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Crust-Mantle relationships close at hands
Walking through the Ulten-Nonsberg orogenic lower crust

Goldschmidt Conference - Firenze, 2013

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Crust-Mantle relationships close at hands
Walking through the Ulten-Nonsberg orogenic lower crust

Pre-conference Field Trip - Goldschmidt Conference Firenze, 2013

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Information

The starting point of the field trip itineraries is Rumo (Trento Province, Northern Italy). From Milano and Venezia by car, highway A4 to Verona and A22 towards Brennero (see the index map below). Exit at Trento north or S. Michele – Mezzocorona and continue to Mezzolombardo and Cles on the SS42. At Mostizzolo, turn right and after 2.3 km turn left for the SP68 to Rumo (8.3 km). Public transport involves trains to Trento and then to Cles along the Trento-Malè local railway. Bus from Cles to Rumo leave at the Cles train station (bus website www.ttesercizio.it). The use of 4-wheel cars is highly recommended. For the traverse (2nd day) cars need to be arranged at the departure of the traverse (Sankt Nikolaus, Ulten valley) and at the end (Mocenigo – Rumo, Non valley). Travelling on the forest roads is toll-free but the local Forest Guard office must grant permissions. Accommodation in Rumo and surroundings are listed in www.maddalene.it .
This field trip requires participants to hike for several km at altitudes exceeding 2000 m asl (max height: Passo Lavazzè, 2340 m) well above the tree line, sometimes along steep slopes with ill-defined footpaths and loose moraine blocks. This field trip might be **physically demanding** and therefore good conditions are needed. Proper training and equipment (mountains boots are compulsory, warm and waterproof clothes, gloves, sunglasses and solar protection) for alpine conditions are required. Be aware that summer thunderstorms and snow are not uncommon.

Emergency Contact Numbers

112 – Mountain rescue
113 – Carabinieri
118 – First Aid
115 – Fire-fighters

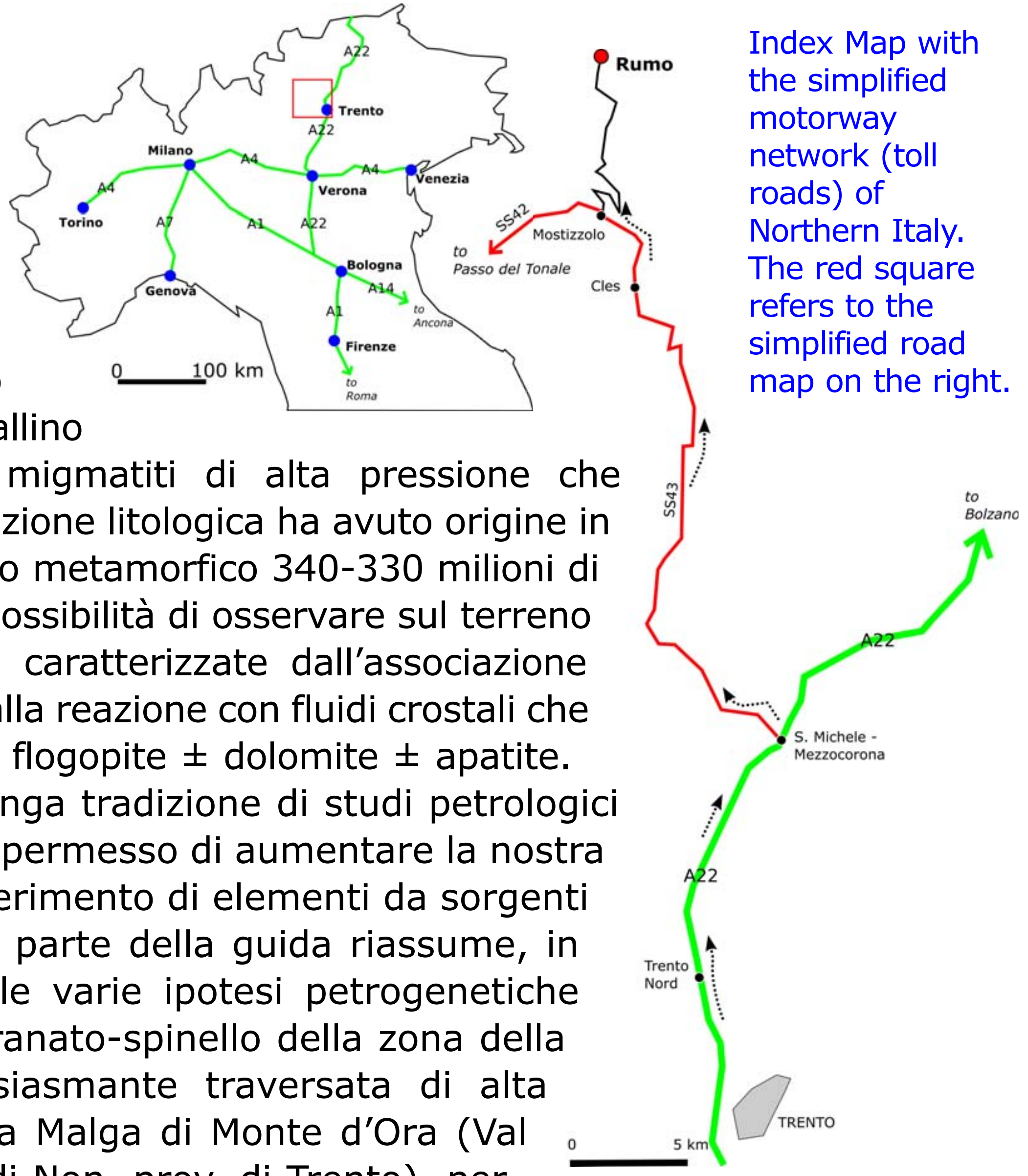
Forest Guard Offices

+39 0473 920949 – Tesimo (Day 1 itinerary)
+39 0473 795330 – S. Valburga/Ultimo (Day 2 itinerary)
+39 0463 530126 – Rumo (Day 2 itinerary)

Maps

Topographic: Val d’Ultimo / Ultental 1:25 000, sheet 042, Tabacco
Geological: Carta Geologica d’Italia 1:50 000, sheets 025 (Rabbi) and 026 (Appiano/Eppan).

Riassunto



Index Map with the simplified motorway network (toll roads) of Northern Italy. The red square refers to the simplified road map on the right.

Questa escursione di due giorni è dedicata all'osservazione di rocce uniche nel panorama geologico italiano, affioranti nell'unità d'Ultimo della nuova cartografia geologica alla scala 1:50.000. L'unità d'Ultimo è conosciuta nella letteratura specialistica anche con il nome di zona d'Ultimo o Nonsberg-Ulten Zone. Si tratta di un basamento cristallino Varisico essenzialmente costituito da paragneiss e migmatiti di alta pressione che includono lenti di peridotiti del mantello. Questa associazione litologica ha avuto origine in una zona di collisione continentale che raggiunse il picco metamorfico 340-330 milioni di anni fa. L'eccezionalità dell'unità d'Ultimo risiede nella possibilità di osservare sul terreno la trasformazione di peridotiti a spinello in peridotiti caratterizzate dall'associazione granato-spinello. Questa transizione è accompagnata dalla reazione con fluidi crostali che producono la cristallizzazione di abbondante anfibolo ± flogopite ± dolomite ± apatite. L'escursione ha lo scopo di rendere accessibile una lunga tradizione di studi petrologici iniziati già dalla seconda metà del XIX secolo e che ha permesso di aumentare la nostra conoscenza sui processi metasomatici indotti dal trasferimento di elementi da sorgenti crostali subdotte verso reservoir mantellici. La prima parte della guida riassume, in modo schematico, la geologia dell'unità d'Ultimo e le varie ipotesi petrogenetiche proposte. La seconda parte illustrerà le peridotiti a granato-spinello della zona della Conca di Brez/Samerberg (primo giorno) e l'entusiasmante traversata di alta montagna attraverso la catena delle Maddalene, dalla Malga di Monte d'Ora (Val d'Ultimo, prov. di Bolzano) verso la Val Lavazzè (Val di Non, prov. di Trento), per osservare le relazioni fra peridotiti, pirosseniti e migmatiti (secondo giorno).

Parole chiave: *Peridotiti a granato, pirosseniti, interazione crosta-mantello, crosta profonda, Ulten-Nonsberg, Alpi Orientali.*

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Abstract

This two-day excursion focuses on the Variscan crystalline basement of the Ulten-Nonsberg Zone, Eastern Italian Alps. The Ulten-Nonsberg Zone, also known as the Ulten Zone or unità d'Ultimo in the new geological map of Italy (1:50 000 scale), mainly consists of high-pressure paragneisses and migmatites containing disseminated lenses of mantle peridotites. This lithological association originated in a continent-continent collision zone that reached its metamorphic peak at 340-330 Ma. What makes the Ulten-Nonsberg special is the opportunity to see in the field the transition from spinel- to garnet-spinel-peridotites. This transformation occurred during the influx of C-O-H fluids derived from a submerging crustal slab. The fluids were responsible for the blastesis of abundant amphibole ± phlogopite and trace amounts of dolomite and apatite.

This field trip aims to make a long tradition of field and petrological studies accessible to a wider audience and to showcase our increased knowledge on how a continent-continent collision works and what are the metasomatic processes driven by the crust-to-mantle mass transfer. The first part of this guide provides a summary of the Ulten-Nonsberg Zone geology and of some of the petrogenetic models proposed. The second part describes the garnet-spinel lenses occurring in the Samerberg area (1st day) and the exciting traverse through the Maddalene range, from the Auerbergtal (Ulten valley) to the Lavazzè valley (Non valley), to address the field relation among mantle peridotites, pyroxenites and migmatites (2nd day).

Key words: *Garnet-peridotites, pyroxenites, crust-mantle interactions, lower crust, Ulten-Nonsberg, Eastern Alps.*

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Excursion notes

The inland access to the deep crust/upper mantle can be reached by studying xenoliths, shreds of crust and mantle brought to the surface by uprising volcanic rocks, or by examining exhumed basements now incorporated into collisional belts. The latter approach is valuable since it may provide up to km-scale crustal sections where the petrogenetic interactions between upper mantle and felsic materials can be investigated under favourable conditions. The Ulten-Nonsberg lower crust, long renowned for containing some of the best exposure of garnet-spinel peridotites of the entire Alps, represents a remarkable site to gain insights into mantle petrogenesis and metasomatism occurring during collisional tectonics involving continental margins.

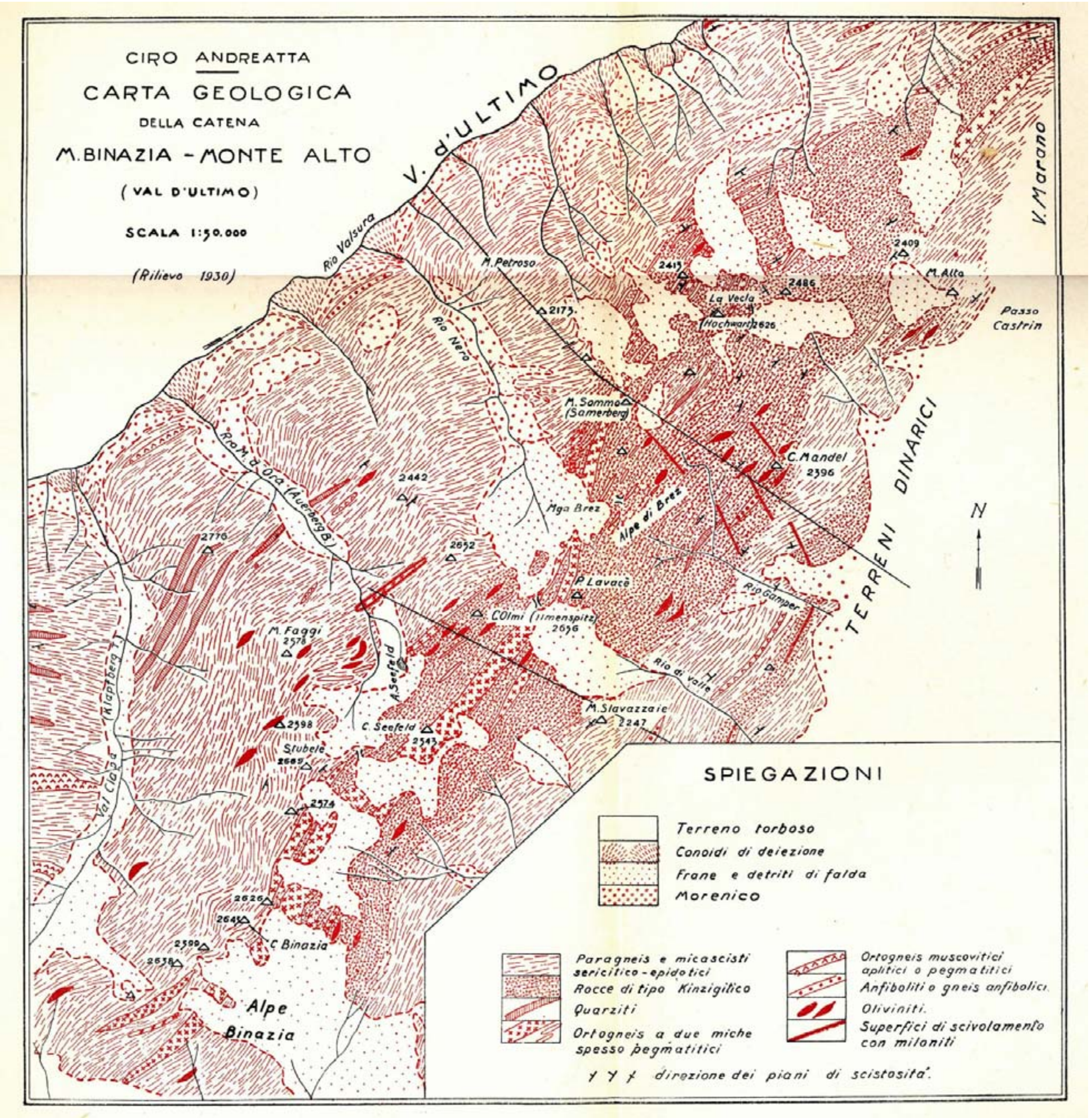

Fig. 1 - The geological map of the NE portion of the Ulten-Nonsberg Zone, sketched by Ciro Andreatta with a beautiful red ink and published in 1936.

