MANTLE HETEROGENEITIES IN RIFTING-RELATED AND SUPRA-SUBDUCTION SETTINGS: EXAMPLES FROM EXTERNAL LIGURIAN AND NEW CALEDONIA OPHIOLITES

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THE COMMON THREAD OF THE WORK

The Earth's mantle does not represent a uniform, well-homogenized system. Instead, geochemical and isotopic differences characterize the whole body. From a general point of view, mantle heterogeneities are explained by the occurrence of pyroxenite and/or eclogite layers. The main implication of such a mantle is that the chemical heterogeneities are then transferred to oceanic basalts (*e.g.*, MORB and OIB) through melting processes.

This work is aimed at understanding how the geochemical and isotopic mantle heterogeneities are created in distinct geodynamic settings. In particular, mantle exposures from the External Ligurian and New Caledonia ophiolites were considered, representing rifting-related and supra-subduction zone mantle sections, respectively.

RIFTING-RELATED MANTLE SECTIONS FROM THE EXTERNAL LIGURIAN OPHIOLITES

Introduction

The ophiolitic bodies from the External Ligurian units represent lithospheric remnants of the Jurassic Western Tethys basin (also known as Ligure-Piedmontese basin). The External Ligurian ophiolites preserve subcontinental mantle exhumed on the ocean floor along the Western Tethys ocean-continent transition (OCT) in Lower Jurassic times, during the extensional stage that led to the opening of the basin. As a consequence of the Upper Cretaceous convergence, the External Ligurian ophiolites were emplaced as slide-blocks within sedimentary mélanges (*e.g.*, Marroni *et al.*, 2017).

The External Ligurian mantle slide-blocks cropping out in the Northern Apennine (Italy) are up to few km in size. The External Ligurian subcontinental mantle typically consists of fertile spinel-plagioclase lherzolites with disseminated Ti-rich amphibole, and widespread pyroxenite layers (*e.g.*, Montanini *et al.*, 2006; Rampone *et al.*, 1995). Only few mantle bodies (namely Suvero, *Monte Nero, Monte Ragola*, Rio Strega, *Monte Prinzera*) were studied in the literature (*e.g.*, Rampone *et al.*, 1995; Borghini *et al.*, 2011, 2013, 2016, 2021; Montanini *et al.*, 2006, 2012; Montanini & Tribuzio, 2015).

The work focused on the poorly known mantle bodies cropping out between Val Trebbia and Val Perino. Two distinct mantle sections were identified: *Monte Gavi* and *Monte Sant'Agostino* sequences (Fig. 1). The work aimed at presenting new field, microstructural, geochemical, isotopic and geothermobarometric data. The specific goal of this work was to provide new insights into the behaviour of the External Ligurian subcontinental mantle during the Mesozoic rifting phase.

Monte Gavi mantle section

The *Monte Gavi* section is constituted by nearly undeformed spinel-plagioclase harzburgites including two types of pyroxenite layers, up to ~80 cm (Type Ia-b) and up to ~10 cm thick (Type II), respectively. *Monte Gavi* mantle rocks bear diffuse evidence of reactive melt infiltration in the plagioclase stability field. Spinel from both peridotites and pyroxenites is rimmed by plagioclase. In the pyroxenites, plagioclase also occurs along the cleavages of pyroxenes or crystallizes along mm-sized veinlets. In addition, clinopyroxene from both peridotites and pyroxenites (mainly coarse-grained spinel websterites) is extensively replaced by plagioclase + orthopyroxene. The melt-rock reaction process is also supported by the relatively high TiO_2 contents (up to 1 wt.%) and Cr# values (up to 34) of spinels from pyroxenites and enclosing peridotites, as well as by remarkably high TiO_2 contents (up to 2.3 wt.%) of clinopyroxenes from pyroxenites (see Ferrari *et al.*, 2022 for further details). The plagioclase-facies melt-rock interaction event involving both peridotites and enclosed pyroxenite layers at *Monte Gavi* is estimated to have occurred at 0.7-0.8 GPa (according to the Forsterite-Anorthite-Ca-Tschermak-Enstatite, FACE, geobarometer of Fumagalli *et al.*, 2017) and ~1250°C (according to the geothermometers of Liang *et al.*, 2013 and Sun & Liang, 2017, based on slowly diffusing elements), followed by thermal relaxation and slow cooling to ~900-1000°C (according to conventional major element pyroxene thermometry of Brey & Köhler, 1990 and Taylor, 1998).

