

LITHOSTRATIGRAPHY AND PETROGRAPHY OF THE MONTE BANCHETTA-PUNTA ROGNOSA OCEANIC SUCCESSION (TRONCEA AND CHISONETTO VALLEYS, WESTERN ALPS)

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ABSTRACT

This paper describes lithostratigraphy and Alpine tectono-metamorphic evolution of the oceanic succession of the Monte Banchetta-Punta Rognosa unit (Italian Western Alps). The oceanic substratum consists of serpentized peridotites covered by ophicarbonates, documenting therefore exhumation and exposure of the upper mantle at the seafloor in Jurassic times. Upwards, the sedimentary cover begins with polymictic metabreccias and intercalated siliciclastic sediments (considered Late Jurassic - Early Cretaceous in age), both containing oceanic and continental detritus, and interpreted as mass-flow deposits on sea floor. Then, the upper part of the cover consists of Cretaceous pelagic carbonate sediments (calcschists), lying over a main unconformity. The stratigraphic features and the architecture of the sedimentary cover suggest that this segment of the Piemonte-Liguria Ocean was in a proximal position with respect to the rifted margins. In a general context of the ocean-continent transition, source areas for continental detritus can be envisaged on the hyperextended part of the European margin or on its more proximal part, adjacent to structural highs made of oceanic mantle, as recorded by oceanic detritus. The combination of structural, petrographic and mineral chemistry data defined the Alpine prograde and retrograde metamorphic evolution of this oceanic segment. The metamorphic peak was reached during the D₁ event at the transition between lawsonite- and epidote- blueschist facies conditions. Then, a first decompressional event D₂ always at blueschist facies conditions was followed by a D₃ event at green schist facies conditions.

INTRODUCTION

The Piemonte-Liguria zone of the Western Alps (as well as of Corsica and Northern Apennines) includes remnants of the oceanic basin opened during Middle to Late Jurassic between the European and the Adriatic/African plates (e.g. Lemoine et al., 1986; Lemoine and Trümpy, 1987; De Wever and Baumgartner, 1995; Froitzheim and Manatschal 1996). This zone consists of portions of the upper oceanic lithosphere (generally serpentized mantle peridotites, and subordinate gabbros and pillow basalts) and related Middle Jurassic to Cretaceous pelagic sediments variably involved, dismembered and metamorphosed to HP/UHP conditions in the Alpine nappe stacking, during Tertiary subduction- and collision-related processes. A very abundant literature distinguished several units (from local to regional scale) in the Piemonte-Liguria zone of the Western Alps on the basis of lithostratigraphy and/or Alpine metamorphic evolution (e.g. Elter, 1971; Lagabrielle et al., 1984; Deville et al., 1992; Fudral et al., 1994; Martin et al., 1994; Barfety et al., 1995; Servizio Geologico d'Italia, 2002, and references therein). In this frame, the stratigraphic features of the sedimentary succession can be used to identify which segment of the oceanic basin with respect to the rifted continental margins has been sampled and preserved in the Alpine units.

With the purpose to give a contribution to the knowledge of the Piemonte-Liguria zone and eventually its relationships with adjacent domains, this paper deals with a poorly investigated oceanic succession exposed along the Monte Banchetta-Punta Rognosa mountain ridge, extending between the Troncea and the Chisonetto valleys (Piemonte, NW Italy) in the core of the Western Alps (Fig. 1). The paper is based on detailed field investigations integrated and supported by petrological and mineral chemistry analyses.

Main goals are 1) to improve the knowledge of lithostratigraphy of this poorly known and highly deformed succession, and 2) to define the main steps of its Alpine metamorphic evolution. The chronology of fabrics and structures described in the following sections have been obtained by the mutual calibration and integration of outcrop investigations and textural relationships from petrological studies.

A further paper will be dedicated to a more detailed description of the structural features (from outcrop to map scale) of the recognized deformation events, which elements are only simplified in the map of Fig. 1 due to the purposes of the present paper.

GEOLOGICAL OUTLINE

The Piemonte-Liguria Ocean (part of the western Tethys) opened from the Middle Jurassic onwards, between the European and Adriatic/African plates. As a consequence of Europa-Adria convergence/subduction in Late Cretaceous and continental collision during Tertiary times (e.g. Tricart, 1984; Roure et al., 1990; Beltrando et al., 2010 and references therein), segments of the oceanic lithosphere and related sediments were metamorphosed, deformed and stacked with portions of both the continental margins to form the Alpine Axial Belt (Fig. 1a).

Primary relationships of adjacent serpentized mantle and continental units and syn-post-rift sediments (supported by geochemical studies) have been used to identify the part of the ocean adjacent to the hyper-extended continental margin (e.g. Dal Piaz, 2010 and references therein), envisaging then the occurrence of extensional allochthons directly on the exhumed mantle (Manatschal, 2004; Manatschal and Müntener, 2009; Mohn et al., 2012).

