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## What's in the sandwich? New P-T constraints for the (U)HP nappe stack of southern Dora-Maira Massif (Western Alps)

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## European Journal of Mineralogy What's in the sandwich? New P-T constraints for the (U)HP nappe stack of southern Dora-Maira Massif (Western Alps) --Manuscript Draft--

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Abstract:	The Brossasco-Isasca Unit (BIU) of the southern Dora-Maira Massif (DMM), Western Alps, is one of the most studied ultra-high pressure (UHP) units in the world. However, the interpretation of UHP metamorphism in the BIU is still a highly debated and challenging issue. The structural and tectonometamorphic setting of the southern DMM is described in the literature as a tectonic "sandwich", with the UHP unit in the middle, bounded by two high-pressure (HP) eclogitic units in the footwall (the San Chiaffredo Unit, SCU) and hanging wall (the Rocca Solei Unit, RSU), respectively. These three units are in turn sandwiched between two blueschist-facies units (the Pinerolo Unit, PU, at the bottom, and the Dronero-Sampeyre Unit, DSU, at the top). In contrast to the well-constrained P-T evolution of the BIU, peak P-T conditions for its bounding HP units are poorly constrained, most studies dating back to over 20 years ago and mostly relying on conventional thermobarometric methods. This study aims to update our knowledge about the P-T evolution experienced by the whole tectonometamorphic package of the southern DMM. For the first time, peak P-T conditions and prograde evolution for the five units (PU, SCU, BIU, RSU, DSU) forming the southern DMM tectonic "sandwich" are estimated using the same, internally consistent and therefore comparable, modern thermobarometric approaches. The study focuses on metapelites (i.e., garnet-bearing phengitic micaschists) and combines multi-equilibrium thermobarometry (Average PT) with the P-T pseudosection approach. Our results demonstrate that most of the southern DMM nappe stack (i.e., SCU, RSU and also the PU, that was originally considered as a blueschist-facies unit) experienced eclogite-facies metamorphism under similar peak P-T conditions perfenced eclogite-facies metamorphism under similar to that of the other eclogitic units of the southern DMM nappe stack that did not experience eclogite-facies metamorphism (peak metamorphism ad later increase in temperature. The DSU is the only u

	continental units.
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#### 62 Abstract

The Brossasco-Isasca Unit (BIU) of the southern Dora-Maira Massif (DMM), Western Alps, is one of the most 63 64 studied ultra-high pressure (UHP) units in the world. However, the interpretation of UHP metamorphism in the BIU is still a highly debated and challenging issue. The structural and tectonometamorphic setting of the 65 southern DMM is described in the literature as a tectonic "sandwich", with the UHP unit in the middle, 66 67 bounded by two high-pressure (HP) eclogitic units in the footwall (the San Chiaffredo Unit, SCU) and hanging 68 wall (the Rocca Solei Unit, RSU), respectively. These three units are in turn sandwiched between two 69 blueschist-facies units (the Pinerolo Unit, PU, at the bottom, and the Dronero-Sampeyre Unit, DSU, at the 70 top). In contrast to the well-constrained P-T evolution of the BIU, peak P-T conditions for its bounding HP 71 units are poorly constrained, most studies dating back to over 20 years ago and mostly relying on 72 conventional thermobarometric methods. This study aims to update our knowledge about the P-T evolution 73 experienced by the whole tectonometamorphic package of the southern DMM. For the first time, peak P-T 74 conditions and prograde evolution for the five units (PU, SCU, BIU, RSU, DSU) forming the southern DMM 75 tectonic "sandwich" are estimated using the same, internally consistent and therefore comparable, modern 76 thermobarometric approaches. The study focuses on metapelites (*i.e.*, garnet-bearing phengitic micaschists) 77 and combines multi-equilibrium thermobarometry (Average PT) with the P-T pseudosection approach. Our 78 results demonstrate that most of the southern DMM nappe stack (i.e., SCU, RSU and also the PU, that was 79 originally considered as a blueschist-facies unit) experienced eclogite-facies metamorphism under similar 80 peak P-T conditions (500-520°C, 20-24 kbar), and followed the same prograde path, suggesting similar burial 81 mechanisms. The UHP BIU followed an early prograde evolution similar to that of the other eclogitic units of 82 the southern DMM tectonic "sandwich". The attainment of UHP peak conditions occurred through an earlier 83 steep, almost isothermal increase in pressure and a later increase in temperature. The DSU is the only unit 84 of the southern DMM nappe stack that did not experience eclogite-facies metamorphism (peak 85 metamorphism at blueschist-facies conditions: 450-470 °C, 17-18 kbar) and it is separated from the eclogitic 86 units by a shear zone (the Valmala Shear Zone), whose interpretation requires further studies. These new 87 data represent the inescapable starting point for any conceptual model aiming for a deeper understanding 88 of the subduction/exhumation processes of UHP continental units.

#### 90 Key-words

91 (U)HP metamorphism; southern Dora-Maira Massif; peak P-T conditions; prograde evolution; P-T

- 92 pseudosections
- 93

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#### 94 **1. Introduction**

95 The first discovery, more than 30 years ago, of coesite in continental crustal rocks (Chopin, 1984; Smith, 96 1984), demonstrated the possibility for continental crust to reach ultra-high pressure (UHP) conditions. 97 However, the geodynamic processes responsible for the formation and exhumation of continental UHP units 98 are still debated (e.g., Schenker et al., 2015; Reuber et al., 2016; Solarino et al., 2018). Conceptual and 99 numerical models that try to explain how a continental crustal unit can reach (and can be exhumed from) 100 UHP conditions are calibrated against geological and petrological data available from the tectonic nappe 101 stack which includes the UHP unit itself (e.g., Li et al., 2010; Burov et al., 2014; Schamalholz et al., 2014; 102 Gerya, 2015; Schenker et al., 2015). Precise knowledge of peak pressure and temperature (P-T) conditions 103 experienced by both the UHP unit and its adjacent, often high-P (HP) units is therefore the crucial starting 104 point to test the validity of the models (e.g., Manzotti et al., 2015, 2018).

105 The Brossasco-Isasca Unit (BIU) of the southern Dora-Maira Massif (DMM) in Western Alps, is one of 106 the most studied UHP units worldwide and has been widely used in the past as a natural laboratory to 107 discover new UHP minerals and to investigate metamorphic processes occurring during subduction at 108 extreme pressures (e.g., Chopin & Ferraris, 2003; Schertl & O'Brien, 2013 and references therein). The models 109 assuming subduction of continental crust to mantle depths (e.g., Chemenda et al., 1995; Chopin, 2003; 110 Stöckhert & Gerya, 2005; Gerya & Stöckhert, 2006; Yamato et al., 2008; Butler et al., 2013) were proposed after the discovery of coesite in the BIU. Decades later, the alternative idea of tectonic overpressure 111 112 explaining UHP tectonics arose again in the southern DMM (e.g., Ford et al., 2006; Schmalholz et al., 2014; 113 Schmalholz & Duretz, 2015; Schenker et al., 2015). More than 30 years after its discovery, the interpretation 114 of UHP metamorphism in the BIU still remains a challenge for many generations of geoscientists.

115 In the southern DMM, the UHP BIU is tectonically sandwiched between two quartz-eclogite facies 116 units, the lower San Chiaffredo Unit (SCU) and the upper Rocca Solei Unit (RSU), which are in turn bounded 117 by two blueschist-facies units, the Pinerolo Unit (PU) at the bottom and the Dronero-Sampeyre Unit (DSU) at the top of the tectonometamorphic package (Fig. 1). In contrast to the well-constrained P-T evolution of the 118 119 BIU (e.g., Ferrando et al., 2017 and references therein), peak P-T conditions for its adjacent Units are poorly 120 constrained, most studies dating back to over 20 years ago and mostly relying on conventional 121 thermobarometric methods (e.g., Chopin et al., 1991; Michard et al., 1993; Compagnoni et al., 1995). 122 Notably, many of these studies, which still represent milestones for all those interested in the interpretation 123 of the tectonometamorphic evolution and architecture of the southern DMM, were carried out by Christian 124 Chopin and co-workers. It is therefore a great pleasure for us to contribute to this Special Issue dedicated to 125 Christian Chopin, with the aim of updating his legacy, taking advantage of the modern petrological methods 126 and exploiting the great amount of data collected by our group over last decades.

127 With these premises in mind, this study constrains the prograde-to-peak evolution experienced by 128 the HP units bounding the UHP BIU. For the first time, peak P-T conditions for all five units (PU, SCU, BIU, 129 RSU, DSU) forming the southern DMM tectonic "sandwich" (Compagnoni & Rolfo, 2003) are estimated using 130 the same, internally consistent and therefore comparable, modern thermobarometric approaches. The study 131 focuses on metapelites (i.e., garnet-bearing phengitic micaschists) because they are widely exposed in all the 132 investigated units and preserve the (U)HP assemblages well. Thermobarometric estimates are obtained 133 combining multi-equilibrium thermobarometry (Average PT) and/or the P-T pseudosection approach applied to five samples (one for each unit). Concerning the HP units bounding the UHP BIU, our results confirm peak-134 135 T already known from the literature, but indicate systematically higher peak-P. The prograde path of the BIU 136 is also significantly revised, with possible implications for the interpretation of burial mechanisms in the 137 whole southern DMM tectonic "sandwich".

138 In our opinion, these new data represent the inescapable starting point for any model aimed at a 139 deeper understanding of the processes responsible for the attainment and preservation of UHP conditions in continental crust; however, further studies are needed in order to understand if (and how) the studied
 units shared part of their prograde evolution at HP to UHP conditions or if (and how) they were coupled
 during exhumation.

143

## 144 **2. Geological setting**

145 The Dora-Maira Massif (DMM) in the Western Alps, represents part of the subducted-exhumed European continental margin (e.g., Michard et al., 1996). It is now stacked in the Alpine orogenic wedge (Lardeaux et 146 147 al., 2006), wherein it was overthrust by meta-ophiolite units of the Piedmont Zone (Balestro et al., 2018, and 148 references therein). The southern portion of the DMM is a pile of imbricated thrust sheets, resulting from 149 Alpine tectonic juxtaposition and metamorphic reworking of slices of Variscan continental crust and of Permian igneous bodies (e.g., Vialon, 1966; Henry, 1990; Chopin et al., 1991; Michard et al., 1993, 1995; 150 151 Turello, 1993; Sandrone et al., 1993; Balestro et al., 1995; Compagnoni et al., 1995, 2012; Compagnoni & 152 Rolfo, 1999, 2003; Groppo, 2002; Compagnoni et al., 2004, 2012; Botta, 2015; Nosenzo, 2018). Relics of both 153 amphibolite-facies Variscan metamorphism and Permian contact metamorphism are locally still preserved 154 (e.g., Biino & Compagnoni, 1992; Compagnoni et al., 1995; Compagnoni & Rolfo, 2003; Groppo et al., 2006, 155 2007b).

156 In the area between the Po Valley to the north and the Maira Valley to the south, the following 157 tectonometamorphic units are distinguished from the lower to the upper structural position (Fig. 1): (i) the 158 Pinerolo Unit (PU) is a monometamorphic unit that experienced Alpine epidote-blueschist facies 159 metamorphism (e.g., Chopin et al., 1991; Avigad et al., 2003); (ii) the San Chiaffredo Unit (SCU) is a portion 160 of pre-Alpine continental crust (Variscan amphibolite-facies basement intruded by Permian granitoids) that 161 reached quartz-eclogite facies peak during Alpine metamorphism (Compagnoni & Rolfo, 2003); (iii) the 162 Brossasco-Isasca Unit (BIU) is lithologically similar to the SCU but experienced Alpine peak P-T conditions in 163 the coesite-eclogite facies (diamond stability field; e.g., Schertl et al., 1991; Nowlan et al., 2000; Rubatto & Hermann, 2001; Hermann, 2003; Ferraris et al., 2005; Di Vincenzo et al., 2006; Castelli et al., 2007; Groppo 164 165 et al., 2007a; Ferrando et al., 2009; Gauthiez-Putallaz et al., 2016); (iv) the Rocca Solei Unit, lithologically similar to the BIU and the SCU, experienced Alpine peak P-T conditions at quartz-eclogite facies conditions 166 167 (Chopin et al., 1991; Matsumoto & Hirajima, 2000); (v) the Dronero-Sampeyre Unit (DSU) includes 168 polymetamorphic schists (Henry, 1990; Chopin et al., 1991) and a monometamorphic Permian volcano-169 detrital sequence (Vialon, 1966; Chopin et al., 1991; Michard et al., 1995), both of which experienced Alpine 170 peak P-T conditions at epidote-blueschist facies (Chopin et al., 1991). The DSU is separated from the 171 structurally underlying RSU by a shear zone, hundreds of metres thick, consisting of the tectonic juxtaposition 172 of meta-ophiolite and metasediment slices (Valmala Shear Zone; *i.e.*, the "ophiolitiferous band" of Henry et 173 al., 1993). The term "tectonic sandwich" is hereafter used to indicate the whole package of juxtaposed 174 tectonometamorphic units of southern DMM described above. All these units have been overprinted by a 175 late-Alpine greenschist-facies recrystallization, which pervasively reworked and extensively obliterated the 176 former (U)HP metamorphic mineral assemblages.

