Per. Mineral. (2004), *73*, 119-129 http://go.to/permin
SPECIAL ISSUE 2: A showcase of the Italian research in metamorphic petrology

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY, ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

Records of mantle–crust exchange processes during continental subduction–exhumation in the Nonsberg–Ultental garnet peridotites (eastern Alps). A review

LAURO MORTEN[1], PAOLO NIMIS[2]* and ELISABETTA RAMPONE[3]

[1] Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna, Piazza Porta S. Donato 1, 40126 Bologna, Italy
[2] Dipartimento di Mineralogia e Petrologia, Università di Padova, C.so Garibaldi 37, 35137 Padova, Italy
[3] Dipartimento per lo Studio del Territorio e delle sue Risorse, Università di Genova, Corso Europa 26, 16132 Genova, Italy

ABSTRACT. — In the Nonsberg-Ultental area (Tonale nappe), Grt-bearing peridotites occur in high-*P* migmatitic gneisses enclosing relics of eclogites. The peridotites record the transformation of high-*T* Spl-lherzolites to coronitic Grt+Spl-lherzolites to fine-grained Amph±Grt-peridotites. The transformation is preceeded by LILE enrichment and intrusion of hot melts, and accompanied by deformation, hydration, LILE enrichment and LILE/HFSE fractionation. High-*P* metamorphism of peridotites and eclogites and early migmatization of the country gneisses were virtually coeval and possibly isofacial. The peridotites may represent former mantle-wedge material that was subducted and cooled due to incorporation in a crustal slab and then metasomatized by hydrous fluids left after crystallization of leucosomes. Possible directions for further work on this and other sectors of the Variscan belt where broadly similar rock associations have been found are proposed.

RIASSUNTO. — Gli gneiss migmatitici dell'Alta Val di Non–Val d'Ultimo contengono corpi peridotitici e relitti di eclogiti. Le peridotiti comprendono protoliti lherzolitici a Spl di alta *T*, più o meno estesamente trasformati in lherzoliti coronitiche a Grt+Spl e, infine, in peridotiti granoblastiche ad Amph±Grt. La trasformazione è stata preceduta da arricchimenti in LILE e intrusioni di fusi di alta *T* ed è stata accompagnata da deformazione, idratazione, arricchimento in LILE e frazionamento LILE/HFSE. Il metamorfismo di alta *P* di peridotiti ed eclogiti e la migmatizzazione iniziale degli gneiss sono praticamente coevi e possono essere avvenuti in condizioni *P-T* simili. Le peridotiti possono rappresentare porzioni di cuneo di mantello incorporate in una crosta continentale subdotta e successivamente metasomatizzate da fluidi idrati rilasciati dalla cristallizzazione di leucosomi. Vengono proposte alcune possibili direzioni per ulteriori indagini su questo e altri settori dell'orogeno varisico caratterizzati dalla presenza di associazioni litologiche confrontabili con quelle studiate.

KEY WORDS: *Nonsberg, Ultental, Ulten zone, garnet peridotite, migmatite, LILE, crustal metasomatism, subduction, Variscan orogeny*

INTRODUCTION

Garnet peridotites form a large portion of the upper mantle, but minor occurrences are also found in collisional mountain belts within high-grade crustal terrains. Many of these 'orogenic' peridotites have chemical compositions

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* Corresponding author, E-mail: paolo.nimis@unipd.it

resembling that of depleted mantle, suggesting they were former portions of the upper mantle which were incorporated into the crust by some sort of tectonic process. According to modern views, subduction zones are among the best conceivable settings in which mass exchanges between mantle and crust can take place (Brueckner and Medaris, 2000). Emplacement of peridotites into the crust may involve brittle tectonic processes or ductile sinking phenomena at a wedge-slab interface (Brueckner, 1998), either during subduction or during later exhumation (Tumiati *et al.*, 2003).

A nice example of mantle-crust interaction is found in the Austroalpine crystalline basement of the Nonsberg-Ultental (hereafter NU) region, where well-preserved Grt-bearing peridotites are found in a high-*P* migmatitic unit. Obata and Morten (1987) showed that the NU peridotites record what at the time appeared to be an unusual *P-T* evolution from high-*T*, coarse-grained Spl-peridotites to low-*T*, coarse-grained Grt+Spl- and fine-grained Grt+Amph-peridotites. More recently, Nimis and Morten (2000) interpreted the *P–T* evolution of the NU peridotites as a result of cooling and subduction of high-*T* mantle-wedge peridotites due to entrainment into a subducting crustal slab. The NU peridotites may therefore be considered as a natural laboratory for studies on mantle-crust interactions during subduction-exhumation processes (Tumiati and Martin, 2003).

The purpose of the present paper is to give an overview of current knowledge on the petrologic–geodynamic evolution of the NU peridotites and of the crustal country-rocks, and on the interaction processes between the two, and to give suggestions for further research on this subject.

GEOLOGICAL BACKGROUND

Some of the best preserved garnet peridotites of the Eastern Alps are exposed in an area located about 40 km west of Bolzano, on the mountain range (Le Maddalene) which separates the upper Non valley (Val di Non or Nonsberg) from the Ulten valley (Val d'Ultimo or Ultental) (Fig. 1). This area, which has been reported in the literature with the alternative names of *Nonsberg*, *Ultental* and *Ulten* (*zone* or *unit*), is part of the Upper Austroalpine domain and has been the subject of several tectonostratigraphic, mineralogical and petrological studies, most of which were reviewed by Martin *et al.* (1998).