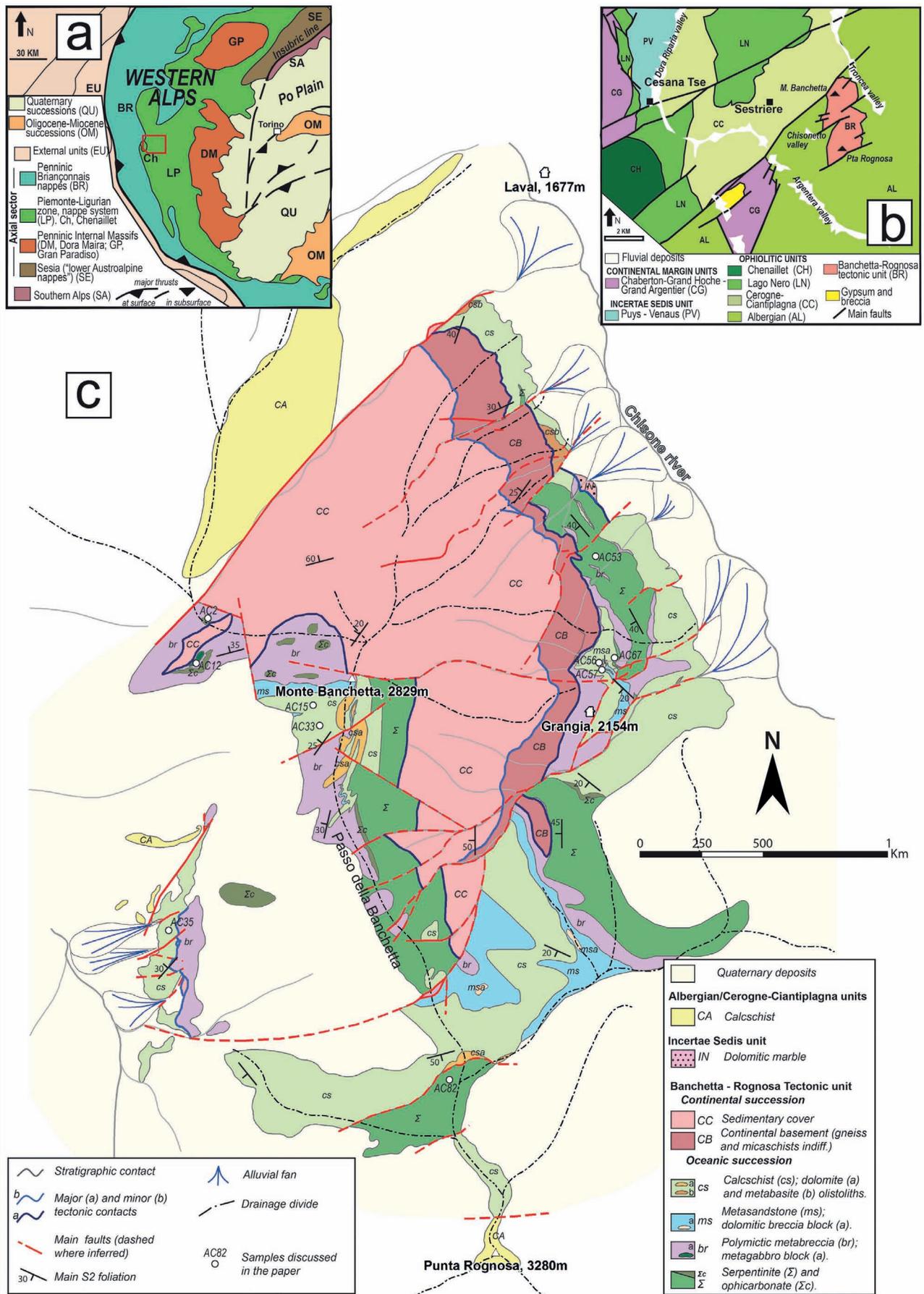


Fig. 1 - Geological setting. a) tectonic sketch map of the Western Alps. Inset shows location of Fig. 1b (simplified after Molli et al., 2010); b) tectonic sketch of the investigated region (redrawn after Servizio Geologico d'Italia, *in press*); c) Simplified interpretative geological map of the Monte Banchetta-Punta Rognosa area based on the results of this study (only regional attitude of the S₂ foliation and main tectonic contacts are reported; see text for details).

The typical features of the ophiolitic sedimentary cover are represented by Middle-Upper Jurassic Mn-rich metacherts and marbles, and (Late Jurassic)-Cretaceous calcschists (original marine calcareous-argillaceous successions), these latter showing variable occurrence of detrital intercalations from oceanic lithosphere and/or continental margin (e.g. Lemoine 1971; Lagabrielle et al., 1984; Lemoine and Tricart, 1986; De Wever et al., 1987). However, it is important to emphasize that part of the Late Jurassic-Cretaceous carbonatic metasediments often included in the oceanic Piemonte-Liguria zone might be more correctly interpreted as successions deposited in outer sectors of the oceanic domain in correspondence of the rifted continental margins (Deville et al., 1992). The Alpine tectono-metamorphic evolution of the ophiolite-bearing successions recorded generally a subduction-related prograde path with HP blueschist or eclogite-facies metamorphic peak (and locally UHP), and a subsequent exhumation-related retrograde path (e.g. Beltrando et al., 2010). At the regional scale of the Western Alps, two principal groups of oceanic units are identified (e.g. Martin et al., 1994; Agard et al., 2002; Angiboust et al., 2009; Dal Piaz, 2010 and references therein). The oceanic eclogitic facies units (or Zermatt-Saas) at lower structural levels, and the overlying oceanic blueschist facies units (or Combin). In addition, at the highest structural levels of the oceanic units, the Chenaillet unit forms a klippe of oceanic lithosphere with no post-rift sediments and escaped from HP-LT subduction-related metamorphism, being only weakly deformed during its tectonic emplacement in the present nappes stack (Mevel et al., 1978; Bertrand et al., 1982; Chalot-Prat, 2005).

The oceanic sequence discussed in this paper is exposed in a small area (only a few km²) along the Monte Banchetta-Punta Rognosa ridge (at an altitude between 1800 and 3280 m a.s.l.). In this area, serpentinites and dolostones within continuous sequences of calcschists were already reported in the earlier Italian geological maps (Servizio Geologico d'Italia, 1911). Caron (1971) first mapped and described the complex juxtaposition between an internal Briançonnais unit (consisting of pre-Triassic continental basement and a thin and discontinuous Mesozoic cover) and a Piemonte s.l. unit, made up of dolomitic marbles and dolomitic breccias often associated with serpentinites, and calcschists. The geological map by Fioraso (2009) well displays the complex geological setting of this area. In the geological map prepared by the Servizio Geologico d'Italia (*in press*), the oceanic succession here investigated has been included in the composite Monte Banchetta-Punta Rognosa tectonic unit (Fig. 1c). This unit consists of two parts: an oceanic complex (object of this study) and a continental complex, that are intensively deformed by Alpine metamorphic and post-metamorphic structures. The Monte Banchetta-Punta Rognosa unit dips toward the W at a regional scale, and it is juxtaposed to several blueschist facies oceanic units, bounded by syn- to post-metamorphic contacts (Fig. 1b). Among these units, the Lago Nero unit rests at the upper structural position and below the non-metamorphic Chenaillet unit (Polino, 1984). The Lago Nero unit consists of metaophiolites overlain by radiolarian cherts (Oxfordian-Kimmeridgian), metalimestones (Late Jurassic-earliest Cretaceous), argillaceous sands alternating with micritic limestones (Replatte Formation of Early Cretaceous age) and a sequence of mainly carbonate sediments (calcschists *Auct.*) including black shales (spanning from Middle to Late Cretaceous). This supra-ophiolite metasedimentary cover is typically characterized by inter-

calations of continental and ophiolitic detritus at several stratigraphic levels (Polino and Lemoine, 1984; Servizio Geologico d'Italia 2002 and *in press*; Burroni et al., 2003). The Albergian unit consists of thick sequences of carbonate metasediments with scattered blocks of ophiolites and related thin sedimentary cover. The Lago Nero and Albergian units recorded a metamorphic peak in lawsonite-blueschist facies conditions (Malusà et al., 2002; Servizio Geologico d'Italia, 2002). The epidote-blueschist facies Cerogne-Ciantiplagna unit, juxtaposed to the Banchetta-Rognosa unit by high-angle post-metamorphic faults, consists of a thick sequence of calcschists embedding very small and isolated blocks of metaophiolites (Caron, 1971; Servizio Geologico d'Italia, 2002).

LITHOSTRATIGRAPHY

Fig. 2 is the reconstruction of the oceanic succession of the Monte Banchetta-Punta Rognosa unit as obtained by correlation and interpretation of several lithostratigraphic logs measured during field investigations. This section describes lithostratigraphic features of the succession as observed in the outcrops.

Serpentinites form outcrops up to 100-m thick. They are both massive and coarse-grained, well preserving crystals (a few cm in size) of the pyroxene of the original peridotites (Fig. 3a), and intensively foliated with fibrous serpentine along the foliation planes. In many outcrops, serpentinites have a brecciated texture, from 1 to 5 m thick, toward the overlying sediments, with 1-50 cm large serpentinite clasts bounded by an irregular network of veins (< 1-3 cm thick) filled by calcite, dolomite and locally talc. These breccias can be referred to as ophicarbonates.

The overlying sedimentary succession starts with a polymictic metabreccia, ranging in thickness from few meters to 30 m, extensively exposed along the western and eastern sides of the Monte Banchetta (Fig. 1c). However, Caron (1971) has reported also a thin level of (probable) radiolarian cherts directly on the serpentinites. The metabreccia has a block-in-matrix fabric: the matrix is an impure marble, often containing abundant Fe-oxides. The clasts, wrapped by the pervasive foliation and locally up to a few meters in size, consist of serpentinites, ophicarbonates (Fig. 3b), and subordinate gneisses, micaschists (Fig. 3c) and dolomitic marbles. At the western side of the Monte Banchetta, a block of metagabbro with a well-preserved magmatic texture has been found (Fig. 3d). In the south-eastern sector, the polymictic metabreccia displays a decrease of clast size from the underlying serpentinites, and progressively passes upwards into fine-grained impure marbles (showing a maximum thickness of ~10 m), defining then a broad fining upward sequence.

