## Marie-Curie Initial Training Network ABYSS

## Training network on reactive geological systems from the mantle to the abyssal sub-seafloor

### *Mid-term Meeting n.2, 7-10 April 2016, Sestri Levante*

# *Field Excursion Guidebook*

### *1st day (9/04/2016)*

## *Eastern Liguria: primary magmatic-hydrothermal features of the Internal Liguride Ophiolite*

*(from **Sanfilippo A., Borghini G, Rampone E., Tribuzio R. (2014)** - The Ligurian Ophiolites: a journey through the building and evolution of slow spreading oceanic lithosphere. Geological Field Trips Vol.6 No.2.3, 46 pp., 37 figs. (DOI 10.3301/GFT.2014.06), ISSN: 2038-4947 [online]*

***Field Leaders: Elisabetta Rampone, Riccardo Tribuzio***

## Introduction to the Ligurian Ophiolites

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 and 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 and 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 and Cannat, 1990; Tribuzio et al., 1995; 1999; Sanfilippo and 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 and 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).

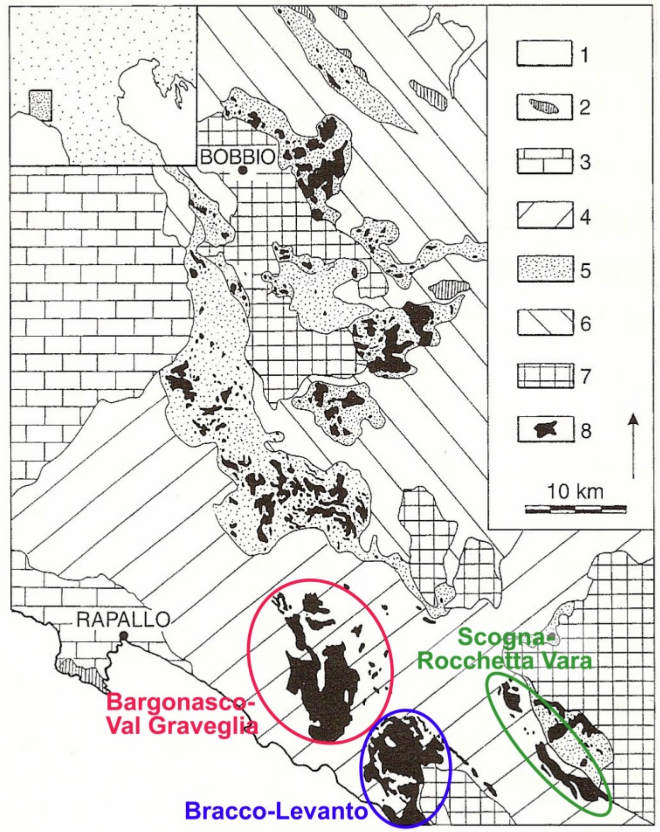

**Figure 1.** Sketch map of the eastern Liguria Apennine (slightly modified after Marroni and Tribuzio, 1996). 1 Plio-Quaternary deposits; 2 post-orogenic Ranzano sequence (late Eocene-early Miocene); 3 Antola Helminthoid flysch unit (Campanian-Paleocene); 4 Internal Ligurian unit (Middle Jurassic-Paleocene); 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.