177

Sample locations are reported in Fig. 1 and additional details are given in the Supplementary material.

178

## 179 **3. Methods**

## 180 **3.1 Micro-X-ray fluorescence (μ-XRF) maps**

181 Qualitative major element X–ray maps of the entire thin sections were acquired using a micro-XRF Eagle III–

182 XPL spectrometer equipped with an EDS Si(Li) detector and with an EdaxVision32 microanalytical system at

- the Department of Earth Sciences, University of Torino. Operating conditions were: 100 ms counting time,
- 40 kV accelerating voltage, and a probe current of 900  $\mu$ A. A spatial resolution of about 65  $\mu$ m in both x and

y directions was used. Quantitative modal amounts of each mineral phase were obtained by processing the
 maps with the software Petromod (Cossio *et al.,* 2002). For each sample, the processed X–ray maps are
 reported in Fig. 2. Additional microstructural details, at greater magnification, are given in Figs. 3-5. Mineral
 abbreviations are after Whitney & Evans (2010), except white mica (Wm) and phengite (Phe).

189

### 190 **3.2 Mineral chemistry**

The rock-forming minerals were analyzed with a Jeol JSMIT300LV Scanning Electron Microscope at the Department of Earth Sciences, University of Torino. The instrument was equipped with an energy dispersive spectrometry (EDS) Energy 200 system and an SDD X-Act3 detector (Oxford Inca Energy). Operating conditions were: 50 s counting time, 15 kV accelerating voltage, spot size 2 μm. SEM-EDS quantitative data were acquired and processed using the Microanalysis Suite Issue 12, INCA Suite version 4.01; natural mineral

- standards were used to calibrate the raw data; the φpZ correction (Pouchou & Pichoir, 1988) was applied. Tables SM1 and SM2-SM6, freely available online as Supplementary Material linked to this article on the GSW website of the journal, https://pubs.geoscienceworld.org/eurjmin/, summarize the compositional variations (Table SM1) and the representative chemical compositions for the main minerals in each sample; Figs. 6-7 and SM1 show the composition of garnet and phengite. For practical purposes, the term phengite is used in the following to indicate phengitic white mica with Si > 3.20 a.p.f.u. (on the basis of 11 oxygens), whereas
- 202 muscovite is used for phengitic white mica with Si < 3.20 a.p.f.u.
- 203

## 204 3.3 Pseudosection modelling

The pseudosection modeling approach was applied to each metapelite sample, excluding DM1565. Bulk-rock composition of each sample (Table 1) was calculated by combining estimated mineral modes with mineral chemistry (see above). Determination of an effective bulk composition for sample DM1565 (DSU) was problematic because: (i) the fine-grained nature of Alpine Grt<sub>2</sub> hampered its correct quantification from micro-XRF maps; (ii) the presence of pre-Alpine garnet porphyroblasts (Grt<sub>1</sub>), that should be subtracted from the bulk-composition effectively reacting during Alpine metamorphism, makes the conventional bulk-rock analysis (*e.g.*, XRF or ICP-MS) not suitable.

For each considered sample, three P-T isochemical phase diagrams have been calculated (*i.e.*, a total of 12 pseudosections) considering the fractionation effects on the bulk-composition due to the growth of zoned garnet porphyroblasts. Each pseudosection was used to model: (i) P-T conditions for garnet core growth (measured bulk-composition: MBC), (ii) P-T conditions for garnet mantle growth (MBC minus garnet cores), and (iii) P-T conditions for garnet rim growth (MBC minus garnet cores + mantles) (Table 1).

217 The P-T isochemical phase diagrams were calculated in the system MnNKCFMASTOH (MnO-Na<sub>2</sub>O- $K_2O$ -CaO-FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O), except for sample DM1281 (BIU), for which Fe<sup>3+</sup> was 218 neglected, because  $Fe^{3+}$ -rich oxides are absent and the amount of  $Fe^{3+}$  in the analyzed minerals is very low. 219 220 The pseudosections were calculated using Perplex 6.8.1 (version March 2018; Connolly, 1990, 2005, 2009), 221 the internally consistent thermodynamic dataset of Holland & Powell (2011) (ds62) and the equation of state 222 for H<sub>2</sub>O of Holland & Powell (1998). The following solution models were used: garnet, chlorite, chloritoid, 223 staurolite, white mica, biotite and ilmenite (White et al., 2014), omphacite (Green et al., 2007), amphibole 224 (Green et al., 2016), carpholite (Smye et al., 2010), feldspar (Fuhrman & Lindsley, 1988) and epidote (Holland 225 & Powell, 2011). Quartz, lawsonite, kyanite, rutile and titanite were considered as pure phases. The fluid was 226 usually considered as pure H<sub>2</sub>O (aH<sub>2</sub>O=1), but a reduced aH<sub>2</sub>O=0.4 was considered in the pseudosection that 227 models the garnet rim growth in DM1281 (BIU) because experimental and fluid inclusions studies (Sharp et 228 al., 1993; Hermann, 2003; Ferrando et al., 2009) demonstrated that, at the UHP peak, the activity of H<sub>2</sub>O was 229 strongly reduced by the abundance of dissolved species.

230

## 231 **3.4 Optimal thermobarometry**

The THERMOCALC "Average PT" (AvPT) method (*i.e.*, "Optimal thermobarometry": Powell & Holland, 1994) was applied to all the samples. THERMOCALC v3.40 and the Holland & Powell (2011) dataset (ds62) were used. Activity-composition relationships were calculated using the software AX. The method was applied to the peak assemblage for all the samples, except sample DM1281 (BIU), for which it was applied to the late prograde assemblage (see Section 4.3). Used sets of mineral compositions and of independent reactions are given in Tables SM2-SM7. AvPT results are discussed in terms of weighted means (*i.e.*, values with smaller errors contribute more than values with larger errors) and are presented in Table 2.

239

## 240 **4. Petrography and mineral chemistry**

## 241 4.1 Sample DM 1485 (PU)

This medium- to coarse-grained micaschist consists of white mica (mostly phengite; 42%), garnet (20%), chlorite (19%), quartz (13%) and minor chloritoid (2%) (Fig. 2). Retrograde chlorite, plagioclase (3%) and minor biotite, as well as accessory magnetite, rutile and ilmenite also occur. The main foliation (S<sub>m</sub>) is defined by preferred orientation of phengite and chlorite, that form continuous pluri-mm -thick layers alternated with discontinuous pluri-mm -thick quartzitic layers (Fig. 2). An earlier schistosity (S<sub>m-1</sub>), defined by the preferred orientation of white mica and chlorite, is still preserved in microlithons.

Garnet porphyroblasts, up to several millimetres in size, are syn-kinematic with respect to S<sub>m</sub> and show a snow-ball structure (Fig. 3a); the rotated internal foliation, continuous with the external S<sub>m</sub>, is defined by inclusions of quartz, relict chloritoid, and minor white mica and chlorite (Fig. 3b). Quartz, phengite and chlorite occur in the pressure shadows of garnet. Garnet porphyroblasts are strongly zoned (Fig. 6a and Table SM1), with a reddish core and a pinkish rim.

Phengite defines the  $S_m$  and rarely occurs, in association with paragonite and relict chloritoid, in 253 254 polymineralic inclusions within garnet core and mantle (Fig. 3b). A few retrograde muscovite flakes occur in 255 matrix and in polymineralic inclusions within garnet. Paragonite is only observed in polymineralic inclusions 256 in garnet, always associated with (or replacing) chloritoid; its prograde vs. retrograde nature is ambiguous. 257 Bluish-greenish chloritoid is only preserved as inclusions in garnet porphyroblasts (Fig. 3a,b), but not in the 258 matrix. Its composition changes according to the microstructural position within garnet (Table SM1). Chlorite 259 is mostly in equilibrium with S<sub>m</sub>, but a late chlorite generation replaces garnet along fractures. Chlorite rim is 260 locally partially replaced by fine-grained biotite. Plagioclase (albite to oligoclase) occurs as large (pluri-mm) 261 blasts overgrowing the S<sub>m</sub> and it is thus interpreted as a retrograde phase.

Among the accessories, retrograde mm-sized magnetite exclusively occurs in the matrix (Fig. 2). Rutile and ilmenite within garnet core, mantle and rim appear in equilibrium, whereas in the matrix rutile is rimmed by ilmenite.

265

## 266 **4.2 Sample DM1667c (SCU)**

This garnet-bearing phengitic micaschist has a strongly heterogeneous grain size. It shows a mm-thick banded structure, with continuous medium- to coarse-grained phengite-rich layers alternating with fine- to mediumgrained discontinuous quartz-rich layers (Fig. 2). It consists of white mica (mostly phengite: 42%), garnet (30%), quartz (18%) and minor chloritoid (1%). Retrograde chlorite (7%), epidote (1%), minor biotite, and accessory magnetite, rutile, ilmenite, tourmaline and apatite also occur. The main foliation (S<sub>m</sub>) is defined by the preferred orientation of white mica.

273 Garnet porphyroblasts are centimetres to pluri-cm in size in the coarse-grained layers, and 274 millimetres to pluri-mm in the finer-grained layers (Fig. 2). Garnet is pre- to syn-kinematic with respect to the 275  $S_m$ , being mostly enveloped by the main schistosity, but with the rim that appears in equilibrium with it. 276 Garnet porphyroblasts are microstructurally and chemically zoned (Fig. 6b). Garnet core and mantle are large, 277 often asymmetric, and crowded with inclusions, whereas rim is thin and with few inclusions. Fine-grained 278 inclusions in garnet core consist of epidote (Fig. 3d), chlorite and chloritoid; inclusions in garnet mantle are 279 medium-grained and mostly consist of chloritoid (Fig. 3c) and white mica. Garnet rim includes few phengite 280 flakes and box-shaped pseudomorphs after former lawsonite, consisting of a fine-grained aggregate of 281 epidote, muscovite, paragonite and chlorite (Fig. 3e). A thin (100-300  $\mu$ m) and discontinuous outer rim 282 slightly enriched in Mn has been interpreted as due to local retrograde re-equilibration.

Phengite defines the S<sub>m</sub> and is locally included in garnet. Less abundant retrograde muscovite overgrows the main foliation and replaces chloritoid inclusions within garnet. Paragonite only occurs as inclusion in garnet, associated with (or replacing) chloritoid, and as pseudomorphs after probable lawsonite; therefore, it has been interpreted as both prograde and retrograde phase. Chloritoid is mostly included in garnet mantle (Fig. 3c), rarely in core and rim, and it is absent from the matrix. It is locally partially to completely replaced by an aggregate of white mica (muscovite ± phengite + paragonite) (Fig. 3c).

Epidote and chlorite occur in two different generations. Prograde epidote (often with an allanitic core) and chlorite are included in garnet core and mantle (Fig. 3d). Retrograde epidote occurs as few finegrained idioblasts in matrix and in pseudomorphs after lawsonite included in garnet rim, whereas late chlorite mostly replaces garnet porphyroblasts along fractures and rims. Late biotite partially replaces white mica and chlorite at their rims.

Among accessories, mm-sized retrograde magnetite only occurs in the matrix. Rutile and ilmenite occur as inclusions within garnet porphyroblasts; in the matrix rutile is rimmed by ilmenite. Apatite and tourmaline are included in garnet.

#### 297

#### 298 4.3 Sample DM1281 (BIU)

This sample consists of white mica (mostly phengite, 41%), quartz (24%), garnet (21%), kyanite (10%), jadeite (3%) and minor chloritoid, staurolite and chlorite (Fig. 2). Albite and pyrophyllite are retrograde phases, whereas rutile, tourmaline and apatite are the main accessory minerals. The grain size is markedly heterogeneous, with pluri-mm garnet and kyanite porphyroblasts set in a fine-grained matrix mostly consisting of phengite and quartz (Fig. 2). The main schistosity (S<sub>m</sub>) is defined by mm-thick, continuous phengitic layers, alternating with discontinuous quartzitic layers of similar thickness.

305 Garnet porphyroblasts are microstructurally and chemically zoned (Fig. 6c). Garnet core and mantle 306 are large, often asymmetric, and crowded with inclusions, whereas rim is thin and with few inclusions (Fig. 307 4a). Garnet rim appears in equilibrium with S<sub>m</sub>. Inclusions in garnet core are fine-grained and polymineralic; 308 garnet mantle includes both fine-grained polymineralic inclusions and medium-grained monocrystalline 309 inclusions; garnet rim contains few medium-grained monocrystalline inclusions. Polymineralic inclusions in 310 garnet core mostly consist of chloritoid, paragonite, chlorite, staurolite and rare muscovite, whereas those 311 observed in garnet mantle contain also kyanite and does not contain potassic white mica (Fig. 4d,e). Monocrystalline inclusions in garnet mantle are represented by pseudomorphs after jadeite and glaucophane 312 313 (Fig. 4f, g), kyanite and quartz, whereas those in garnet rim consist of kyanite, phengite and quartz. 314 Polycrystalline aggregates of quartz surrounded by radial cracks, interpreted as deriving from inversion of 315 coesite, are located at the transition between garnet mantle and rim (Fig. 4a).