Bodies of white-greenish metasandstones (Fig. 3e, f and g), with maximum thickness of ~15 m and 50-60 m long, have been variably observed with pinch-out terminations both intercalated and on the top of the polymictic metabreccia. Similar sediments have been locally observed also directly on serpentinites and ophicarbonates. The metasandstones are often characterized by the widespread occurrence of Fe-oxides aggregates (up to cm in size) and large white micas and chlorite flakes along the pervasive foliation planes. Locally, discontinuous micro-conglomerates (< 50 cm thick) with mm to cm clasts of quartz and levels of white to gray impure quartzites have been observed

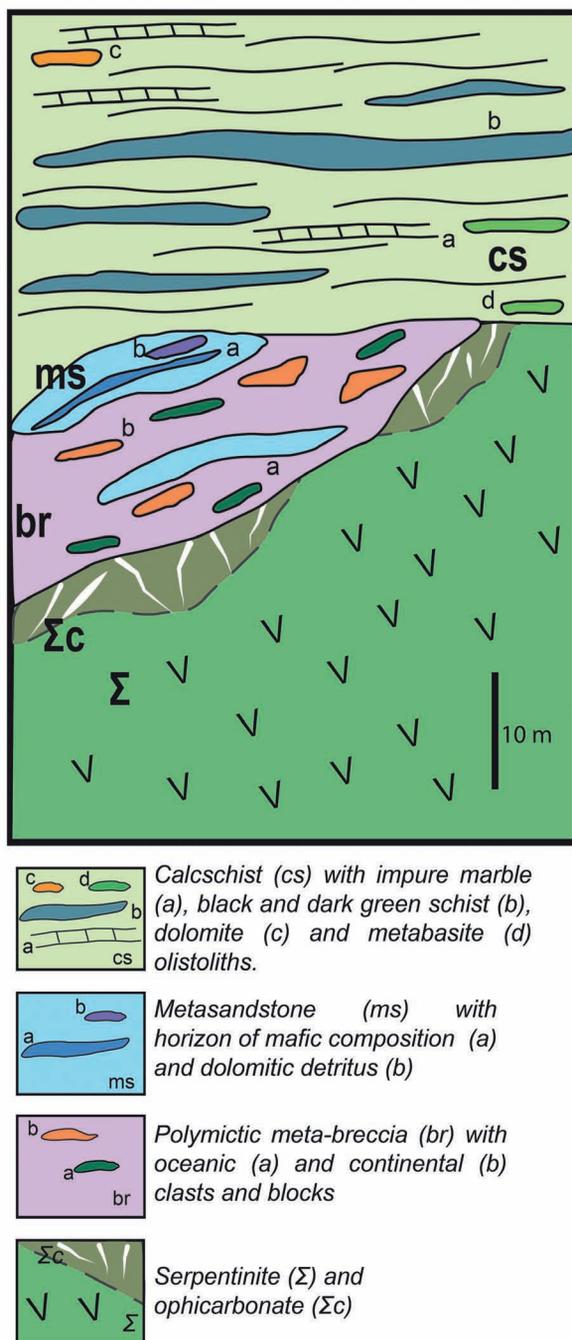


Fig. 2 - Lithostratigraphy of the oceanic succession.

associated with the metasandstones. The metasandstones have a few intercalations of green to bluish horizons (< 50 cm thick) of mafic composition, rich in glaucophane and chlorite (Fig. 3f). The metasandstones are capped by calcschists (described below) in their uppermost part, and contain clasts and rare blocks up to a few meters in size of dolomitic marbles and dolomitic metabreccias elongated between the foliation planes (Fig. 3g and Fig. 1c).

The uppermost part of the sedimentary succession consists of calcschists, at least 100-200m thick and unconformably overlaying serpentinite-ophicarbonates and related sediments (Figs. 1c and 3e). In the calcschists, primary compositional features are suggested by alternating cm to dm thick carbonate- and silica-rich domains, and by

discontinuous intercalations of impure marbles, black and dark green schists (10 cm to 2 m thick). In addition, scattered blocks of serpentinites, metabasites and dolomitic metabreccias are embedded in the calcschists, generally stretched between the foliation planes.

STRUCTURAL SETTING

Four main deformation events (D_1 - D_4) can be identified in the oceanic succession. Petrographic description of the different planar fabrics related to these events are detailed in the following section. The oldest event D_1 is recorded by the foliation S_1 , preserved in microlithons, intrafolial folds and isolated fold hinges. S_1 results sub-parallel to primary compositional banding/lithological contacts (Fig. 3f) and is defined by Na-pyroxene + serpentine \pm magnetite \pm amphibole in ultrabasic rocks, Na-pyroxene + Na-amphibole \pm quartz in basic rocks and quartz + phengite + Na-amphibole + chloritoid in pelitic rocks. S_1 foliation (together with lithological contacts) is deformed and transposed during D_2 into tight to isoclinal folds (Fig. 3f). The axial plain schistosity S_2 is usually the most penetrative planar fabrics in the outcrops. S_2 is mainly defined by aegerin-augite + serpentine + amphibole in ultrabasic rocks, aegerin-augite + phengite + epidote in basic rocks and quartz + phengite + garnet \pm chloritoid + chlorite in pelitic rocks. A L_2 stretching lineation is marked by alignment of phengite, amphibole, chloritoid or locally tourmaline on the S_2 . Kinematic indicators and relationships between L_2 on S_2 and fold geometries suggest an E to SE verging non-cylindrical folding during D_2 (Fig. 3h). D_3 is recorded by folds and crenulations with ENE-WSW trending sub-horizontal axes and axial planes usually dipping at high angle to SSE (Fig. 3f). Chlorite + tremolite + muscovite + stilpnomelane assemblage defines a locally pervasive S_3 . A late D_4 led to the development of gentle kilometer-scale folds with N-S trending axes and with axial planes dipping at high angle.

PETROLOGY AND MINERAL CHEMISTRY

This section deals with main textural relationships and mineral chemistry of rocks forming the oceanic succession. A Scanning Electron Microscope (JEOL JSM-IT300LV) equipped with an energy-dispersive X-ray spectrometer (EDX), with a SDD (a silicon drift detector from Oxford Instruments), hosted at the Earth Science Department of the University of Turin, was used for the determination of major elements. The experimental conditions include: accelerating voltage 15 kV, counting time 50 s, process time 5 μ s and working distance 10mm. The measurements were conducted in high vacuum conditions. The EDX acquired spectra were corrected and calibrated both in energy and in intensity thanks to measurements performed on cobalt standard introduced in the vacuum chamber with the samples. The Microanalysis Suite Oxford INCA Energy 300, that enables spectra visualization and elements recognition, was employed. A ZAF data reduction program was used for spectra quantification. The resulting full quantitative analyses are obtained from the spectra, using natural oxides and silicates from Astimex Scientific Limited, as standards. All the analyses were recalculated using the MINSORT computer program (Petraakis and Dietrich, 1985). Representative analyses of mineral composition are reported in Tables 1 to 5 of the supplementary material.