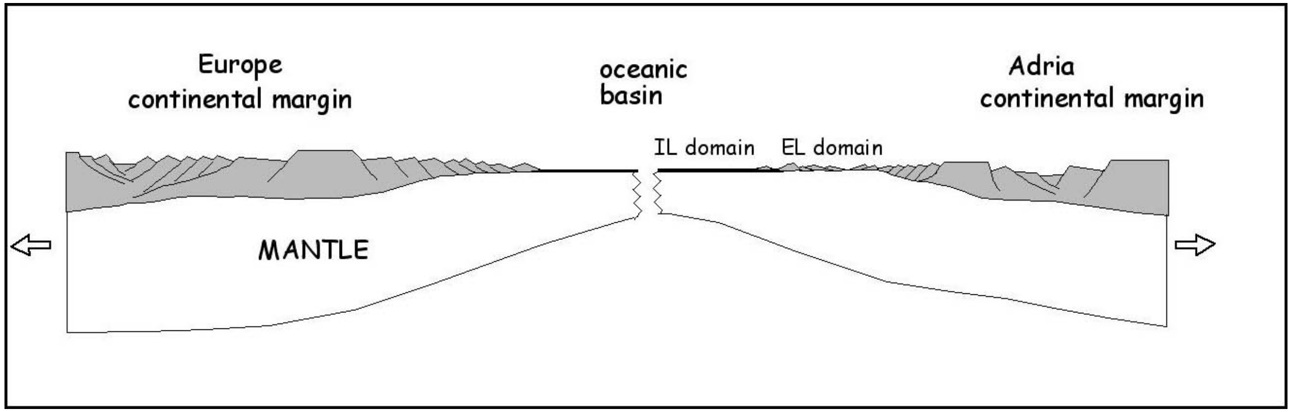

**Figure 2.** Palaeogeography of the Ligurian ophiolites in the Upper Jurassic. The ophiolites from External (EL) and Internal Ligurian (IL) units are attributed to marginal and distal domains of the Ligure Piemontese basin (slightly modified after Marroni et al. 2002).

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 and Tribuzio 2001) of late Palaeozoic age (Meli et al. 1996; Renna and 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., 2012, 2013). The subcontinental mantle bodies and associated rocks of the continental crust record decompression and retrograde tectono-metamorphic evolutions linked to the rifting process that led to their exhumation in the Middle Jurassic (Rampone et al., 1993, 1995; Renna and 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 and Manatschal 2008).

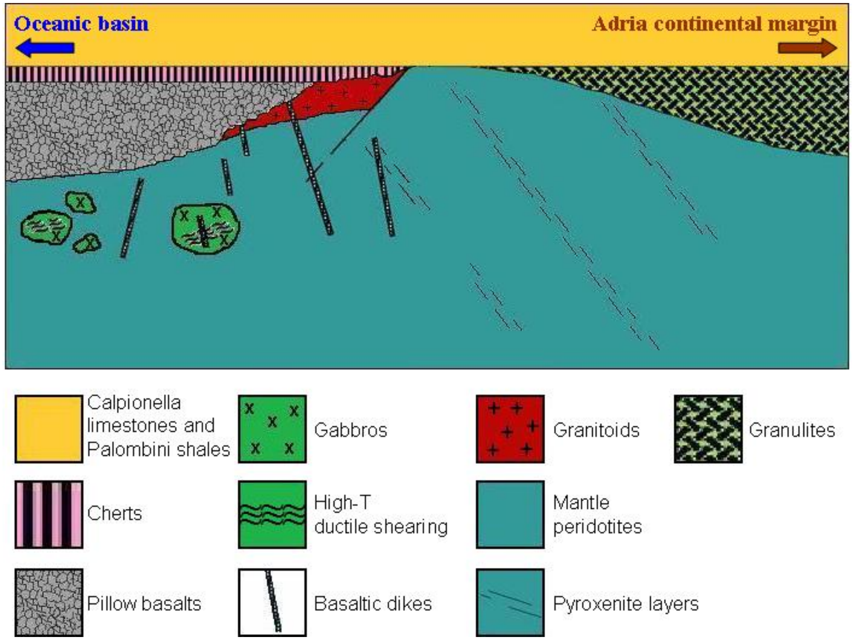

**Figure 3**. Schematic reconstruction of the External Ligurian domain of the Ligure-Piemontese basin in the Upper Jurassic-Lower Cretaceous (modified after Marroni et al. 1998).

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, polymictic ophiolitic breccias 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, 2000; Tiepolo et al. 1997; Rampone et al. 1998; Renna and Tribuzio, 2011; Sanfilippo and 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 and Tribuzio, 2011; Rampone and Hofmann, 2012).