The Upper Austroalpine system consists of metasedimentary cover and upper-to-lower crust slices derived from the Mesozoic passive margin of the Adria microplate (Dal Piaz, 1993). According to Flügel (1990) and Neubauer and von Raumer (1993), the Austroalpine system of the Eastern Alps represents a piece of the Variscan belt. North of the Tonale and Giudicarie lines, the Austroalpine system comprises a northern, cover-bearing nappe (Ortler nappe) and a southern, overlying, cover-free nappe (Tonale nappe) (Thöni, 1981). The Tonale nappe can be further subdivided into a lower-grade *Tonale zone* and a higher-grade *Ulten zone*, which are separated from each other by the Rumo line (Morten *et al.*, 1976)[1] (Fig. 1). The basement of the Tonale zone (Grt+Sil paragneisses and metagranitoids with marbles, calc-silicate rocks and mafic-ultramafic intercalations) was retrogressed during late- or post-Variscan exhumation and locally deformed under greenschist-facies conditions during the Alpine orogeny (Thöni, 1981). By contrast, the Ulten zone, a NNE-striking, fault-bounded belt ~12-km long and 2-3-km wide consisting of migmatites and Grt+Ky-bearing paragneisses with subordinated orthogneisses, amphibolitized eclogites and Spl±Grt-bearing peridotites, largely escaped the Alpine overprint (Obata and Morten, 1987; Martin *et al.*, 1993, 1994, 1998; Godard *et al.*, 1996).

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[1] In recent papers (e.g. Martin et al., 1998), the Rumo Line has been considered to separate two portions of the Ulten zone, of which the northernmost one is characterized by higher metamorphic degree and less intense retrogression.

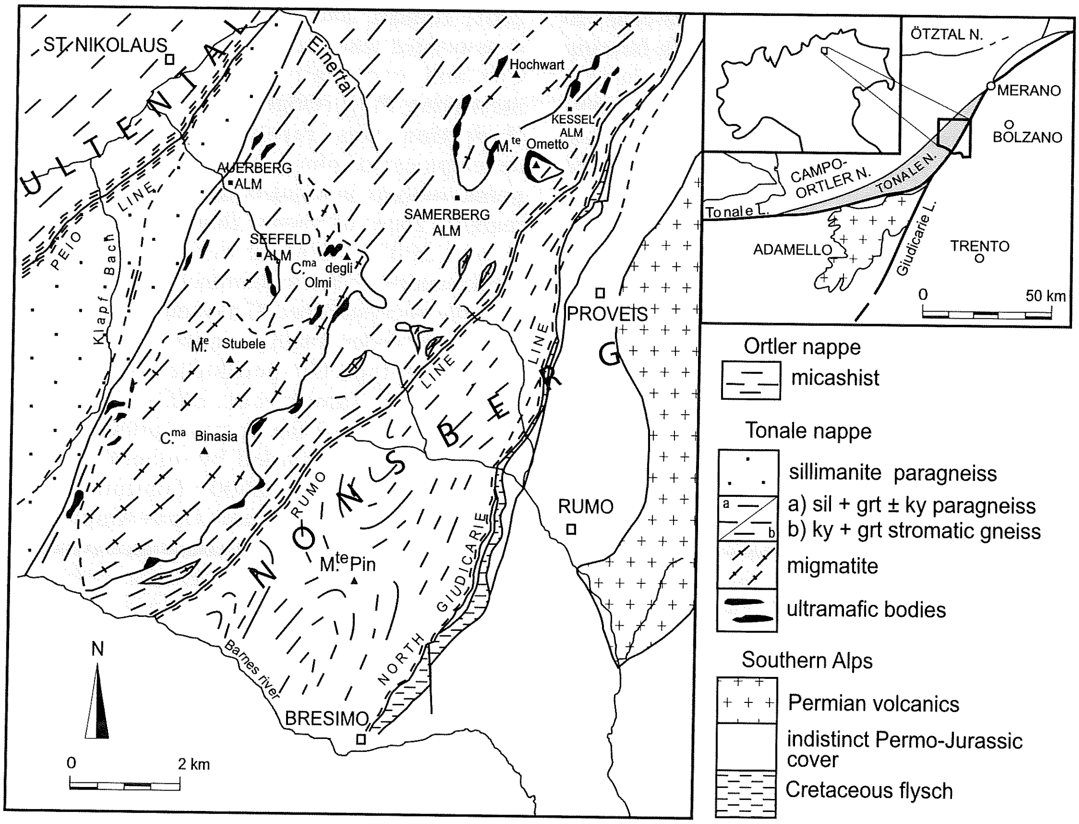

Fig. 1 – Geological map of the Nonsberg-Ultental area (modified after Del Moro *et al.*, 1999).

Petrological outline of the Nonsberg-Ultental peridotites

The NU peridotites mostly occur as lenses or barrel-shaped bodies (up to 10 m thick and tens to hundreds meters long) of harzburgitic, lherzolitic and minor dunitic compositions intruded by pyroxenite veins. They form a discontinuous horizon which marks the transition between an underlying unit made of Grt+Ky-bearing, strongly foliated, weakly migmatized gneisses and an overlying unit made of migmatites (Godard *et al.*, 1996). The banding and/or foliation of the peridotites, when present, are roughly concordant to the main planar anisotropy of the country-rocks. The contacts between the peridotite bodies and the country rocks, although poorly exposed and often obscured by young faults, are generally sharp and marked by the development of hybrid Phl±Amph±Chl-bearing rocks (Godard *et al.*, 1996). The petrographic characteristics of the peridotites and pyroxenites have been described by Morten and Obata (1983) and Obata and Morten (1987), and further details have been illustrated by Godard *et al.* (1996), Nimis and Morten (2000), Godard and Martin (2000), Tumiati *et al.* (2003), and Tumiati and Martin (2003). Only a brief outline is given here and the reader is referred to the above papers for a more thorough description.

The NU peridotites record a complex metamorphic history, documented by the transformation of coarse-grained (up to a few cm) Spl-bearing lherzolites (*coarse-type*) to fine-grained (0.2-1 mm) Grt+Amph-bearing peridotites (*fine-type*). The fine-type largely prevails over the coarse-type. Pyroxenite veins record a similar evolution from ultracoarse (≤6 cm) clinopyroxenites to fine-grained Grt+Amph±Ol-bearing websterites (Morten and Obata, 1983; Nimis and Morten, 2000). The coarse-type is restricted to weakly deformed domains within some of the peridotite bodies and mostly maintains an old, protogranular, Spl-lherzolite mineral assemblage. Amphibole is often absent, but may occur in minor amounts along pyroxene grain boundaries. Thermobarometric data indicate equilibration at ~1200°C and 1.3-1.6 GPa for the Spl-lherzolites and early crystallization at $T \geq 1400°C$ and similar P for the pyroxenites (Nimis and Morten, 2000).