Phengite defines the S<sub>m</sub> and is locally included in garnet rim. Retrograde muscovite is scarce and its occurrence is limited to the pseudomorphs after jadeite and glaucophane. A few prograde muscovite flakes are preserved in the polymineralic inclusions within garnet core. Paragonite is common in the polymineralic inclusions hosted within garnet core and mantle (Fig. 4e), where it probably has a prograde nature. 320 At least three different generations of kyanite have been recognized: i) large (pluri-mm) porphyroblasts enveloped by the main foliation (Fig. 4b); ii) smaller idioblasts in equilibrium with the S<sub>m</sub> (Fig. 321 322 4b); iii) local very fine-grained acicular crystals rimming the large kyanite porphyroblasts. Jadeite and 323 glaucophane are not preserved, but are pseudomorphically replaced by retrograde phases. Pseudomorphs 324 after jadeite, occurring both in the matrix (Fig. 4c) and as inclusion in garnet mantle (Fig. 4g), consist of a very 325 fine-grained aggregate of albite + pyrophyllite + muscovite. Lozenge-shaped pseudomorphs after 326 glaucophane have been observed only as inclusions in garnet mantle (Fig. 4f) and consist of a very fine-327 grained aggregate of paragonite + muscovite + minor biotite.

Chloritoid, chlorite and staurolite only occur in the fine-grained polymineralic inclusions within garnet core and mantle (Fig. 4d,e). Chlorite is a prograde phase and the X<sub>Mg</sub> of the chlorite included in garnet mantle is higher than that of the chlorite included in garnet core (Table SM1). Chloritoid is generally associated with paragonite and chlorite. Staurolite is only present as inclusion in both garnet core and mantle, where it mostly occurs in association with kyanite, paragonite and chlorite, more rarely with chloritoid. Microstructural relationships clearly show that staurolite grew at the expense of kyanite, often preserved as rounded relics partially rimmed by staurolite (Fig. 4e).

335

Accessory rutile, tourmaline and apatite occur in the matrix and as inclusion in garnet

#### 336

#### 337 4.4 Sample DM1504 (RSU)

This fine- to coarse-grained, garnet-bearing phengitic micaschist consists of white mica (mostly phengite, 49 % and paragonite, 6%), quartz (20%), chloritoid (12%) and garnet (8%) (Fig. 2), with minor amounts of glaucophane and jadeite (almost completely replaced by retrograde phases). Retrograde chlorite (3%), epidote (1%) and biotite, and accessory rutile, ilmenite, magnetite and apatite also occur. The main foliation (S<sub>m</sub>) is defined by mm- to pluri-mm -thick, continuous, micaceous layers alternated with mm-thick, discontinuous, quartzitic layers. Relics of an earlier S<sub>m-1</sub> schistosity are locally preserved in microlithons and are defined by the alignment of white mica.

345 Mm- to pluri-mm -sized garnet porphyroblasts are partially enveloped by the S<sub>m</sub>, but their rim 346 appears in equilibrium with  $S_m$  (*i.e.*, garnet is pre- to syn-kinematic with respect to  $S_m$ ). They include an 347 internal rotated foliation mostly defined by quartz and chloritoid. Garnet core and mantle are large and rich 348 of inclusions, whereas garnet rim is thin and with few inclusions (Fig. 5a-c). Inclusions in garnet are either 349 polymineralic or monocrystalline. Polymineralic inclusions mostly consist of chloritoid + white micas 350 (phengite ± paragonite ± muscovite) (Fig. 5b). Relics of glaucophane + jadeite, partially replaced by paragonite 351 + albite ± muscovite, have been observed at the transition between garnet mantle and garnet rim (Fig. 5b). 352 Garnet core and mantle locally include tabular-shaped aggregates of epidote + quartz + paragonite or 353 phengite (Fig. 5c), possibly representing pseudomorphs after former lawsonite. Monocrystalline inclusions 354 mostly consist of quartz, chloritoid and minor phengite.

Phengite defines the S<sub>m</sub> and is locally included in garnet and chloritoid. Retrograde paragonite and muscovite occur both in the matrix and as inclusions in garnet. In the matrix, paragonite forms large flakes statically overgrowing the S<sub>m</sub> (Fig. 2). When included in garnet, paragonite and muscovite generally replace other phases, such as glaucophane, jadeite or chloritoid. Chloritoid occurs both in the matrix and as inclusion in garnet (Fig. 5a). In the matrix, it forms medium-grained bluish-greenish nematoblasts aligned with the S<sub>m</sub> and it is slightly zoned. Rare glaucophane and jadeite relics are included in garnet mantle/rim (Fig. 5b).

Epidote, chlorite, albite and biotite are retrograde phases. Epidote within garnet occurs in tabularshaped aggregates, in association with quartz and white micas, interpreted as deriving from former lawsonite (Fig. 5c). In the matrix, it forms few fine-grained idioblasts, often with an allanitic core. Aggregates of chlorite statically overgrows the S<sub>m</sub> and replaces garnet along fractures and at the rim. Its rim is locally replaced by biotite. Albite occurs as replacement of jadeite and glaucophane. Rutile mostly occurs as inclusion in garnet, whereas it is pervasively replaced by ilmenite in the matrix. Retrograde magnetite is fine-grained and widespread in the matrix, and it is strongly oxidized. Apatite occurs as relatively large grains both in the matrix and included in garnet.

## 370 **4.5 Sample DM1565 (DSU)**

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This garnet-bearing phengitic micaschist consists of white mica (mostly phengite, 54% and paragonite, 8%), quartz (26%), garnet (5%) and chloritoid (3%) (Fig. 2). Retrograde chlorite (3%) and biotite and accessory rutile, ilmenite and tourmaline also occur. The main schistosity (S<sub>m</sub>) is defined by pluri-mm thick, continuous, micaceous layers alternating with mm-thick quartzitic layers. Large (pluri-mm) garnet porphyroblasts are preferentially set in the fine-grained micaceous layers (Fig. 2).

376 In contrast to the other samples, this metapelite preserves mineralogical evidence of a 377 polymetamorphic evolution. Two different garnet generations can be, in fact, recognized: (i) large 378 porphyroblasts (Fig. 5d) enveloped by the S<sub>m</sub>, interpreted as amphibolite-facies Variscan garnets (Grt<sub>1</sub>); (ii) small (ca. 100  $\mu$ m) idioblasts in equilibrium with S<sub>m</sub> and a thin and discontinuous corona around 379 380 porphyroblastic  $Grt_1$  (Fig. 5e), both interpreted as Alpine garnets ( $Grt_2$ ). The strongly-fractured  $Grt_1$  is 381 chemically zoned (Table SM1). Locally it is poikiloblastic and includes quartz, white mica, ilmenite and minor 382 staurolite, now replaced by fine-grained pseudomorphic aggregates of white mica + chloritoid. The small Grt<sub>2</sub> 383 idioblasts are also zoned and include very fine-grained quartz (Fig. 6e and Table SM1).

Phengite defines the S<sub>m</sub> and it also occurs at the rim of the chloritoid-bearing pseudomorphs after former staurolite. Minor retrograde muscovite and paragonite occur in the matrix. Chloritoid mostly constitutes large (pluri-mm) fine-grained aggregates enveloped by the S<sub>m</sub> and interpreted as pseudomorphs after pre-Alpine porphyroblastic staurolite (Fig. 5f) (see also Henry, 1990; Chopin *et al.*, 1991). These pseudomorphs also contain white mica (phengite + muscovite + paragonite), generally concentrated toward the rim. Chloritoid also forms minor idioblasts aligned with the S<sub>m</sub> or partially overgrowing it.

Retrograde chlorite occurs as large flakes statically overgrowing the S<sub>m</sub> and partially replacing garnet at the rim and along fractures. Biotite is limited to late and discontinuous shear bands crosscutting the main foliation. Accessory ilmenite is included in pre-Alpine garnet (Grt<sub>1</sub>) and is rimmed by rutile, if it communicates with the external matrix through fractures. In the matrix, rutile is rimmed by ilmenite.

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#### 395 5. Resulting P-T evolution

396 The prograde-to-peak P-T evolution of the PU, SCU, BIU and RSU samples was constrained using the 397 pseudosection approach and on the basis of the predicted stability fields of the observed mineral 398 assemblages, combined with garnet, chloritoid and phengite compositional isopleths. The results of 399 thermodynamic modelling show that the fractionation effects on the bulk-composition due to the growth of 400 zoned garnet porphyroblasts are generally minor during the initial growth of garnet (i.e., after the 401 fractionation of garnet core). However, they become significant after the fractionation of both garnet core 402 and mantle. The general topology of the calculated pseudosections for all samples is similar as far as the 403 relationships between the main phases of interest is concerned, and is in line with previous studies related 404 on phase equilibria modeling in the same system (e.g., Guiraud et al., 1990; Proyer, 2003; Wei & Powell, 405 2004, 2006; Smye et al., 2010; Manzotti et al., 2015): (i) garnet is always stable over a large range of P-T 406 conditions, whereas chlorite is limited to P <18-25 kbar; (ii) chloritoid is stable at T<550-600°C, and kyanite is 407 instead stable at increasing temperature (see Smye et al., 2010); (iii) paragonite, glaucophane and jadeite 408 represent the Na-rich phases stable at lower, intermediate and higher pressure, respectively.

The Average PT approach of THERMOCALC was further applied to peak assemblages for the PU, SCU, RSU and DSU samples and to the late prograde assemblage for the BIU sample. In the following, the results of both approaches are summarized.

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## 413 **5.1 Sample DM1485 (PU)**

The observed prograde and peak assemblage (Qz + Phe + Grt + Chl + Cld + Rt + Ilm) is not modeled in the P-T region of interest because chloritoid is always predicted to be stable with a Na-rich phase (either paragonite or glaucophane), which was not observed in the studied sample. However, the occurrence of large oligoclase porphyroblasts in the matrix statically overgrowing the main foliation suggests that one or more Na-rich phases (e.g. glaucophane, paragonite) was likely stable in the prograde and peak assemblages and it is not preserved. The glaucophane/paragonite-bearing assemblage (Qz + Phe + Grt + Chl + Cld + Gln/Pg + Rt + Ilm) is modeled in a wide range of P-T conditions (450-570°C, 10-25 kbar) (Fig. 8).

421 Prograde and peak P-T conditions are more tightly constrained by the intersection of compositional 422 isopleths. Specifically: (i) early prograde P-T conditions are constrained at 480-495°C, 19-21 kbar using 423 compositions of garnet core ( $Sp_5Prp_6Grs_8Alm_{80}$ ) and of its inclusions of chloritoid ( $X_{Mg}$ =0.11) and phengite 424 (Si=3.48 a.p.f.u.) (Fig. 8a); (ii) late prograde P-T conditions are constrained at 490-505°C, 20-22 kbar using the 425 compositions of garnet mantle (Sps<sub>2.5</sub>Prp<sub>8</sub>Grs<sub>7.5</sub>Alm<sub>81</sub>) and of its inclusions of chloritoid (X<sub>Mg</sub>=0.15) and 426 phengite (Si=3.44-3.45 a.p.f.u.) (Fig. 8b); (iii) peak P-T conditions are estimated at 500-515°C, 20-23 kbar using 427 the compositions of garnet rim  $(Sps_{0.5}Prp_{11}Grs_{11}Alm_{78})$ , of its chloritoid inclusions  $(X_{Mg}=0.18)$  and of matrix 428 phengite (Si=3.38-3.51 a.p.f.u.) (Fig. 8c).

429 The AvPT approach applied to four different sets of mineral compositions gives peak P-T conditions 430 of 496  $\pm$  7 °C, 19.0  $\pm$  0.7 kbar (Table 2), consistent with the results of pseudosection modeling (Fig. 8c).

## 432 5.2 Sample DM1667c (SCU)

433 Although glaucophane was not observed in prograde and peak assemblages, the modeled pseudosections 434 predict its stability over a large P-T interval. However, the predicted modal amount of glaucophane is so low 435 (< 5 vol%) that its (former) occurrence could likely have been overlooked. Ignoring glaucophane, the observed 436 early prograde (Qz + Phe + Grt<sub>c</sub> + Chl + Cld + Ep + Rt + Ilm) and late prograde (Qz + Phe + Grt<sub>M</sub> + Cld  $\pm$  Chl  $\pm$ 437 Ep/Lws + Rt + IIm) assemblages are modeled by large tri- and quadri-variant fields at 420-500°C, 12-17 kbar 438 and 400-500°C, 14-25 kbar, respectively (Fig. 9). Garnet, chloritoid and phengite compositional isopleths 439 allow to further constrain the prograde P-T conditions: (i) early prograde conditions are constrained at 460-440 470°C, 17-19 kbar using the compositions of garnet core (Sps<sub>5</sub>Prp<sub>3.5</sub>Grs<sub>26</sub>Alm<sub>65</sub>) and its inclusions of phengite (Si=3.34-3.46 a.p.f.u.) (Fig. 9a); (ii) late prograde P-T conditions are constrained at 480-490°C, 19-21 kbar 441 442 using the compositions of garnet mantle (Sps<sub>2.5</sub>Prp<sub>5</sub>Grs<sub>24</sub>Alm<sub>68</sub>) and of its inclusions of chloritoid (X<sub>Mg</sub>=0.20) 443 and phengite (Si=3.40-3.49 a.p.f.u.) (Fig. 9b). Although garnet core includes epidote, its growth is predicted 444 to occur within the lawsonite stability field, but close to the Ep-out boundary.