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 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. Blackmann et al., 2006; 2011). The Scogna-Rocchetta Vara ophiolite is characterized by the lack of basalt lava flows (Sanfilippo and Tribuzio, 2011), like the non-volcanic sections from Mid-Atlantic and Southwest Indian ridges (e.g. Dick et al., 2003; Kelemen et al. 2007; Zhou and 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 excursion will mainly focus on the relationships between mantle peridotites, gabbros, basalts and sedimentary material in the Internal Ligurian ophiolites. Specifically, it will be devoted to the Bracco-Levanto ophiolite.

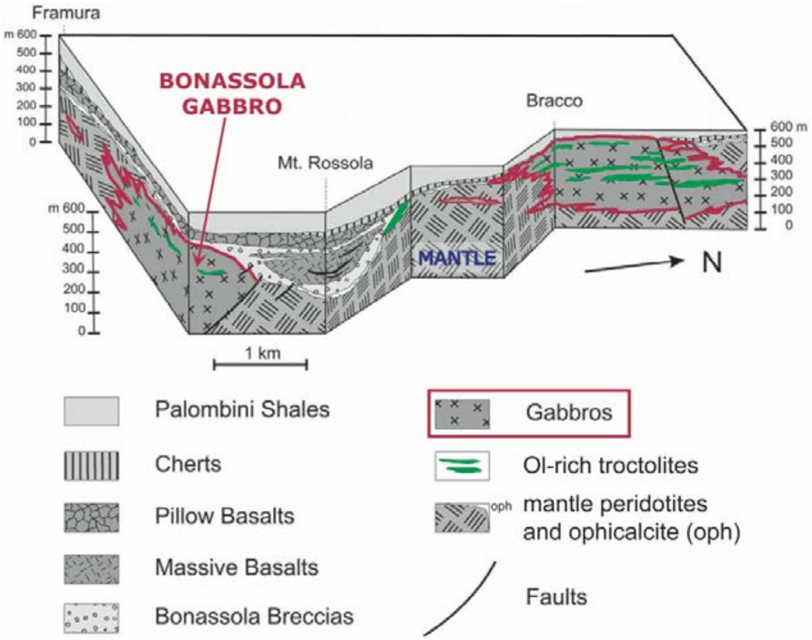

**Figure 4.** Schematic reconstruction of the Bracco-Levanto ophiolite (Internal Ligurian units) in the Upper Jurassic-Lower Cretaceous. Slightly modified after Principi et al. (2004).

## Stop 1. The gabbroic body of Bonassola and its relationships with adjacent serpentinized peridotites (Bracco-Levanto ophiolite)

We wind along the western and eastern shorelines of Bonassola village, where 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 serpentinized mantle peridotites (see also Fig. 4). The intrusive relationships of the gabbros within the serpentinized peridotites are locally preserved, although contacts are commonly reworked by late tectonic deformation.