In a few coarse-type samples a younger Grt-bearing assemblage can be found. Grt occurs as coronas around Spl, lamellae in pyroxenes, and granoblastic aggregates in equilibrium with pyroxene and Ol neoblasts. Opx and Cpx porphyroclasts show complex exsolution textures, with lamellae of the complementary pyroxene, Grt, Amph and minor Spl (Godard *et al.*, 1996). In some samples, edenitic-pargasitic amphibole forms neoblasts in the fine-grained Grt-bearing assemblage. The Grt-bearing assemblages developed by cooling to ~850°C and P increase to ~2.7 GPa (Nimis and Morten, 2000).

Widespread shearing, hydration and sinkinematic recrystallization during the high-P stage produced fine-type peridotites characterized by dominant tabular to mosaic granular textures. These rocks mostly consist of granoblastic Grt+Amph+Ol+Opx aggregates, with minor or no Cpx and rare Dol, Phl and Ap (Obata and Morten, 1987). Transition from coarse to fine types is testified by porphyroclastic Grt-bearing samples. In the fine-type, amphibole is modally abundant (13-23 %vol) and ranges in composition from pargasite-edenite cores with up to 1 wt% K_2O to Mg-Hbl rims (Obata and Morten, 1987; Nimis and Morten, 2000; Rampone and Morten, 2001; Tumiati, 2002). Increase in modal Amph is associated with progressive disappearance of Cpx and, eventually, Grt as a response to increasing P_{H_2O} (Obata and Morten, 1987). Hydration was rarely accompanied by development of pluricentimetric euhedral Grt porphyroblasts in veinlets of pargasite-edenite, marking zones of intense fluid influx (Tumiati *et al.*, 2003). Mineral compositions and semiquantitative thermobarometric data suggest that the recrystallized Grt+Amph-peridotites developed under roughly similar conditions as the coarse-type Grt-peridotites (Obata and Morten, 1987; Tumiati *et al.*, 2003).

Retrogression of the garnet-bearing mineral assemblages is recorded by mineral zoning (Nimis and Morten, 2000; Tumiati *et al.*, 2003), Opx+Cpx+Spl and Opx+Amph+Spl symplectites at the Ol-Grt boundaries (Godard and Martin, 2000) and, sometimes, complete replacement of Grt by globular, coarse Amph+Spl aggregates (Susini and Martin, 1996). In a single occurrence, a new REE-epidote (dissakisite-(La)) was found in a Spl+Amph-bearing dunite (Tumiati *et al.*, in prep.). Further retrogression is testified by development of Ol+Tr+Cum+Chl+Tlc assemblages and widespread serpentinization.

PETROLOGICAL OUTLINE OF THE CRUSTAL COUNTRY ROCKS

The Ulten zone mainly consists of strongly-foliated gneisses and migmatites (Fig. 1). The gneisses show a protomylonitic to blastomilonitic texture (Martin *et al.*, 1993, 1994, 1998; Godard *et al.*, 1996) and are composed by mm- to cm-sized bands of alternating Grt+Ky+Bt+Rt and Qtz+Pl±Kfs, transposed along an S_1 protomylonitic foliation. The banded structure can be interpreted as an alternation of melanosomes and leucosomes related to a pre-S_1 migmatization event (Godard *et al.*, 1996). The gneisses grade upward into stromatic and nebulitic migmatites, which mostly show the mineral assemblage Qtz+Pl+Mu+Bt+Grt±Ky.

Lenses of amphibolites are locally found within the migmatites and the gneisses. In the least migmatized areas they carry relics of an eclogite paragenesis (Benciolini and Poli, 1993; Hauzenberger *et al.*, 1996; Godard *et al.*, 1996; Del Moro *et al.*, 1999). The migmatites and the enclosed peridotites are cut by trondhjemitic (Pl±Qtz±Bt) veins (Martin *et al.*, 1994, 1998; Godard *et al.*, 1996), which have been interpreted as the product of crystallization of calcalkaline deep-crust partial melts mixed with *in-situ* melts (Del Moro *et al.*, 1999). The metamorphic-melting history of the NU basement can be summarized as follows (Del Moro *et al.*, 1999): i) pre-S_1 (Godard *et al.*, 1996) or syn-S_1 (Hauzenberger *et al.* 1996) migmatization by dehydration-melting; ii) S_1 mylonitic deformation at eclogite-facies conditions; iii) post-S_1 injection by exotic melts and further migmatization at eclogite-granulite conditions during decompressional uplift; iv) S_2 shearing and retrogression. Thermobarometric estimates for the high-*P* metamorphic peak are hampered by extensive retrogression during uplift and post-S_1 migmatization (Tumiati *et al.*, 2003). Semiquantitative estimates point to $T \geq 850°C$ and $P \geq 1.6$ GPa (Godard *et al.*, 1996; Hauzenberger *et al.*, 1996). According to Tumiati *et al.* (2003) there is no evidence that the peridotites, eclogites and gneisses have experienced significantly different peak *P-T* conditions during high-*P* metamorphism. All lithologies record a common, decompressional, retrograde *P-T* evolution (Godard *et al.*, 1996).