Pyroxenite samples were variably affected by the melt-rock reaction process. In particular, Type-I pyroxenites were subdivided in two sub-types (Ia and Ib) based on the different replacement extents. Type-Ib pyroxenites are characterized by i) pyroxene-rich domains in which coarse clinopyroxene relics are associated to newly formed secondary orthopyroxene + plagioclase + clinopyroxene, and ii) plagioclase-rich domains constituted by plagioclase + olivine + Cr-spinel presumably representing the reaction products between the percolating melt and original Al-spinel-rich domains. Conversely, in Type-Ia pyroxenites coarse clinopyroxene and spinel grains are well preserved, despite the local crystallization of orthopyroxene and plagioclase. Likewise, the major element mineral chemistry confirms that Type-Ia pyroxenites were less affected by reaction with a percolating melt compared to Type-Ib and Type-II (see Ferrari *et al.*, 2022 for further details). Moreover, the infiltrating melt triggered a considerable modification in clinopyroxenes REE composition. In addition, Nd-Hf isotopic compositions of whole rock powders and clinopyroxene separates from *Monte Gavi* pyroxenites enhanced knowledge on the nature of the percolating melt and the timing of the melt-rock reaction event.

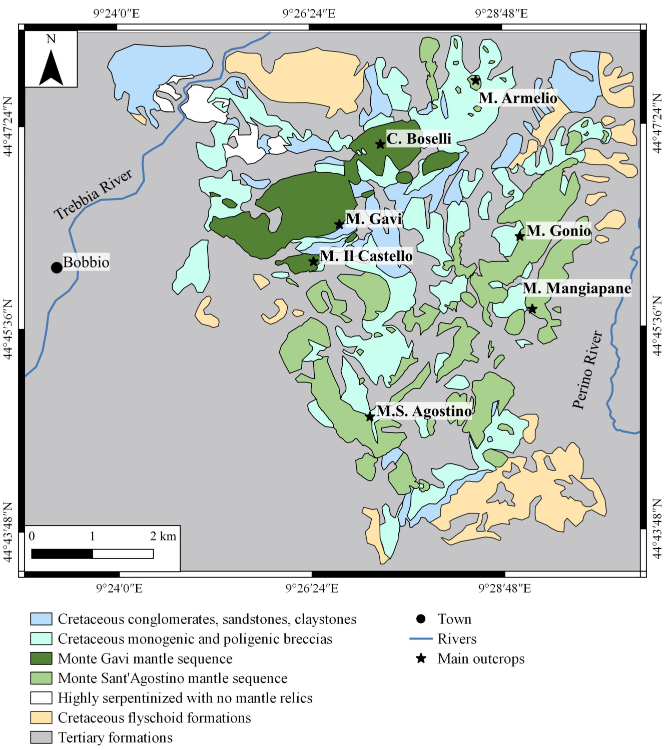

Fig. 1 - Geological sketch map of the study area (modified after Ferrari *et al.*, 2022).

Monte Sant'Agostino mantle section

The *Monte Sant'Agostino* sequence is composed of deformed spinel-plagioclase lherzolites showing protomylonitic to ultramylonitic textures and small (mm-sized) relicts of spinel tectonite domains. Up to ~10 cm thick pyroxenite layers concordant to the host peridotite foliation occur in the protomylonitic peridotites, whereas in the ultramylonitic domains, only stretched, mm-sized pyroxene-rich bands can be observed. *Monte Sant'Agostino* mantle sequence displays ductile shearing under plagioclase-facies conditions, with no textural or chemical evidence of melt-rock reaction. Deformation occurred along ultramylonitic shear zones up to ~150 m thick. The peridotites are characterized by deformed pyroxene porphyroclasts and very fine-grained (10-50 µm) neoblasts of olivine + pyroxenes + plagioclase. *Monte Sant'Agostino* pyroxenites are spinel websterites showing a plagioclase-facies protomylonitic texture (see Ferrari *et al.*, 2022 for further details). The main deformation recorded by the *Monte Sant'Agostino* peridotites occurred at 750-780°C (Ca-in-Opx geothermometer of Brey & Köhler, 1990) and 0.3-0.6 GPa (FACE geobarometer of Fumagalli *et al.*, 2017). The enclosed pyroxenite layers yielded relatively high temperature and pressure estimates (870-930°C and 0.8-0.9 GPa). In the *Monte Sant'Agostino* mantle section, plagioclase crystallization therefore occurred earlier in the pyroxenites than in enclosing lherzolites, which probably enhanced strain localization and formation of mylonite shear zones in the entire mantle section (see Ferrari *et al.*, 2022 for further details). Locally, pyroxene-spinel symplectitic intergrowths in the pyroxenites argue for the presence of former garnet and an earlier equilibration stage at P > 1.5 GPa (Borghini *et al.*, 2016).

CONCLUSIONS

Overall, *Monte Gavi* and *Monte Sant'Agostino* sections testify the heterogeneity of the External Ligurian subcontinental mantle, not only due to the presence of pyroxenite layers, but also to the geochemical and isotopic modifications triggered by a melt-rock reaction event.