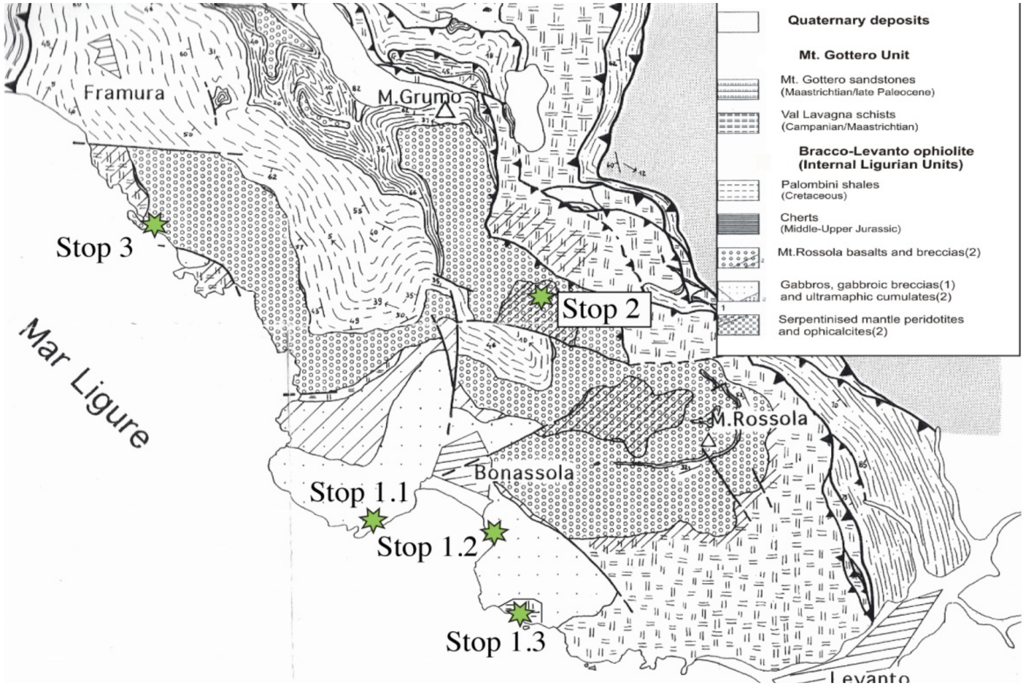

**Figure 5.** Geological map and cross-sections of the Bonassola area (Bracco-Levanto ophiolite, Internal Ligurian units). After Molli (1995).

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

**STOP 2**

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

**STOP 3**

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

## *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 (Photo 1) and elongated microgabbro bodies (up to a few tens of meters long and <0.5 m thick) forming low angles with respect to the igneous layering and showing diffuse contacts with the host gabbro (Photo 2). 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 characterized by a positive Eu anomaly, which reflects a process of plagioclase accumulation. The chemical compositions of 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 ± 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.

**Photo 1 (stop 1.1).** Pegmatoid gabbro lens within coarse-grained clinopyroxene-rich gabbros.

**Photo 2 (stop 1.1).** Diffuse contacts between microgabbro and host coarse-grained clinopyroxene-rich gabbro.

## *Stop 1.2. Bonassola village, near the coast: gabbros with high temperature ductile shear zones crosscut by hornblende veins and albitites*

The Bonassola gabbro is here characterized by a pervasive shear (shear??) foliation forming a low angle with respect to the igneous layering and produces porphyroclastic mylonites to rare ultramylonites (Photo 3a, 4). 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 and 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 (Photo 3b). 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 and 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 hornblende + plagioclase).

The gabbroic body frequently contains veins filled with hornblende (± plagioclase), which are up to 15 m in length (Photo 5). 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


**Photo 3a (stop 1.2).** Shearing foliation at low angle with respect to the igneous layering of the gabbro. Mylonitic bands are present in the left side of the photo.

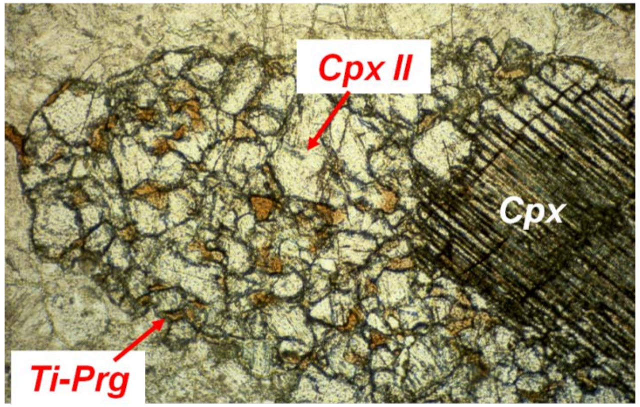

**Photo 3b (stop 1.2).** Parallel nicols image of a sheared gabbro. Accessory Ti-Prg is locally present within the recrystallized clinopyroxene.

(Photo 6). 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. 2013). 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 $\delta^{18}$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 (Photo 7), 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 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 SiO2-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 δ18O, thereby indicating a formation constrained by both magmatic and seawater components.