RECORDS OF CRUSTAL METASOMATISM

In terms of most major and trace elements (Si, Mg, Ca, Al, Sc, Co, V, Ni), no systematic correlation exists between peridotite bulk-rock compositions and textural types (coarse vs. fine) or metamorphic assemblages (Spl vs. Grt vs. Amph-bearing) (Morten and Obata, 1990; Bondi *et al.*, 1992). Variations in the concentrations of the above elements most likely reflect a primary compositional heterogeneity of the mantle protoliths. The fine-grained Amph±Grt-bearing types show a significant enrichment in alkalies (especially K_2O) and LILE, which is unrelated to major element chemistry and roughly correlated with the Sr isotopic compositions of the peridotites (Bondi *et al.*, 1992; Petrini and Morten, 1993; Rampone and Morten, 2001). These chemical and textural modifications are accompanied by crystallization of abundant Amph, selective LREE and Sr enrichment in Cpx and strong LILE enrichment and LILE/HFSE fractionation in Amph. The latter is testified by LREE up to 40-70xC1, severe Ti and Zr depletion, very high Ba (280-800 ppm), Sr (150-250 ppm) and K (1910-7280 ppm) and very low Nb (2-7 ppm) contents (Fig. 2). Similar processes are recorded by the pyroxenite veins that cut the peridotites (Morten and Obata, 1990).

Selective LILE enrichment and LILE/HFSE fractionation have been reported in Amph±Phl-bearing peridotites from Finero (Zanetti *et al.*, 1999) and Zabargad Island (Dupuy *et al.*, 1991; Piccardo *et al.*, 1993), and in Amph-bearing xenoliths from sub-arc mantle (Vidal *et al.*, 1989; Maury *et al.*, 1992). These features have been interpreted as the result of interactions of mantle-wedge peridotites with slab-derived hydrous fluids or hydrous, Si-rich melts. Accordingly, the LILE-enriched, HFSE-depleted signature of NU amphiboles is also consistent with a crustal derivation of the metasomatizing agent. Rampone and Morten (2001) favoured a crustal-derived, low-density fluid, rather than a Si-rich melt, based on the evidence that Amph crystallization was accompanied by neither significant modifications of the peridotite major-element compositions nor abundant Opx crystallization (cf. Sekine and Wyllie, 1982; Schiano *et al.*, 1995), and on the inferred capability of H_2O-rich fluids to fractionate LILE from HFSE (Brenan *et al.*, 1995; Keppler, 1996). The high modal Amph contents and the occasional occurrence of Dol and Ap suggest that the metasomatic agent was an H_2O-CO_2-bearing fluid with a low CO_2/H_2O ratio (Rampone and Morten, 2001).

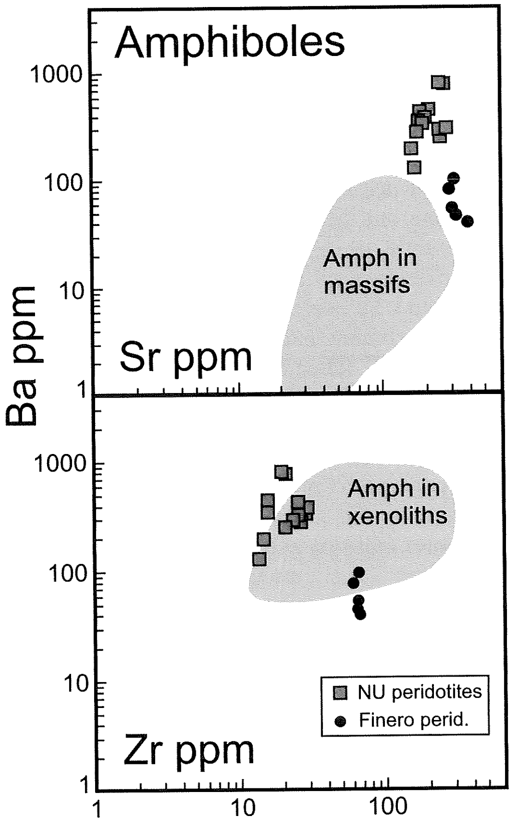

Fig. 2 – Variation of Ba (ppm) vs. Sr (ppm) and Zr (ppm) for amphiboles in fine-type NU peridotites. Data after Rampone and Morten (2001). Data for amphiboles from the Finero peridotite (Zanetti *et al.*, 1999) and peridotite xenoliths and massifs (Ionov *et al.*, 1997) are shown for comparison.

Field evidence, geochronological data and the reconstructed *P*-*T*-t evolution of the peridotites and of the host migmatites strongly indicate that peridotite metasomatism was concomitant to migmatization (Godard *et al.*, 1996; Rampone and Morten 2001; Tumiati *et al.*, 2003). Partial melting of the lower crust during high-grade metamorphism is usually believed to occur under mostly H_2O-absent conditions by biotite- or white mica-dehydration melting reactions (e.g. Vielzeuf and Holloway, 1988; Hermann and Green, 2001). The melts may contain several percent units of dissolved H_2O and progressive fractionation of anhydrous minerals may lead to release of a free H_2O-rich fluid phase. Accordingly, Rampone and Morten (2001) suggested that the metasomatizing hydrous fluids could represent the residual fluids left after the crystallization of leucosomes in the host migmatites.

Interestingly, some coarse-type Spl-lherzolites that escaped high-*P*, low-*T* metamorphism also exhibit a cryptic metasomatic imprint, which is testified by selective LREE enrichment in both whole-rocks and constitutent Cpx and low whole-rock Nd isotope ratios (0.51188; Petrini and Morten, 1993). Again, the LILE enrichment is not accompanied by HFSE enrichment (Rampone and Morten, 2001). Cryptic metasomatism in the form of radiogenic Sr-enrichment is also recorded by coarse-type Grt-bearing lherzolites that largely escaped deformation and hydration (Tumiati *et al.*, 2003). It would be tempting to interpret this (these) early metasomatic event(s) as the result of interactions with uprising slab-derived fluids during a mantle-wedge stage. However, the only available Sm/Nd isotope data on a Spl-peridotite sample yielded a very old age (ca. 1 Ga; Petrini and Morten, 1993), which would exclude a relation with Variscan orogeny. More investigations are needed to unravel the significance of pre-Grt metasomatic events and their possible relations with crustal subduction processes.