The observed peak assemblage (Qz + Phe + Grt<sub>R</sub> + Cld + Lws + Rt + Ilm) is modeled by a relatively small quadri-variant field at 450-520°, 22-27 kbar. The intersection of compositional isopleths for garnet rim (Sps<sub>0.8</sub>Prp<sub>10</sub>Grs<sub>18</sub>Alm<sub>74</sub>) and its inclusions of chloritoid (X<sub>Mg</sub>=0.20) and phengite (Si=3.36-3.43 a.p.f.u.) defines peak P-T conditions at 500-520°C, 21-24 kbar (Fig. 9c). The AvPT approach applied to four different sets of mineral compositions gives peak P-T conditions of 512 ± 8 °C, 21.9 ± 0.9 kbar (Table 2), consistent with the results of pseudosection modeling (Fig. 9c).

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## 452 5.3 Sample DM1281 (BIU)

Garnet core and its inclusions define the early prograde assemblage ( $Qz + Phe + Grt_c + Cld + Pg + Chl + Rt$ ). 453 Staurolite is not considered as part of this assemblage due to its supposed retrograde nature (see 454 455 microstructural relationships presented in Section 4.3). This assemblage is modeled by a quadri-variant field at 450-570°C, 10-18 kbar. The best fit between observed and modeled garnet (Sps<sub>6.5</sub>Prp<sub>12</sub>Grs<sub>6</sub>Alm<sub>74</sub>), 456 chloritoid (X<sub>Mg</sub>=0.25) and chlorite (X<sub>Mg</sub>=0.62) compositions constrains P-T conditions for the growth of garnet 457 458 core at 520-540°C, 16-23 kbar (Fig. 10a), in the Qz + Phe + Grt + Cld + Pg± Chl ± Gln + Rt fields. These P-T 459 conditions are at significantly lower T and higher P than the predicted stability field of staurolite, further 460 confirming that staurolite is not compatible with the early prograde assemblage (see Section 4.3).

461 The late prograde assemblage consists of garnet mantle and its inclusions ( $Qz/Coe + Phe + Grt_M + Cld$ 462 + Pg+ Ky + Jd + Gln + Rt); once again staurolite is not considered as part of this assemblage. Pseudomorphs 463 after coesite are hosted in the outermost mantle domain, at the transition between  $Grt_M$  and  $Grt_R$ , suggesting 464 that garnet mantle already grew at UHP conditions. The coexistence of chloritoid + kyanite constrains the 465 temperature to a very narrow range (540-560°C), whereas the coexistence of jadeite, glaucophane and 466 paragonite in the same garnet domain limits the pressures to the interval 24-28 kbar, i.e., close to the 467 transition between paragonite-bearing and jadeite-bearing fields (Fig. 10b). The modeled garnet 468  $(Sps_{1.5}Prp_{19}Grs_2AIm_{76})$  and chloritoid  $(X_{Mg}=0.30)$  compositional isopleths intersect within these fields and 469 tightly constrain the late prograde P-T conditions at 540-560°C, 25-30 kbar, *i.e.*, at the transition between the 470 quartz and coesite stability fields (Fig. 10b). This is consistent with the observed occurrence of polycrystalline 471 aggregates of quartz after coesite at the transition between garnet mantle and rim. The AvPT approach 472 applied to four different sets of mineral compositions gives late prograde P-T conditions of 557 ± 5 °C, 27.4 ± 473 0.4 kbar (Table 2), consistent with the pseudosection results (Fig. 10b).

The peak assemblage (Coe + Phe + Grt<sub>R</sub> + Ky + Jd + Rt) is modelled by a large penta-variant field at T > 530°C and P > 25 kbar. Although garnet (Sps<sub>1.7</sub>Prp<sub>26</sub>Grs<sub>3.5</sub>Alm<sub>68</sub>) compositional isopleths are far apart, their intersection with phengite (Si = 3.45-3.49 a.p.f.u.) isopleths allows constraining peak P-T conditions at 660-730°C and 38-43 kbar (Fig. 10c), consistent with the peak P-T conditions proposed in previous papers and based on other lithologies (*i.e.*, pyrope-bearing whiteschists, eclogites, marbles; see review in Ferrando *et al.*, 2017). The AvPT approach applied on the peak assemblage did not converge to a result, because its variance is too high to define enough reactions.

481

## 482 **5.4 Sample DM1504 (RSU)**

483 The observed prograde and peak assemblage (Qz + Phe + Grt + Cld + Gln + Jd + Lws? + Rt) is modelled by a 484 large quadri-variant field at 450-540°C, 19-25 kbar. The modelled garnet, chloritoid and phengite 485 compositional isopleths intersect within this field and constrain prograde and peak P-T conditions as follows: 486 (i) early prograde conditions are constrained at 490-510°C, 20-23 kbar using the compositions of garnet core 487 (Sps<sub>9</sub>Prp<sub>8.5</sub>Grs<sub>16</sub>Alm<sub>67</sub>), of its chloritoid inclusions (X<sub>Mg</sub>=0.20) and of phengite (Si=3.31-3.43 a.p.f.u.) (Fig. 11a); 488 (ii) late prograde conditions are constrained at 500-520°C, 20-24 kbar using the compositions of garnet 489 mantle (Sps<sub>6</sub>Prp<sub>9.5</sub>Grs<sub>20</sub>Alm<sub>64</sub>), of its chloritoid inclusions (X<sub>Mg</sub>=0.22) and of phengite (Si=3.31-3.43 a.p.f.u.) 490 (Fig. 11b); (iii) peak conditions are estimated at 510-525°C, 20-23 kbar using the compositions of garnet rim 491  $(Sps_{4.5}Prp_9Grs_{18.5}Alm_{68})$ , its chloritoid inclusions  $(X_{Mg}=0.24)$  and phengite (Si=3.31-3.43 a.p.f.u.) (Fig. 11c). The 492 AvPT approach applied to four different sets of mineral compositions gives peak conditions of 495  $\pm$  8 °C, 493  $20.3 \pm 0.6$  kbar (Table 2), consistent with pseudosection results (Fig. 11c).

494

#### 495 5.5 Sample DM1565 (DSU)

(Alpine) peak P-T conditions for this sample were estimated using the AvPT approach, applied to three
 different sets of mineral compositions. Although not observed in the sample, lawsonite was included in the
 peak assemblage, allowing to consider the reactions involving grossular, which are relevant because garnet

- is relatively enriched in this component. This strategy is supported by the fact that other metapelites from
- 500 the same unit show unambiguous evidence for the occurrence of lawsonite in the peak assemblage (Nosenzo,
- 501 2018). The AvPT results point to peak P-T conditions of  $452 \pm 8$  °C,  $17.2 \pm 0.4$  kbar (Table 2).
- 502

## 503 6. Discussion

504

## **6.1** New constraints on the prograde evolution of the tectonic units in the southern DMM

506 6.1.1 Prograde evolution of the HP units bounding the UHP BIU

- 507 The prograde P-T evolution inferred for the four units bounding the UHP BIU is summarized below:
- The PU experienced a prograde evolution starting in the lawsonite-blueschist facies and reaching peak
   conditions in the eclogite-facies (500-515°C, 20-23 kbar; Fig. 12a). Peak-T conditions are similar to those
   estimated by Avigad *et al.* (2003) (*i.e.*, 530 °C) using multi-equilibrium thermobarometry applied on
   garnet-bearing metapelites from the same structural position. However, peak-P conditions are
   significantly higher than the 14-16 kbar estimated by the same authors (Fig. 12a).
- The P-T prograde path inferred for the SCU and RSU is remarkably similar to that constrained for the PU,
   with eclogite-facies peak P-T conditions at 500-520°C, 20-24 kbar (Fig. 12b, d). The estimated peak-P
   conditions are significantly higher than those (500-550°C, 15 kbar) constrained by Chopin *et al.* (1991)
   and Compagnoni & Rolfo (2003), whereas peak-T are in agreement with literature data (Fig. 12b, d).
- In contrast to the other units, the DSU did not experience eclogitic metamorphism. Estimated peak
   conditions (450-470 °C, 17-18 kbar) point to lawsonite-blueschist facies conditions (Fig. 12e); peak-T are
   similar to those reported by Chopin *et al.* (1991) (500°C, 10-12 kbar), but pressures are significantly higher
   (Fig. 12e).
- 521 Overall, our new data for the HP units bounding the UHP one substantially confirm peak-T already 522 estimated more than 25 years ago, but point to a significant increase of peak-P estimates ( $\Delta P = 5-10$  kbar). 523 This is the same trend already followed in the definition of peak P-T conditions for the UHP BIU, that were 524 initially estimated to be at about 30 kbar (*e.g.*, Chopin *et al.*, 1991; Compagnoni *et al.*, 1995) and progressively 525 increased (35 kbar: *e.g.*, Compagnoni & Rolfo, 2003) up to 40-43 kbar (*e.g.*, Hermann, 2003; Castelli *et al.*, 526 2007; Groppo *et al.*, 2007a; Ferrando *et al.*, 2009, 2017), in parallel with the progressive improvement of 527 thermodynamic modeling approaches that extended the limits of conventional thermobarometry.
- 528

## 529 6.1.2 A revised prograde P-T path for the UHP BIU

530 Peak P-T conditions (730°C, 40-43 kbar) and retrograde evolution of the UHP BIU are now very well defined 531 and were constrained in the last decades through detailed petrological studies on a great variety of 532 lithologies, among them pyrope-bearing whiteschists (Schertl et al., 1991; Hermann, 2003; Ferrando et al., 533 2009; Gauthiez-Putallaz et al., 2016), eclogites (Nowlan et al., 2000; Di Vincenzo et al., 2006; Groppo et al., 534 2007a), marbles and calc-silicate rocks (Rubatto & Hermann, 2001; Ferraris et al., 2005; Di Vincenzo et al., 535 2006; Castelli et al., 2007). Garnet-bearing metapelites have never been used to constrain the BIU peak P-T 536 conditions and have only been marginally used to constrain its retrograde evolution (Groppo et al., 2006). 537 This is due to the fact that the highly variant assemblage (*i.e.*, Coe + Phe + Grt + Ky + Jd) stable at UHP 538 conditions is not suitable for application of conventional thermobarometry. Conversely, metapelites have 539 been already used to constrain the early prograde evolution of the BIU, thanks to the preservation of 540 abundant prograde inclusions in the core of porphyroblastic garnets. Chopin et al. (1991) and Michard et al. 541 (1993) described a garnet-bearing phengitic micaschist (sample DM8412) very similar to our sample DM1281. 542 Both their and our garnet porphyroblasts are, in turn, remarkably similar to the cores of the "superzoned" 543 garnets described by Compagnoni & Hirajima (2001) (sample DM880). Chopin et al. (1991) and Compagnoni

8 Hirajima (2001) interpreted the coexistence of chloritoid, kyanite, staurolite and chlorite in the polymineralic inclusions hosted within garnet cores as evidence that the BIU prograde trajectory passed close to the invariant point involving Cld + Ky + St + Chl, located around 600°C, 15 kbar. This was considered as a pinning point for the BIU prograde path for more than 25 years, resulting in a steep prograde trajectory located at temperatures significantly higher than the peak-T conditions estimated at that time for the adjacent units.

550 Our study unambiguously demonstrates that staurolite in the polymineralic inclusions hosted within 551 garnet core and mantle has a retrograde nature, growing at the interface between garnet and kyanite, the 552 latter mineral preserving a rounded/corroded shape (Fig. 4e). We suggest that staurolite grew during the 553 retrograde evolution through a reaction that involved garnet, kyanite and chlorite as reactants. The aqueous 554 fluid needed to trigger the reaction would not have been necessarily introduced from outside through 555 fractures, but it could derive from the breakdown of chlorite associated with kyanite in the polymineralic 556 inclusion (*i.e.*, internally-derived fluid). Reaction modelling by the least square method (freeware application 557 available on demand; Godard, 2009) applied to the composition of garnet core/mantle, chlorite, kyanite and 558 staurolite yielded balanced reactions of this type: Chl + Ky + Grt = St (details are given in Table SM8), 559 accounting for the retrograde formation of staurolite in a closed system, *i.e.* the polymineralic inclusion. The 560 above-mentioned reaction is predicted to occur in the KFMASH system at about 600-650 °C, 13-15 kbar 561 (White et al., 2014), and it would have been therefore intersected during the retrograde evolution of the BIU 562 (Fig. 12c). It is worth noting that the growth of retrograde staurolite was already observed in the matrix of a 563 garnet-bearing metapelite from the BIU, and was constrained exactly at these P-T conditions (Groppo et al., 564 2006).

565 The new interpretation of the nature of staurolite occurring in the polymineralic inclusions hosted in the 566 BIU garnet porphyroblasts has important consequences for the definition of the BIU prograde P-T path. The 567 results of thermodynamic modeling and AvPT tightly constrain the growth of garnet core at 520-540°C, 16-568 23 kbar, *i.e.*, at significantly lower T and higher P than previously estimated, and at P-T conditions close to 569 the peak P-T conditions of the adjacent units. Moreover, the growth of garnet mantle is modeled at UHP 570 conditions, consistent with the occurrence of pseudomorphs after coesite included in the mantle domain. 571 The whole prograde evolution of the BIU is thus significantly different from that previously assumed; it does 572 not follow a regularly steep P/T gradient, but it is rather characterized by: (i) an early prograde evolution 573 along a moderately steep P/T gradient, similar to that followed by the adjacent HP units; (ii) an intermediate 574 steep, almost isothermal, pressure increase, and (iii) a late prograde temperature increase along a 575 moderately steep P/T gradient, still at increasing pressure.