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The Ulten-Nonsberg lower crust is known as a site of interest for mineral collectors since the mid-nineteenth century (Doblicka, 1852). Austrian scientists produced an intense field and petrographic work before the XX century (Sandberger, 1866; Stache, 1880, 1881; Ploner, 1891; Hammer, 1899). A major breakthrough in the geological knowledge of the Ulten-Nonsberg lower crust was the geological and structural map of Ciro Andreatta (Andreatta, 1936). This map (Fig. 1) already reports the main features of this basement: metre- to hundred meters-long peridotite bodies drawn by Andreatta in full red and classified as *Oliviniti*, i.e. olivine-rich rocks. Since 1970, several studies marked a new interest for the Ulten-Nonsberg lower crust (Amthauer et al., 1971; Morten et al., 1976-1977; Herzberg et al., 1977; Rost & Brenneis, 1978). The new petrological research set the cultural environment for the seminal paper by Obata & Morten (1987) that gave the first modern petrologic account on the spinel- to garnet-facies transition of the peridotites and the metasomatic reactions governing the formation of garnet-amphibole peridotite. A fertile cooperation between Bologna and Genova Universities produced important results on crustal metasomatism of mantle rocks, as summarised by Scambelluri et al. (2010). In the same time, new field data and isotopic ages obtained during the production of the new Geological Map of Italy and led by the University of Padova and the Autonomous Provinces of Trento and Bolzano added new views and, sometimes, dissenting ideas for the Variscan evolution of the Ulten-Nonsberg basement (see the historical review by Tumiati & Martin, 2003).

Geological Setting

The Alpine Belt is the result of the Late Cretaceous-Present convergence of the European and the Adriatic plate margins, leading to the consumption of the Jurassic Piedmont-Ligurian branch of the Western Tethys ocean. The closure of the ocean occurred during the Eocene-Miocene and led to the Europe-Adria continental collision and the subduction of the European continental margin. The Alps are traditionally subdivided in four tectonostratigraphic domains (Fig. 2):

- Helvetic, representing the proximal continental margin of the European continent;
- Penninic (including the Briançonnais units), continental- and oceanic-derived rocks tectonically intermingled, best exposed in the Western Alps and in tectonic windows (Engadine; Tauern);
- Austroalpine, originated from the Adriatic plate cropping out in two sectors of the Alpine belt (Eastern and Western Austroalpine);
- Southern Alps, derived from the Adriatic margin.

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The Helvetic and Penninic zones, and the Austroalpine nappe system are characterised by Europe-vergent structures whereas the Southern Alps are Adria-vergent. These domains are juxtaposed along the Periadriatic (Insubric) lineament, a dextral strike-slip fault system active during Oligocene-Neogene times.

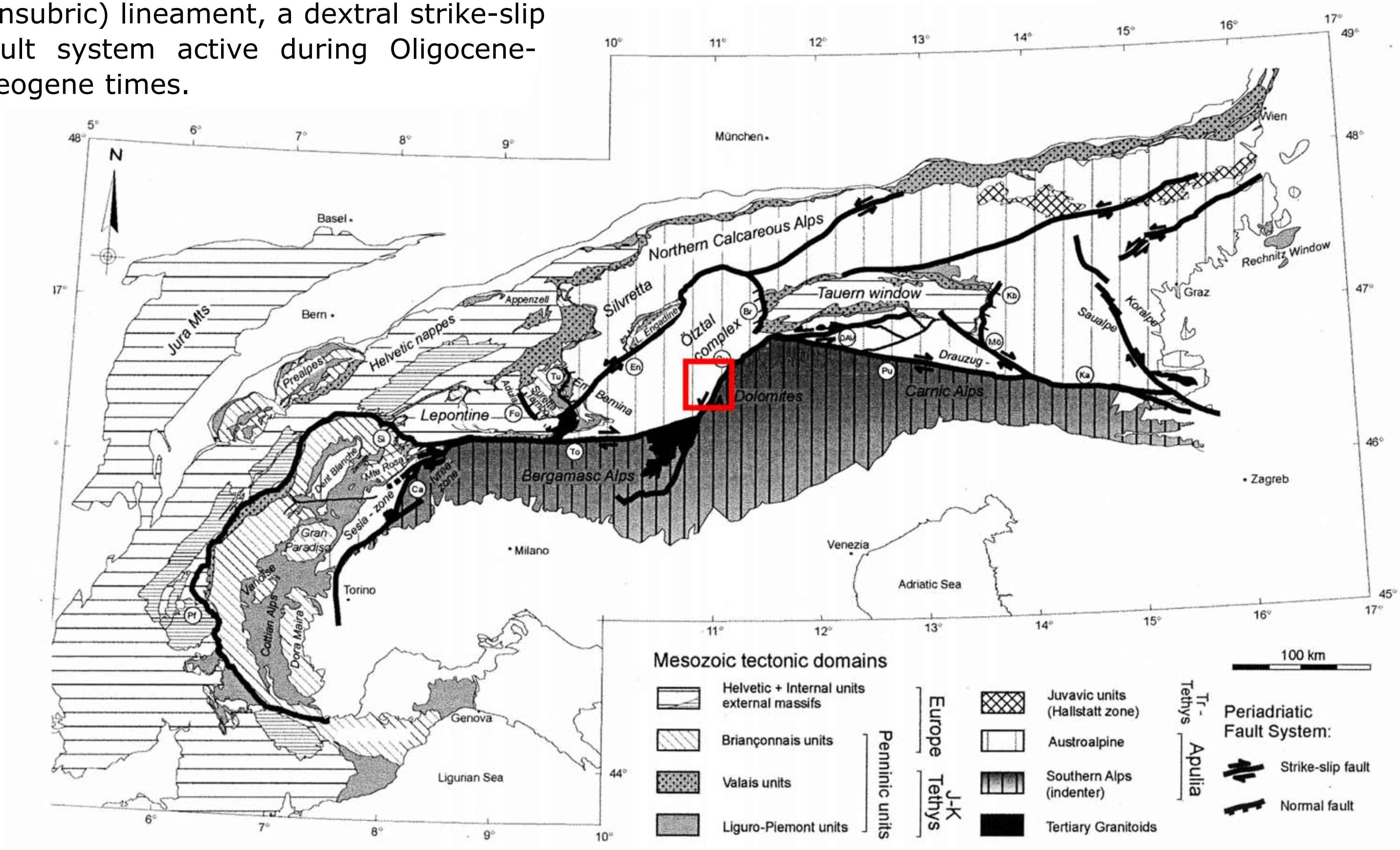

Fig. 2 - Tectonic map of the Alps from Handy & Oberhänsli (2004). The black lines represent major tectonic boundaries. The reader is refereed to the above authors for a comprehensive description of the several fault systems here reported.The red box shows the location of the map in Fig. 3.

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The Upper Austroalpine

The Ulten-Nonsberg lower crust belongs to the Upper Austroalpine of the Italian geological literature. In particular, the Ulten-Nonsberg crust is part of the basement of the Tonale nappe, a slice of Variscan crust bounded by Alpine faults (Fig. 3). Within the Tonale nappe, the NE-trending Rumo line is a Paleocene extension-related fault that marks the contact between the high-grade, high-pressure Ulten-Nonsberg peridotite-bearing basement and the amphibolite-facies peridotite-free basement known as the Tonale unit (Fig. 4).

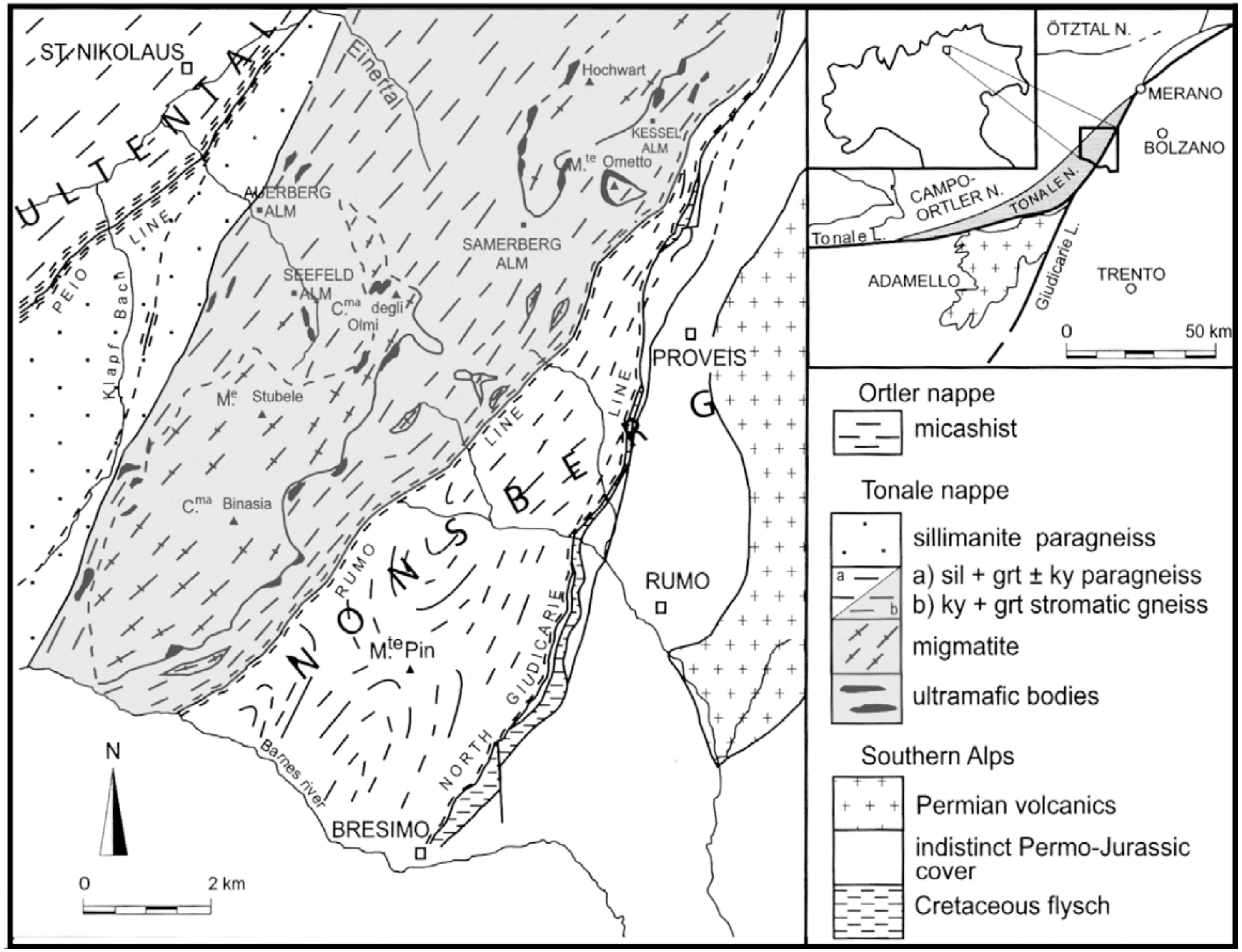

Fig. 3 - Geological sketch of the Ulten-Nonsberg zone (gray). Modified after Del Moro et al. (1999).

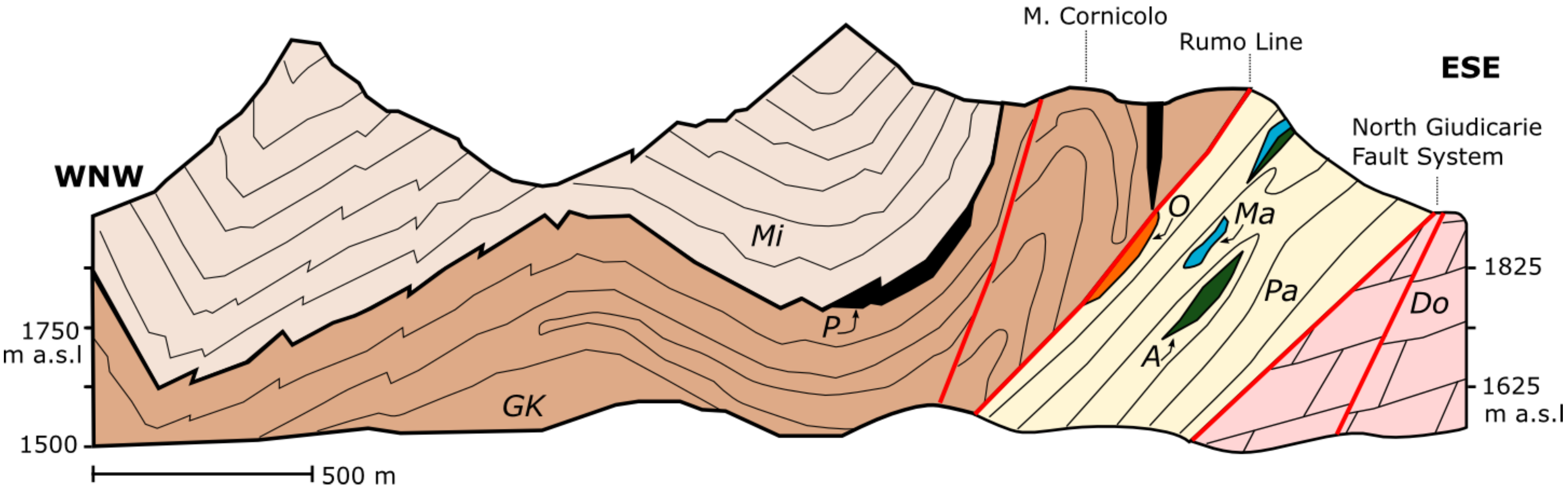

Fig. 4 - Cross-section of the Tonale nappe located just north of the geological map of Fig. 3. Ulten Zone: GK, garnet-kyanite gneisses; Mi, migmatites; P, peridotites. Tonale unit: Pa, sillimanite paragneisses; A, mafic amphibolites; Ma, marbles; O, orthogneisses. Southern Alps: Do, Dolomia Principale (Upper Triassic). Redrawn and simplified from the Sheet 026 "Appiano/Eppan" of the Carta Geologica d'Italia 1:50.000, Avanzini et al., (2007).

Rock types

The Ulten-Nonsberg orogenic lower crust consists of migmatites, kyanite-bearing paragneiss and subordinate mafic amphibolites, orthogneiss and mantle-derived peridotites including pyroxenite layers. Although the peridotites form a minor component of the basement, most of the available petrological studies deal with the ultramafics (Scambelluri et al., 2010). Here we provide background information on the field occurrence and how the Ulten-Nonsberg rocks appear under the polarizing optical microscope.

Field occurrence of the Ulten-Nonsberg ultramafics

Most of the mantle peridotites of the Ulten-Nonsberg lower crust outcrop in an area delimited by the Bresimo valley to the South, the southern flank of the Ulten valley and the upper Non valley, which includes the villages of Rumo and Proveis (Fig. 3). The mountain range is known as Maddalene.

In the field, mantle peridotites offer two styles of occurrence. The first style consists of barrel-shaped lenses or pods embedded into quaternary glacial deposits (Fig. 5). Although it is likely that the peridotite bodies slid by mass wasting, their location in a rather narrow band between the garnet-kyanite gneisses and the overlying migmatites is a remarkable coincidence. A few hundreds meter long peridotite bodies embedded into country gneisses/migmatites represent the second outcrop style. An important example is the peridotite body occurring in a steep gully on the western wall of the Mt. Hochwart (Marocchi et al., 2009). Here, metasomatic reactions bands locally mark the peridotite-migmatite contact. The reaction bands are zoned according to this sequence: migmatite | phlogopitite | anthophyllite-talc-rich rocks | garnet-amphibole peridotite (Marocchi et al., 2009). In other sites, e.g. the outcrop west of Masa Murada in the upper Non valley, the peridotite-crust contact is sharp, with no development of metasomatic reaction bands (Braga & Sapienza 2007). In this outcrop, a modal increase of phlogopite can be observed in the peridotite towards the contact with the country gneisses.