The distinct plagioclase-facies evolutions recorded by the studied mantle sections (*i.e.*, melt-rock reaction and no deformation at *Monte Gavi vs*. mylonitic to ultramylonitic deformation with no melt-rock reaction at *Monte Sant'Agostino*) were related to the Mesozoic rifting stage that preceded the opening of the Jurassic Western Tethys basin. By comparing *Monte Gavi* and *Monte Sant'Agostino* sequences with the other External Ligurian mantle sections reported in the literature (*e.g.*, Rampone *et al.*, 1995; Piccardo *et al.*, 2004; Montanini *et al.*, 2006), three distinct mantle domains were identified (Fig. 2): (1) a spinel tectonite domain (ST) recording a decompression evolution with static plagioclase development and no deformation and melt rock reaction under plagioclase-facies conditions; (2) a plagioclase mylonite (PM) domain (including *Monte Sant'Agostino*) recording a relatively cold, melt-absent decompression, where plagioclase-facies recrystallization was associated with high-T shearing and mylonite formation; (3) an undeformed plagioclase-impregnated (PI) domain (including *Monte Gavi*) characterized by a relatively hot plagioclase-facies evolution associated with reactive melt percolation. Such domains developed in response to the extensional evolution that ultimately formed a Middle Jurassic ocean-continent transition. Mantle domains (1, 2) are interpreted to be related to a rifting-driven uplift in the late Triassic accommodated by large-scale shear zones consisting of plagioclase mylonites (see Ferrari *et al.*, 2022 for further details).

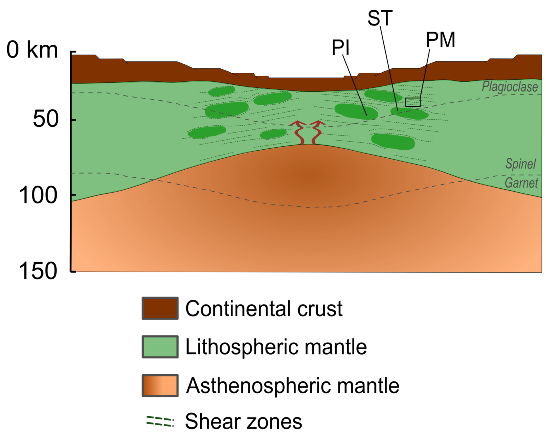

Fig. 2 - Interpretative section of the subcontinental mantle at the onset of rifting in late Triassic displaying the different plagioclase-bearing mantle domains recognized for the External Ligurian mantle section (ST: plagioclase-spinel tectonite; PM: plagioclase mylonite, PI: plagioclase-impregnated). Modified after Ferrari *et al.*, 2022.

SUPRA-SUBDUCTION ZONE MANTLE SECTION FROM THE NEW CALEDONIA OPHIOLITE

Introduction

The New Caledonia Island is located in the south-west Pacific Ocean. The New Caledonia ophiolite is an allochthonous sheet of oceanic lithosphere that experienced an evolution in a supra-subduction environment and was subsequently obducted onto a continental basement in the Late Eocene (Cluzel *et al.*, 2012). The ophiolitic sequence (also referred to as Peridotite Nappe) is mainly composed of ultra-depleted harzburgites, and minor lherzolites, locally overlain by mafic-ultramafic cumulates representing the lower crust of a nascent arc (Secchiari *et al.*, 2018 and references therein). The ultra-depleted harzburgites lack primary clinopyroxene and record a multi-phase evolution, *i.e.*, anhydrous melting in a marginal basin and a subsequent fluid-assisted melting in a forearc environment coupled to contamination with subduction-related melts and fluids (*e.g.*, Secchiari *et al.*, 2020).

The work focused on pyroxenitic rocks intruding the harzburgites exposed in Ouassé locality. The petrological and geochemical investigation was targeted to understand the origin of the pyroxenite-forming melts and thus to investigate the subduction-related melts that percolated the forearc mantle.

Ouassé mantle section

The Ouassé mantle sequence, located in the central eastern part of the New Caledonia Island, pertains to the Bogota Peninsula Shear Zone (Fig. 3), a regional-scale, high-temperature shear zone interpreted as an oceanic paleotransform fault (Prinzhofer & Nicolas, 1980; Titus *et al.*, 2011; Chatzaras *et al.*, 2020).