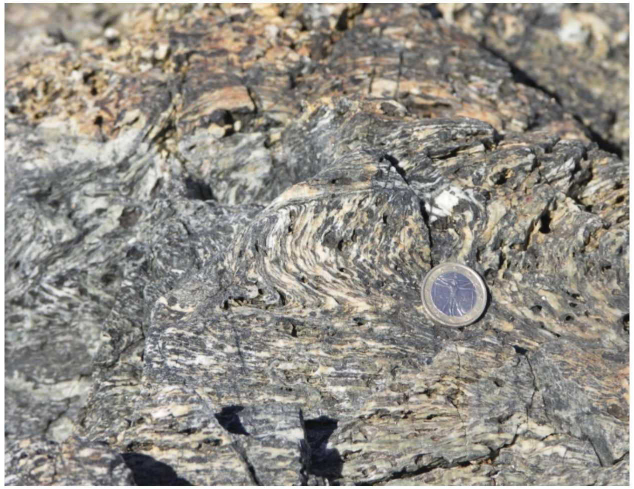

**Photo 4 (stop 1.2).** Mylonitic fold in a high strain domain of the gabbro body.

**Photo 5 (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.

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 ± actinolite occur sporadically and crosscut both the hornblende and quartz veins.

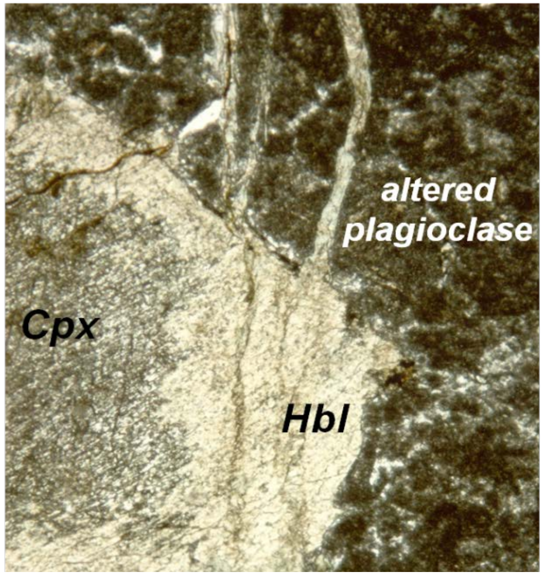

**Photo 6 (stop 1.2).** Hornblende vein crosscutting a pegmatoid gabbro. Clinopyroxene of the host gabbro is replaced by hornblende and altered plagioclase is replaced by a new-plagioclase + hornblende assemblage

**Photo 7 (stop 1.2).** Elongated albitite body showing sharp planar boundaries with the host gabbro.

## *Stop 1.3. Bonassola, "Villaggio la Francesca": serpentinized 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 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 (Photo 8). 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 (Photo

9). Spinel in this dunite body have anomalously low Cr/(Cr+Al) and $TiO_2$ (~26 and ~0.2 wt%, respectively), which were attributed to equilibration with melts depleted with respect to N-MORB (see Sanfilippo and Tribuzio, 2011). In addition, the serpentinized peridotite contains various gabbroic bodies of varied thickness (up to 1 m), orientation and composition.

One sill of a coarse-grained clinopyroxene-rich gabbro is well exposed (Photo 10). It is ~0.5 m thick and shows a sharp planar contact with the serpentinized 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 serpentinized 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 δ18O values and high concentrations of incompatible trace elements) shows an origin from highly differentiated MORB-type melts (Tribuzio et al. 2013).

**Photo 8 (stop 1.3).** Replacive dunite body within serpentinized peridotites. Both rock types are crosscut by parallel fractures mostly filled with tremolite and radial chlorite.

**Photo 9 (stop 1.3).** Spinel-rich levels in replacive dunite oriented parallel to the contact with the host serpentinized peridotite. The contact region is characterised by a gradual outward increase in modal proportion of orthopyroxene.

The serpentinized 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 by scattered fractures filled with calcite plus minor Fe-sulphides and serpentine.

Near the serpentinized peridotite body, the Bonassola gabbro contains a chilled basaltic dyke that locally crosscuts at a high angle the high temperature shearing foliation (Photo 11). In addition, there are large gabbro blocks with albitite bodies displaying either irregular hornblende-rich reaction zones or sharp planar boundaries.

**Photo 10 (stop 1.3).** Gabbro sill showing sharp planar contacts with the serpentinized host peridotite. The gabbro body is characterised by modal and grain size layering parallel to the contact with the enclosing rock.