Fig. 5 - Typical exposure of ultramafic rocks in the Ulten-Nonsberg, Seefeldalm area. Coarse-grained peridotite: ochre, olivine; dull gray, orthopyroxene. Pen length is about 17 cm.

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Peridotites

Peridotites varies from harzburgite (abundant) to lherzolite (Bondi et al., 1992) and they have been subdivided into two groups based on the grain size (Obata & Morten, 1987; Morten & Trommsdorff, 2003): coarse and fine types, with the former considered as the protolith of the latter (Fig. 6). The coarse peridotites show the transition from protogranular to porphyroclastic microstructure (*sensu* Mercier & Nicolas, 1975) with a grain size up to 5-6 mm (Fig. 7a). The mineral assemblage consists of large kinked olivine and orthopyroxene, and smaller clinopyroxene and dark brown spinel. The latter occurs disseminated in the rock matrix, as exsolutions in pyroxenes and intergrowth with orthopyroxene. Porphyroclastic samples contain garnet that typically surrounds brown spinel (Fig. 7b). In addition, garnet may appear also as large porphyroblast with rounded spinel inclusions and as elongated grains exsolved from large pyroxenes. The fine-grained peridotites have average grain size ≤ 1 mm and are mainly spinel harzburgites with high modal amounts of amphibole (up to 23 vol%, Rampone & Morten, 2001) and accessory chlorite and black spinel. Their (micro)structure ranges

Fig. 6 - Fine-grained peridotite. The preferred orientation of olivine defines the fabric. An elongated orthopyroxene porphyroclasts is aligned parallel to the foliation. The diameter of the coin is 2.7 cm.

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from porphyroclastic to tabular equigranular and granoblastic (Fig. 7c). Olivine and orthopyroxene porphyroclasts typically show internal deformation features (kink bands) while the tabular equigranular microstructure is defined by the shape preferred orientation of undeformed olivine and orthopyroxene aggregates. Relic garnet rimmed by a kelyphitic rim is also found. Two generations of amphibole are recognised under the polarizing microscope: pale to brownish green magnesiohornblende and colourless tremolite, the latter also rimming magnesiohornblende cores. Retrograde chlorite occurs in textural equilibrium with tremolite and as large grains enclosing black spinel. Phlogopite appears in the peridotites close to the contact with the country gneisses. The preferred orientation of the phlogopite flakes forms a foliation concordant to the lithological boundaries (Fig. 7d).

Rare dolomite occurs both in the coarse-grained garnet-spinel-peridotites and in the tabular equigranular type (Obata & Morten, 1987; Morten & Trommsdorff, 2003; Braga et al., 2007; Sapienza et al., 2009). Dolomite may occur as porphyroclasts (Fig. 7e) up to several mm in length or as matrix-forming grain, with regular and smooth grain-grain contacts with surrounding minerals (Fig. 7f). Apatite has been also found in association with dolomite (Sapienza et al., 2009).

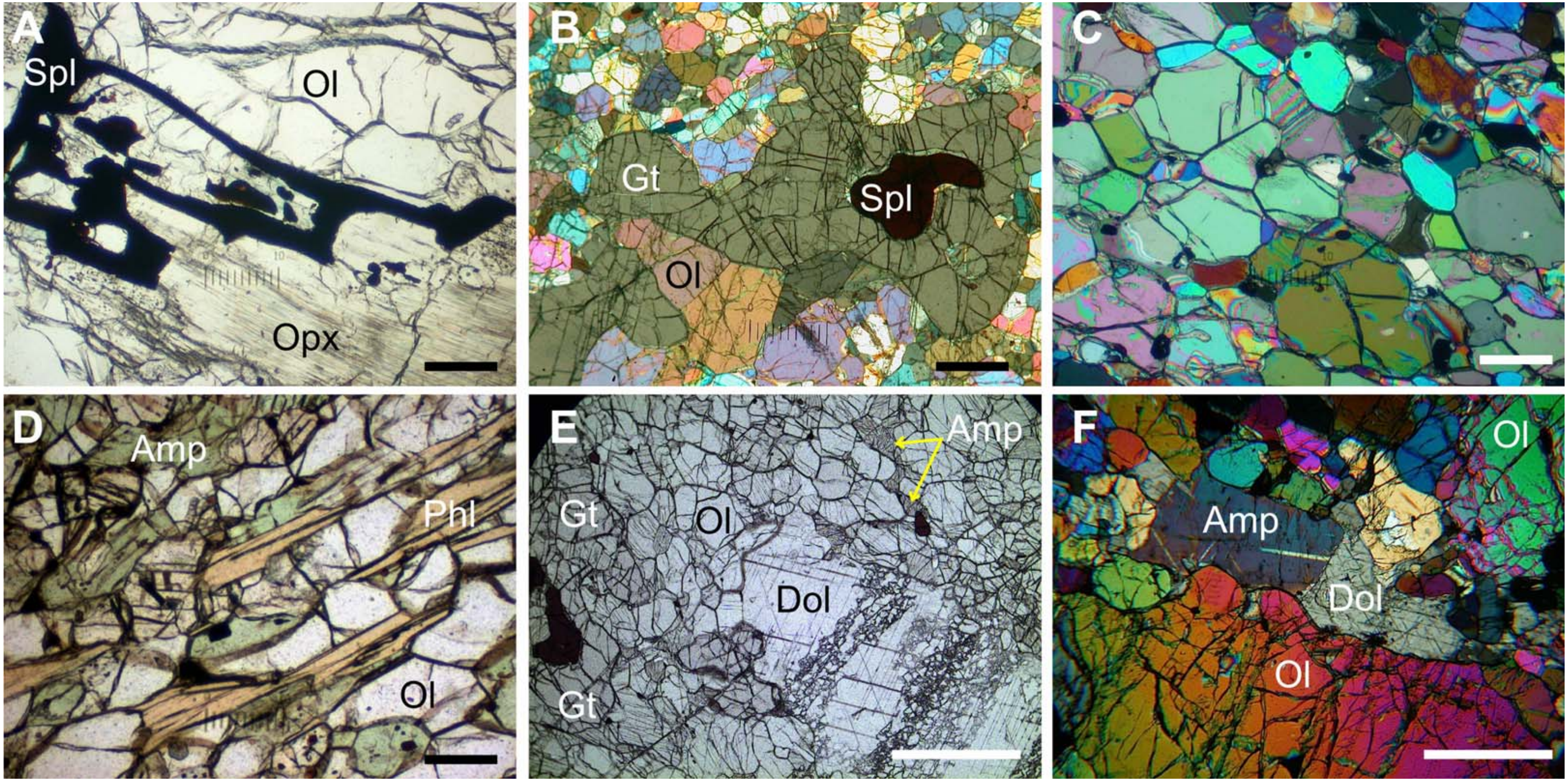

Fig. 7 - Main textural features of the Ulten-Nonsberg peridotites. Scale length is 0.4 mm from **A** to **D** and 1 mm for **E** and **F**. **A** Coarse-grained peridotite type with large olivine (Ol), orthopyroxene (Opx) and anhedral spinel (Spl); plane polarized light. **B** Porphyroclastic peridotite with large anhedral garnet (Gt) and spinel inclusion; partly crossed nicols. **C** Fine-grained peridotite type consisting of an aggregate, locally polygonal, of unstrained olivine and orthopyroxene; crossed nicols **D** Fine-grained peridotite type showing abundant amphibole (Amp) and a foliation outlined by phlogopite (Phl); plane polarized light. **E** Dolomite (Dol) porphyroclast in a garnet-bearing matrix; plane polarized light. **F** Smooth grain-grain contacts involving dolomite, amphibole and olivine; crossed nicols.

Pyroxenites

Layers of garnet-amphibole websterite and amphibole clinopyroxenite cutting peridotite lenses can be observed in different locations of the Ulten-Nonsberg unit. Although pyroxenites represent only a few percent by volume of the ultramafic lenses, some of the best exposures are those around the Seefeld/Lago della Siromba area, southern side of the Ulten valley (Fig. 3). Pyroxenites form layers transposed along the peridotite foliation, with sharp contacts towards host peridotites.

Morten & Obata (1983) were among the first to provide petrological data on the garnet-amphibole websterite and clinopyroxenite from the Seefeld/Lago della Siromba area. The websterite consists of clinopyroxene megacrysts (up to 6 cm; Fig. 8) with orthopyroxene and garnet exsolutions, dispersed in an equigranular mosaic matrix composed of orthopyroxene, clinopyroxene, amphibole, garnet and brown spinel. Clinopyroxenite is made of diopside, magnesiohornblende, garnet and accessory amounts of ilmenite.

Fig. 8 - Garnet-amphibole-websterite from the Seefeldalm area. The large porphyroclast (arrow) is a clinopyroxene with orthopyroxene exsolutions. Purplish-red garnet is visible at the contact between the porphyroclast and the fine-grained granular matrix, which is made of clinopyroxene, orthopyroxene, amphibole and garnet. Sample length: 10 cm.

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Paragneisses and migmatites

The Ulten-Nonsberg crust (Fig. 9) is characterised by an inverted metamorphic zoning: the metamorphic grade increases moving upwards along the crustal sequence. Staurolite-garnet bearing micaschists crop out in the Ulten Valley, between the localities St. Walburg/Santa Valburga and Pankrazer See/Lago di Alborelo. These micaschists (Fig. 10a-b) give way through a gradational contact to garnet-kyanite gneisses characterised by minor modal amounts of white mica and a marked mylonitic foliation defined by alternating mica-rich and quartz+feldspars layers wrapping around garnet porphyroclasts. The transition from the garnet-kyanite paragneisses to the overlying migmatites is marked by the presence of the ultramafic lenses. Migmatites range from mica-rich, foliated metatexites to poorly foliated quartz- and plagioclase-rich diatexites (Del Moro et al., 1999). The leucocratic domains from the migmatites are inequigranular aggregates of quartz + plagioclase ± alkali-feldspar (all with irregular grain boundaries) alternating with melanocratic domains containing biotite and anhedral garnet and kyanite. Within the migmatites, rare garnet-rich rocks (garnet ~ 90 vol%) with minor amounts of interstitial kyanite, quartz and biotite occur.

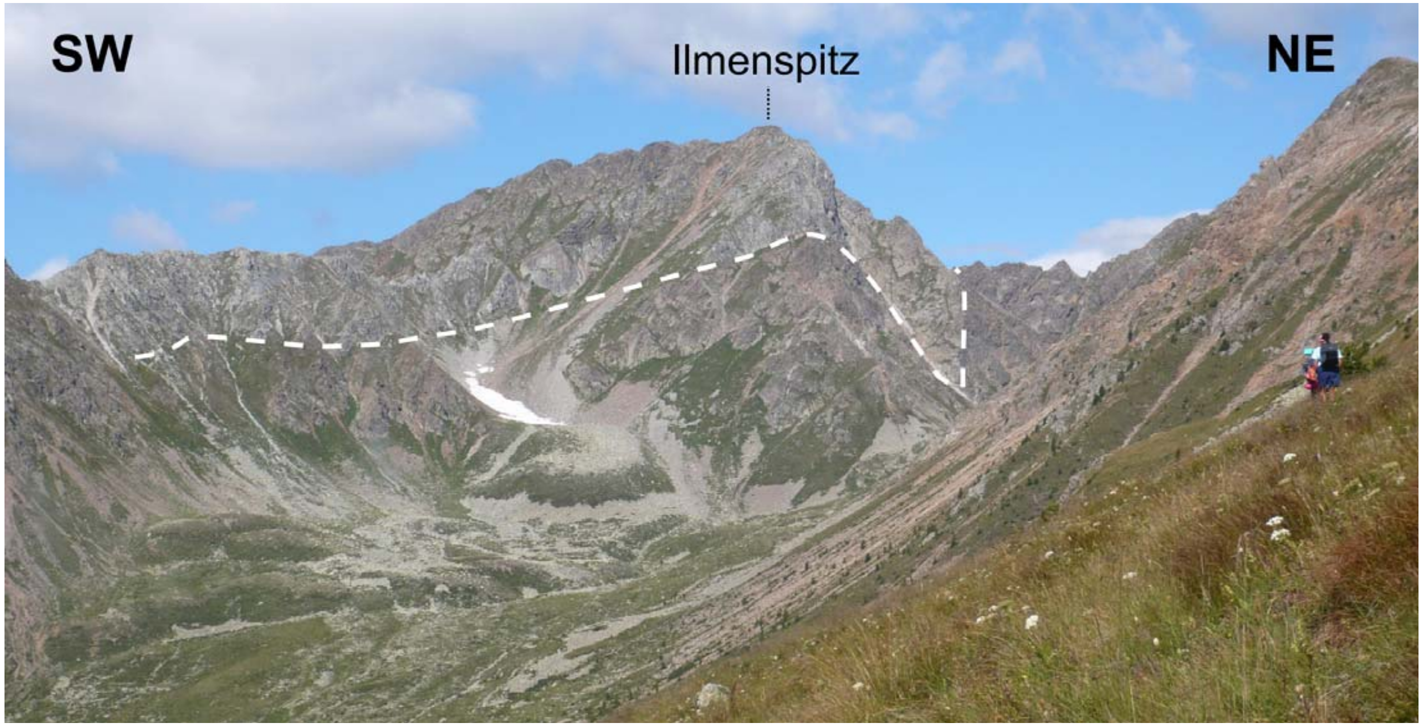

Fig. 9 - View from SE (Rio Valle valley) towards Ilmenspitz/Cima degli Olmi. The dashed line, drawn in correspondence of a change of colour of the altered surface of rocks, indicates the contact between stromatic migmatites (metatexites) and the overlying nebulitic migmatites (diatexites).