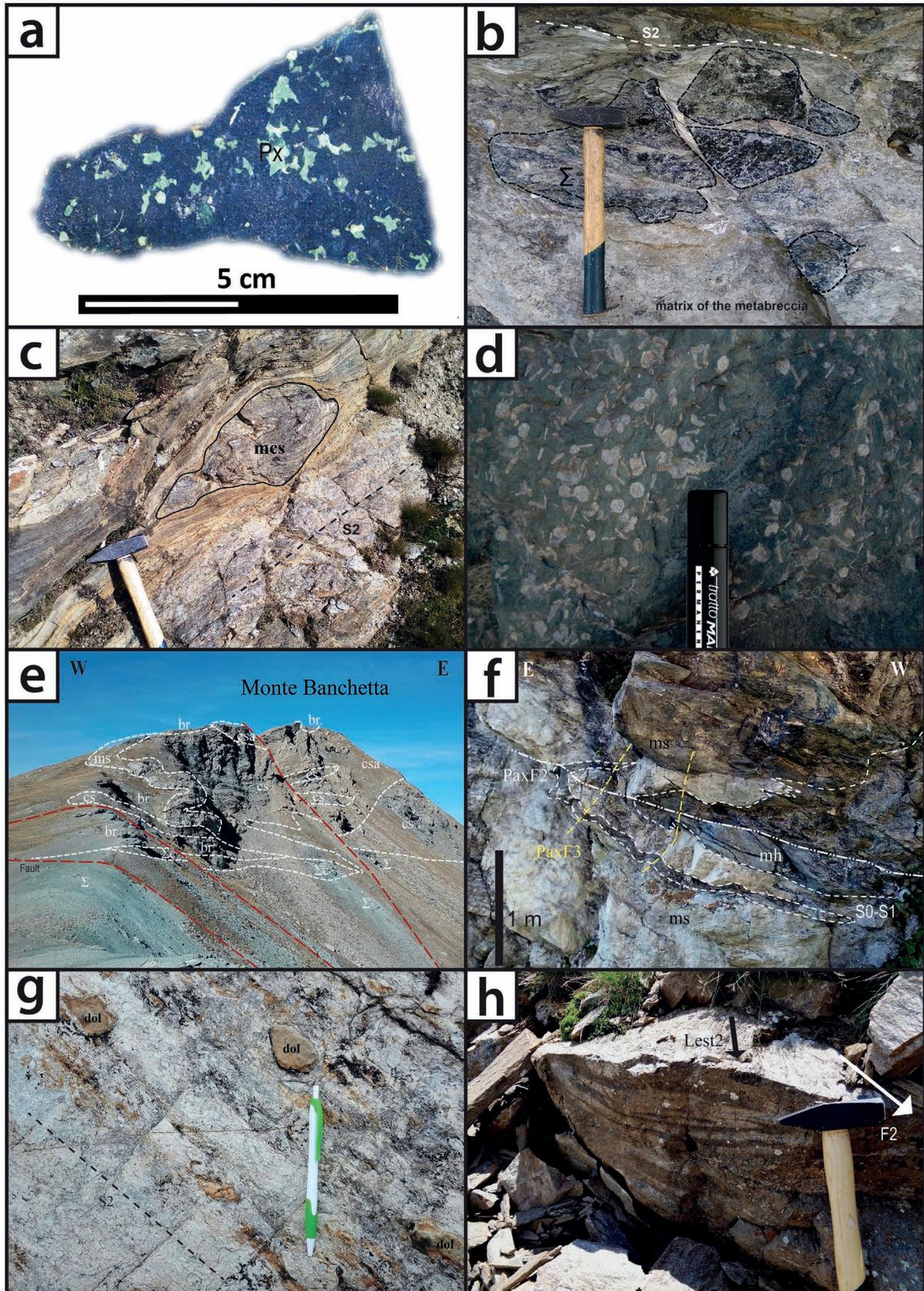


Fig. 3 - Representative lithologies at the mesoscale. a) detail of massive serpentinites with magmatic pyroxene relics (Px) (sample AC82); b) serpentinite clasts (Σ) in the lower part of the polymictic metabreccias (Monte Banchetta south-eastern side, 1940 m); c) continental clast (mcs- micaschists) in the polymictic metabreccias (Monte Banchetta summit, 2823 m); d) metagabbro block in the polymictic metabreccias (Monte Banchetta western side, 2573 m); e) metasandstones (ms) intercalated in the polymictic metabreccias (br) between Passo della Banchetta and Monte Banchetta summit (cs- calcschists; Σ - serpentinites); f) bluish horizons of mafic composition (mh) in the metasandstones (ms), deformed by D₂ folding and D₃ crenulation (PaxF: axial plane; north of La Grangia, 2040 m); g) upper part of the metasandstones containing dolomitic clasts (dol) (south-east of Passo della Banchetta, 2710 m); h) non-cylindrical D₂ fold in calcschists (Lest₂, stretching lineation; F₂, fold axis) (Monte Banchetta north-western side, 2570 m).

Fig. 4 and Fig. 5 show representative microstructures and Fig. 6 reports chemical composition and classification diagrams of representative minerals. Fig. 7 summarizes the parageneses developed during the different deformation stages.

Serpentinites

The serpentinites consist of serpentine + pyroxene + amphibole + chlorite ± magnetite ± carbonate with variable occurrence of pyrite, calcopyrite, ilmenite and titanite. Coarse grained serpentinites preserve crystals (up to a few cm in size) of diopside ($\text{Na} < 10 \text{ wt\%}$ and $\text{XMg} > 0.9$, showing very low content in Cr ranging between 0.4 and 0.7 wt%) and magnetite of the original peridotites (Figs. 4a, 4b and 6a). S_1/S_2 foliations are defined by serpentine and aegirine-augite, grown after magmatic pyroxene and in turn replaced by tremolitic amphibole and chlorite weakly isoriated (Fig. 4b). The associated ophicarbonates show large magnetite and serpentinite fragments separated by different sets of carbonate-bearing veins (Fig. 4c).

Polymictic metabreccias

The matrix of the metabreccias (Fig. 4d) is an impure marble consisting of calcite + quartz + Fe-chlorite + glaucophane + tremolite. S_1/S_2 foliation is defined by isoriated glaucophane within a calcite matrix. Fe-chlorite ($\text{Cr}_2\text{O}_3 \sim 3 \text{ wt\%}$ and $\text{MnO} \sim 1.57 \text{ wt\%}$) and tremolite (Amph D_3 , Fig. 6b) mark the S_3 foliation.

The clast of metagabbro preserves evidences of an original coarse-grained magmatic texture (Figs. 3d, 4e and 4f). Large aggregates, up to few cm in size, of epidote + white mica + albite replaced magmatic plagioclase. They are dispersed within a fine-grained assemblage of Na-Ca pyroxene + Mg-chlorite + epidote replacing original magmatic pyroxenes. The Na-Ca pyroxene displays omphacitic core (recording D_1 event) and aegirine-augite rim (D_2 event), and have acmitic content up to 30% (Fig. 4f and Fig. 6a). The S_2 foliation is defined by Na-Ca pyroxene + phengite ($\text{Si} \sim 3.30\text{--}3.40 \text{ a.p.f.u.}$, Fig. 6d). The later S_3 foliation is marked by Mg-chlorite + muscovite (after phengite, $\text{Si} < 3.30 \text{ a.p.f.u.}$, Fig. 6d) + zoisite (with contents $< 1\%$ of Cr_2O_3 e MnO) ± allanite (epidote rich in Ce, La and Nd). Late pumpellyite crystals are also present. The clasts of gneiss (stretched along the S_2) contain assemblages of chlorite + muscovite + opaque after pyroxene enveloped by a foliation defined by chlorite + albite + fine-grained sericite (Fig. 4g).

Metasandstones

The metasandstones consist of quartz (ranging from 70–90% in volume of total rock) + white mica + Fe-chlorite + chloritoid + glaucophane with variable amounts of stilpnomelane, tourmaline, calcite, apatite and rutile. This rock usually displays a lepidoblastic texture with the pervasive S_2 foliation defined by quartz + chloritoid + white mica (generally zoned, with phengite at the core and muscovite at the rim, Fig. 6d), transposing an earlier S_1 foliation of quartz + phengite + glaucophane + chloritoid + rutile. The late S_3 foliation is marked by isoriated Fe-chlorite + muscovite + stilpnomelane. A primary micro-conglomeratic fabric is recorded by elongated and sub-rounded quartz grains wrapped by the S_2 foliation. The white to gray impure quartzites show fine-grained assemblages of quartz (more than 90% of the total rock) ± white mica ± calcite.