576

## 577 **6.2 Implications for the geodynamic interpretation of the southern DMM**

578 An in-depth discussion of the geodynamic processes responsible for the architecture of the southern DMM 579 is beyond the aim of this paper. However, the following conclusions are worth noting and could represent 580 new constraints for future investigations:

581 (1) the PU experienced eclogite-facies metamorphism under peak P-T conditions very similar to those 582 registered by the SCU and RSU (500-520°C, 20-24 kbar). Moreover, the PU, SCU and RSU units followed 583 the same prograde path, along a medium T/P gradient of about 12°C kbar<sup>-1</sup>, suggesting similar burial 584 mechanisms. The similarity of the peak P-T conditions experienced by the PU and SCU, combined with 585 the fact that the PU sample was collected from an outcrop located very close to the contact with the BIU 586 (Fig. 1), could potentially raise the doubt that the two samples actually belong to the same unit (*i.e.*, SCU). 587 The contact between the PU and overlying units (either SCU or BIU) has been located thanks to the abrupt 588 occurrence, moving downward in the DMM nappe stack, of abundant graphitic micaschists with quartzite 589 intercalations (see Fig.1). These micaschists have never been described within the other units (either

- 590 SCU, BIU or RSU) and, in turn, have been considered diagnostic of the former PU (e.g., Vialon, 1966; 591 Chopin *et al.*, 1991; Avigad *et al.*, 2003). Following this criterion, sample DM1485 has been attributed to 592 the PU. Our results thus highlight that, in the investigated area, the PU does not correspond to a 593 blueschist unit, as previously described (Avigad *et al.*, 2003), and therefore the actual occurrence of a 594 blueschist unit stacked below an eclogitic ones has to be restricted to northernmost sectors of the DMM 595 (*i.e.*, the Brianconnais-like tectonic window in the Pinerolo area; *e.g.*, Manzotti *et al.*, 2016).
- 596 (2) the UHP BIU seems to have followed an early prograde evolution similar to that of the other eclogitic 597 units of the southern DMM tectonic "sandwich". The attainment of UHP peak conditions occurred through an earlier almost isothermal increase in pressure ( $\Delta P$ =8-10 kbar) along a significantly lower T/P 598 599 gradient (ca. 3°C kbar<sup>-1</sup>) and a later increase in temperature ( $\Delta$ T=150-170 °C) along a medium T/P gradient 600 (ca. 15°C kbar<sup>-1</sup>). Our results suggest that UHP metamorphism was not the result of a single, 601 homogeneous, process, but rather the product of a two-step process. Further geochronological studies 602 are needed in order to test if the UHP BIU shared a synchronous prograde evolution with the adjacent 603 eclogitic units.
- (3) the DSU is the only unit of the southern DMM tectonic "sandwich" that, according to our results, did not
  experience eclogite-facies metamorphism. It is worth noting that, on the field, the DSU is separated from
  the eclogitic units by a hundreds of metres thick shear zone (tectonic mélange *sensu* Festa *et al.*, 2019),
  which includes slices of meta-ophiolite (Valmala Shear Zone: Nosenzo, 2018). The detailed description
  and interpretation of this shear zone is beyond the aim of this paper and further studies are necessary
  to understand its role in decoupling the southern DMM during subduction and/or in driving exhumation
  of related (U)HP units.
- 611

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#### 812 Figure captions

**Fig. 1** – Simplified geological map (a) of the southern Dora-Maira Massif around the UHP Brossasco-Isasca Unit (modified from Compagnoni *et al.*, 2012, and with unpublished data from Botta, 2015, and Nosenzo, 2018). Sample locations are shown by black stars both in the map and cross sections. The Polymetamorphic and Monometamorphic Complexes in the SCU, BIU, RSU and DSU refer to a Variscan amphibolite-facies metamorphic basement and to Permian igneous bodies, respectively, each of which reworked during Alpine metamorphism. The insets (b, c) show the location of the southern DMM in north-west Italy (b) and within a simplified tectonic sketch-map of the Western Alps (c).

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Fig. 2 – Processed micro-XRF maps of the studied metapelites. For sample DM1565 (DSU),  $Grt_{c}$  and  $Grt_{M}$  refer to pre-Alpine  $Grt_{1}$  porphyroblasts, whereas Alpine  $Grt_{2}$  idioblasts in the matrix are reported as  $Grt_{R}$ . Darkgrey to black domains are holes in the thin sections (*i.e.*, pixels not assigned to mineral phases).

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825 Fig. 3 – Representative microstructures of samples DM1485 (a, b) and DM1667c (c-e) from the PU and SCU, 826 respectively. Sample DM1485: (a) Garnet porphyroblast with a snow-ball structure including quartz and 827 chloritoid. The plagioclase porphyroblasts in the matrix are related to retrogression. (b) Detail of chloritoid + 828 phengite + paragonite polymineralic inclusion in garnet mantle. Sample DM1667c: (c) Detail of chloritoid 829 included in garnet mantle, partially replaced by white mica. (d) Fine-grained epidote included in garnet 830 mantle. (e) Box-shaped pseudomorph after lawsonite included in garnet rim, consisting of epidote + phengite 831 + paragonite + chlorite. (a, b, c: Plane Polarized Light, PPL; d, e and insets in a, b; Crossed Polarized Light, 832 XPL).

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834 Fig. 4 – Representative microstructures of sample DM1281 from the BIU. (a) Zoned garnet porphyroblast, 835 with a large core and mantle crowded with fine-grained inclusions, and a thin rim with few inclusions. The 836 main foliation is defined by phengite. The inset shows a pseudomorph after coesite, consisting of 837 polycrystalline quartz, included in garnet mantle. (b) Detail of a pluri-mm kyanite porphyroblast (Ky<sub>1</sub>) 838 enveloped by the main foliation. Small idioblasts of Ky<sub>2</sub> are in equilibrium with the S<sub>m</sub>. (c) Pseudomorph after 839 jadeite, consisting of a fine-grained aggregate of albite, pyrophyllite and paragonite. (d) Fine-grained 840 polymineralic inclusions in garnet mantle. The inset shows a polymineralic inclusion in garnet core: note the 841 equilibrium relations among chloritoid, chlorite and paragonite. (e) Details of polymineralic inclusions in 842 garnet mantle, consisting of kyanite, staurolite, paragonite and chlorite. Staurolite systematically separates 843 corroded/rounded kyanite grains from garnet, suggesting that its growth is related to a reaction between 844 garnet and kyanite. (f, g) Pseudomorphs after glaucophane (f) and jadeite (g) included in garnet mantle, 845 consisting of fine-grained aggregates of paragonite + muscovite  $\pm$  biotite and albite + pyrophyllite + 846 paragonite, respectively. (a, b, c, f, g: XPL; c, d: PPL; e and inset in d: Back Scattered Electron image, BSE).

848 Fig. 5 – Representative microstructures of samples DM1504 (a-c) and DM1565 (d-f) from the RSU and DSU, 849 respectively. Sample DM1504: (a) Garnet porphyroblast with quartz and chloritoid inclusions, partially 850 enveloped by the main foliation, defined by phengite and chloritoid. (b) Detail of the chloritoid inclusions in 851 garnet core and mantle. The inset shows a very fine-grained polymineralic inclusion in garnet mantle, 852 consisting of glaucophane and jadeite, partially replaced by albite, pyrophyllite and paragonite. (c) Tabular-853 shaped inclusion in garnet mantle, consisting of an aggregate of epidote + paragonite + quartz, possibly 854 deriving from former lawsonite. Sample DM1565: (d) Large pre-Alpine garnet porphyroblasts (Grt<sub>1</sub>) 855 enveloped by the main foliation. (e) Top: small Alpine garnet idioblasts (Grt<sub>2</sub>) in equilibrium with the main 856 foliation defined by phengite; bottom: Grt<sub>2</sub> forming a discontinuous rim around Grt<sub>1</sub>. (f) Large aggregate of fine-grained chloritoid enveloped by the S<sub>m</sub> and interpreted as a pseudomorph after pre-Alpine staurolite.
(a, b, c, d, e: PPL; f and insets in a, d: XPL; inset in b: BSE).

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Fig. 6 – Garnet compositions plotted in the Prp-Alm-(Grs+Sps) diagram. The zoning trend for each sample is
 highlighted by the arrow. Samples are grouped according to their bulk-composition (*i.e.*, Ca-poor vs. Ca-rich
 metapelites). For sample DM1565, only compositions of Alpine Grt<sub>2</sub> are plotted.

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**Fig. 7** – Potassic white mica compositions plotted in the Si vs.  $Fe^{2+} + Mg$  (a.p.f.u.) diagram. Compositions of micas defining the S<sub>m</sub> are distinguished from those included in garnet and from the late flakes overgrowing the S<sub>m</sub>. Samples are grouped according to their bulk-composition (*i.e.*, oxidized vs. not oxidized). The dashed line represents the ideal celadonitic substitution. Note that point analyses for samples DM1485 (PU), DM1667c (SCU) and DM1504 (RSU) plot slightly above the line of ideal celadonite substitution, thus suggesting that these white micas contain some Fe<sup>3+</sup>.

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**Fig. 8** – P-T pseudosections modeled for sample DM1485 (PU) using the measured bulk-composition (a), and the effective bulk-compositions after fractionation of garnet core (b) and of garnet core + mantle (c). Dotted lines are Rt and IIm -in/out curves; dashed line is the Qz/Coe transition. The black ellipses show the P-T conditions constrained for the growth of garnet core (a), mantle (b) and rim (c), based on the intersection of compositional isopleths, as indicated in each legend. Dark grey squares with dotted ellipses in (c) represent peak P-T conditions (with 1 $\sigma$  error) as defined by AvPT applied on four different sets of mineral compositions (see Table 2).

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Fig. 9 – P-T pseudosections modeled for sample DM1667c (SCU). (a), (b), (c) and all the symbols as in Fig. 8.

Fig. 10 – P-T pseudosections modeled for sample DM1281 (BIU). (a), (b), (c) and all the symbols as in Fig. 8;
 the inset in (b) clarifies the mineral assemblages stable in the narrow fields modelled in the central part of
 the pseudosection. Note that the scale is different from that in Fig. 8, 9 and 11, that pseudosection in (c) has
 been calculated at *a*H<sub>2</sub>O=0.4, and that AvPT data in (b) refer to late prograde P-T conditions.

**Fig. 11** – P-T pseudosections modeled for sample DM1504 (RSU). (a), (b), (c) and all the symbols as in Fig. 8.

888 Fig. 12 – (a-e) P-T grids showing the prograde trajectories for the Pinerolo Unit (a), San Chiaffredo Unit (b), 889 Brossasco-Isasca Unit (c), Rocca Solei Unit (d) and Dronero-Sampeyre Unit (e) as inferred in this study, 890 compared to peak P-T conditions derived from the literature (PU: Avigad et al., 2003; SCU: Compagnoni & 891 Rolfo, 2003; BIU: Ferrando et al., 2017 and references therein; RSU: Chopin et al., 1991; Matsumoto & 892 Hirajima, 2000; DSU: Chopin et al., 1991). For the BIU, the prograde and retrograde P-T path inferred from 893 the literature is also reported. KFMASH reactions relevant for the discussion are reported in (c) (from White 894 et al., 2014). Note that the BIU retrograde trajectory crosses the Grt + Ky + Chl = St reaction (see Section 6.1.2 895 for further discussion). (f) Comparison of the prograde P-T trajectories inferred for all the studied units: note 896 that the early prograde path of the BIU is similar to the P-T trajectory of the other units. Metamorphic facies 897 are from Liou & Zhang, 2002. The chloritoid stability field, as derived from pseudosections of Fig. 8-11, is 898 reported in greenish-blue.

