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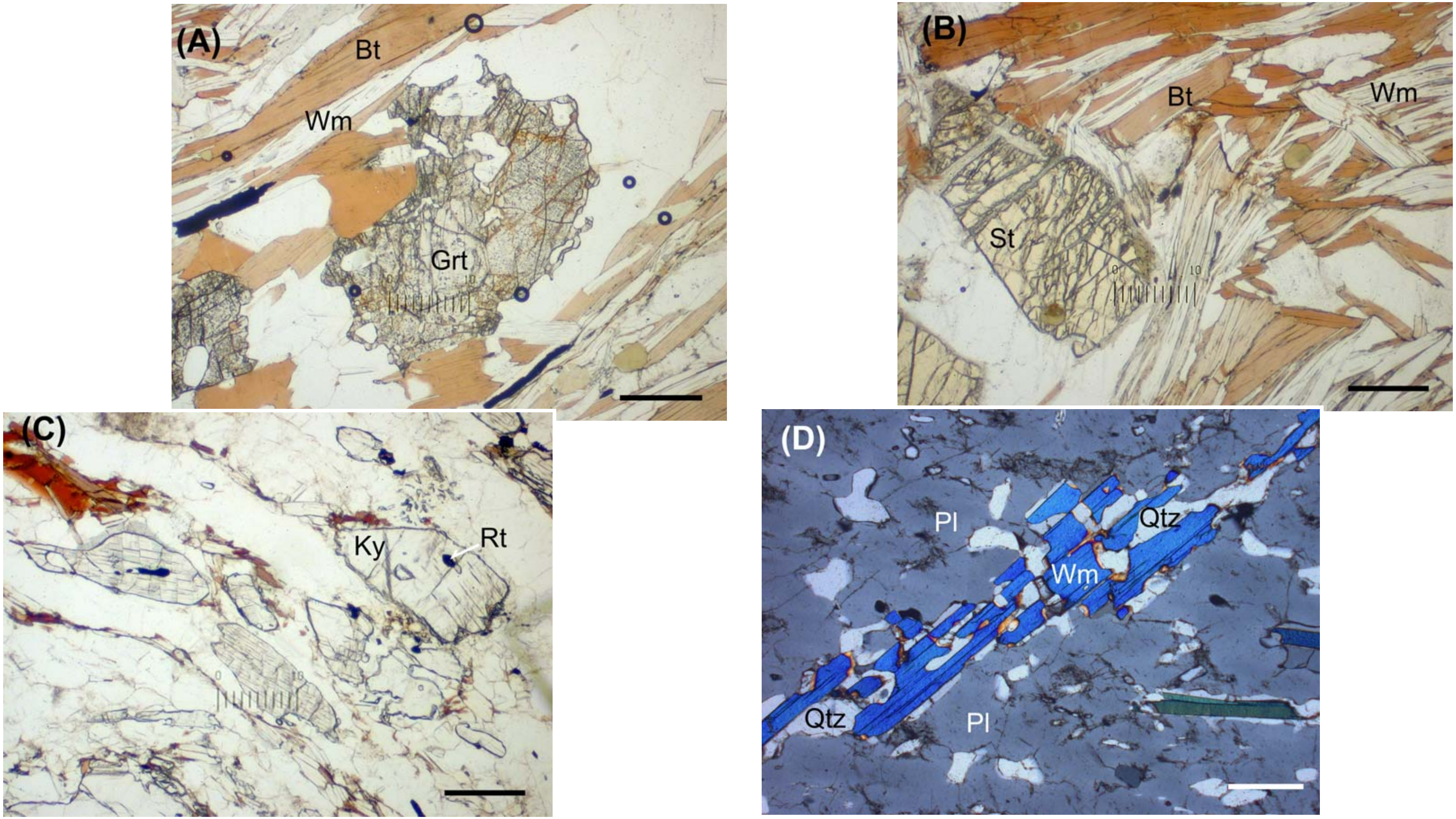

Fig. 10 - The Ulten-Nonsberg crust under the polarizing microscope. Scala bar is 0.4 mm. **(A)** Anhedral garnet (Grt) porphyroclast elongated in concordance with the main foliation made of white mica (Wm) and biotite (Bt). Garnet is riddled with tiny (fluid?) inclusions. Plane polarized light. **(B)** Staurolite (St) porphyroclast in a mica-rich domain (Bt; Wm). Plane polarized light. **(C)** Kyanite (Ky) with rutile (Rt) inclusions. Plane polarized light. **(D)** Anhedral white mica (Wm) in a large plagioclase (Pl) porphyroblast from leucosome. Crossed nicols.

Orthogneisses

Orthogneisses are present as concordant intercalations within gneisses and migmatites. On textural and mineralogical grounds, we define two orthogneiss types: the first type shows a porphyroclastic texture characterised by the presence of large (several mm across) anhedral quartz and plagioclase set in an inequigranular matrix composed mainly of quartz and feldspars. Biotite occurs in minor modal amounts and small rounded garnet, rutile and white mica are accessory phases. The second type is a medium-grained, weakly foliated amphibole-bearing orthogneiss rich in quartz and plagioclase (Del Moro et al., 1999). Aggregates made of Al-rich phases such as corundum, epidote, staurolite and white mica have been interpreted as former femic microgranular enclaves of igneous origin (Godard et al., 1996).

Mafic rocks

Foliated to massive mafic amphibolites occur in association with migmatites, e.g. in the Val Lavazzè (Fig. 11). In the Seefeld Alm/Malga Siromba area, mafic amphibolites with relics of a former eclogite assemblage are described in Godard et al. (1996).

Fig. 11 - Close view of a foliated mafic amphibolite with leucocratic quartz-feldspar lenses. Val Lavazzè, east of Malga Masa Murada. Coin is 2.2 cm across.

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Petrology and metasomatic evolution

Mantle and pyroxenites

The Ulten-Nonsberg peridotites record the transformation of shallow anhydrous coarse-grained spinel-facies assemblages (**spinel stage** of Fig. 12; ~ 1,200°C; ≤ 1.5 GPa) into HP porphyroclastic garnet-spinel-amphibole assemblage as the result of cooling at increasing pressure (**HP stage;** 800-900°C; ~ 2.0 GPa). Exhumation and retrogression to spinel–chlorite-amphibole–assemblages (**LP stage;** ~ 730°C; ~ 1.6 GPa) is the last stage recorded by the Ulten-Nonsberg ultramafics. This evolution consistent with the downward corner flow of a lithospheric mantle wedge overlying a subducting crustal slab (Fig. 13) that was undergoing partial melting. The crustal anatectic melts reacted with peridotites producing orthopyroxene layers and residual fluids enriched in incompatible elements. The infiltration of the residual fluids into the mantle wedge produced the amphibole + garnet (± dolomite) peridotites (Scambelluri et al. 2006).

Only few petrological data are available for the pyroxenites. Based on major-element compositions of minerals and rocks, Morten & Obata (1983) suggested that the protolith of the garnet-amphibole websterite was a garnet-free clinopyroxenite segregated from basaltic liquids intruding the upper mantle. A subsequent study by Nimis & Morten (2000) provided *P-T* conditions of 1.3-1.6 GPa and 1430-1470 °C for the igneous stage. After the igneous stage, the pyroxenites shared a common petrological history along with the peridotite host.

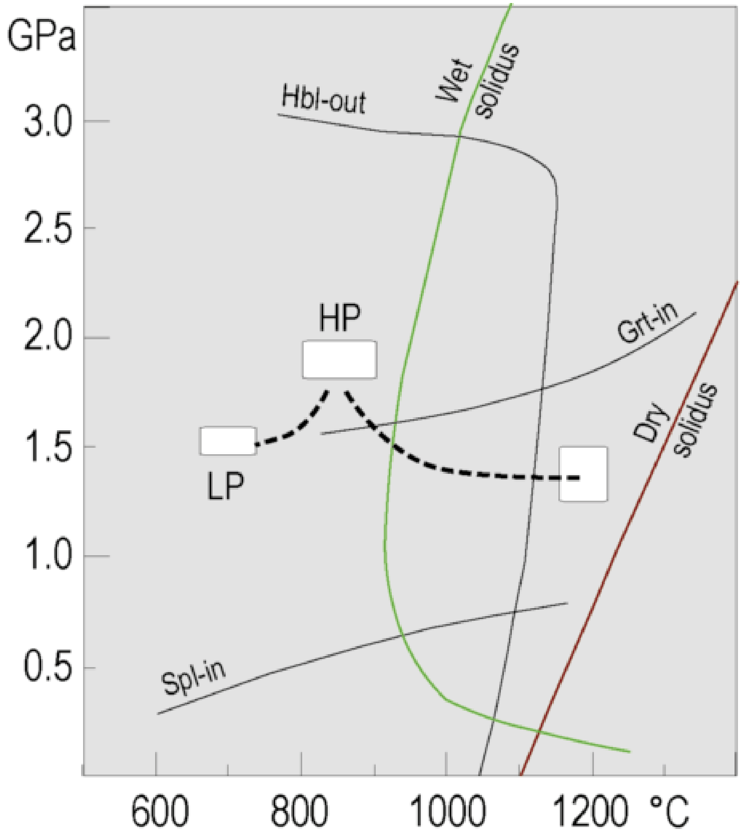

Fig. 12 - *P-T* path proposed for the Ulten-Nonsberg peridotites. Modified from Scambelluri et al. (2010) with the *P-T* data of Braga & Sapienza (2007).

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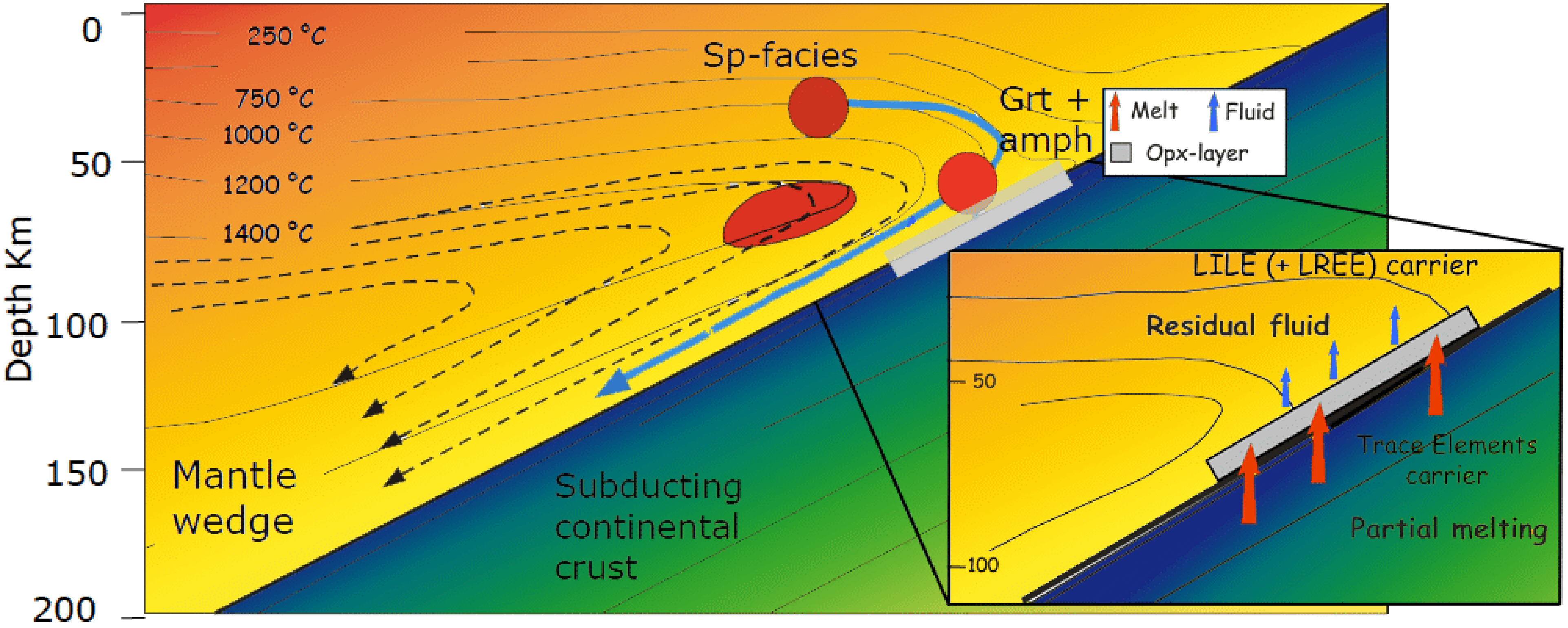

Fig. 13 - Mantle wedge dynamics during the genesis of the Ulten-Nonsberg lower crust. The model requires the existence of orthopyroxenite layers produced during the reaction between crustal anatectic melts and peridotite. Residual fluids, rich in incompatibile elements, move upwards and enrich the mantle wedge. The crust-mantle coupling occurred during the exhumation of the crust. Modified from Scambelluri et al. (2010).

A large number of studies focused on the metasomatic evolution of the Ulten-Nonsberg ultramafics, as recently reviewed by Scambelluri et al. (2010). Critical trace elements data were acquired both on bulk samples (Figs. 14-15) and, starting from the work of Rampone & Morten (2001), by *in situ* analyses of minerals. The transition from spinel- to garnet-spinel peridotites is marked by the presence of amphibole (± dolomite) and an overall LREE and LILE enrichment (Fig. 14). The further enrichment in amphibole and other fluid-mobile elements as Pb, Sr, U in the amphibole + spinel retrograde peridotites (LP stage, Fig. 15) indicates a prolonged supply of fluid and incompatible elements during the whole *P-T* evolution of the Ulten-Nonsberg peridotites.

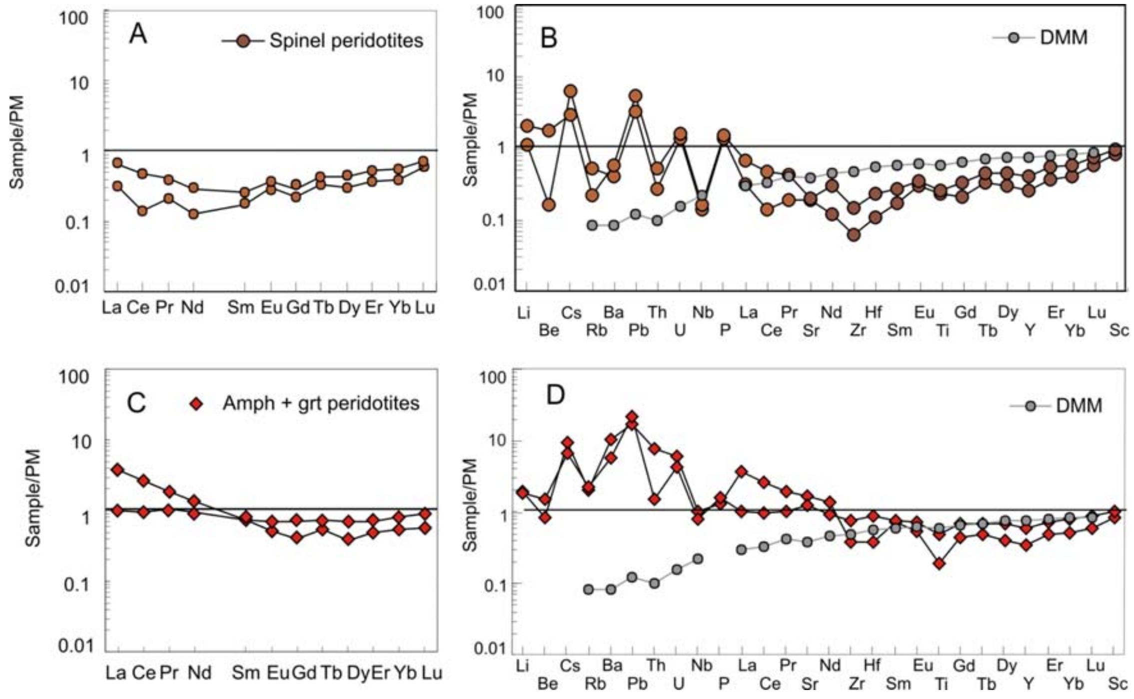

Fig. 14 - Normalised whole-rock REE and incompatible elements patterns for the Ulten-Nonsberg peridotites. **(A)** and **(B)**, spinel peridotites. **(C)** and **(D)**, garnet-bearing hydrous peridotites. From Scambelluri et al. (2010).