GEODYNAMIC SIGNIFICANCE OF THE NONSBERG–ULTENTAL PERIDOTITES

Several scenarios, most of which have been recently reviewed by Brueckner and Medaris (2000), have been envisaged to explain the origin and significance of different types of mantle-derived Grt-peridotite in crustal environments. Each of these scenarios involves a particular tectonothermal setting and implies a distinct deformational, metamorphic, and textural evolution. Using mainly petrographic and thermobarometric criteria, the processes leading to formation, or incorporation, of Grt-peridotites in the crust can be grouped as follows:

i) Grt-peridotites formed by prograde, subduction-driven metamorphism of low-*P*, low-*T*, possibly hydrous protoliths. This type has a porphyroblastic and/or poikiloblastic texture and may include relicts of Spl and of hydrous minerals such as Ti-clinohumite, Amph or Chl (e.g. Cima di Gagnone; Evans and Trommsdorff, 1978).

ii) Grt-peridotites were emplaced from the upper mantle into crustal rocks at high *P* with their original Grt-bearing assemblage being preserved. This type has a dominant porphyroclastic texture and may or may not show evidence of prograde metamorphism (e.g. Western Gneiss Region; Carswell, 1986).

iii) Grt-peridotites formed by metamorphism of a nominally dry, high-*T*, Spl-peridotite protolith, which underwent cooling under *decreasing P* conditions. This type shows a porphyroblastic and/or porphyroclastic texture, may carry relicts of Spl and pyroxene porphyroclasts with complex unmixing textures, may be associated with lower-*P*, low-*T*, Pl- and Spl-peridotites, and may develop a high-*T* metamorphic aureole in the country-rocks (e.g. Ronda; Van der Wal and Vissers, 1993). The origin is somewhat controversial and may have involved a stage of asthenosphere upwelling before incorporation in the (subducting?) crust.

iv) Grt-peridotites formed by metamorphism of a nominally dry, high-*T*, Spl-peridotite protolith, which underwent cooling at *increasing* or *near-constant P*. This type is similar to the previous one, but a lower-*P*, low-*T* facies is not significantly developed, apart from retrogression in strongly-deformed, hydrated domains. The NU peridotites are a good example of this type.

Ascription of Grt-peridotites to any of these types or to any of the classes in previous classifications is heavily dependent on thermobarometric data. Unfortunately, Grt-peridotites in crustal terranes may form at relatively low *T* (<900°C), where equilibration is less effectively achieved, or may undergo significant retrograde processes. It follows that many thermobarometers combinations that work well on mantle xenoliths may not necessarily work as well on orogenic peridotites. Moreover, the existence of prograde Spl-bearing assemblages is often recognized, but except in special cases where old textures have been preserved, little information is available as to the *P-T* conditions of equilibration of the pre-Grt protoliths. Furthermore, the tendency of hydrated or partially molten crustal rocks to reequilibrate more quickly during retrogression, may make it difficult to establish if a Grt-peridotite was isofacial with the host crustal rocks. Hence, as already recognized by Brueckner and Medaris (2000), classification of orogenic peridotites often remains largely speculative.

On the basis of yet unreliable *P* estimates for the Grt-stage (1.3-1.6 GPa, i.e. well off the Grt stability field!) and in the absence of well-constrained thermobarometric data for the early Spl-stage, Brueckner and Medaris (2000) classified the NU peridotites as *UHT subduction peridotites*, the same type as the Ronda peridotite. Asthenosphere upwelling into a mantle wedge, possibly triggered by slab break-off, was proposed to explain the early high-*T* Spl-stage, followed by cooling in the Grt-field at relatively low *P* after entrainment into the subducting slab. Inclusion of the NU peridotites in this class was prompted by the probably erroneous assumption that the Spl-lherzolite protoliths equilibrated near the Spl-Grt transition at *T*~1400°C, that is near the dry lherzolite solidus, and reequilibrated in the Grt-field at very low *P*.

Using a more updated set of thermobarometers, Nimis and Morten (2000) obtained less severe *P-T* estimates of ~1200°C, ~1.5 GPa for the Spl-stage. These conditions are not unreasonable for supra-subduction mantle, at least under favorable combinations of slab dip and plate velocities (cf. Insergueix *et al.*, 1997). They are also compatible with experimental data on mantle melting and generation of arc magmas, which require T of 1250-1300°C at 1.5 GPa and 1350-1400°C at 2.5 GPa be reached within the mantle wedge (Ulmer, 2001). The hot (≥1400°C) melts that intruded the peridotites before their entrainment into the crust could thus be produced at conditions similar to those expected for the innermost portions of a mantle wedge.

On this ground, Nimis and Morten (2000) interpreted the P-T evolution of the NU peridotites as the result of cooling and subduction of high-T mantle-wedge peridotites due to corner flow within the wedge and subsequent entrainment into a subducting crustal slab. Unfortunately, the original geochemical signature of the pyroxenites was probably largely overprinted by extensive crustal metasomatism within the slab and a supra-subduction origin of the parent melts still remains unproven. Nonetheless, the virtually identical Sm-Nd ages for Grt-facies metamorphism of the peridotites, eclogite-facies metamorphism of the associated metabasites, early migmatization of the country-rocks, and crustal metasomatism of the peridotites (~330 Ma; Tumiati *et al.*, 2003) indicate that high-P metamorphism of both peridotites and crust and migmatization occurred during a single metamorphic cycle, consistent with the inferred subduction origin of the Grt-peridotites. A similar time-relationship is documented for other Variscan Grt-peridotites and surrounding high-P granulites in the Moldanubian zone (Kröner *et al.*, 1988; Brueckner *et al.*, 1991; Beard *et al.*, 1992; Becker, 1997), and the P-T evolution of the NU area may represent one of the last increments to the Variscan orogeny (Tumiati *et al.*, 2003).