The mafic horizons intercalated in the metasandstones (Fig. 4h) consist of abundant glaucophane (Fig. 6b), white mica and quartz with minor and variable amount of calcite,

pyrite, zircon, apatite and detrital allanite. In these horizons, nematoblasts of medium-grained glaucophane + phengite ($\text{Si} < 3.50$ Fig. 6d) + quartz define the S_2 foliation, while assemblage of quartz + glaucophane + phengite ($\text{Si} > 3.50$, up to 3.72 a.p.f.u., Fig. 6d) rutile marks a S_1 foliation in micro-lithons. A locally very pervasive S_3 crenulation cleavage is defined by muscovite + chlorite + albite ($\text{An} < 5\%$) + quartz.

Calcschists

The calcschists consist of carbonate ± quartz, white mica, chlorite and graphite, with minor tourmaline and apatite. Monocrystalline quartz is irregularly distributed within the carbonate matrix, ranging from 10% to 30% of the rock. White mica is oriented along S_1 and the main S_2 foliation. Aggregates containing white mica + graphite ± zoisite relics within the S_1 foliation can be interpreted as pseudomorphs after lawsonite (Fig. 5a). Calcite + white mica + quartz define S_2 foliation.

Pyroxene-bearing metabasites (Fig. 5b) embedded in the calcschists consist of Na-amphibole + tremolite + chlorite + epidote + titanite + pumpellyite ± albite. They show a nematoblastic texture with pyroxene of aegirine-augite (Fig. 6a) composition partially replaced by glaucophane (Amphibole D_2 in Fig. 6b), that with epidote, white mica, chlorite and titanite defines the S_2 foliation. Amphibole of tremolitic composition (Amphibole D_3 in Fig. 6b) has been observed in paragenesis with green chlorite and Cr-rich pumpellyite (Cr_2O_3 content is $\sim 4.5\text{--}5.5 \text{ wt\%}$) to define S_3 .

The intercalations of black schists (Figs. 5c and 5d) are mainly composed of quartz + garnet + stilpnomelane + chlorite + calcite + pyrite and have high contents of ankerite and Fe-Mn oxides. Usually, in this rock the S_2 foliation is marked by white mica and chlorite films.

Garnet subhedral to euhedral porphyroblasts are syn-kinematic with respect to S_2 and include an earlier S_1 foliation consisting of white mica + quartz + graphite. This garnet is usually Mn-rich (Fig. 6c) with spessartitic end-member up to 40–50%, and has a Mg content $< 0.30 \text{ wt\%}$ (see Table 2, supplementary material). Grossular content is usually around 15% while almandine can reach 40%. Although a compositional cross-section has been carried out, no chemical zoning has been identified. The anomalous enrichment in Mn can be due to the original chemical composition of the protolith. Often, largest crystals of garnet are rimmed by late Mn-rich ankerite (Fig. 5c). Stilpnomelane (from yellowish bronze to dark brown in colour) grows both after garnet and in fractures (Fig. 5d).

The dark green schists, forming discontinuous levels in the calcschists, consist of white mica + stilpnomelane + chlorite + quartz + calcite/dolomite with variable quantities of Fe-Mn ankerite, ilmenite and titanite. Relics of the S_1 foliation are defined by amphibole (in turn replaced by chlorite) and white mica. White mica is typically zoned showing phengitic core with high content (up to 3.75 a.p.f.u., Fig. 6d) and has a content of Cr_2O_3 of $\sim 3 \text{ wt\%}$. White mica-rich layers are often strongly crenulated with development of S_3 axial plane foliation defined by chlorite and stilpnomelane.

METAMORPHIC EVOLUTION

Metamorphic conditions of the oceanic succession have been reconstructed by combining microstructural observations, chemical analyses and conventional P-T thermobarometric estimates (Fig. 8).