The trace element composition of minerals reveals a multifaceted metasomatic history. The enrichment in some LILE and light REE, along with lithium enrichment in clinopyroxene and orthopyroxene, indicates that the coarse spinel peridotites underwent an early cryptic metasomatic event driven by mafic melts (Scambelluri et al., 2006).

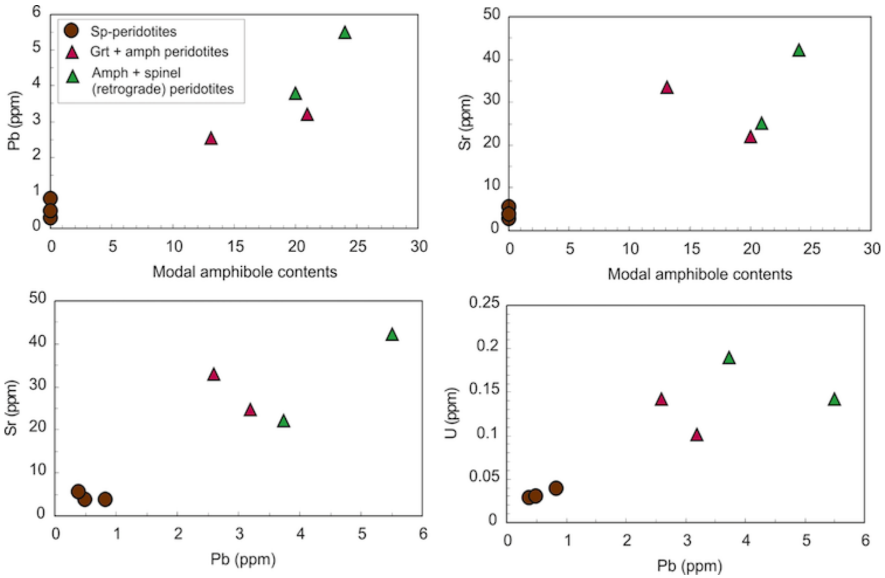

Fig. 15 - Selected modal and incompatible elements data showing the increased amounts of fluid-mobile elements of the HP and LP stages peridotites with respect to the spinel-stage peridotite (Scambelluri et al., 2010).

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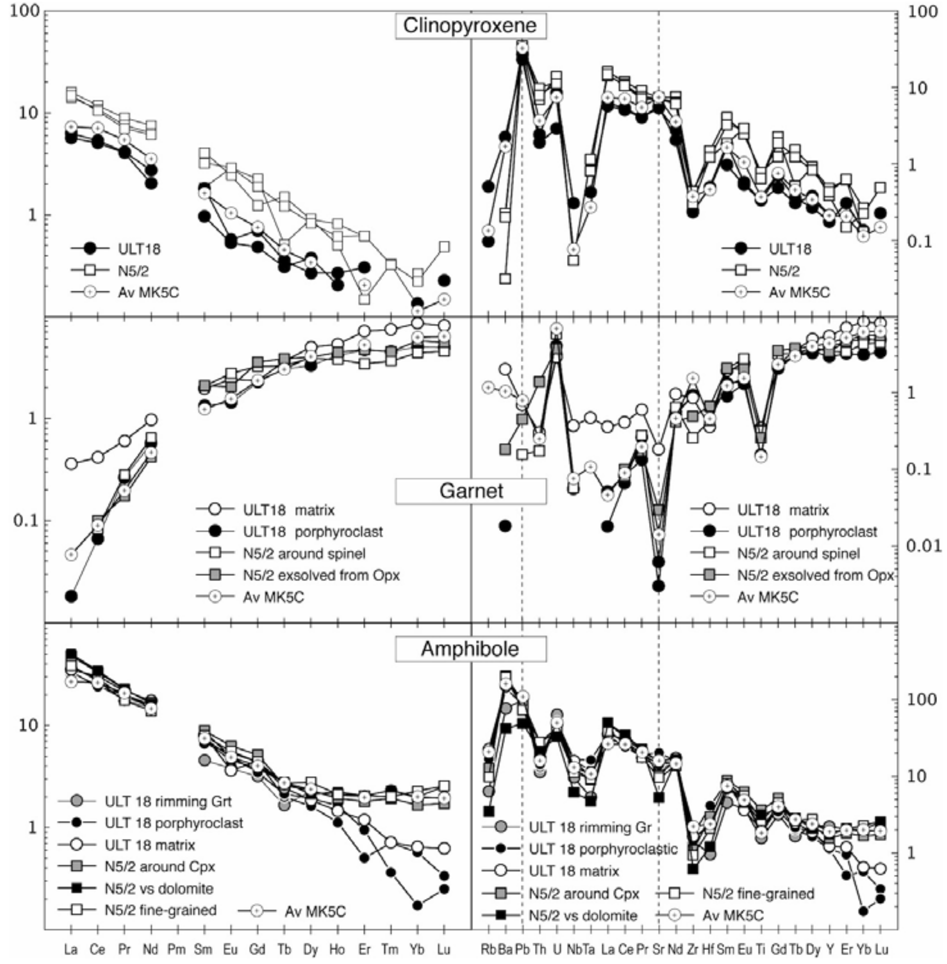
The age of the early metasomatism is poorly constrained, possibly pre-Variscan (Petrini & Morten, 1993). During the HP stage, coronitic garnet assemblages replaced the coarse spinel peridotites and were progressively obliterated by fine-grained amphibole-rich (± dolomite and apatite) assemblages. The presence of amphibole and carbonates required an open-system input of H_2O-CO_2 fluid. The REE distribution among garnet, clinopyroxene, amphibole and dolomite in the garnet peridotites reflects an equilibrium partitioning (Fig. 16) and confirms that the fluid influx occurred at peak pressure conditions. Moreover, the LREE and LILE-enrichments (e.g. Sr, Pb, Ba) of the garnet-spinel-amphibole peridotites indicate that the incoming fluids carried crust-derived components (Rampone & Morten, 2001; Scambelluri et al., 2006). The LP peridotites, characterised by the chlorite + amphibole ± dolomite assemblage, indicate that metasomatic C-O-H fluids percolated the peridotites also during retrogression, i.e. at shallower lithospheric levels.



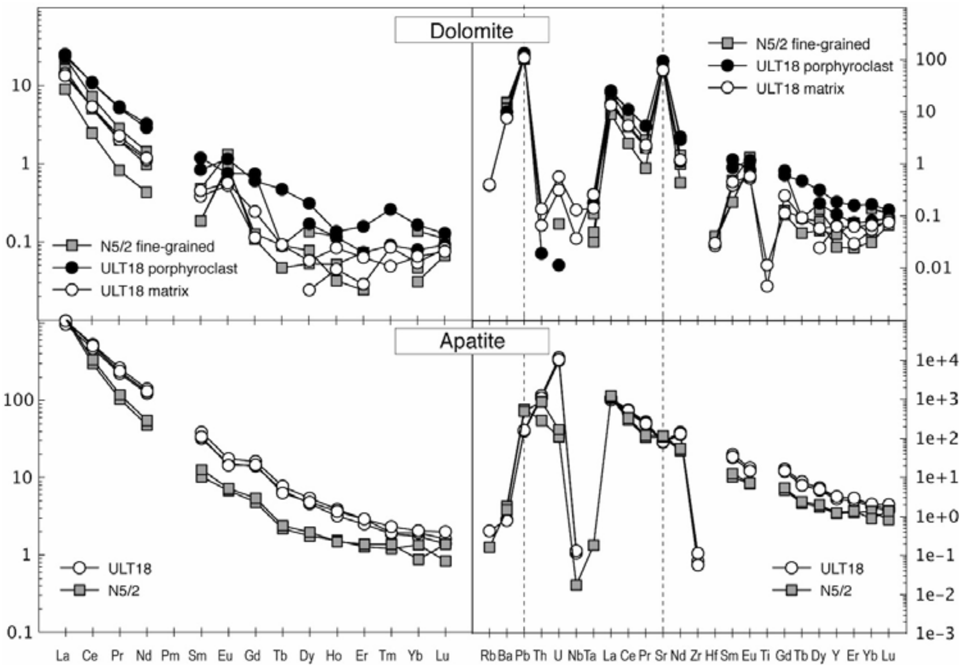


Fig. 16 - Normalised REE and incompatible element patterns in minerals from garnet-bearing peridotites (Sapienza et al., 2009).

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Crust

There is a general consensus that the Ulten-Nonsberg crust followed a clockwise *P-T* path during the Variscan orogeny, with a pressure peak that predates the thermal maximum (Godard et al., 1996; Hauzenberger et al., 1996; Tumiati et al. 2003; Morten et al., 2004; Braga et al., 2007; Braga & Massonne, 2008).
The determined peak *P* and *T* values for the crust differ among the available studies (Fig. 17). Godard et al. (1996) proposed for the paragneisses a wide peak *P-T* range of 1.0-2.0 GPa and 600-900° C, depending on assumptions about the water activity. Migmatites generally yield low *P* and *T* values (< 1.0 GPa; < 650 °C) related to the retrogression stages (Godard et al., 1996).
Based on relics of eclogite-facies minerals, Hauzenberger et al. (1996) suggested that the metamorphic peak occurred at 1.5 GPa or more and 750° C. Tumiati et al. (2003) estimated values near the coesite stability field for the crustal rocks. The explanation of these very HP conditions lies in the same age (*c.* 330 Ma) determined for the metamorphic peak of garnet-peridotites and crustal rocks (Tumiati et al. 2003).

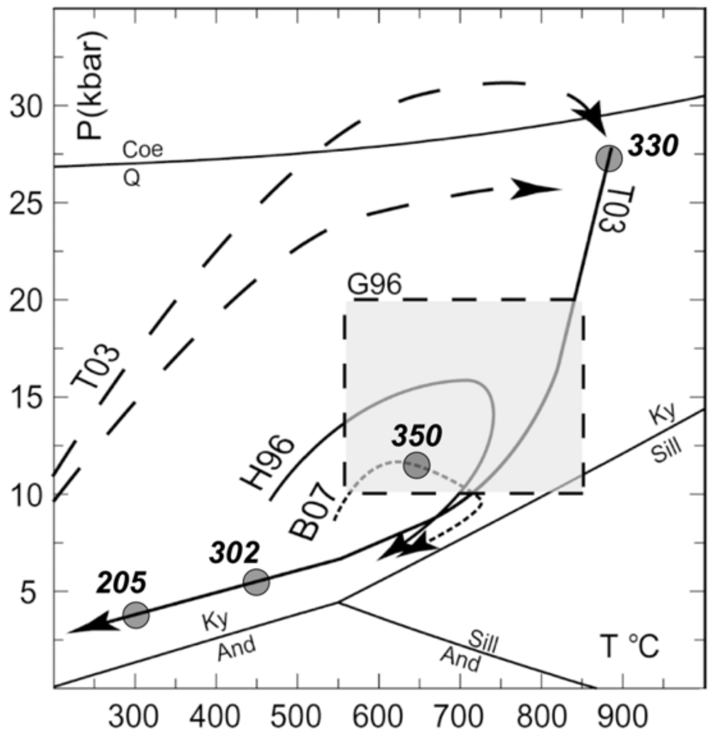

Fig. 17 - Summary of the available P–T paths for the Ulten-Nonsberg crust (modified after Braga & Massonne, 2008): G96, Godard et al., 1996; H96, Hauzenberger et al., 1996; T03, Tumiati et al., 2003; B07, Braga et al., 2007. Age data: 330 Ma, Tumiati et al., 2003; 2007; 302 Ma, Hauzenberger et al., 1993; 205 Ma, Tumiati et al., 2003; 350 Ma, Langone et al., 2011.

Recent thermobarometric work on garnet-kyanite gneisses by Braga et al. (2007) and Braga & Massonne (2008) produced a clockwise *P-T* path characterized by a *P* climax (~ 1.2 GPa) during progressive heating and a thermal peak between 700-750 C° at about 1.0 GPa, i.e. during the first stages of the exhumation process. This relatively LP evolution for the Ulten-Nonsberg garnet-kyanite gneisses is also supported by the lack of HP minerals as inclusions in both garnets and zircons (Braga & Massonne, 2008). The source rocks of the migmatites, i.e. the garnet-kyanite gneisses, produced about 20-30

vol% of melt by the breakdown of white mica (Braga & Massonne, 2012). Partial melting required an amount of H_2O that exceeded the water crystallographically bounded in micas. According to Braga & Massonne (2012) the excess water needed to sustain the anatexis was stored in pore spaces along grain boundaries.
Limited petrographic and petrological data are available for the orthogneisses. Most of the samples studied so far are from the Cima Binasia area where amphibole-bearing orthogneisses occur. According to Del Moro et al. (1999) these orthogneisses have granitoid protoliths with magmatic ages of 400 Ma. Field evidence suggests that the orthogneisses shared a common high-grade history with the paragneisses and migmatites.

The exhumation of the Ulten-Nonsberg crust, along with the entrained peridotites, was modelled by Ranalli et al. (2005) as a two-stage process. In the first stage, the Ulten-Nonsberg crust underwent a buoyancy-driven tectonic extrusion along the subduction channel, at an exhumation rate of about 0.1-1 cm a^{-1} (Fig. 18a). This stage, which proceeded for 30 Ma, is believed to have brought the crust from depths $\geq$ 100 km, assuming the very HP conditions of Tumiati et al. (2003). The second exhumation stage was slow (about 0.01-0.1 cm a^{-1}) and lasted nearly 100 Ma, bringing rocks to shallow lithospheric levels (< 20 km).

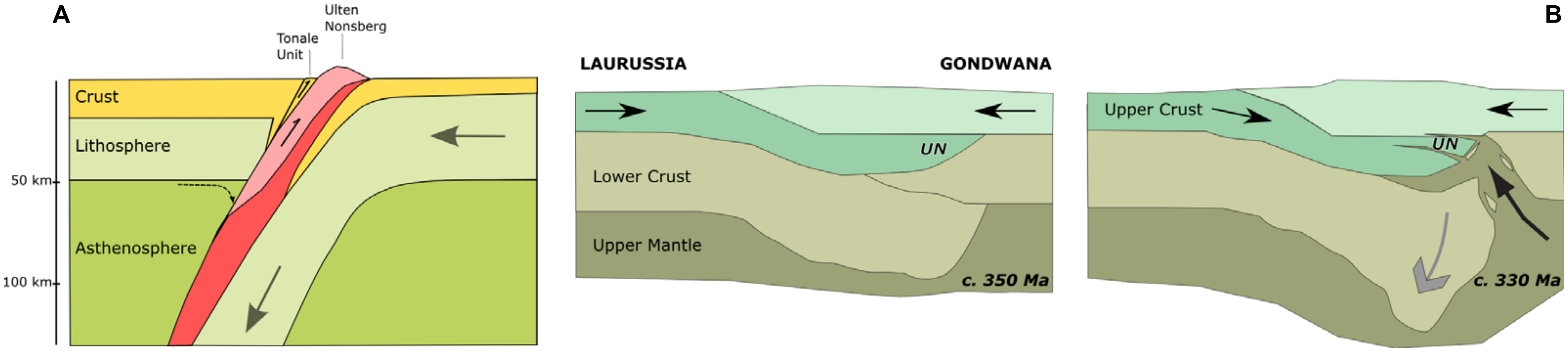

Fig. 18 - Cartoons showing two working hypotheses on the Ulten-Nonsberg geodynamics. **A)** Tectonic exhumation of the Ulten-Nonsberg lower crust during ongoing, high-angle continental subduction (redrawn from Ranalli et al., 2005). This scenario agrees with the very HP crustal signature proposed by Tumiati et al., 2003. **B)** Lower crust delamination model envisaged by Braga et al., 2007; Braga & Massonne, 2008; 2012. This scenario agrees with a P-T loop characterised by $P \leq$ 1.2 GPa and relates the HT conditions, which led to migmatization, to the upwelling of upper mantle following the foundering of the thickened lower crust. UN indicates the inferred position of the Ulten-Nonsberg lower crust.