**Photo 11 (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*

We will visit the "Rosso di Levanto" (mantle ophicalcites) quarries, where structures associated with the brittle deformation that led to exhumation of mantle peridotites to the seafloor may be observed. These carbonate-veined serpentinized 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 (Fig. 6). 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 and 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., 2013).

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 oxidization and carbonatation of serpentinite (i.e. development of hematite + calcite) (Photo 12). The most recent fractures are filled with calcite and talc (Photo 13).

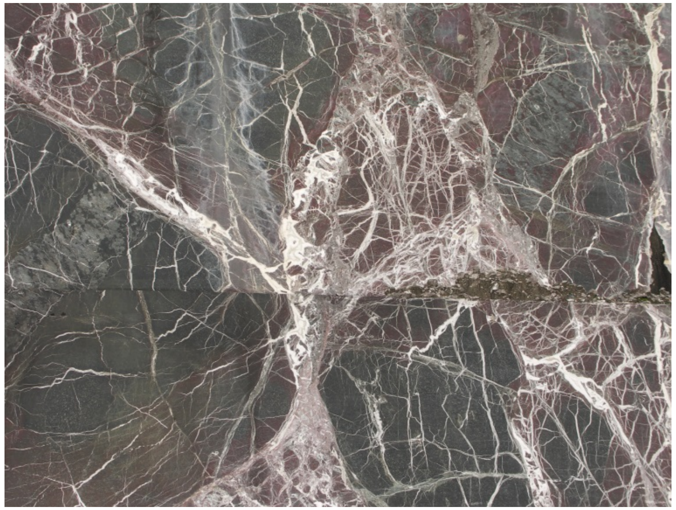

**Photo 12 (stop 2).** Typical brittle deformation structures of mantle ophicalcites (total width of the photo is ~4 m).

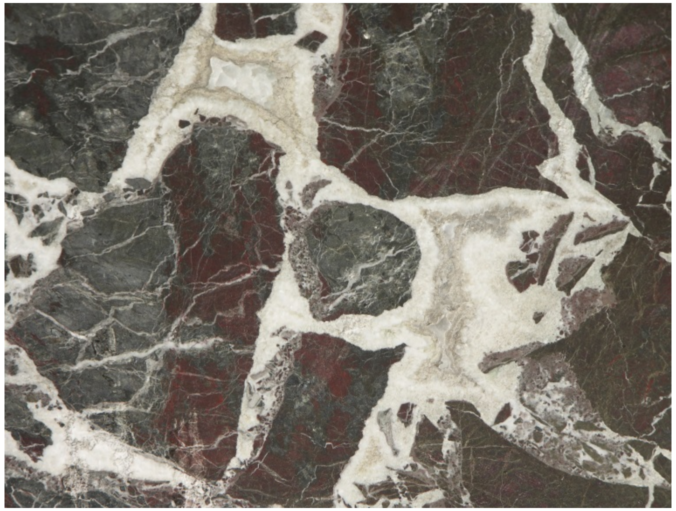

**Photo 13 (stop 2).** Latest fractures filled with calcite and talc (total width of the photo is ~0.2 m).

## 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. 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 Desmurus et al., 2002, Montanini et al., 2008). This incompatible 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 (Kenmpton and Casey, 1997, Escartin et al., 2008. Some of the Alpine Jurassic ophiolites could represent slow-spreading centers characterized by a low magma supply and an elevated lithospheric thickness (see also Sanfilippo and Tribuzio, 2011, 2013).

**Photo 14 (stop 3).** Pillow lava flows in the Framura village

## STOP 4. Mattarana quarry (optional)

A small lens of ultramafic rocks (clinopyroxene-bearing melatroctolites) within Mg-gabbros crops out in a disused quarry. The granular texture is made of euhedral olivine (commonly about 85% by vol) and accessory chromite, surrounded by interstitial plagioclase and sunbordinate huge poikilitic clinopyroxene. A large portion of the outcrop is characterized by pegmatoid texture, in which olivine (5 to 30 cm in size) shows a peculiar skeletal habit. Skeletal olivine consists of sets of parallel lamellae derived from one general form that is made of two series of parallel lamellae symmetric with respect to a central lamella (Bezzi and Piccardo, 1971). The origin of these dendritic olivines has been ascribed to rapid crystal growth induced by variations in the degree of undercooling of the crystallizing melt, related to interaction of a new injection of primitive MORB melt with a cooler resident magma (Renna and Tribuzio, 2011).