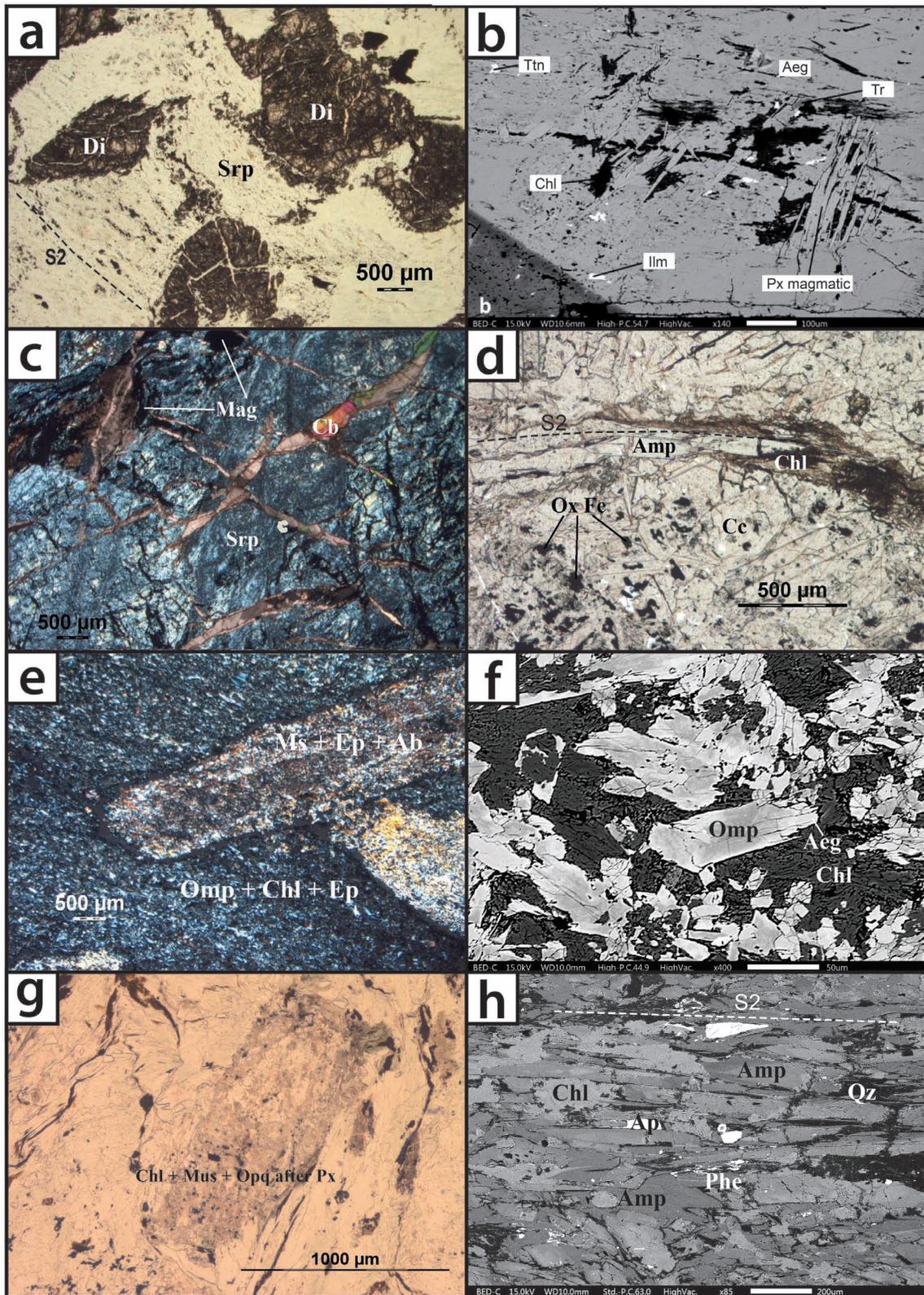


Fig. 4 - Representative microstructures. a) massive serpentinites consisting of serpentine (Srp) and large pyroxene relics (Di, diopside) (sample AC82); b) aegerine-augite pyroxene grown after magmatic diopside and replaced by tremolite and chlorite in the serpentinites (sample AC82); c) ophicarbonates made of serpentine (Srp) and magnetite (Mag), with multiple sets of carbonate veins (Cb) (sample AC67); d) carbonatic matrix (cc) of the polymictic metabreccias with Na-amphiboles (Amp) isoriated to define S_2 foliation and partially replaced by chlorite (Chl). Note widespread occurrence of Fe-oxides (Ox Fe) (sample AC2); e) metagabbro with muscovite (Ms) + epidote (Ep) + albite (Ab) pseudomorphosis after plagioclase and fine-grained matrix made of omphacite (Omp) + chlorite (Chl) ± epidote (Ep) replacing magmatic pyroxene (sample AC12); f) Na-Ca pyroxene with omphacitic (Omp) core and aegerine-augite (Aeg) rim, in the metagabbro (sample AC12). Chl, chlorite; g) Clasts of gneiss in the polymictic metabreccias characterized by aggregates of chlorite (Chl) + muscovite (Mus) + opaque (Opq) after pyroxene (Px); h) mafic horizons within the metasandstones, showing a foliation defined by glaucophane (Amp) + phengite (Phe) + quartz (Qz). Note chlorite (Chl) replacing Amp, and isolated Apatite (Ap) grains (SEM image; sample AC57).

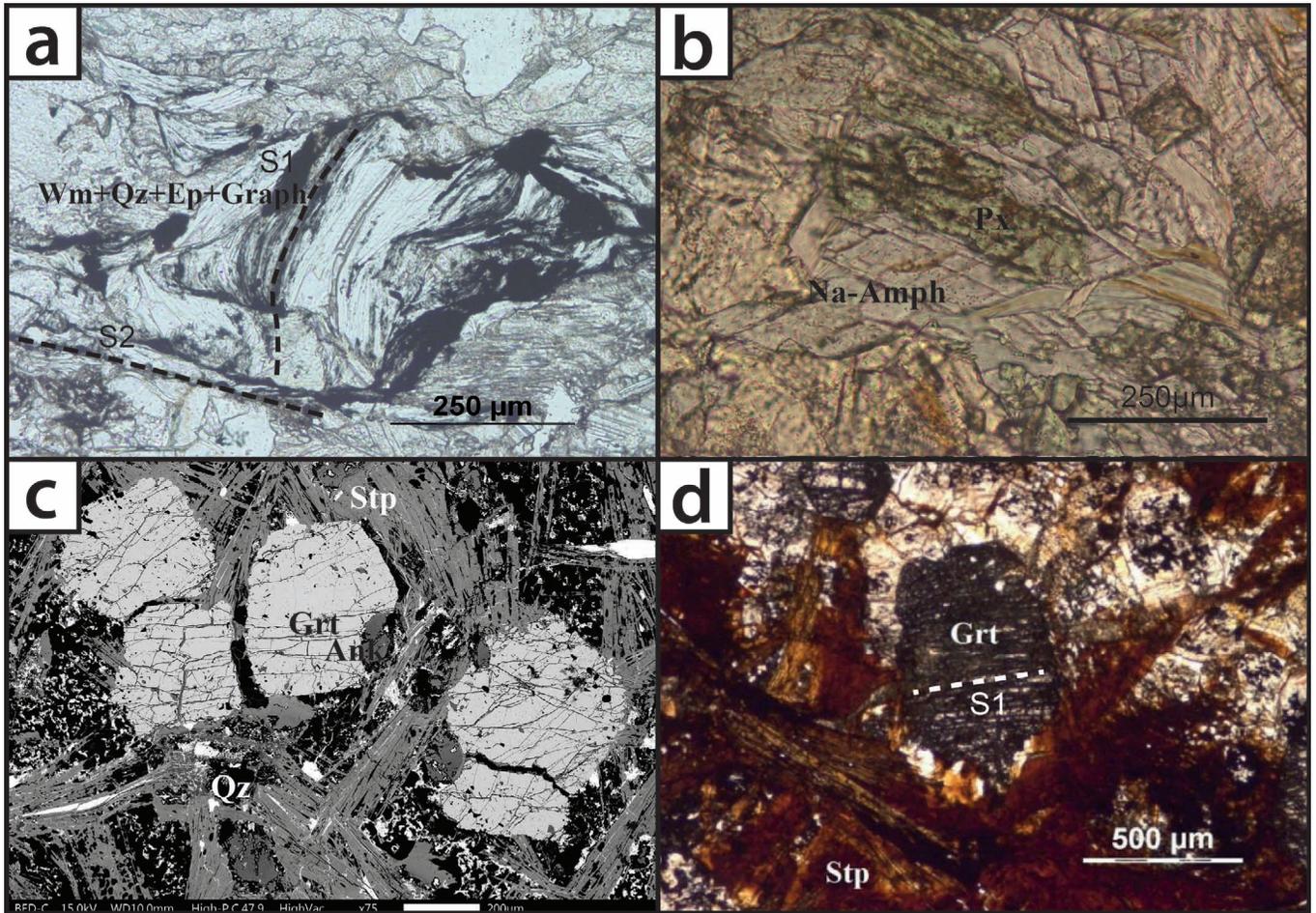


Fig. 5 - Representative microstructures. a) Pseudomorphs after lawsonite defined by white mica (Wm) + Quartz (Qz) + graphite (Graph) ± zoisite (Ep) relics of the S_1 foliation; b) Pyroxene-bearing metabasite embedded in the calcschists showing pyroxene of aegerine-augite composition partially replaced by Na-amphibole; c) spessartinic garnet (Grt) in the black schists; garnet is rimmed by ankerite rims (Ank) and wrapped by stilpnomelane (Stp) and quartz (Qz) (SEM image; sample AC15); d) spessartinic garnet (Grt) related to D_2 event in the black schists preserves an internal S_1 foliation defined by quartz and white mica (sample AC15). Late stilpnomelane is statically growing.

The recognition of pseudomorphs after lawsonite, observed as structural relic within the calcschists, constrains the burial path in the stability field of lawsonite bearing blueschist facies, characterized by low metamorphic gradient (Chen et al., 2013).

During the first tectono-metamorphic event D_1 , the metamorphic peak is defined by the omphacite + zoisite + glaucophane + rutile paragenesis developed in the basic system.

The occurrence of Na-amphibole in the metabasites implies P conditions lower than those of the amphibole vs chloritoid transition (Poli and Schmidt, 1995). Evidences of the HP metamorphism are also represented by the occurrence of the chloritoid + glaucophane assemblage in the metasediments.

The maximum extension of the stability field of the chloritoid-glaucophane association, calculated for the NKFMAH system (Proyer, 2003), partly overlaps with the lawsonite blueschist facies and is indicative of temperatures between 420 °C and 600 °C and pressures of ~1.9 GPa. The aforesaid stability field, however, can sensibly expand as a function of the increase of Fe^{3+} in these two minerals, up to partially overlap with the field of the epidote blueschist facies (Guiraud et al., 1990). The results of the analyses indicated a XFe^{3+} content ranging from 0.1 to 0.2 in chloritoid and 0.4-0.5 for amphibole, and then

a range of P-T conditions near the transition between the lawsonite - epidote blueschist facies can be inferred (Fig. 8). The P-T peak conditions can therefore be estimated at approximately 470-520 °C, at 1.7-1.9 GPa. These conditions are in agreement with the high Si content of phengite occurring in the mafic horizons in the metasediments ($Si \approx 3.50-3.75$ a.p.f.u., Fig. 6d) and in the levels of dark green schists within calcschists ($Si \approx 3.60-3.75$ a.p.f.u., Fig. 6d), that, according to phengite geobarometry of Massonne and Schreyer (1987), implies minimum P values of 1.7-1.9 GPa for T of around 500 °C.