Because the *P-T* paths are not fully consistent, the geodynamic evolution for the Ulten-Nonsberg orogenic lower crust remains an open question. An alternative explanation capable to reconcile the different *P-T* paths is considering the delamination of the lithospheric mantle (Braga et al., 2007; Braga & Massonne, 2008; 2012). The delamination followed the long-lasting, continuous collision of Gondwana and Laurussia forming the Variscan orogen (Fig. 18b). Within the thickened continental crust, the delamination concerned mainly the dense (garnet-rich) material in the lower crust.

Age dating

The excellent radiometric study by Tumiati et al. (2003) represents the main source of age data for the Ulten-Nonsberg lower crust. Garnet-whole-rock and garnet-clinopyroxene Sm-Nd isotope systematic indicate an isotopic event at ca. 330 Ma for the coarse-grained peridotites, the mafic rocks with eclogite-facies relics and the migmatites. A similar age of 333 Ma was obtained by U-Pb dating of zircons from an amphibole-rich contact rock between peridotite and migmatites from the Hochwart/Vedetta Alta mountain (Tumiati et al. 2007). The Visean age may represent either the thermal peak of the Variscan subduction or the melting event during the early exhumation stages (Tumiati et al. 2003).

Zircons separated from pyroxenites yielded an U-Pb age of 336 Ma (Gebauer & Grünenfelder, 1978). The internal planar oscillatory zoning of zircons led the above authors to consider the zircon age as representative of the magmatic event that gave rise to the pyroxenites.
Chemical and U-Th-Pb age dating of monazite from garnet-kyanite gneisses (Fig. 19) reveal an older age of 351-343 Ma related to the prograde stage of the Variscan subduction, possibly the pressure peak (Langone et al., 2011). Monazite ages are in agreement with garnet-whole rock Sm–Nd ages of 351 ± 1 Ma for a garnet–kyanite paragneiss (Hauzenberger, 1994). Permian to Lower Triassic white mica Rb–Sr ages (292–247 Ma) were obtained from the migmatites by Del Moro et al. (1993) and are believed to represent cooling ages soon after the peak conditions or, alternatively, a re-heating stage. Upper Triassic to Jurassic ages (205–160 Ma) obtained by K-Ar and Rb–Sr on micas separated from migmatites (Hauzenberger et al., 1993) and from paragneisses (Thöni, 1981; Tumiati et al., 2003). These ages have been interpreted as cooling ages related to the relatively slow exhumation of the Ulten-Nonsberg crust (Ranalli et al., 2005).

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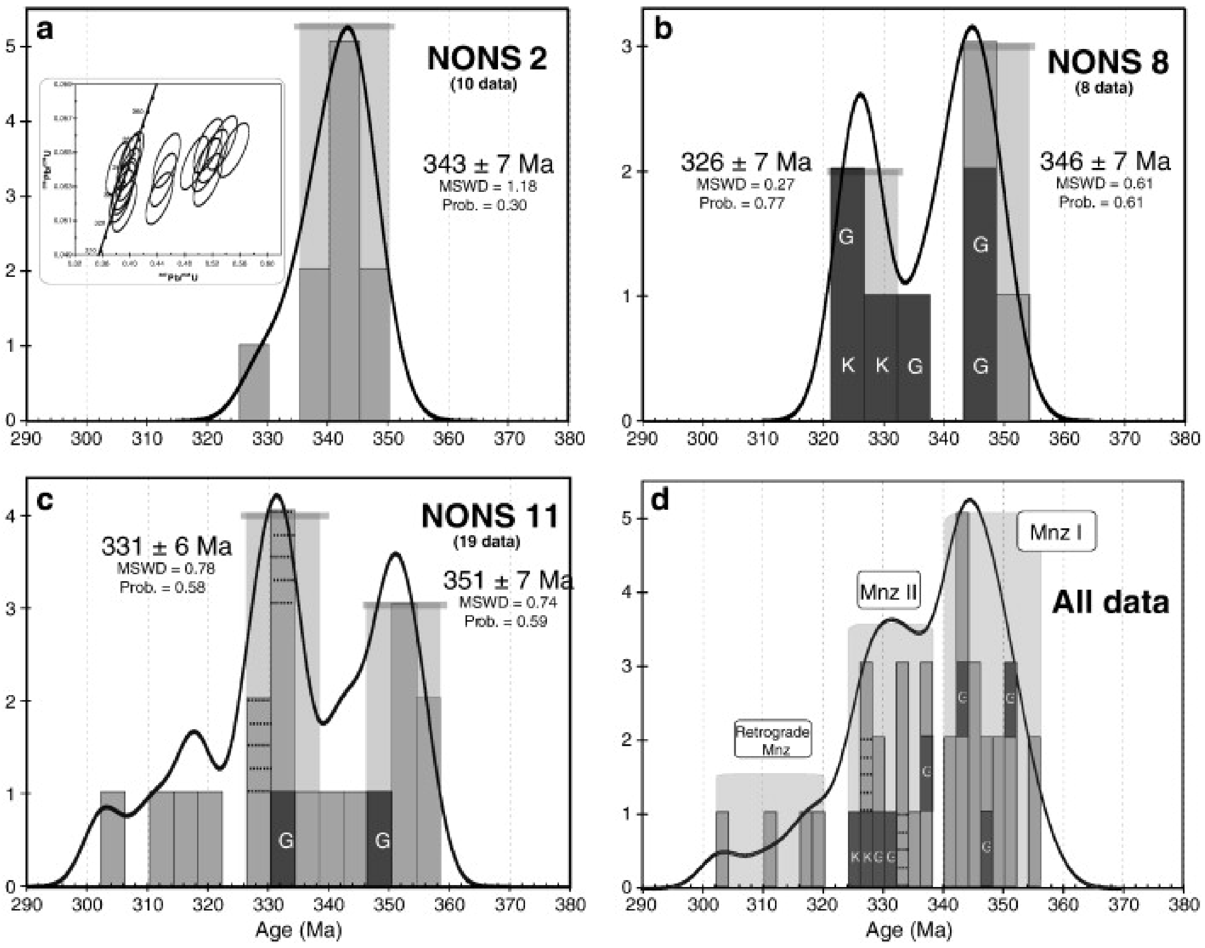

Fig. 19 - U-Th-Pb isotopic ages of monazites from three representative garnet-kyanite gneiss of the Ulten-Nonsberg crust. (**a**) NONS 2, biotite-rich Grt-Ky-gneiss; (**b**) NONS 8, mylonitic Grt-Ky-gneiss; (**c**) NONS 11, white mica-rich Grt-Ky gneiss; (**d**) all data. From Langone et al., 2011.

On a whole, the available ages suggest that the Ulten-Nonsberg crust underwent early- to middle-Carboniferous high-grade metamorphism and partial melting followed by Permian-Triassic decompression at relatively high temperature and a final cooling stage started at the end of the Triassic and lasted until the Upper Jurassic. Starting from 330 Ma, the metamorphic evolution of the UZ peridotite (Tumiati et al., 2003) might be similar to the UZ crustal evolution after these rocks were probably tectonically emplaced in the UZ crust.

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Itinerary

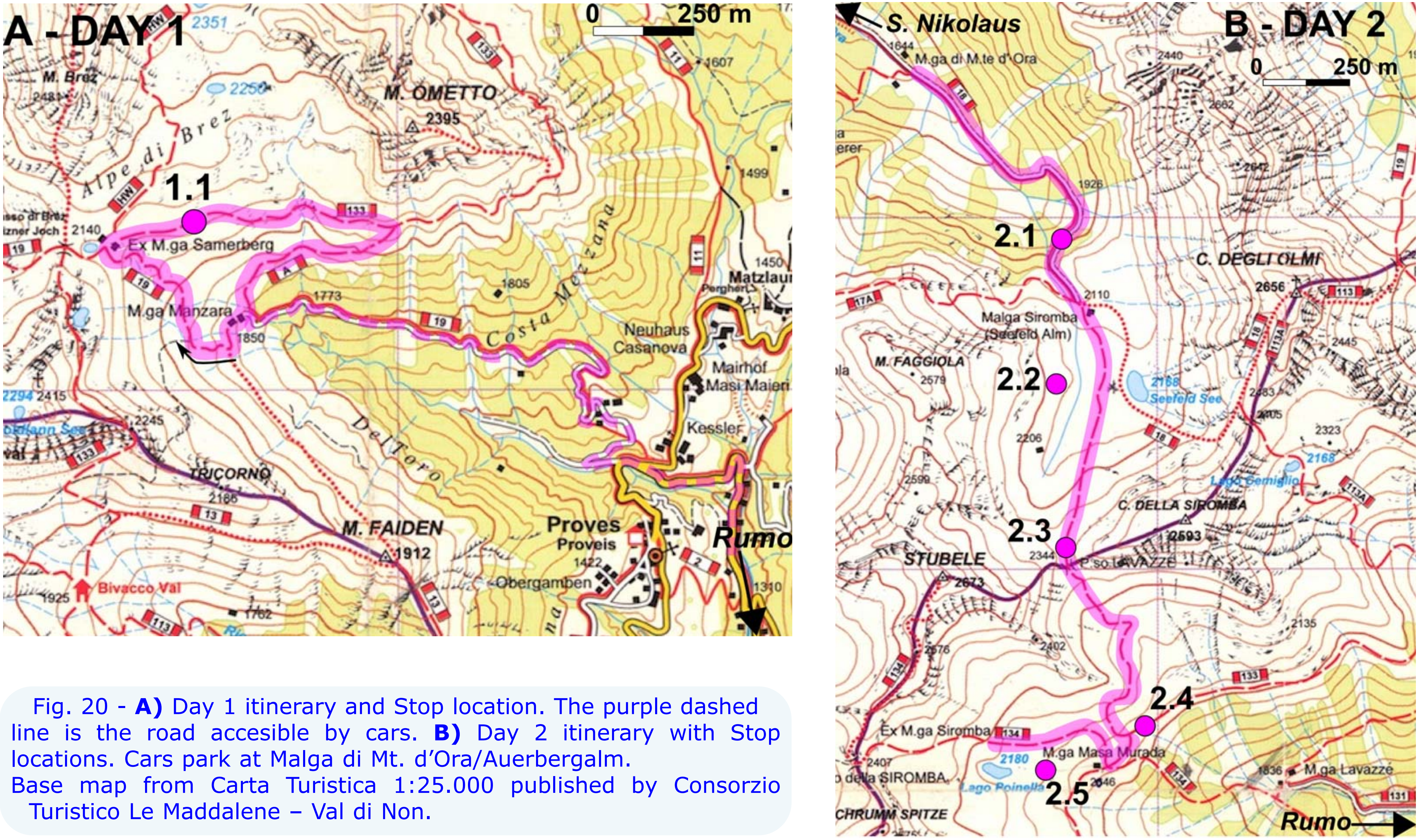

Fig. 20 - **A)** Day 1 itinerary and Stop location. The purple dashed line is the road accesible by cars. **B)** Day 2 itinerary with Stop locations. Cars park at Malga di Mt. d'Ora/Auerbergalm.
Base map from Carta Turistica 1:25.000 published by Consorzio Turistico Le Maddalene – Val di Non.

Day 1
The garnet-spinel peridotites of the Samerberg area

Starting from Rumo (46°26’31.26” N; 11° 0’59.59” E) by 4-wheel car, take the road SP86 to Proveis/Proves (Fig. 20). Before getting to Proves turn right and enter the Kirchbach valley. After a few hairpin turns, pass the small village of Tal and start to drive on a forest road heading towards the Stiebergalm/Malga Manzara (46° 29’ 17” N; 10° 59’ 45” E; alt 1855 m) where the cars ca be parked. Start walking on the footpath n.19 until the ruins of the Samerbergalm. From this point, move along an ill-defined footpath on moraine hills looking for metre-sized block of ultramafic rocks. Back to Stiebergalm/Malga Manzara and Rumo by the same itinerary.

STOP 1.1: The garnet-spinel peridotites of the Samerberg area

Waypoint (WGS84): 46°29’35.10’’ N; 10°59’29.34’’ E
Target: Porphyroclastic garnet-spinel-amphibole peridotite and kyanite-bearing garnetites

In this area, several m-sized peridotite bodies are scattered in glacial deposits. Coarse- and fine-grained peridotite (Fig. 21) and porphyroclastic peridotite with reddish garnet rimming anhedral spinel (Fig. 22) can be observed. The porphyroclastic type shows, on a fresh surface, the 6-phases assemblage typical of the Ulten-Nonsberg garnet-bearing peridotites: olivine (yellowish with typical vitreous lustre) + orthopyroxene (light brown) + clinopyroxene (green) + amphibole (fine-grained; dark green) + spinel (dark brown) and garnet (reddish). This outcrop provided the rare dolomite porphyroclasts described by Obata & Morten, 1987 and Sapienza et al., 2009.

