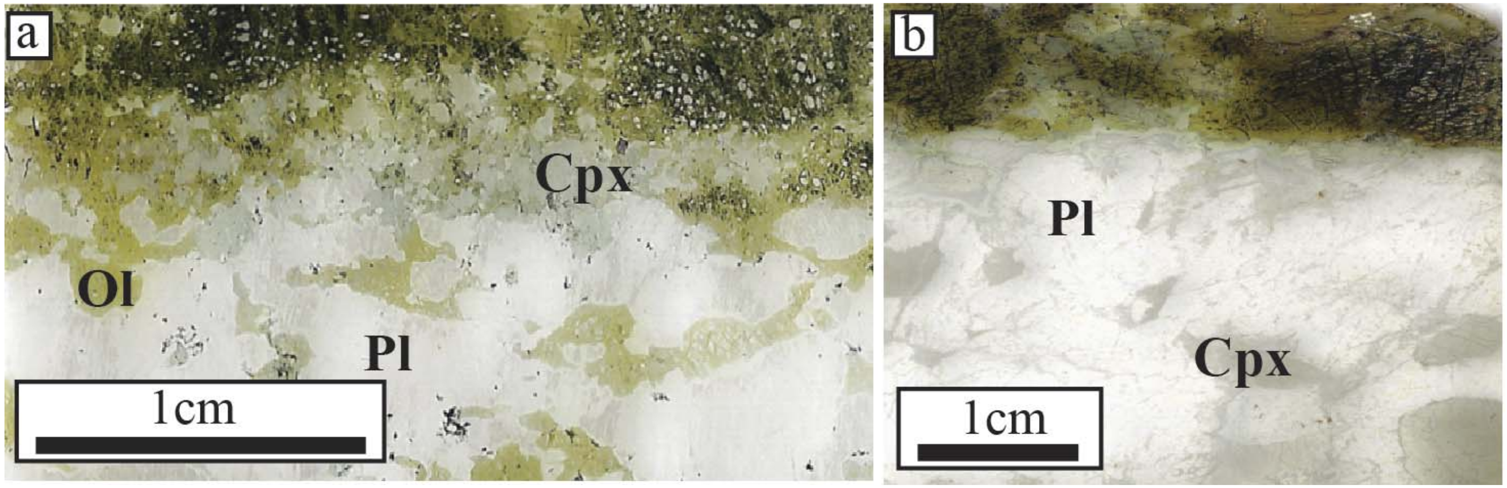

Fig. 34 - Stop 5.2, a, b) Thin section images: **a**) diffuse contacts between an olivine-gabbro and mantle peridotites; **b**) sharp-planar contacts between a clinopyroxene-rich and the mantle peridotites. Ol, Olivine; Pl, plagioclase; Cpx, clinopyroxene.

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Fig. 35 - Stop 5.2, gabbro showing high temperature recrystallisation in ductile shear zones; the foliation forms a low angle with respect to both the igneous layering and the stratification of the radiolarian cherts.

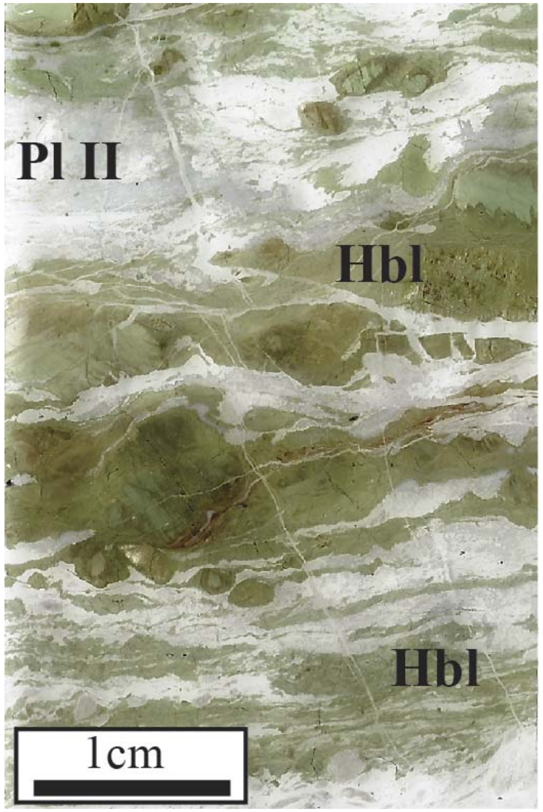

Fig. 36 - Stop 5.2, thin section of a Amphibolite-facies mylonitic gabbros made up of bands rich in neoblastic hornblende (Hbl) and plagioclase (Pl).