The second metamorphic stage (D_2) is generally identifiable as the main tectonic-metamorphic event. The mineral assemblage (epidote, aegirine-augite, Na-Ca-amphibole and chlorite in metabasites) indicates that, according to Palin and White (2016), this second metamorphic stage developed under epidote-blueschist to epidote-amphibolite-facies transition. The occurrence of chlorite in the basic system points out that the upper limit of chlorite + quartz stability field calculated by Poli and Schmidt (1995) was not exceeded. These conditions are in agreement with the Si content (≤ 3.40 a.p.f.u.) of phengite growth in the metagabbros and in the metasediments (Fig. 6d), that, according to phengite geobarometry of Massonne and Schreyer (1987), implies minimum P values of 0.9-1.1 GPa

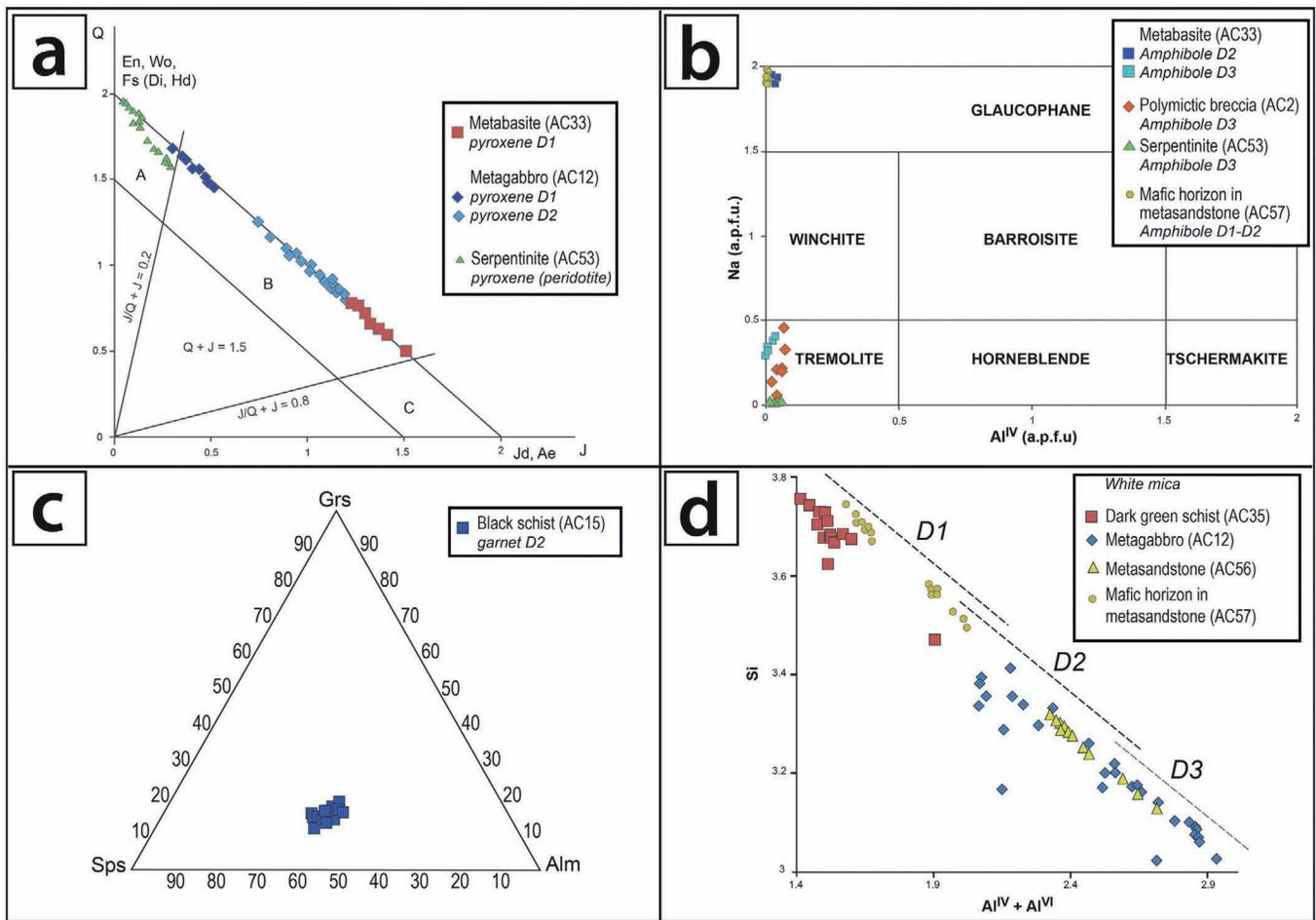


Fig. 6 - Chemical composition and classification diagrams. a) Morimoto (1988) pyroxene diagram A: Ca-Mg-Fe pyroxenes, B: Na-Ca pyroxenes, C: Na pyroxenes. En: enstatite, Wo: wollastonite, Fs: ferrosilite, Di: diopside, Hd: hedbergite, Jd: jadeite, Ae: aegerine-augite. b) Amphibole composition in the Hawthorne et al. (2012) diagram Na vs Al^{IV} . c) Garnet composition in almandine (Alm) - spessartine (Sps) - grossular (Grs) diagram. d) White mica composition in the Si vs $Al^{IV} + Al^{VI}$ diagram.

Note that the shifting shown in Fig. 6d by the analyses of white mica from different samples is due to the different content of iron present in the micas (see Table 3 of the supplementary material). In particular, the micas of mafic horizon are characterized by a lower iron content, while metagabbros and green schists show higher iron values. In these last micas a greater amount of trivalent iron replaced the octahedral aluminium, while in the micas of mafic horizon this substitution is found to be smaller.

for T around 500 °C. In addition, syn-cinematic D_2 garnet (characterized by high Mn content) suggests that the temperature reached during its growth has never exceeded 500 °C (Spear and Cheney, 1989).

The subsequent D_3 event is characterized by typical parageneses of the greenschist facies conditions. In the metagabbro, zoisite is replaced by clinozoisite and Ca-amphibole. Chlorite and albite pervasively grew after omphacite. In metabasite, Na-amphibole is replaced by Ca-amphibole (Fig. 6b) and albite, whereas garnet and rutile are replaced by chlorite and titanite, respectively. The white mica related to D_3 event is characterized by a low Si content (< 3.30 a.p.f.u.), Fig. 6d). The stilpnomelane + chlorite assemblage in metasandstones and black and dark green schists implies temperature lower than 400 °C.

REMARKS AND CONCLUSION

Data discussed in this paper allow i) to propose a detailed model for the depositional history of the oceanic segment of the Monte Banchetta-Punta Rognosa unit and ii) to trace its Alpine tectono-metamorphic evolution.

The presence of serpentinized peridotites covered at their top by ophiocarbonates generally records exhumation and exposure of the upper mantle at the seafloor in Jurassic times. Then, after discontinuous deposition of Middle-Late Jurassic radiolarian cherts (Caron 1971), the exposed mantle has been directly covered by the polymictic breccia (metabreccia) and intercalated siliciclastic sediments (metasandstones), both representing mass-flow deposits on sea floor and characterized by oceanic and continental clasts and blocks. The upper part of the sedimentary cover records the unconformable deposition of pelagic carbonate-rich sediments (calcschists), poor of oceanic and continental detritus. The largely accepted Cretaceous age for the calcschist deposition suggests to refer the underlying polymictic breccia and intercalated sandstones to the Late Jurassic - Early Cretaceous.