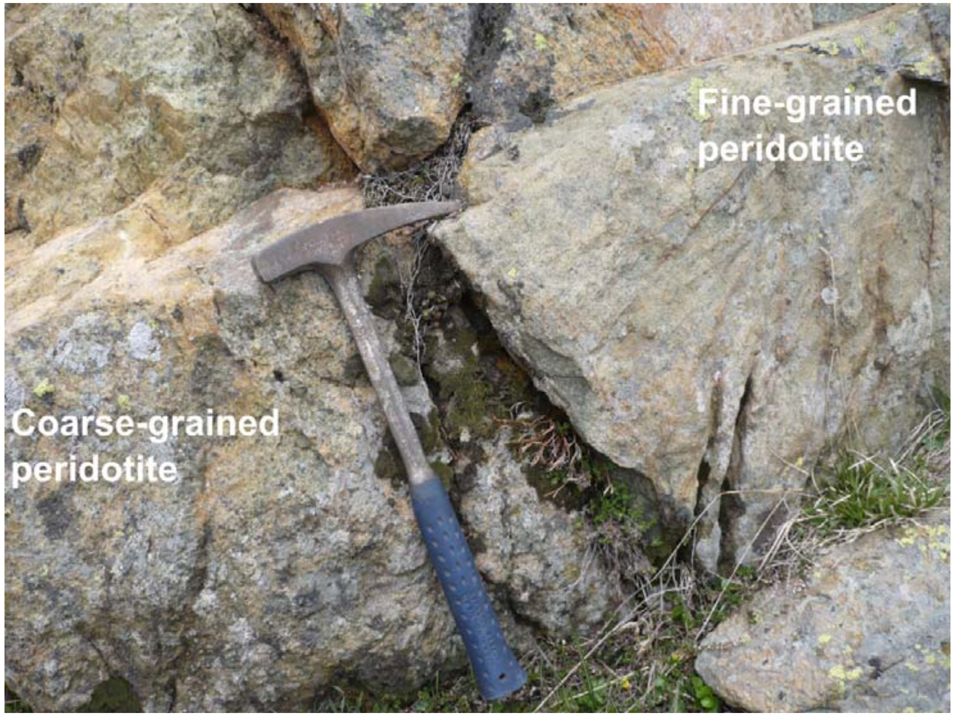

Fig. 21 - Block of peridotite showing the coarse- and fine-grained peridotite types of Obata & Morten, 1987. The hammer is 40 cm long.

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Climbing few meters from the peridotite pods we can find an exposure of a reddish, coarse-grained garnetite (garnet > 90 vol%; Fig. 23). The exposure is readily recognizable because of the dark reddish to orange weathered surface. The garnetite is isotropic, with minor amount of kyanite, biotite and quartz. From this site we can look to the western face of the Mandelspitz/Mt. Ometto (Fig. 24) showing the typical structural pattern of the Ulten-Nonsberg lower crust.

Fig. 22 - Peridotite with porphyroclastic texture. Pinkish garnet rims dark brown spinel.

Fig. 23 - Kyanite-bearing garnetite. Andreatta (1936) named this peculiar rock type “Ultenite” (from Ulten valley). The coin is 24 mm across.

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Fig. 24 - Panorama of the western face of the Mandelpitz/Mt. Ometto. The face's height is about 250 m. A thick peridotite layer is interleaved between the overlying stromatic migmatites and garnet-kyanite gneisses. This is the structural landmark of the Ulten-Nonsberg lower crust.

Day 2
Peridotites, pyroxenites and migmatites

This is a journey through the Ulten-Nonsberg zone in a superb mountain wilderness. Small rock exposures of garnet-amphibole peridotites crosscut by garnet-websterites are the main core of this field trip. The walk connects the Ulten and the Non valleys and follows both marked footpaths and unmarked track on debris deposits (especially around the Seefeldjoch/Passo Lavazzè area). This daylong hike is a remake of a similar field trip that took place on Friday, September 17, 1993 during the Fourth International Eclogite Conference. In those days the field leader were Silvana Martin, Lauro Morten and Giacomo Prosser (Martin et al., 1993).

Since this itinerary cut the Maddalene Mts., the best option is to arrange to leave a car at Malga Lavazzè (from Rumo: go to Mocenigo and then turn left into the Lavazzè Valley and park the car at Malga Lavazzè) and use another car to get to the Ulten Valley. Start from Rumo by car along the SP6 towards east. After 4 km, turn left on the SP 86, direction Val d'Ultimo. The two tunnels after 11 km "pierce" the Giudicarie fault system, which belong to the Periadriatic lineament dividing the Austroalpine and the Southern Alps domains. Once in the Ulten Valley (via Nazionale, 22 km from Rumo), turn left towards Sankt Walburg/Santa Valburga and Sankt Nikolaus/San Nicolò. At Sankt Nikolaus turn left and take the forest road that climbs the Auerbergtal up to the Auerberg Alm/Malga di Mt. d'Ora. Here, start walking along the footpath n. 18 (red-white marks) towards Seefeld Alm/Malga Siromba. Within 5-minute walk to the South, the Seefeldsee/Siromba Lake can be reached.

Time: 6:00 hours
Uphill: 700 m, from Malga di Monte d'Ora/Auerberg Alm to Seefeldjoch/Passo Lavazzè
Downhill: 520 m, from Seefeldjoch/Passo Lavazzè to Malga Masa Murada.

STOP 2.1: The stromatic migmatites of the Ulten Zone

Waypoint (WGS84): 46°26'01.00'' N; 10°56'47.82'' E, 2050 m; along the footpath n.18
Target: stromatic migmatites

Massive, fine- to medium-grained garnet-biotite-gneiss outcrops along the footpath n.18. These rocks represent the Ulten Zone country rocks geometrically below the peridotite-bearing zone (Fig. 25).

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Fig. 25 - Eastern side of the Monte Faggiola made of the stromatic migmatites of the Ulten Zone.

STOP 2.2: Pyroxenitic and peridotites

Waypoint (WGS84): 46°28’39.48” N; 10°56’51.12” E, 2200 m; West of Seefeld Lake
Target: Garnet-websterites cutting garnet-amphibole-peridotites

The outcrop (Fig. 26) forms a few meters-high cliff west of the Seefeld/Siromba Lake. It consists of light-brown peridotite cut by a 10 to 40 cm-thick green garnet-amphibole websterite dyke (Fig. 27a-b), which shows a late fracture cleavage oriented at high angle with respect to the lithological contact. The green websterite shows megacrysts (several centimetres across, Fig. 27b) made of an intergrowth of clinopyroxene, orthopyroxene and garnet set in a medium- to coarse-grained orthopyroxene + clinopyroxene + amphibole + garnet ± spinel matrix. On a fresh surface it is easy to recognise green emerald clinopyroxene, light brown orthopyroxene, dark green amphibole and red garnet. With the aid of a hand lens it is possible to observe that the matrix minerals are equigranular and form a mosaic texture.

The peridotite is medium-grained (grain size ~ 1 mm) and the preferred orientation of minerals defines the foliation. On a fresh cut the peridotite is dark coloured: dull-green olivine (± light-brown orthopyroxene) is visible in a dark grey matrix composed of amphibole. Phlogopite flakes (Fig. 27c) form a 40 cm-thick band occurring at 50 cm below the websterite-peridotite contact. Green clinopyroxene and dark red garnet may be found as isolated coarse grains or rounded aggregates of 1-2 cm diameter (Fig. 27d).

Another decametric peridotite lens crops out some 50 m north of the Stop 2.2 (Fig. 28). Here a leucocratic granular dyke made of plagioclase, quartz and subordinate biotite (trondhjemite) is located between the migmatitic gneiss and the overlying peridotite. In the trondhjemite dyke, the modal abundance of biotite increases towards the contact with the peridotite.

After the Stop 2.2, take an ill-marked track and go up to the Seefeldjoch/Passo Lavazzè (2344 m, the field trip’s highest point), at the boundary between the Ulten (South Tyrol district) and Non valleys (Trentino district).

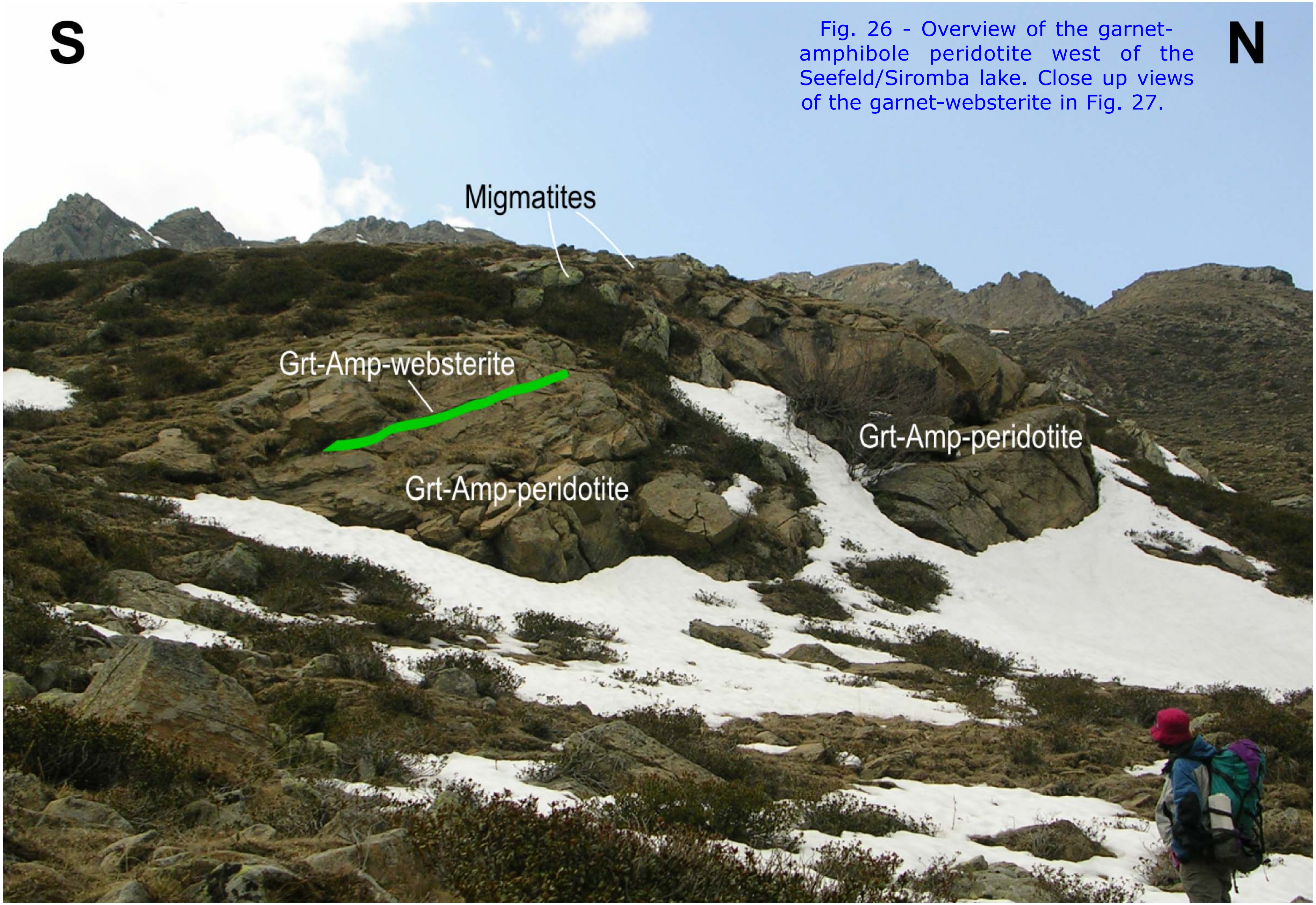

Fig. 26 - Overview of the garnet-amphibole peridotite west of the Seefeld/Siromba lake. Close up views of the garnet-websterite in Fig. 27.

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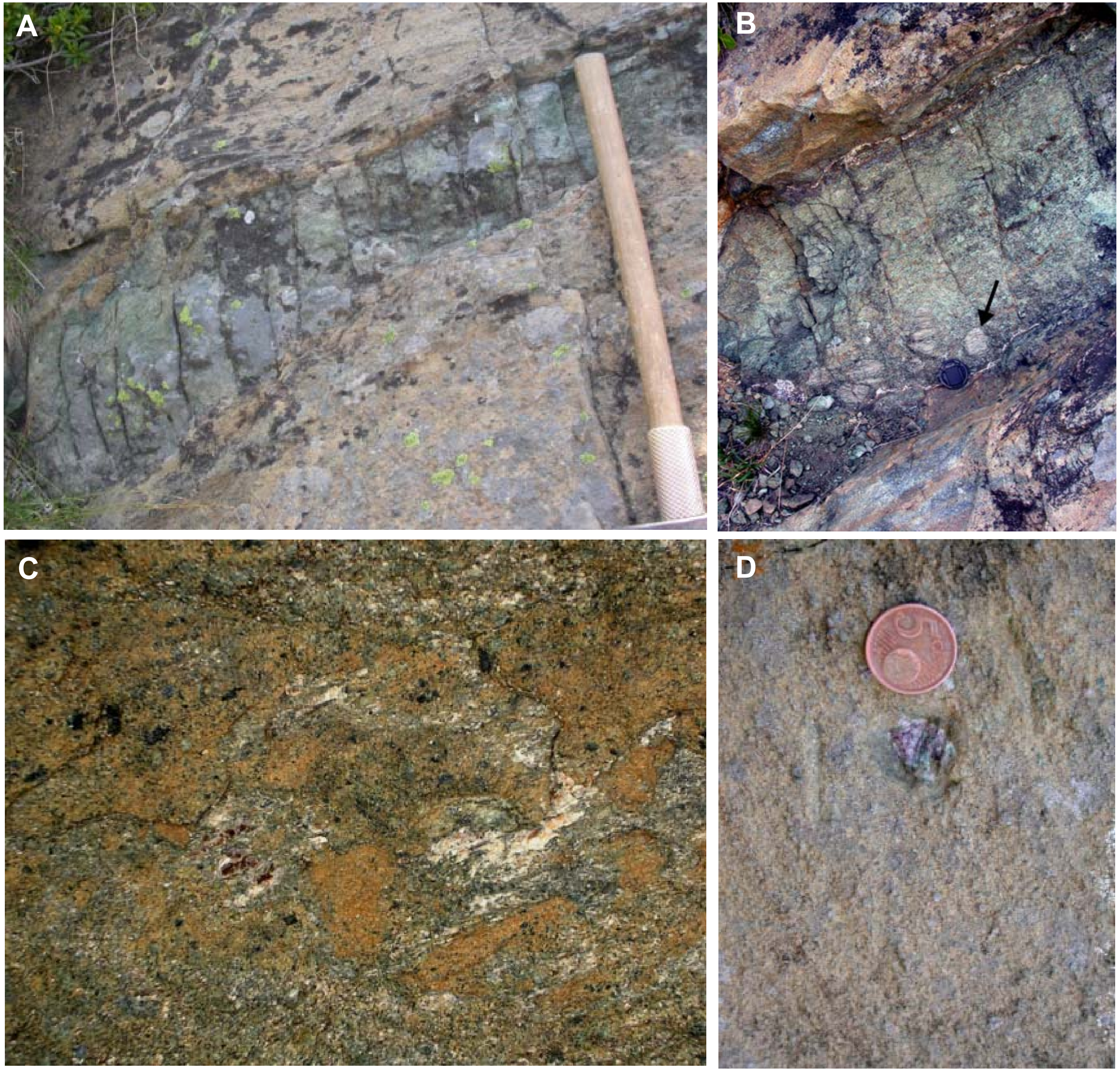

Fig. 27 - Examples of lithological and mineral variations in the Stop 2.2, west of Seefeld/Siromba lake.
A) Garnet-websterite dyke (greenish) intruded in the garnet-amphibole peridotite. The dyke is concordant to the peridotite foliation.
B) Large porphyroclast (arrow) in garnet-websterite;
C) Phlogopite- bearing domain of the peridotite. Phlogopite lamellae have (sub)metallic lustre. Olivine-rich domains have granular texture and ochre colour. Field of view: about 25 cm.
D) Rounded porphyroclast consisting of an aggregate of green clinopyroxene and dark red garnet in foliated peridotite. The coin diameter is 21 mm across.