Sample		DM1485	5 (PU)	DM1667c (SCU)				DM1281	(BIU)	DM1504 (RSU)			
	MBC	MBC-Grt <sub>c</sub>	MBC-(Grt <sub>c</sub> +Grt <sub>R</sub> )	MBC	MBC-Grt <sub>c</sub>	MBC-(Grt <sub>c</sub> +Grt <sub>R</sub> )	MBC	MBC-Grt <sub>c</sub>	MBC-(Grt <sub>c</sub> +Grt <sub>R</sub> )	MBC	MBC-Grtc	MBC- (Grtc+Grt <sub>R</sub> )	
SiO <sub>2</sub>	55.61	57.29	59.45	58.38	58.81	64.62	64.40	67.37	71.83	62.46	62.40	63.89	
TiO <sub>2</sub>	0.21	0.24	0.27	0.23	0.24	0.32	0.59	0.67	0.79	0.70	0.71	0.76	
Al <sub>2</sub> O <sub>3</sub>	14.99	15.11	15.27	14.20	14.16	14.10	16.57	16.89	17.36	17.24	17.19	17.41	
Fe <sub>2</sub> O <sub>3</sub>	1.07	0.92	0.73	0.94	0.92	0.61	0.00	0.00	0.00	0.53	0.51	0.43	
FeO	16.67	14.50	11.42	14.74	14.45	9.60	9.84	6.71	2.01	7.84	8.07	6.78	
MnO	0.38	0.12	0.02	0.33	0.27	0.06	0.29	0.09	0.02	0.28	0.23	0.05	
MgO	6.99	7.54	8.12	4.03	4.09	4.80	4.23	3.93	3.00	4.20	4.19	4.21	
CaO	0.76	0.56	0.46	4.27	4.09	1.84	0.49	0.26	0.15	1.68	1.60	0.98	
Na <sub>2</sub> O	0.68	0.77	0.88	0.32	0.33	0.45	0.75	0.85	1.00	0.90	0.91	0.98	
K <sub>2</sub> O	2.64	2.96	3.38	2.57	2.64	3.59	2.84	3.23	3.82	4.15	4.19	4.50	

Table 1. Effective bulk-compositions (mol%) of the studied metapelites

 $MBC = measured bulk-composition; MBC-Grt_c = effective bulk-composition after fractionation of Grt_c; MBC-(Grt_c+Grt_M) = effective bulk-composition after fractionation of Grt_c and Grt_M.$ 

Sampla	Assemblage	Phe Si	Grt	Ctd	Chl	average	error (σ)	average	error (σ)	σfit	N° of
Sample	$(+Qz/Coe^{*} + H_{2}O)$	a.p.f.u.	XMg	XMg	XMg	T (°C)	T (°C)	P (kbar)	P (kbar)		reactions
	Phe(6.1)-Grt(1.22)-Ctd(1.49)-Chl(4.7)	3.51	0.12	0.17	0.40	496	15	19	1.5	1.32	4
85	Phe(2.31)-Grt(1.2)-Ctd(1.48)-Chl(4.8)	3.48	0.10	0.16	0.40	494	11	19.1	1.1	0.81	4
114 PU	Phe(6.11)-Grt(1.21)-Ctd(2.29)-Chl(4.9)	3.44	0.12	0.16	0.40	500	14	18.8	1.4	1.30	5
2 )	Phe(6.6)-Grt(1.23)-Ctd(1.33)-Chl(3.7)	3.42	0.15	0.16	0.44	492	24	19.3	2.5	2.27	5
	weighted mean**					496	7	19.0	0.7		
	Phe(7.17)-Grt(2.24)-Ctd(1.5)-Lws	3.46	0.08	0.28		526	16	22.3	1.7	0.78	4
57c )	Phe(10.1)-Grt(9.22)-Ctd(2.52)-Lws	3.44	0.09	0.23		503	15	21.7	1.7	0.27	4
16( SCU	Phe(10.9)-Grt(2.25)-Ctd(2.49)-Lws	3.44	0.10	0.23		515	16	22.0	1.8	0.76	3
MO	Phe(1.18)-Grt(9.1)-Ctd(2.40)-Lws	3.43	0.08	0.22		507	16	21.7	1.7	0.25	3
	weighted mean**					512	8	21.9	0.9		
	Phe(12.2)-Grt(6.3)-Ctd(5.7)-Ky	3.47	0.24	0.31		560	9	27.5	2.9	1.03	3
81	Phe(12.1)-Grt(6b.1)-Ctd(6.49)-Ky	3.45	0.25	0.30		552	9	26.3	2.7	0.43	3
112 BIU	Phe(6.88)-Grt(6.32)-Ctd(6.36)-Ky	3.45	0.24	0.31		561	10	25.2	3.1	1.09	3
2 =	Phe(8.3)-Grt(10.13)-Ctd(6.33)-Ky	3.46	0.24	0.29		557	9	27.5	0.4	0.83	4
	weighted mean**					557	5	27.4	0.4		
	Phe(2.34)-Grt(2.2)-Ctd(2.35)-Gln(2.52)-Jd(2.44)-Lws	3.42	0.09	0.22		491	15	20.7	1.2	1.24	7
04	Phe(6.21)-Grt(2.26)-Ctd(4.4)-Gln(2.52)-Jd(2.44)-Lws	3.43	0.10	0.23		505	16	19.5	1.6	1.22	5
115 3SU	Phe(6.16)-Grt(1.19)-Ctd(6.8)-Gln(2.52)-Jd(2.44)-Lws	3.41	0.09	0.23		489	16	20.3	1.2	1.30	6
2 5	Phe(6.3)-Grt(2.1)-Ctd(2.32)-Gln(2.52)-Jd(2.44)-Lws	3.43	0.09	0.23		495	16	20.5	1.2	1.31	7
	weighted mean**					495	8	20.3	0.6		
Б	Phe(5.12)-Grt(3.15)-Ctd(2.3)-Lws	3.55	0.06	0.17		466	14	18.8	1.5	0.15	3
56 (U)	Phe(5.6)-Grt(3.11)-Ctd(2.32)-Lws	3.55	0.05	0.18		446	14	16.4	1.3	0.29	3
Щ (D3 С	Phe(3.6)-Grt(7.1)-Ctd(2.25)-Lws	3.58	0.05	0.15		444	14	16.8	1.3	0.55	3
Δ	weighted mean**					452	8	17.2	0.8		

Table 2. Average P-T estimates for the peak (DM1485, DM1667c, DM1504, DM1565) and late prograde (DM1281) assemblages of the studied samples

\*Coe for sample DM1281

\*\*Weighted mean (with error) implies that values with smaller errors weight more than values with bigger errors.

# What's in the sandwich? New P-T constraints for the (U)HP nappe stack of southern Dora-Maira Massif (Western Alps)

### submitted to European Journal of Mineralogy (Ref: ejm190006) by

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## SUPPLEMENTARY MATERIAL

#### Sample locations

The five metapelite samples studied in this paper are part of the rich collection of thin sections from the southern DMM hosted at the Department of Earth Sciences of the University of Torino (Italy). Sample locations are reported in Fig. 1 and additional details are given below.

- Sample DM1485 (PU) was collected from a small (few metres) outcrop of garnet-bearing micaschists exposed at Case dei Canaveis, in the Comba Albetta valley (right tributary of the Po river, west of Sanfront).
- Sample DM1667c (SCU) was collected at Piano Pramalano, at the head of Isasca Valley (few tens of metres below the ridge separating the Isasca Valley from the Po Valley). Outcrop exposure is very poor and the sample was collected from the debris along the road; however, because the debris is totally composed of similar micaschists, we suppose that this is the dominant lithology of the area.
- Sample DM1281 (BIU) was collected from an outcrop located east of Piano la Ruota, at the head of the Rio Lavesio Valley (a right tributary of the Po river, south-west of Martiniana Po; the same small valley where there is the well-known locality of Case Parigi). The outcrop consists of a ten of metres thick level of metapelites hosted within augen-gneiss. A sample from the same outcrop was described by Compagnoni *et al.* (1994) in the guidebook for the field excursion organized for the 16<sup>th</sup> meeting of IMA.
- Sample DM1504 (RSU) was collected from a 20-50 m -thick layer of metapelites exposed on the ridge separating the Gilba Valley from the Po Valley, west of M. Scolagarda.
- Sample DM1565 (DSU) was collected close to the Santuario di Valmala at the head of the Valmala Valley, few hundred metres below the ridge between the Varaita and Maira Valleys. Henry (1990) described similar micaschists exposed south of Meira Palancia as "micaschistes amigdalaire" and reported the occurrence of relics of pre-Alpine staurolite only partially replaced by a fine-grained aggregate of chloritoid.

Compagnoni, R., Messiga, B., Castelli, D. (1994): High pressure metamorphism in the Western Alps. *in*: "Guidebook to the field excursion B1", 16th General Meeting of the International Mineralogical Association, Pisa, Italy, 148 pp.

Henry, C. (1990): L'unité à coesite du massif Dora-Maira dans son cadre pétrologique et structurale (Alpes Occidentales, Italie). Thése Doctorat., Université Paris 6, 149 pp.



Fig. SM1 – Compositional profiles of garnet porphyroblasts from the investigated samples.

DM1485 (P	U)				DM1667c (SCU)					DM1281 (BIU)						
Garnet	Sps	Prp	Grs	Alm	Garnet	Sps	Prp	Grs	Alm	Garnet	Sps	Prp	Grs	Alm		
GrtC	4-6	5-7	7-9	80-83	GrtC	4-7	3-4	25-27	64-66	GrtC	3-8	12-16	5-6	73-77		
GrtM	2-3	7-9	7-8	81-84	GrtM	2-3	4-6	18-19	73-75	GrtM	0.5-2	17-21	1-3	74-79		
GrtR	0.3-1	9-12	10-11	77-81	GrtR	0.5-1	7-10	16-20	72-76	GrtR	1-2	22-26	3-5	68-72		
					GrtO-R	1-2	5-7	18-19	73-75							
Phengite	Si (a.p.f.u.)									Phengite	Si (a.p.f.u.)					
Sm	3.38-3.51				Phengite	Si (a.p.f.u.)				Sm	3.35-3.49					
in GrtC	3.48				Sm	3.35-3.46				in GrtR	3.45-3.47					
in GrtM	3.44-3.45				in GrtC	3.34										
					in GrtM	3.40-3.49				Chloritoid	XMg					
Chloritoid	XMg				in GrtR	3.36-3.43				in GrtC/M	0.25-0.31					
in GrtC	0.10-0.12															
in GrtM	0.13-0.16				Chloritoid	XMg				Chlorite	XMg					
in GrtR	0.17-0.18				in GrtC/M	0.20-0.28			<u> </u>	in GrtM	0.59-0.66					
					in GrtR	0.25-0.28				in GrtC	0.33-0.50					
Chlorite	XMg															
Sm	0.40-0.44				Chlorite	XMg				Staurolite	XMg					
late	0.37-0.38				in GrtC/M	0.20-0.26				in GrtC/M	0.15-0.25					
_					late	0.37-0.42										
Biotite	XMg															
late	0.38-0.40				Epidote	XPs										
					in GrtC/M	0.50-0.84										
					late	0.32-0.46										
					Biotite	XMg										
					late	0.35-0.42										

## Table SM1a - Compositional variations of the main minerals in samples DM1485 (PU), DM1667c (SCU) and DM1281 (BIU)

DM1504 (RSI	))				DM1565 (DSU)						
Garnet	Sps	Prp	Grs	Alm	Garnet 1	Sps	Prp	Grs	Alm		
GrtC	7-10	8-9	14-18	66-69	GrtC	3-7	6-9	5-10	75-80		
GrtM	5-7	9-10	19-21	63-65	GrtM	1-2	9.11	9-12	78-80		
GrtR	4-5	8-10	17-20	66-70	GrtR	2-5	10-12	4-9	78-82		
Phengite	Si (a.p.f.u.)				Garnet 2	Sps	Prp	Grs	Alm		
Sm	3.31-3.43				GrtC	2-4	4-5	14-16	75-78		
					GrtR	2-3	5-6	21-26	67-72		
Chloritoid	XMg										
Sm CtdC	0.19-0.21				Phengite	Si (a.p.f.u.)					
Sm CtdR	0.22-0.24				Sm	3.48-3.58					
in GrtC	0.19-0.21										
in GrtM	0.21-0.23				Chloritoid	XMg					
in GrtR	0.22-0.24				Sm; after St	0.13-0.18					
Glaucophane	XMg	X	Na		Chlorite	XMg					
in GrtM/R	0.38-0.42	0.91	-0.94		late	0.40-0.44					
Jadeite	XJd	XA	veg								
in GrtM/R	0.66-0.74	0.26	-0.34								
Epidote	XPs										
late (in Grt)	0.53-0.63										
late (matrix)	0.55-0.71										
Chlorite	XMg										
late	0.42-0.47										

 Table SM1b - Compositional variations of the main minerals in samples DM1504 (RSU) and DM1565 (DSU)

				White	mica		Garnet							
Analysis	1.39 Phe	1.35 Phe	6.1 Phe*	2.31 Phe*	6.11 Phe*	6.6 Phe*	4.6 Ms	1.43 Pg	1.12 Grt	1.19 Grt	1.22 Grt*	1.2 Grt*	1.21 Grt*	1.23 Grt*
Site	In Grt <sub>c</sub>	In Grt <sub>M</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>	late	In Grt <sub>M</sub>	Core	Mantle	Rim	Rim	Rim	Rim
SiO <sub>2</sub>	52.86	52.32	53.71	53.42	52.51	52.01	47.63	47.30	36.55	36.41	36.79	36.77	37.04	37.53
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al <sub>2</sub> O <sub>3</sub>	26.37	27.19	26.21	26.76	27.49	27.84	32.96	39.85	20.36	20.27	20.77	20.65	20.96	21.01
FeO	4.65	4.75	2.96	2.86	3.26	2.55	3.88	0.96	36.66	36.95	35.00	35.54	35.21	31.73
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.17	0.99	0.07	0.36	0.08	0.11
MgO	2.74	2.69	3.93	3.88	3.20	3.50	1.16	0.00	1.18	1.85	2.91	2.42	3.03	3.69
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.68	2.49	3.71	3.48	3.47	5.78
Na₂O	0.66	0.70	0.00	0.00	0.61	0.85	1.32	8.07	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	9.15	9.18	9.90	9.98	9.54	9.39	9.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	96.43	96.83	96.72	96.89	96.61	96.15	96.11	96.21	99.67	99.06	99.36	99.29	99.88	99.95
Si	3.48	3.44	3.51	3.48	3.44	3.42	3.16	2.99	2.99	2.99	2.98	2.99	2.98	2.98
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.05	2.11	2.02	2.06	2.12	2.16	2.58	2.97	1.97	1.96	1.98	1.98	1.99	1.97
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.06	0.07	0.05	0.06	0.06
Fe <sup>+2</sup>	0.26	0.26	0.16	0.16	0.18	0.14	0.22	0.03	2.47	2.47	2.30	2.37	2.31	2.05
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.07	0.00	0.02	0.01	0.01
Mg	0.27	0.26	0.38	0.38	0.31	0.34	0.11	0.00	0.14	0.23	0.35	0.29	0.36	0.44
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.22	0.32	0.30	0.30	0.49
Na	0.08	0.09	0.00	0.00	0.08	0.11	0.17	0.99	0.00	0.00	0.00	0.00	0.00	0.00
К	0.00	0.00	0.83	0.83	0.80	0.79	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XMg	0.51	0.50	0.70	0.71	0.64	0.71	0.35	0.00	0.05	0.08	0.12	0.10	0.12	0.15
XFe									0.82	0.83	0.77	0.79	0.78	0.69
XCa									0.08	0.07	0.11	0.10	0.10	0.17
XMn									0.05	0.02	0.00	0.01	0.00	0.00

Table SM2a - Representative analyses of the main minerals in sample DM1485 (PU)

Structural formulae have been calculated on the basis of 11 oxygens for white mica and 12 oxygens for garnet.