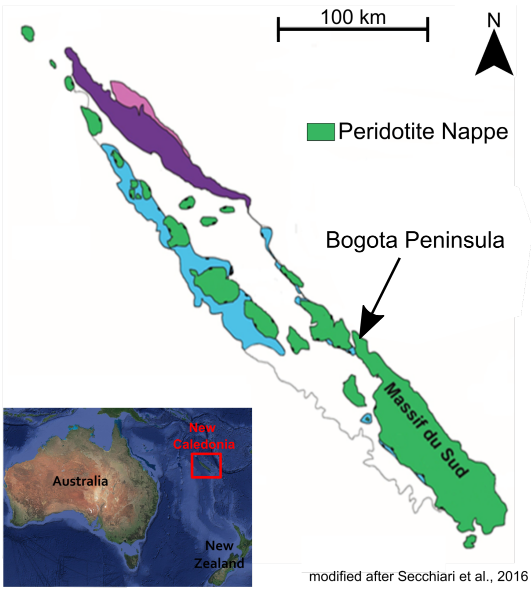

Fig. 3 - Geological sketch map of New Caledonia Island showing the extent of the Peridotite Nappe ophiolite (modified after Secchiari *et al.*, 2016). The study area (Ouassé) is located in the Bogota Peninsula.

The Ouassé section is mainly composed of mylonitic harzburgites including abundant pyroxenitic dikes. The latter are ~5-15 cm thick layers, ranging from concordant to discordant with respect to the host peridotite foliation. Harzburgites show porphyroclastic to mylonitic textures characterized by olivine and highly stretched orthopyroxene porphyroclasts set into a fine-grained (mostly 100-400 μm) neoblastic matrix composed of olivine + orthopyroxene + Cr-spinel. Secondary clinopyroxene and amphibole are locally present. Ouassé harzburgites are geochemically similar to the highly depleted New Caledonia mantle harzburgites reported in the literature (Marchesi *et al.*, 2009; Ulrich *et al.*, 2010; Secchiari *et al.*, 2020). Pyroxenites were classified as orthopyroxenites and amphibole-bearing websterites. They have variable textures, from cumulitic to granoblastic-polygonal. The two groups of samples, orthopyroxenites (Opx ~95 vol% ± Ol ~5 vol% or ± Cpx ~5 vol% + accessory Spl) and amphibole websterites (Opx ~25-70 vol% + Cpx ~25 vol% + Amp ~5-40 vol% + accessory apatite and sulphides; locally, Pl up to ~3 vol% is also present), have distinct geochemical compositions. For instance, orthopyroxenites have higher whole rock (~92) and orthopyroxene Mg# (~91) compared to amphibole-bearing websterites, thus arguing for a more refractory signature. This is also supported by the whole rock incompatible trace element compositions of orthopyroxenites which are about one order of magnitude lower than those of amphibole-bearing websterites.

Thermometric calculations were done on both enclosing peridotites and pyroxenite dikes. In particular, Ca-in-Opx thermometer (Brey & Köhler, 1990) applied on the mylonite neoblastic assemblage gave values of ~950°C, presumably reflecting the relatively high-temperature conditions of deformation. Estimates for the pyroxenites (*e.g.*, $T_{Ca\text{-}in\text{-}Opx}$ = 920-990°C) indicate equilibration temperatures comparable with those of the host harzburgites.

Clinopyroxene geochemical data were used in order to identify the pyroxenite-forming melts. In particular, the Mg# values of clinopyroxene were employed to compute the Mg# of the equilibrium melts according to the equation of Wood & Blundy (1997). Orthopyroxenites have higher values (Mg# = 80) compared to amphibole-bearing websterites (Mg# ~60-70), suggesting an origin from a refractory source. Trace elements compositions of parental melts were calculated from clinopyroxene trace element analyses and clinopyroxene/liquid partition coefficients of Hart & Dunn (1993). Equilibrium melts of orthopyroxenites show similarities with the New Caledonia boninites, which were interpreted as the product of low degree partial melting of a depleted peridotite source previously enriched by slab-derived melts (Cluzel *et al.*, 2016). Parental melts of amphibole-bearing websterites show distinct REE patterns and higher concentrations (~ 10 to 100 times chondrite values) compared to the equilibrium melts of orthopyroxenites. The strongly enriched compositions of websterites parental melts would suggest an adakite-like (*i.e.*, slab-related hydrous silica-rich melt) component of the websterite-forming liquids.

Websterite layers gave Early Eocene $^{40}Ar/^{39}Ar$ amphibole ages (Cluzel *et al.*, in prep.), in agreement with the first stages of subduction inception (Cluzel *et al.*, 2012). Thus, Ouassé pyroxenites represent one the first products of early melts percolating the forearc mantle during subduction initiation. Based on these new results, the Bogota Peninsula Shear Zone was reinterpreted as being associated to a subduction-related setting.

Conclusions

Collectively, the studied pyroxenite layers are subduction-related rocks. The work has reported a significant heterogeneity of pyroxenitic rocks. They indicate different melts that percolated the forearc mantle, variably alternating relatively refractory melts (boninite-like) with more enriched melts, reflecting a variable contribution of slab-derived components. The Ouassé pyroxenites offer the rare opportunity to decipher the interaction between a forearc mantle and the percolating liquids during subduction initiation.

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