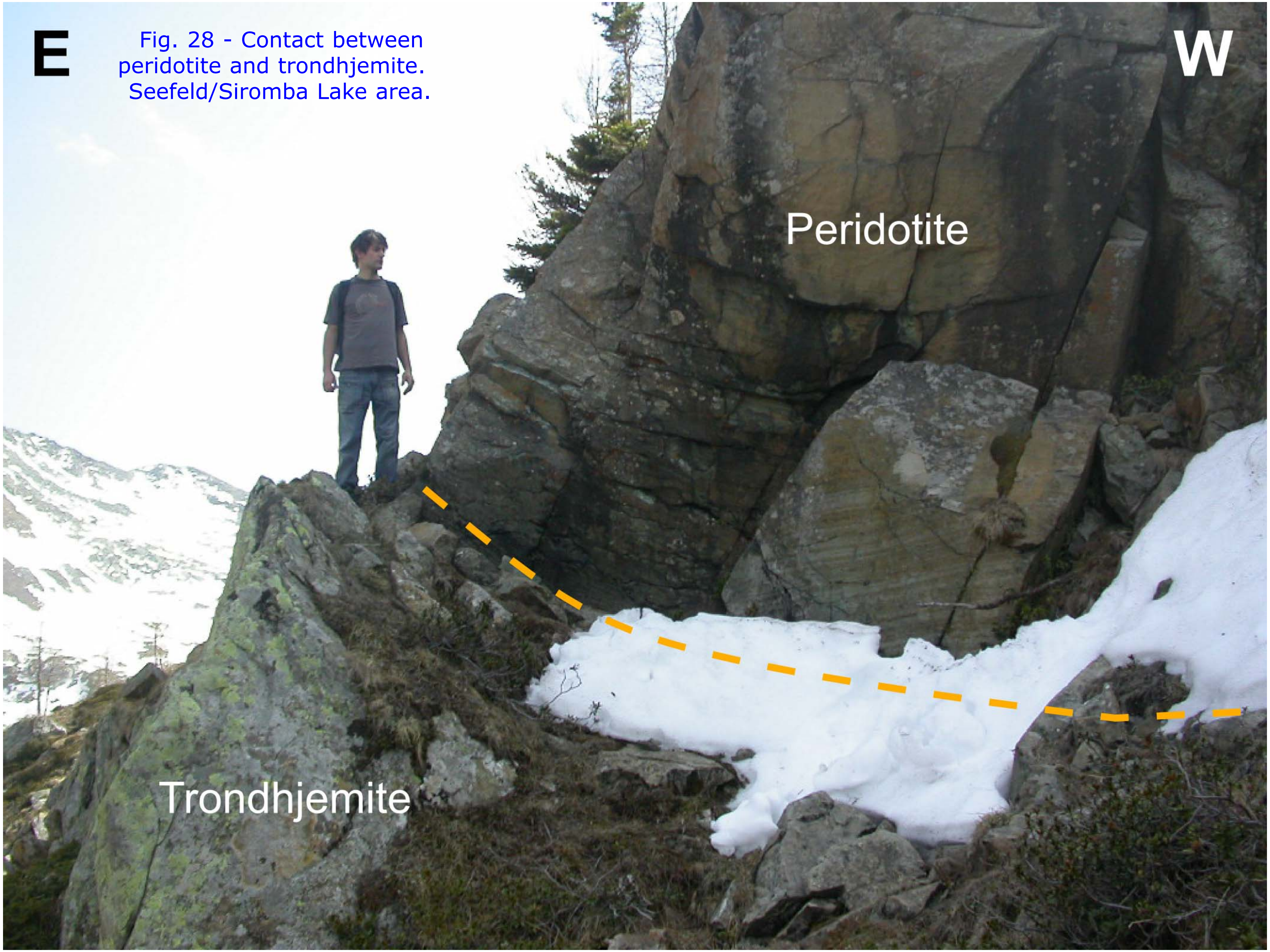

Fig. 28 - Contact between peridotite and trondhjemite. Seefeld/Siromba Lake area.

STOP 2.3: Nebulitic migmatites

Waypoint (WGS84): 46°28′5.13″ N; 10°56′45.52″ E, 2344 m; Seefeldjoch/Lavazzè Pass.
Target: Nebulitic, coarse-grained migmatites with trondhjemitic leucosome

A quick Stop at the Lavazzè/Seefeld Pass (2344 m; Fig. 29A), with the panorama of the Ulten Valley (to the north) and the Non Valley (to the south). The mountain peaks at both side of the pass (Stubele and Siromba/Seefeld Spitz) consist of migmatites with abundant trondhjemitic leucosome. During the way down, loose blocks throughout the area and along the track provide evidence of the variety of the migmatite structures, e.g. the stromatic migmatite of Fig. 29B.

From the Seefeldjoch/Lavazzè Pass descend the southern slopes of the Seefeldspitz/Cima della Siromba Mount. Loose blocks on the track require attention. The track will intersect the footpath n. 133 (red and with marks), turn right westward to Malga Masa Murada (2046m).

Fig. 29 - **A** Panorama from the Passo Lavazzè/Seefeldjoch towards the Aubergtal. The loose blocks of the debris covering the slope provide the opportunity to observe the mesoscopic structures of migmatites. **B** Block of stromatic migmatite.

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STOP 2.4: Peridotite-migmatite contact

Waypoint (WGS84): 46°27’35.33” N; 10°57’13.50” E, 2036 m; along the footpath n. 133 toward Masa Murada (46°27’25.00’’ N; 10°56’57.26’’ E, 2046 m)
Target: Contact between amphibole peridotite and country rocks

The decametre-long outcrop shows the contact between peridotite (rocks at the footpath level with a light-brown weathered surface) and the overlying gneissic migmatite with a reddish weathered surface (Fig. 30). At hand sample scale, the medium- to fine-grained peridotite (~ 1mm on average) shows abundant olivine (dull green to yellowish), orthopyroxene (light brown) and amphibole (dark grey). Very rare aggregates made of dark red garnet and green clinopyroxene occur as porphyroclasts. A phlogopite-rich layer occurs in the peridotite towards the contact with the overlying migmatite. Dolomite grains, not visible with the naked eye, are described in samples from this outcrop (Braga & Sapienza, 2007). The peridotite foliation is outlined by the shape-preferred orientation of olivine and orthopyroxene grains. This foliation is parallel to that of the surroundings migmatites, which show a foliation defined by alternating leucocratic and biotite-rich mm-thick layers. Locally, pegmatitic dykelets of trondhjemitic composition crosscut at high angle the migmatite gneissic foliation.

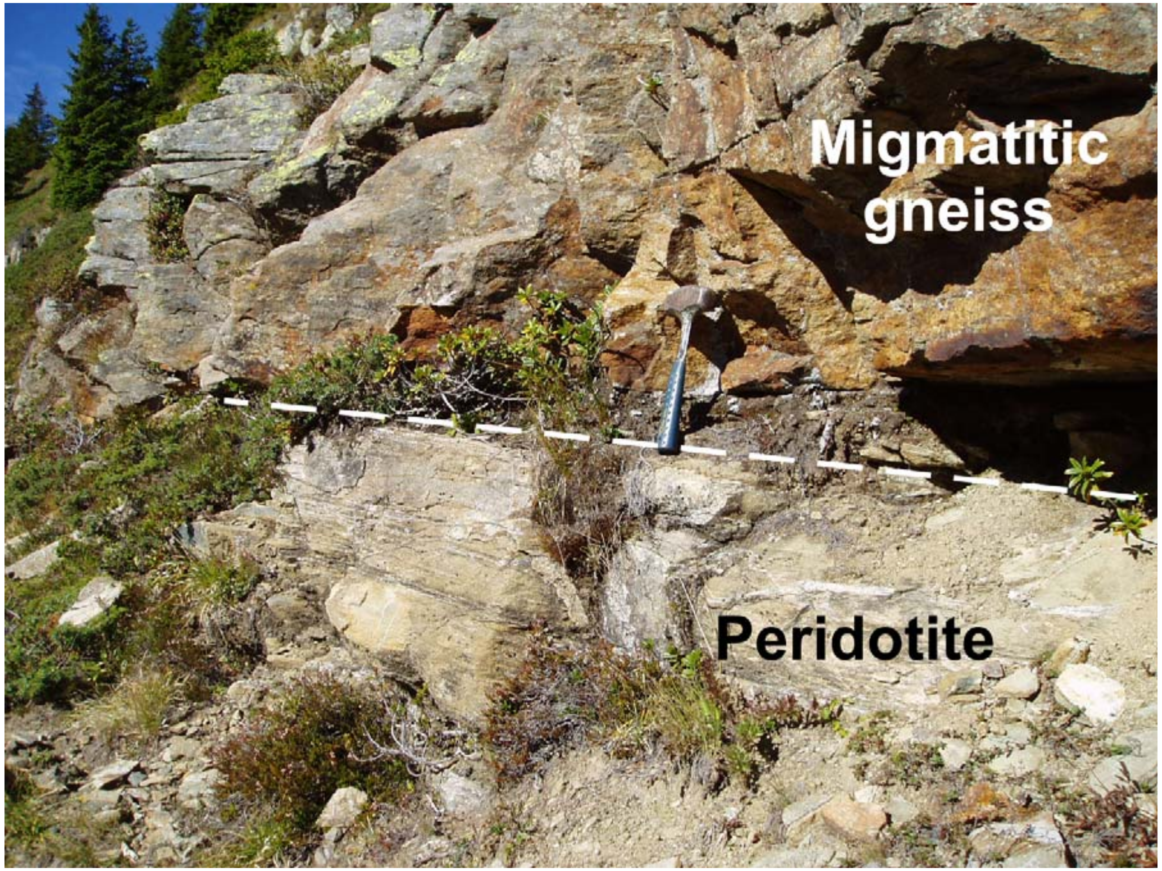

Fig. 30 - Contact between peridotite (fine-grained type) and migmatite.

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STOP 2.5 (optional): The Peridotite body of the Poinella lake

Waypoint: 46°27’24.00” N; 10°56’41.00” E, 2140 m asl, just east of the Lago della Poinella
Target: Peridotite and country gneisses cut by andesite dykes

The peridotite body from the Lago della Poinella area (Fig. 20) shows the transition from the coarse granular to the fine-grained types. The transition is marked by a foliated band of about 5 cm width (Fig. 31). The coarse granular portion contains elongated pods of orthopyroxenite (Fig. 32A). Locally, the fine-grained peridotite shows a clear fabric defined by the preferred orientation of minerals. The fabric is further outlined by mm-thick pyroxenite layers (Fig. 32B).

From Malga Masa Murada move southward on the footpath n. 134 to Malga Lavazzè (1639 m) where the cars have been previously parked. Back to Rumo, end of the field trip.

Fig. 31 - Grain-size and texture variations in the peridotite lense from the Lago della Poinella. From top to bottom: coarse granular, foliated (coin), fine-grained. The coin is 23 mm across.

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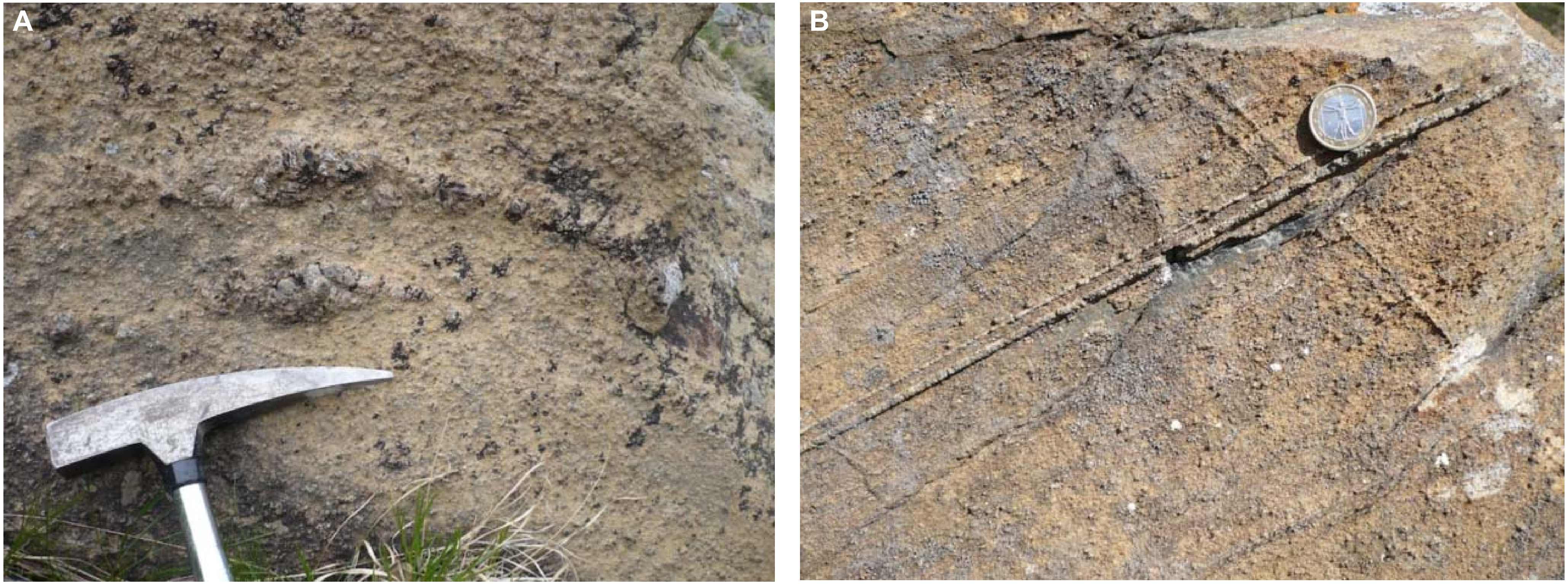

Fig. 32 - **A** Coarse-grained orthopyroxenite pods in granular peridotite. **B** mm-thick pyroxenite layers concordant with the main peridotite foliation. Thin (< 1 mm) amphibole-chlorite (?) veins cut at high angle the layering.

In Rumo – The Museo Giardino Geologico "Le Pietre delle Maddalene"

In front of the Marcena church there is the rock garden *Museo Giardino Geologico "Le Pietre delle Maddalene"* (Fig. 33A). The boulders on display are a catalogue of the rock types occurring in the surroundings of Rumo. Rocks include specimens from the Lower Permian Athesian Volcanic Group (Fig. 33B) and the Mesozoic sedimentary cover (Southern Alps) as well as the older Austroalpine basement (Fig. 33C) with our beloved peridotites. The arrangement of the boulders mimics the neighbouring regional geology (see Fig. 3).

Fig. 33 - **A)** The church of Marcena and the rock garden. **B)** Boulder of lapilli-tuff from the Athesian Volcanic Group. **C)** Migmatites (in front) and other rock types from the Austroalpine basement.

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memorandum

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