The polymictic breccia and intercalated sandstones indicate the close presence of structural highs made of oceanic and continental rocks in response to the Jurassic rifting (e.g. Beltrando et al., 2014). Source areas for serpentinite, ophiocarbonate and gabbro clasts (mainly prevailing in the lowermost stratigraphic parts) can be envisaged on a paleotopography of exhumed mantle, probably controlled by

		Pre-D1	D1	D2	D3+D4
Ultrabasic rocks	Pyroxene	Di	Aeg-aug	Aeg-aug	
	Serpentine				
	Amphibole				
	Chlorite				
	Magnetite		-----		
Ophicarbonate	Carbonate				
	Amphibole		-----	Act	Tr
	Chlorite				
Meta-gabbro	Pyroxene	Di?	Omp	Aeg-aug	
	Chlorite				
	Plagioclase				Ab
	Epidote				
	White mica			Phe	Ms
	Pumpellyite				
	Titanite				
Metabasite	Quartz				
	Amphibole			Gln	Tr
	Pyroxene		Aeg-aug		
	White mica			Phe	Ms
	Chlorite				
	Epidote		-----		
	Albite				
	Carbonate				
	Pumpellyite				
	Rutile				
Metasandstone	Quartz				
	White mica		-----	Phe	Ms
	Chlorite				
	Chloritoid				
	Stilpnomelane				
	Carbonate				
	Rutile				
	Amphibole		Gln	Gln	
Calcschist	Carbonate				
	Quartz				
	Chlorite				
	White mica				
	Graphite				
	Lawsonite		---		
	Epidote		-----		
Black and green schists	Quartz				
	White mica				
	Chlorite				
	Stilpnomelane				
	Garnet		-----		
	Amphibole		-----		
	Carbonate		-----		
	Ankerite		-----		

Fig. 7 - Mineral assemblages developed during the different deformation stages.

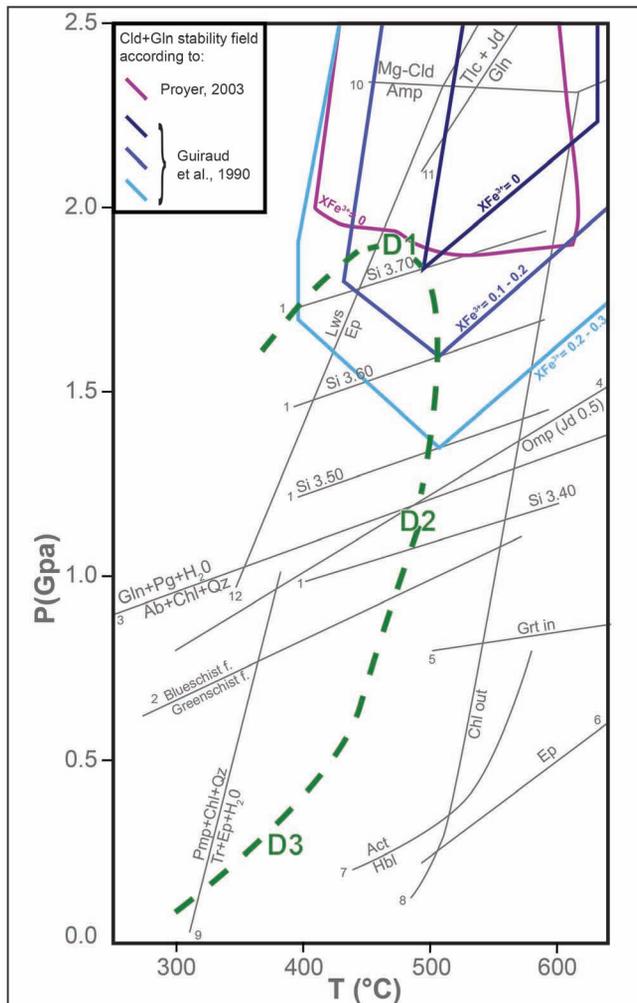


Fig. 8 - Petrogenetic grid. The dashed line shows average P-T conditions for the lawsonite-epidote blueschist peak (D₁), blueschist facies (D₂) and greenschist facies (D₃) metamorphic events, respectively. The garnet, chlorite, epidote and lawsonite stability curves (5, 6, 8, 10, 12) were taken from Poli and Schmidt (1995), the chloritoid-glaucophane stability fields from Guiraud et al. (1990), and Prayer (2003). Other curves: 1) isopleths of Si⁴⁺ content in phengite (Massonne and Schreyer, 1987); 2) transition of blueschist/greenschist facies (Maruyama et al., 1986); 3) Guiraud et al. (1990); 4) Holland (1983); 7) Ernst (1979); 9) Evans (1990); 11) Corona et al. (2013).

extensional faults. The continental detritus in the polymictic breccia, represented by platform deposits (dolostones and dolomitic breccias) usually considered Triassic-(Early Jurassic?) in age (e.g. Dal Piaz, 2010, and references therein) and pre-Triassic rocks (gneiss and micaschists), suggests that this oceanic segment was in a proximal position to the rifted European margin. In a general context of the ocean-continent transition, continental source areas can be envisaged on the hyperextended part of the European margin or on its more proximal part. The observed enrichment in Mn and Cr contents and widespread occurrence of Fe-oxides in these mass-flow deposits document presence of exposed mantle.

Close association of continental and oceanic detritus in the supra-ophiolite sedimentary cover were described in several oceanic sections in these regions of the Western Alps (e.g. Cabry et al., 1971; Lagabrielle, 1981; Lagabrielle et al., 1984; Polino and Lemoine, 1984; Balestro et al., 2015 and Tartarotti et al., 2017). In the investigated region, mixed

detritus typically characterizes the Jurassic-Cretaceous sediments of the Lago Nero unit (Polino and Lemoine, 1984; Servizio Geologico d'Italia, 2002 and *in press*), resting to the west of Monte Banchetta-Punta Rognosa unit in an upper structural position (Fig. 1b). On the basis of this stratigraphic feature, a proximal position with respect to the European margin has been usually proposed in literature for this unit. Therefore, according to this interpretation, the oceanic segments of the Lago Nero and Monte Banchetta-Punta Rognosa units could be tentatively restored in a similar place.

However, Burrioni et al. (2003) suggested that Late Cretaceous calc-schists (Gondran flysch) of the Lago Nero unit are covered by mass-gravity deposits (the Rocher Renard complex made up of dark schists with oceanic blocks). Due to this setting, Burrioni et al. (2003) proposed that the upper mass-gravity deposits derived from erosion of the accretionary wedge during converging processes and then, in an alternative view, placed the Lago Nero oceanic segment in an internal position of the Piemonte-Liguria realm. Therefore, taking into account this alternative interpretation, the Lago Nero unit and the Monte Banchetta-Punta Rognosa unit would identify two different oceanic segments, in internal and external (pericontinental) position respectively.

Petrological and minero-chemical analyses constrain a metamorphic peak (D₁) at the transition between lawsonite- and epidote- blueschist facies conditions, followed by a first decompressional event (D₂) always inside the blueschist facies conditions for the oceanic succession of the Monte Banchetta-Punta Rognosa unit. Then a third event (D₃) under green schist facies conditions occurred. Considering the limited reduction of temperature identified by the transition from D₁ to D₂, the trajectory of exhumation of the investigated succession seems to be characterized by a rather rapid exhumation.

As a general conclusion, this paper documented primary stratigraphic relationships, related and following the Jurassic rifting, in a poorly known unit highly deformed by tectono-metamorphic events. However, data presented must be considered as a starting point for further multidisciplinary studies, aimed in particular to give constrains to the Jurassic paleogeographic scenario of this sector of the Alps, still variously debated and interpreted in literature.

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