			Chlor	itoid	Cld* 2 29 Cld* 1 22 Cld* 4 7 Cbl* 4 8 Cbl* 4 9 Cbl*								
Analysis	1.28 Cld	1.46 Cld	1.49 Cld*	1.48 Cld*	2.29 Cld*	1.33 Cld*	4.7 Chl*	4.8 Chl*	4.9 Chl*	3.7 Chl*			
Site	In Grt <sub>c</sub>	In Grt <sub>M</sub>	In Grt <sub>R</sub>	In Grt <sub>R</sub>	In Grt <sub>R</sub>	In Grt <sub>R</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>			
SiO <sub>2</sub>	24.60	24.60	24.59	25.10	24.63	24.91	24.60	25.05	24.62	25.45			
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Al <sub>2</sub> O <sub>3</sub>	39.72	39.51	39.61	40.40	40.21	40.08	22.03	21.78	21.81	21.82			
FeO	27.10	26.47	25.87	25.42	25.40	25.82	30.44	30.65	30.38	28.90			
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
MgO	1.77	2.38	2.91	2.80	2.79	2.72	11.27	11.39	11.47	12.50			
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Na₂O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
K <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Total	93.28	93.1	93.17	93.77	93.13	93.63	88.34	88.87	88.28	88.68			
Si	2.04	2.03	2.02	2.05	2.02	2.04	2.65	2.68	2.65	2.71			
Ті	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Al	3.87	3.85	3.84	3.88	3.89	3.86	2.80	2.75	2.77	2.74			
Fe <sup>+3</sup>	0.06	0.09	0.11	0.03	0.06	0.06	0.00	0.00	0.00	0.00			
Fe <sup>+2</sup>	1.82	1.74	1.67	1.71	1.68	1.71	2.74	2.75	2.74	2.57			
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Mg	0.22	0.29	0.36	0.34	0.34	0.33	1.81	1.82	1.84	1.98			
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
К	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
XMg	0.11	0.14	0.18	0.17	0.17	0.16	0.40	0.40	0.40	0.44			

Table SM2b - Representative analyses of the main minerals in sample DM1485 (PU)

Structural formulae have been calculated on the basis of 14 oxygens for chloritoid and 18 oxygens for chlorite.

				Whit	e mica				Garnet						
Analysis	9.28 Phe	9.29 Phe	7.19 Phe	7.17 Phe*	10.1 Phe*	10.9 Phe*	1.18 Phe*	2.27 Pa	9.11 Grt	9.4 Grt	2.24 Grt*	9.22 Grt*	2.25 Grt*	9.1 Grt*	
Site	In Grt <sub>c</sub>	In Grt <sub>M</sub>	In Grt <sub>R</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>	// S <sub>m</sub>	In Grt <sub>M</sub>	Core	Mantle	Rim	Rim	Rim	Rim	
SiO <sub>2</sub>	50.42	53.00	51.56	52.25	52.44	52.22	52.28	47.14	36.70	36.79	37.01	36.82	36.55	37.04	
TiO <sub>2</sub>	0.45	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
$AI_2O_3$	28.68	26.56	26.26	26.59	27.00	27.25	27.66	40.04	20.15	20.50	20.73	20.69	20.24	20.57	
FeO	3.36	3.52	4.36	3.55	3.41	3.88	3.35	0.63	30.67	31.54	33.16	33.87	32.36	33.46	
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.35	1.48	0.49	0.32	0.82	0.34	
MgO	2.90	3.15	3.36	3.32	3.40	3.18	3.19	0.00	0.88	1.23	1.95	2.12	2.36	2.07	
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	8.81	7.97	6.18	5.80	6.52	5.97	
Na <sub>2</sub> O	0.91	0.87	0.56	0.62	0.57	0.00	0.58	7.72	0.00	0.00	0.00	0.00	0.00	0.00	
K <sub>2</sub> O	9.47	9.00	9.76	9.78	9.98	10.18	9.86	0.21	0.00	0.00	0.00	0.00	0.00	0.00	
Total	96.19	96.10	96.24	96.11	96.80	96.71	96.92	96.06	99.55	99.52	99.53	99.62	98.85	99.46	
Si	3.34	3.49	3.43	3.46	3.44	3.44	3.43	2.99	2.970	2.974	2.987	2.970	2.964	2.992	
Ti	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Al	2.24	2.06	2.06	2.07	2.09	2.11	2.14	2.99	1.923	1.953	1.972	1.967	1.934	1.959	
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.137	0.099	0.054	0.094	0.139	0.057	
Fe <sup>+2</sup>	0.19	0.19	0.24	0.20	0.19	0.21	0.18	0.03	1.940	2.034	2.184	2.192	2.056	2.203	
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.161	0.102	0.034	0.022	0.056	0.023	
Mg	0.29	0.31	0.33	0.33	0.33	0.31	0.31	0.00	0.106	0.149	0.235	0.255	0.285	0.249	
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.764	0.690	0.535	0.501	0.567	0.517	
Na	0.12	0.11	0.07	0.08	0.07	0.00	0.07	0.95	0.00	0.00	0.00	0.00	0.00	0.00	
К	0.80	0.76	0.83	0.83	0.84	0.85	0.82	0.02	0.00	0.00	0.00	0.00	0.00	0.00	
XMg	0.606	0.615	0.579	0.625	0.64	0.594	0.629	0.00	0.04	0.05	0.08	0.09	0.10	0.08	
XFe									0.65	0.68	0.73	0.74	0.69	0.74	
XCa									0.26	0.23	0.18	0.17	0.19	0.17	
XMn									0.05	0.03	0.01	0.01	0.02	0.01	

Table SM3a - Representative analyses of the main minerals in sample DM1667c (SCU)

Structural formulae have been calculated on the basis of 11 oxygens for white mica and 12 oxygens for garnet.

		Chlor	itoid			Epidote	Chlo	rite
Analysis	1.5 Cld*	2.52 Cld*	2.49 Cld*	2.40 Cld*	11.12 Ep	9.27 Ep	1.22 Chl	3.1 Chl
Site	In Grt <sub>R</sub>	In Grt <sub>M</sub>	In Grt <sub>M</sub>	In Grt <sub>M</sub>	In Grt <sub>c</sub>	In (Lws)	In Grt <sub>c</sub>	late
SiO <sub>2</sub>	25.13	25.35	25.13	25.01	38.47	38.63	23.59	24.66
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$AI_2O_3$	40.92	40.67	40.86	40.67	25.47	29.15	20.32	21.54
FeO	22.61	23.72	23.15	23.55	10.63	6.15	37.03	31.18
MnO	4.82	4.03	3.92	3.74	0.00	0.00	0.55	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	7.01	11.43
CaO	0.00	0.00	0.00	0.00	22.15	23.56	0.00	0.00
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	93.48	93.77	93.05	92.97	96.72	97.49	88.50	88.82
Si	2.02	2.05	2.04	2.04	3.02	2.99	2.64	2.65
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	3.88	3.87	3.91	3.91	2.36	2.65	2.68	2.72
Fe <sup>+3</sup>	0.08	0.04	0.01	0.02	0.70	0.40	0.04	0.00
Fe <sup>+2</sup>	1.44	1.56	1.57	1.58	0.00	0.00	3.42	2.80
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
Mg	0.58	0.49	0.47	0.45	0.00	0.00	1.17	1.83
Ca	0.00	0.00	0.00	0.00	1.86	1.95	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
К	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XMg	0.28	0.23	0.23	0.22			0.25	0.40
XPs					0.64	0.36		

Table SM3b - Representative analyses of the main minerals in sample DM1667c (SCU)

Structural formulae have been calculated on the basis of 14 oxygens for chloritoid, 12 oxygens for epidote and 18 oxygens for chlorite.

			W	/hite mica				Garnet						
Analysis	12.2Phe*	12.1 Phe*	6.88 Phe*	8.3 Phe*	9.23 Phe	10.20 Ms	6.51 Pa	Grt 11.10	6.3 Grt*	6b.1 Grt*	6.32 Grt*	10.13Grt*	6.1 Grt	
Site	// Sm	// Sm	// Sm	// Sm	In Grt <sub>R</sub>	In Grtc	In Grt <sub>c</sub>	Core	Mantle	Mantle	Mantle	Mantle	Rim	
SiO <sub>2</sub>	53.17	52.77	52.96	53.02	53.11	47.77	47.39	37.07	37.28	37.86	37.43	37.71	37.85	
TiO <sub>2</sub>	0.40	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Al <sub>2</sub> O <sub>3</sub>	27.15	27.20	28.20	27.27	27.23	36.21	40.38	21.08	21.33	21.40	21.22	21.37	21.67	
FeO	1.65	1.72	1.48	1.77	1.81	1.48	0.00	33.55	33.98	31.76	33.77	33.72	32.23	
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.21	0.08	0.64	0.23	0.20	0.53	
MgO	3.77	3.82	3.64	3.81	3.92	0.81	0.60	3.09	5.93	6.23	6.12	6.07	6.57	
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.79	0.43	1.63	0.31	0.59	0.98	
Na₂O	0.00	0.00	0.00	0.51	0.66	2.11	7.35	0.00	0.00	0.00	0.00	0.00	0.00	
K <sub>2</sub> O	10.34	10.52	10.32	10.38	9.42	8.20	0.40	0.00	0.00	0.00	0.00	0.00	0.00	
Total	96.48	96.50	96.60	96.75	96.16	96.58	96.13	99.79	99.03	99.52	99.07	99.66	99.82	
Si	3.47	3.45	3.45	3.46	3.47	3.10	3.01	2.99	2.977	2.992	2.985	2.988	2.980	
Ti	0.02	0.02	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	
Al	2.09	2.10	2.16	2.10	2.10	2.77	3.02	2.00	2.007	1.993	1.995	1.9957	2.010	
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.040	0.022	0.036	0.0282	0.031	
Fe <sup>+2</sup>	0.09	0.09	0.08	0.10	0.10	0.08	0.03	2.24	2.229	2.078	2.216	2.2069	2.092	
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.006	0.043	0.016	0.0137	0.035	
Mg	0.37	0.37	0.35	0.37	0.38	0.08	0.00	0.37	0.706	0.733	0.727	0.7172	0.770	
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.037	0.138	0.026	0.0503	0.083	
Na	0.00	0.00	0.00	0.06	0.08	0.27	0.91	0.00	0.00	0.00	0.00	0.00	0.00	
К	0.86	0.88	0.86	0.86	0.79	0.68	0.03	0.00	0.00	0.00	0.00	0.00	0.00	
XMø	0.80	0.80	0.82	0 79	0 79	0 49	0.00	0.12	0 24	0.25	0 24	0 24	0.26	
XFe	0.00	0.00	0.01	0110	0.7.0	0110	0.00	0.75	0.75	0.69	0.74	0.74	0.70	
XCa								0.05	0.01	0.05	0.01	0.02	0.03	
XMn								0.07	0.00	0.01	0.01	0.01	0.01	

Table SM4a - Representative analyses of the main minerals in sample DM1281 (BIU)

Structural formulae have been calculated on the basis of 11 oxygens for white mica and 12 oxygens for garnet.