If the interpretation of the NU Grt-peridotites as former high-T mantle-wedge portions is correct, the P-T-t paths of the peridotites and the country rocks must have remained distinct until incorporation of the peridotites into the crust at ~330 Ma (Fig. 3). The exact timing of the incorporation with respect to the continental subduction-exhumation cycle remains unconstrained, since subduction and exhumation rates are generally too high compared to the sensitivity of available geochronological methods (cf. Rubatto and Hermann, 2001). The peridotites may have been entrained into the continental crust (i) while it was still being subducted (Nimis and Morten, 2000; see dashed P-prograde paths in Fig. 3), (ii) at the subduction climax, or (iii) during the subsequent exhumation path (Tumiati *et al.*, 2003; see solid P-prograde paths in Fig. 3). Each of these hypotheses satisfies within errors the constraints imposed by thermobarometric and geochronological data. Ranalli (2002) has recently presented a semi-quantitative model of subduction and exhumation that accounts for the inferred evolution of the NU basement. At least, the advocated subduction-exhumation scenario seems physically tenable. Further constraints may emerge from tectonothermal modeling of subduction zones that take into account the

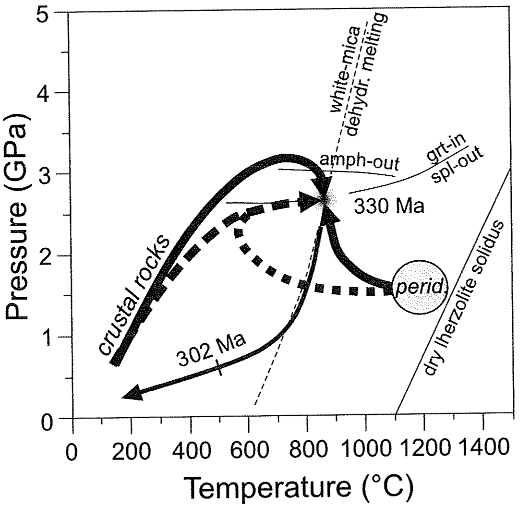

Fig. 3 – Two «end-member» possible P-T-t paths for NU peridotites and country gneisses (modified and simplified after Tumiati *et al.*, 2003; see text). Reference curves: Spl-to-Grt peridotite transition (O'Neill, 1981; using Spl compositions from Obata and Morten, 1987); Amph-out (Green, 1973); dry lherzolite solidus (McKenzie and Bickle, 1988); white mica-dehydration melting (Hermann and Green, 2001).

body of geological evidence provided by the NU mantle-crust association.

Some Variscan peridotites-pyroxenites from the Moldanubian zone, particularly from Mohelno (Medaris *et al.*, 1990) and Granulitgebirge (Massonne and Bautsch, 2002), show textural analogies with the NU ultramafics (e.g. Spl inclusions in Grt and/or coarse unmixed pyroxenes) and a similar possible derivation from high-*T*, Spl-peridotite-facies protoliths[2]. However, in these examples the Grt-stage apparently developed at still high *T* (1000-1265°C) and at greater *P* than recorded by the country granulites (Mohelno: 2.0-2.5 vs. 1.6 GPa; Granulitgebirge: 2.5 vs. 1.2 GPa; Grew, 1986; Medaris and Carswell, 1990; Carswell, 1991; Massonne and Bautsch, 2002). This would imply formation of the Grt-peridotites before emplacement into the crust (Schmädicke and Evans, 1997). Now the question is whether the *P* gap is real or it is an artifact due to either incomplete equilibration of the peridotites during the Grt-stage or retrograde reequilibration of the country-rocks after the high-*P* metamorphic peak. Further field, petrographic and isotopic data may help to better constrain the mantle-crust evolution in this sector of the Variscan belt. Could these Grt-peridotites have developed by geodynamic processes similar to those recorded by the NU ultramafics?

ACKNOWLEDGMENTS

The authors have greatly benefited from discussions and collaborations they shared through the years with M. Obata, S. Martin, S. Tumiati and G. Ranalli. Reviews by A. Zanetti and S. Martin helped improve the MS. The authors acknowledge the financial supports by CNR and MIUR grants.

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[2] According to Massonne and Bautsch (2002), exsolved megacrysts in pyroxenites cutting the Grt-peridotites in the Granulitgebirge may represent either former high-*T* Cpx formed at c. 1400°C and 1.7 GPa (cf. analogous conditions estimated by Nimis and Morten, 2000, for the NU pyroxenites!) or, alternatively, former majoritic Grt crystallized in a deep mantle plume.

REFERENCES

BEARD B.L., MEDARIS L.G., JOHNSON C.M., BRUECKNER H.K. and ZDENEK M. (1992) — *Petrogenesis of Variscan high-temperature Group A eclogites from the Moldanubian Zone of the Bohemian Massif, Czechoslovakia.* Contrib. Mineral. Petrol., **111**, 468-483.

BECKER H. (1997) — *Sm-Nd garnet ages and cooling history of high-temperature garnet peridotite massifs and high-pressure granulites from lower Austria.* Contrib. Mineral. Petrol., **127**, 224-236.

BENCIOLINI N. and POLI S. (1993) — *The lower continental crust in the Tonale Nappe (upper Austroalpine, Ultental); new petrological constraints.* Terra Abstr., **5**, 398-399.

BONDI M., DE FRANCESCO A.M. and MORTEN L. (1992) — *Major elements, 3d transition elements, Cu and Sr geochemistry of peridotitic rocks within the Austridic crystalline basement, Nonsberg area, Northern Italy.* In: «*Contributions to the Geology of Italy with Special Regard to the Paleozoic Basements*», Carmignani L. and Sassi F.P. (Eds.), IGCP Newsletter, **5**, 229-235.

BRENAN J.M., SHAW H.F., RYERSON F.J. and PHINNEY D.L. (1995) — *Mineral-aqueous fluid partitioning of trace elements at 900°C and 2.0 GPa; constraints on the trace element chemistry of mantle and deep crustal fluids.* Geochim. Cosmochim. Acta, **59**, 3331-3350.

BRUECKNER H.K. (1998) — *Sinking intrusion model for the emplacement of garnet-bearing peridotites into continent collision orogens.* Geology, **26**, 631-634.