Bulk-rock compositions of the ultramafic rocks are characterized by high MgO and low $SiO_2$, $Al_2O_3$ and CaO contents. They display very low LREE concentrations (< 1xC1), almost flat LREE patterns, and marked positive Eu anomalies (Rampone et al., 1998). Bulk rock and clinopyroxene separates give homogeneous $^{143}Nd/^{144}Nd$ ratios (0.51304-0.51317) consistent with typical MORB compositions (Rampone et al., 1998).

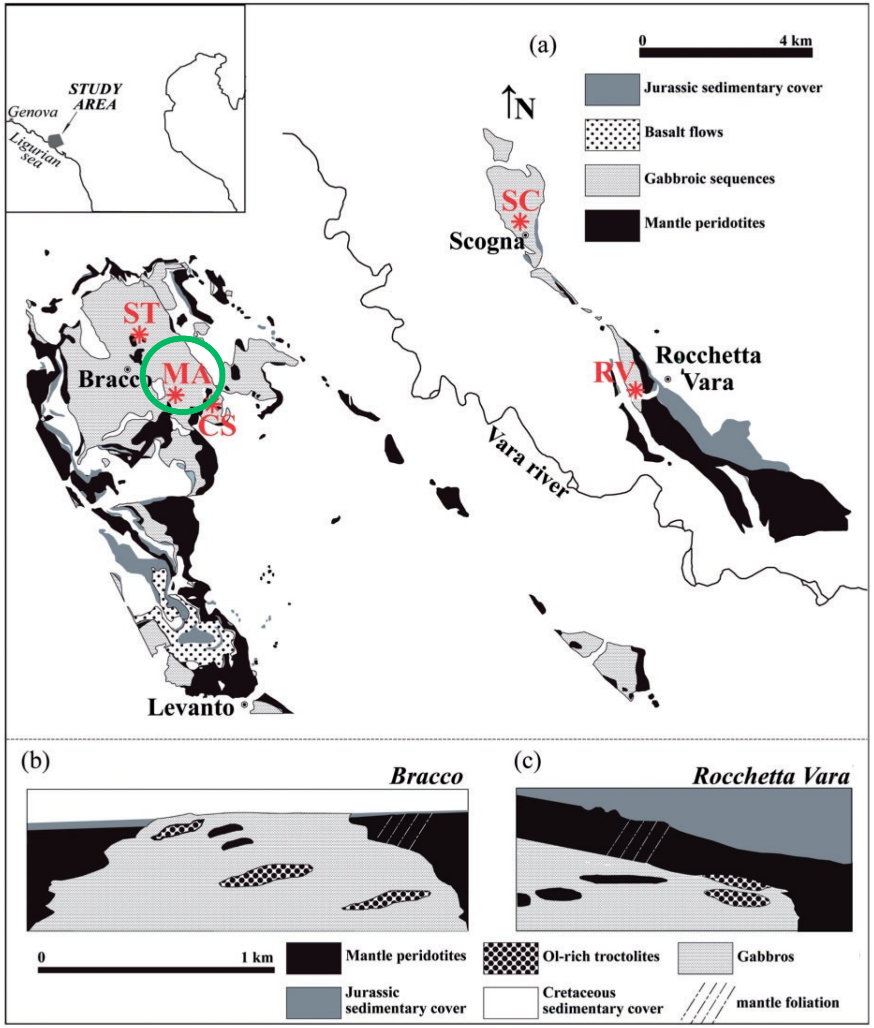

**Figure 6:** (a) Schematic geological map of the Bracco-Levanto and Scogna-Rocchetta Vara ophiolitic bodies: MA, Mattarana quarry; (b, c) Schematic reconstructions of the Bracco and Rocchetta Vara successions (Renna & Tribuzio, 2011)

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