Note that within the Rocchetta Vara gabbroic sequence (to the North, not observed along the road), there are a few lenses (up to 50 m thick) of mantle peridotite, which are structurally and compositionally similar to the mantle sequence overlying the gabbroic sequence. The occurrence of these mantle remnants together with the presence of the gabbroic sills in the mantle sequence overlying the gabbroic pluton (Fig. 31b) may be reconciled with a process of pluton growth through a series of sill-like separate intrusions, similar to what suggested for another gabbroic sequence from alpine ophiolites (i.e. Pineto gabbroic sequence - Corsica, Sanfilippo & Tribuzio, 2013a).

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Stop 5.3: Olivine-rich troctolites within the gabbroic sequence of Scogna

The gabbroic sequence of Scogna (up to 500 m thick) contains two olivine-rich troctolite bodies (~50 × 100 m) at different stratigraphic heights (Fig. 28). Olivine-rich troctolites bodies are similarly found as sill-like lenses at different stratigraphic levels in the Bracco gabbroic sequence (Cortesogno et al., 1987) and in the km-scale lower crust section of Pineto (Corsica), Sanfilippo & Tribuzio, 2013a. Olivine-rich troctolites are also found in association with mantle peridotites in the Erro-Tobbio ophiolite (Western Liguria), Borghini et al., 2007; Borghini & Rampone, 2007.