BRUECKNER H.K. and MEDARIS L.G. (2000) — *A general model for the intrusion and evolution of 'mantle' garnet peridotites in high-pressure and ultra-high-pressure metamorphic terranes.* J. Metam. Geol., **18**, 123-133.

BRUECKNER H.K., MEDARIS L.G.Jr. and BAKUN-CZUBAROW N. (1991) — *Nd and Sr and isotope patterns from Variscan eclogites of the eastern Bohemian Massif.* N. Jb. Min. Abh., **163**, 169-196.

CARSWELL D.A. (1986) — *The metamorphic evolution of Mg-Cr type Norwegian garnet peridotites.* Lithos, **19**, 279-297.

CARSWELL D.A. (1991) — *Variscan high P-T metamorphism and uplift history in the Moldanubian Zone of the Boheman Massif.* Eur. J. Mineral., **3**, 323-342.

DAL PIAZ G.V. (1993) — *Evolution of Austroalpine and Upper Penninic basement in the Northwestern Alps from Variscan convergence to post Variscan extension.* In: «*The Pre-Mesozoic*

Geology in the Alps», von Raumer J.F. and Neubauer F. (Eds.), Springer, Berlin, 327-343.

Del Moro A., Martin S. and Prosser G. (1999) — *Migmatites of the Ulten zone (NE Italy), a record of melt transfer in deep crust.* J. Petrol., **40**, 1803-1826.

Dupuy C., Mével C., Bodinier J.-L. and Savoyant L. (1991) — *Zabargad peridotite: evidence for multistage metasomatism during Red Sea rifting.* Geology, **19**, 722-725.

Evans B.W. and Trommsdorff V. (1978) — *Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps.* Earth Planet. Sci. Lett., **40**, 333-348.

Flügel H.V. (1990) — *Das vor Alpine Basement im Alpin-Mediterranen Belt - überblick und Problematik.* Jahrb. Geol. Bundes., **133**, 181-221.

Godard G. and Martin S. (2000) — *Petrogenesis of kelyphites in garnet peridotites: a case study from the Ulten zone, Italian Alps.* J. Geodyn., **30**, 117-146.

Godard G., Martin S., Prosser G., Kienast J.R. and Morten L. (1996) — *Variscan migmatites, eclogites and garnet-peridotites of the Ulten zone, Eastern Austroalpine system.* Tectonophysics, **259**, 313-341.

Green D.H. (1973) — *Experimental melting studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions.* Earth Planet. Sci. Lett., **19**, 37-53.

Grew E.S. (1986) — *Petrogenesis of kornerupine at Waldheim (Sachsen), German Democratic Republic.* Z. Geol. Wiss., **14**, 525-558.

Hauzenberger C.A., Holler W. and Hoinkes G. (1996) — *Transition from eclogite to amphibolite-facies metamorphism in the Austroalpine Ulten Zone.* Mineral. Petrol., **58**, 111-130.

Hermann J. and Green D.H. (2001) — *Experimental constraints on high pressure melting in subducted slab.* Earth Planet. Sci. Lett., **188**, 149-168.

Insergueix D., Dupeyrat L., Menvielle M. and Tric E. (1997) — *Dynamical and thermal structure of a subduction zone: Influence of slab geometry on the convective state of the Earth's upper mantle; preliminary results.* Phys. Earth Planet. Int., **99**, 231-247.

Ionov D.A., Griffin W.L. and O'Reilly S. (1997) — *Volatile-bearing minerals and lithophile trace elements in the upper mantle.* Chem. Geol., **141**, 153-184.

Keppler H. (1996) — *Constraints from partitioning experiments on the compositions of subduction zone fluids.* Nature, **380**, 237-240.

Kröner A., Wendt I., Liew T.C., Compston W., Todt W., Vankova V. and Vanek J. (1988) — *U-Pb zircon and Sm-Nd model ages of high-grade Moldanubian metasediments, Bohemian massif, Czechoslovakia.* Contrib. Mineral. Petrol., **99**, 257-266.

Martin S., Morten L. and Prosser G. (1993) — *Metamorphic and structural evolution of the Spl-to Grt-peridotites and surrounding basement rocks from the Nonsberg area.* In: *«Italian Eclogites and Related Rocks»*, Morten L. (Ed.), Accad. Naz. delle Scienze detta dei Quaranta, Roma, 237-251.

Martin S., Prosser G., Godard G., Kienast J.R. and Morten L. (1994) — *Tectono-metamorphic evolution of the high-grade gneisses, kyanite-migmatites and spinel-to-garnet peridotites of the Ulten zone (Eastern austroalpine, Italy).* Per. Mineral., **63**, 1-8.

Martin S., Godard G., Prosser G., Schiavo A., Bernoulli D. and Ranalli G. (1998) — *Evolution of the deep crust at the junction Austroalpine/Southalpine: the Tonale Nappe.* Mem. Sci. Geol., **50**, 3-50.

Massonne H.-J. and Bautsch H.-J. (2002) — *An unusual garnet pyroxenite from the Granulitgebirge, Germany: origin in the transition zone (>400 km depths) or in a shallower upper mantle region?* Int. Geol. Rev., **44**, 779-796.

Maury R.C., Defant M.J. and Joron J.-L. (1992) — *Metasomatism of the sub-arc mantle inferred from trace elements in Philippine xenoliths.* Nature, **360**, 661-663.

McKenzie D. and Bickle M.J. (1988) — *The volume and composition of melt generated by extension of the lithosphere.* J. Petrol., **29**, 625-679.

Medaris L.G.Jr. and Carswell D.A. (1990) — *The petrogenesis of Mg-Cr garnet peridotites in European metamorphic belts.* In: *«Eclogite Facies Rocks»*, Carswell D.A. (Ed.), Chapman and Hall, New York, 260-290.

Medaris L.G.Jr., Wang H.F., Misai Z. and Jelinek E. (1990) — *Thermobarometry, diffusion modelling and cooling rates of crustal garnet peridotites: Two examples from the Moldanubian zone of the Bohemian Massif.* Lithos, **25**, 189-202.

Morten L., Bargossi G.M. and Landini Bargossi F. (1976) — *Notizie preliminari sulle metamorfiti della Val di Rumo, Val di Non, Trento.* Miner. Petrogr. Acta, **21**, 137-144.

Morten L. and Obata M. (1983) — *Possible high-temperature origin of pyroxenite lenses within garnet peridotite, northern Italy.* Bull. Minéral., **106**, 775-780.

MORTEN L. and OBATA M. (1990) — *Rare earth abundances in the eastern Alpine peridotites, Nonsberg area, Northern Italy.* Eur. J. Mineral., **2**, 643-653.

NEUBAUER F. and VON RAUMER J.F. (1993) — *The Alpine basement – Linkage between the Variscides and East-Mediterranean mountain belts.* In: «*The Pre-Mesozoic Geology in the Alps*», von Raumer J.F. and Neubauer F. (Eds.), Springer, Berlin, 641-661.

NIMIS P. and MORTEN L. (2000) — *P-T evolution of «crustal» garnet peridotites and included pyroxenites from Nonsberg area (Upper Austroalpine), NE Italy: from the wedge to the slab.* J. Geodyn., **30**, 93-115.

OBATA M. and MORTEN L. (1987) — *Transformation of spinel lherzolite to garnet lherzolite in ultramafic lenses of the austridic crystalline complex, Northern Italy.* J. Petrol., **28**, 599-623.

O'NEILL H.ST.-C (1981) — *The transition between spinel lherzolites and garnet lherzolites, and its use as a geobarometer.* Contrib. Mineral. Petrol., **77**, 185-194.

PETRINI R. and MORTEN L. (1993) — *Nd-isotopic evidence of enriched lithospheric domains: an example from the Nonsberg area, eastern Alps.* Terra Abstr., **4**, 19-20.

PICCARDO G.B., RAMPONE E., VANNUCCI R., SHIMIZU N., OTTOLINI L. and BOTTAZZI P. (1993) — *Mantle processes in the sub-continental lithosphere: the case study of the rifted sp-lherzolites from Zabargad (Red Sea).* Eur. J. Mineral., **5**, 1039-1056.

RAMPONE E. and MORTEN L. (2001) — *Records of crustal metasomatism in the garnet peridotites of the Ulten Zone (Upper Austroalpine, Eastern Alps).* J. Petrol., **42**, 207-219.

RANALLI G. (2002) — *A model of Palaeozoic subduction and exhumation of continental crust: the Ulten Unit, Tonale Nappe, Eastern Austroalpine.* Mem. Sci. Geol., **54**, 205-208.

RUBATTO D. and HERMANN J. (2001) — *Exhumation as fast as subduction?* Geology, **29**, 3-6.

SCHIANO P., CLOCCHIATTI R., SHIMIZU H., MAURY R.C., JOCHUM K. and HOFMANN A.W. (1995) — *Hydrous, silica-rich melts in the sub-arc mantle and their relationships with erupted arc lavas.* Nature, **377**, 595-600.

SCHMÄDICKE E. and EVANS B.W. (1997) — *Garnet-bearing ultramafic rocks from the Erzgebirge, and their relation to other settings in the Bohemian Massif.* Contrib. Mineral. Petrol., **127**, 57-74.

SEKINE T. and WYLLIE P.J. (1982) — *The system granite–peridotite–H_2O at 30 kbar, with applications to hybridization in subduction zone magmatism.* Contrib. Mineral. Petrol., **81**, 190-202.

SUSINI S. and MARTIN S. (1996) — *Microstrutture nelle peridotiti della Serie d'Ultimo (Austroalpino superiore, Alpi orientali).* Atti Tic. Sci. Terra, **4**, 47-63.

THÖNI M. (1981) — *Degree and evolution of the Alpine metamorphism in the Austroalpine Unit W of the Hohe Tauern in the light of K/Ar and Rb/Sr age determinations in micas.* Jb. Geol. Bundesanst., **124**, 111-174.

TUMIATI S. (2002) — *Le peridotiti a granato di Cima Vedetta Alta (Val d'Ultimo, Alto Adige). Assetto geologico, caratteri mineralogici e geochimici.* Unpubl. Thesis, Università di Padova, Padova.

TUMIATI S. and MARTIN S. (2003) — *Garnet-peridotite in the Italian Eastern Alps: 150 years of discoveries.* Mem. Sci. Geol., **55**, 31-46.

TUMIATI S., THÖNI M., NIMIS P., MARTIN S. and MAIR V. (2003) — *Mantle–crust interactions during Variscan subduction in the Eastern Alps (Nonsberg–Ulten zone): geochronology and new petrological constraints.* Earth Planet. Sci. Lett., **210**, 509-526.

ULMER P. (2001) — *Partial melting in the mantle wedge — the role of H_2O in the genesis of mantle-derived 'arc-related' magmas.* Phys. Earth Planet. Int., **127**, 215-232.

VAN DER WAL D. and VISSERS R.L.M. (1993) — *Uplift and emplacement of upper mantle rocks in the western Mediterranean.* Geology, **21**, 1119-1121.

VIDAL P., DUPUY C., MAURY R. and RICHARD M. (1989) — *Mantle metasomatism above subduction zones: trace-element and radiogenic isotope characteristics of peridotite xenoliths from Batan Island (Philippines).* Geology, **17**, 1115-1118.

VIELZEUF D. and HOLLOWAY J.R. (1988) — *Experimental determination of the fluid-absent melting relations in the pelitic sysem. Consequences for crustal differentiation.* Contrib. Mineral. Petrol., **98**, 257-276.

ZANETTI A., MAZZUCCHELLI M., RIVALENTI G. and VANNUCCI R. (1999) — *The Finero phlogopite-peridotite massif: an example of subduction-related metasomatism.* Contrib. Mineral. Petrol., **134**, 107-122.