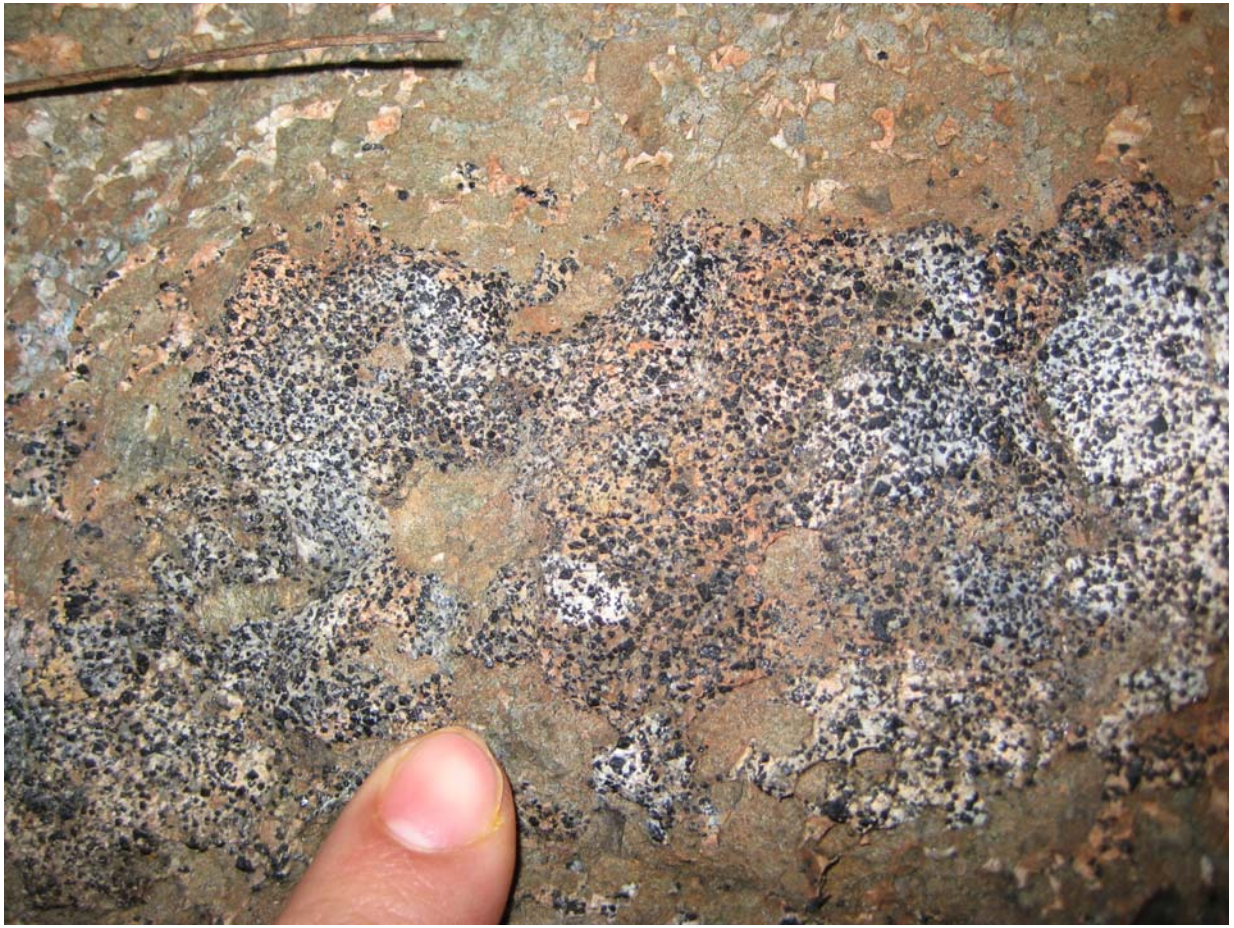

Fig. 37 - Stop 5.3, chromitite layer displaying diffuse contacts with respect to the olivine-rich troctolite.

The olivine-rich troctolites mainly consist of olivine (82-72 vol%), anhedral plagioclase (23-18 vol%), minor poikilitic clinopyroxene (up to 5 vol%) and accessory, commonly euhedral, spinel (Bezzi & Piccardo, 1971). The olivine-rich troctolites locally enclose irregular clots (up to few tens of centimeters in scale) made up of spinel-bearing dunite (Renna & Tribuzio, 2011). Spinel- and plagioclase-rich layers ("chromitites") displaying diffuse to planar contacts with respect to the host olivine-rich troctolites are also locally present (Fig. 37). The chromitite layers are up to few tens of cm-thick and in places show modal layering to anorthosite compositions.
The olivine from the olivine-rich troctolites has nearly constant forsterite

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component (89-87 mol%) and NiO contents (0.30-0.27 wt%). The clinopyroxene oikocrysts have high Mg#[Mg/(Mg+Fe) and Cr_2O_3 contents (90-88 mol% and 1.6-1.3 wt%), and incompatible element and Nd-isotope signatures similar to that of MORB-derived clinopyroxenes (see also Rampone et al., 1998; Renna & Tribuzio, 2011). The spinels from the olivine-rich troctolites have Cr#[Cr/(Cr+Al)] ranging between 57 to 44 mol% and TiO_2 ranging from 3.5 to 0.6 wt%. The spinels from the chromitites differ from those in the olivine-rich troctolites in the slightly lower Cr# and TiO_2.
Mineral inclusions are frequently present within the spinels from both olivine-rich troctolites and chromitites (Renna & Tribuzio, 2011). These inclusions are monophase to multiphase and commonly consist of kaersutite to titanian pargasite, phlogopite to Na-phlogopite (aspidolite) and/or orthopyroxene. The inclusions-bearing spinels were interpreted to have formed by hybrid melts oversaturated in spinel (± olivine ± plagioclase), which were produced by interaction of melt evolved through melt-rock reactions with new injections of primitive olivine-saturated melts. The evolved melts were inferred to be relatively rich in SiO_2 and Cr_2O_3 because of pyroxene dissolution in the mantle and rich in incompatible elements in response to olivine crystallization under lowering temperature conditions.

The olivine-rich troctolites are inferred to form by reactions between an olivine-rich matrix and migrating melts crystallizing plagioclase and clinopyroxene. A similar melt-rock reaction origin was proposed for the olivine-rich troctolites from the Atlantis Massif at Mid Atlantic Ridge (Suhr et al., 2008; Drouin et al., 2009; 2010) and the Godzilla Megamullion at Philippine Sea (Sanfilippo et al., 2013). The dunitic clots from the Scogna olivine-rich troctolites may represent remnants of the precursor olivine-rich matrix. This matrix likely formed by melt-peridotite interactions at the mantle-crust transition (see also Sanfilippo & Tribuzio, 2013b; Sanfilippo et al., 2014). The occurrence of olivine-rich troctolite bodies within the gabbroic sequences is reconciled with a process by which the mantle-crust transition is dissected by gabbroic intrusions eventually leading to entrapment within the growing lower crust. This process was associated with interactions between the olivine-rich matrix and the melts forming the gabbros.

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