		Chlor	itoid		Chl	Chlorite		rolite
Analysis	5.7 Cld*	6.49 Cld*	6.36 Cld*	6.33 Cld*	6.52 Chl	10.24 Chl	6b.5 St	11.26 St
Site	In Grt <sub>M</sub>	In Grt <sub>M</sub>	In Grt <sub>M</sub>	In Grt <sub>M</sub>	In Grt <sub>c</sub>	late	In Grt <sub>c</sub>	In Grtc
SiO <sub>2</sub>	25.88	25.58	25.75	25.54	27.56	24.03	30.70	29.57
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35
Al <sub>2</sub> O <sub>3</sub>	41.99	41.84	41.94	41.35	22.34	22.89	57.68	55.21
FeO	20.36	21.29	20.79	21.25	18.58	32.13	9.36	10.64
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	5.24	5.07	5.12	4.89	20.06	9.64	1.11	1.75
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na₂O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	93.47	93.78	93.60	93.02	88.54	88.70	98.85	97.52
Si	2.07	2.04	2.06	2.06	2.77	2.61	4.26	4.17
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Al	3.95	3.94	3.95	3.92	2.65	2.92	9.43	9.17
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>+2</sup>	1.36	1.42	1.39	1.43	1.56	2.91	1.09	1.25
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.62	0.60	0.61	0.59	3.01	1.56	0.23	0.37
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
К	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XMg	0.31	0.30	0.31	0.29	0.66	0.35	0.18	0.23

Table SM4b - Representative analyses of the main minerals in sample DM1281 (BIU)

Structural formulae have been calculated on the basis of 14 oxygens for chloritoid, 18 oxygens for chlorite and 12 oxygens for staurolite.

			White r	nica				Gar	net			
Analysis	2.34 Phe*	6.21 Phe*	6.16 Phe*	6.3 Phe*	7.20 Ms	6.15 Pa	2.16 Grt	2.8 Grt	2.2 Grt*	2.26 Grt*	1.19 Grt*	2.1 Grt*
Site	In Grt <sub>R</sub>	// S <sub>m</sub>	// S <sub>m</sub>	In Cld	late	$\perp$ Sm	Core	Mantle	Rim	Rim	Rim	Rim
SiO <sub>2</sub>	51.86	52.08	51.42	52.38	47.24	48.40	37.09	37.09	37.47	36.88	37.19	37.21
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$AI_2O_3$	27.60	27.64	27.34	27.47	35.02	39.39	20.78	20.52	20.39	20.48	20.87	20.40
FeO	3.79	3.66	4.31	3.85	2.85	0.65	30.05	29.49	30.70	31.04	29.44	31.13
MnO	0.00	0.00	0.00	0.00	0.00	0.00	3.99	2.91	1.66	1.83	2.79	1.72
MgO	3.01	3.01	3.05	3.19	0.67	0.00	2.09	2.30	2.14	2.37	2.35	2.21
CaO	0.00	0.00	0.00	0.00	0.00	0.00	5.63	7.15	7.13	6.39	7.19	6.54
Na <sub>2</sub> O	0.58	0.00	0.78	0.72	1.92	7.68	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	9.75	10.35	9.46	9.32	8.33	0.24	0.00	0.00	0.00	0.00	0.00	0.00
Total	96.59	96.74	96.36	96.93	96.02	96.37	99.63	99.46	99.50	98.99	99.83	99.22
Si	3.42	3.43	3.41	3.43	3.11	3.06	2.99	2.98	3.02	2.98	2.98	3.01
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.14	2.14	2.13	2.12	2.72	2.94	1.97	1.94	1.93	1.95	1.97	1.94
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.09	0.04	0.08	0.08	0.05
Fe <sup>+2</sup>	0.21	0.20	0.24	0.21	0.16	0.03	1.98	1.89	2.03	2.02	1.89	2.05
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.20	0.11	0.13	0.19	0.12
Mg	0.30	0.29	0.30	0.31	0.07	0.00	0.25	0.28	0.26	0.29	0.28	0.27
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.62	0.62	0.55	0.62	0.57
Na	0.07	0.00	0.10	0.09	0.25	0.94	0.00	0.00	0.00	0.00	0.00	0.00
К	0.82	0.87	0.80	0.78	0.70	0.02						
XMg	0.59	0.59	0.56	0.60	0.295	0.00	0.08	0.09	0.09	0.10	0.09	0.09
XFe							0.66	0.64	0.67	0.68	0.64	0.68
XCa							0.16	0.21	0.20	0.19	0.21	0.19
XMn							0.09	0.07	0.04	0.04	0.06	0.04

Table SM5a - Representative analyses of the main minerals in sample DM1504 (RSU)

Structural formulae have been calculated on the basis of 11 oxygens for white mica and 12 oxygens for garnet.

				Chloritoid				Jadeite	Glaucophane	
Analysis	7.9 Cld	1.22 Cld	1.20 Cld	6.8 Cld*	2.35 Cld*	4.4 Cld*	2.32 Cld*	2.44 Jd*	2.52 Gln*	
Site	Core	In Grt <sub>c</sub>	In Grt <sub>M</sub>	Rim	In Grt <sub>R</sub>					
SiO <sub>2</sub>	25.22	25.22	25.11	25.18	25.14	24.77	24.58	56.79	55.54	
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
$AI_2O_3$	40.44	40.63	40.61	40.21	40.66	40.29	39.98	17.49	9.58	
FeO	24.17	23.91	23.74	23.86	23.60	23.61	23.43	8.69	18.07	
MnO	0.54	0.00	0.46	0.00	0.00	0.42	0.42	0.00	0.00	
MgO	3.25	3.61	3.80	4.07	3.69	3.84	3.81	0.00	7.34	
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.76	
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.62	6.53	
K <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total	93.62	93.38	93.72	93.32	93.09	92.93	92.22	98.06	97.83	
Si	2.05	2.05	2.03	2.04	2.05	2.02	2.05	2.00	7.83	
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Al	3.87	3.89	3.87	3.85	3.90	3.87	3.87	0.73	1.59	
Fe <sup>+3</sup>	0.02	0.01	0.06	0.07	0.01	0.09	0.04	0.26	0.53	
Fe <sup>+2</sup>	1.62	1.61	1.54	1.55	1.60	1.52	1.56	0.00	1.60	
Mn	0.04	0.00	0.03	0.00	0.00	0.03	0.03	0.00	0.00	
Mg	0.39	0.44	0.46	0.49	0.45	0.47	0.46	0.00	1.54	
Са	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.11	
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.79	
К	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
XMg	0.20	0.21	0.23	0.23	0.22	0.23	0.23	0.00	0.48	
XNa								0.98	0.94	

Table SM5b - Representative analyses of the main minerals in sample DM1504 (RSU)

Structural formulae have been calculated on the basis of 14 oxygens for chloritoid, 6 oxygens for jadeite and 24 oxygens for glaucophane.

	White mica					Pre-Alp	Pre-Alpine Garnet (Grt <sub>1</sub> )			Alpine Garnet (Grt <sub>2</sub> )			
Analysis	5.12 Phe*	5.6 Phe*	3.6 Phe*	2.27 Phe	8.18 Ms	5.3 Pa	1.16 Grt	t 1.6 Grt	1.30 Grt	3.13 Grt	3.15 Grt*	3.11 Grt*	7.1 Grt*
Site	// Sm	// Sm	// Sm	In (St)	Late	Late	Core	Mantle	Rim	Core	Rim	Rim	Rim
SiO <sub>2</sub>	54.76	54.59	55.21	51.93	47.53	47.68	36.89	36.86	36.61	37.28	37.58	37.53	37.37
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al <sub>2</sub> O <sub>3</sub>	25.84	25.43	25.42	28.58	37.05	40.10	21.05	20.54	20.64	20.98	21.08	20.93	21.39
FeO	2.57	2.20	2.72	2.77	0.94	0.00	34.38	35.62	35.81	34.17	31.62	29.92	30.68
MnO	0.00	0.00	0.00	0.00	0.00	0.00	2.68	0.65	1.92	1.07	0.75	0.81	0.78
MgO	4.20	4.34	4.17	3.02	0.55	0.00	1.94	2.33	2.66	0.95	1.37	1.11	1.13
CaO	0.00	0.00	0.00	0.00	0.00	0.00	2.77	3.24	1.46	5.30	7.09	9.11	8.59
Na <sub>2</sub> O	0.00	0.50	0.00	0.59	2.33	8.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K <sub>2</sub> O	9.41	9.78	9.19	9.53	7.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	96.78	96.85	96.71	96.42	96.84	96.18	99.71	99.24	99.10	99.75	99.48	99.42	99.93
Si	3.55	3.55	3.58	3.40	3.07	3.01	2.99	3.00	2.99	3.03	3.03	3.02	3.00
Ti	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.97	1.95	1.94	2.21	2.82	2.98	2.01	1.97	1.99	2.01	2.00	1.99	2.02
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.00	0.00	0.00	0.00
Fe <sup>+2</sup>	0.14	0.12	0.15	0.15	0.05	0.00	2.33	2.39	2.40	2.32	2.13	2.02	2.06
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.05	0.13	0.07	0.05	0.06	0.05
Mg	0.41	0.42	0.40	0.30	0.05	0.00	0.23	0.28	0.32	0.11	0.16	0.13	0.13
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.28	0.13	0.46	0.61	0.79	0.74
Na	0.00	0.06	0.00	0.07	0.29	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
К	0.78	0.81	0.76	0.80	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
XMg	0.744	0.778	0.732	0.66	0.511	0.00	0.08	0.09	0.11	0.04	0.06	0.05	0.05
XFe							0.78	0.80	0.80	0.78	0.72	0.67	0.69
XCa							0.08	0.09	0.04	0.16	0.21	0.26	0.25
XMn							0.06	0.02	0.04	0.03	0.02	0.02	0.02

Table SM6a - Representative analyses of the main minerals in sample DM1565 (DSU)

Structural formulae have been calculated on the basis of 11 oxygens for white mica and 12 oxygens for garnet.

		Chloritoid		Chlorite	 
Analysis	2.3 Cld*	2.32 Cld**	2.25 Cld	8.14 Chl	
Site	In (St)	In (St)	In (St)	Late	
SiO <sub>2</sub>	25.07	24.94	25.16	24.97	
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	
$AI_2O_3$	41.12	41.39	40.95	21.77	
FeO	24.15	24.13	25.23	29.31	
MnO	0.00	0.00	0.00	0.00	
MgO	2.80	2.89	2.52	11.99	
CaO	0.00	0.00	0.00	0.00	
Na <sub>2</sub> O	0.00	0.00	0.00	0.00	
K <sub>2</sub> O	0.00	0.00	0.00	0.00	
Total	93.14	93.35	93.87	88.04	
Si	2.049	2.032	2.048	2.685	
Ti	0.00	0.00	0.00	0.00	
Al	3.959	3.974	3.928	2.758	
Fe <sup>+3</sup>	0.00	0.00	0.00	0.00	
Fe <sup>+2</sup>	1.650	1.644	1.718	2.636	
Mn	0.00	0.00	0.00	0.00	
Mg	0.342	0.350	0.306	1.922	
Са	0.00	0.00	0.00	0.00	
Na	0.00	0.00	0.00	0.00	
К	0.00	0.00	0.00	0.00	
XMg	0.17	0.18	0.15	0.42	

Table SM6b - Representative analyses of the main minerals in sample DM1565 (DSU)

Structural formulae have been calculated on the basis of 14 oxygens for chloritoid and 18 oxygens for chlorite.

#### Table SM7a. Independent set of reactions modelled by AvPT and used to estimate P-T conditions

Sample DM1485 (PU)	
Phe(6.1)-Grt(1.22)-Ctd(1.49)-Chl(4.7)-Qz-H <sub>2</sub> O	Phe(2.31)-Grt(1.2)-Ctd(1.48)-Chl(4.8)-Qz-H <sub>2</sub> O
1) ames + $2q = py + mctd + 3H_2O$	1) $ames + 2q = py + mctd + 3H_2O$
2) 5alm + 5ames + 4q = 4py + 8mctd + 3daph	2) fctd + daph + 2q = 2alm + $5H_2O$
3) 23alm + 15ames + 12q = 20py + 24fctd + 9daph	3) 5alm + 5ames + 4q = 4py + 8mctd + 3daph
4) 3cel + 5alm + 3ames = 3mu + 5py + 3daph	4) 3cel + 5alm + 3ames = 3mu + 5py + 3daph
Phe(6.11)-Grt(1.21)-Ctd(2.29)-Chl(4.9)-Qz-H <sub>2</sub> O	Phe(6.6)-Grt(1.23)-Ctd(1.33)-Chl(3.7)-Qz-H <sub>2</sub> O
1) ames + $2q = py + mctd + 3H_2O$	1) $ames + 2q = py + mctd + 3H_2O$
2) fctd + daph + 2q = 2alm + $5H_2O$	2) fctd + daph + 2q = 2alm + $5H_2O$
3) 5alm + 5ames + 4q = 4py + 8mctd + 3daph	3) 3mctd + 3daph + 6q = py + 5alm + 15H₂O
4) 3mu + py + 2ames + 4q = 3cel + 8mctd	4) 3mu + py + 2ames + 4q = 3cel + 8mctd
5) 3cel + alm = 3fcel + py	5) 3cel + alm = 3fcel + py
Sample DM1667c (SCU)	
Phe(7.17)-Grt(2.24)-Ctd(1.5)-Lws-Qz-H <sub>2</sub> O	Phe(10.1)-Grt(9.22)-Ctd(2.52)-Lws-Qz-H <sub>2</sub> O
1) $py + 3law = gr + 3mctd + 3q + 3H_2O$	1) py + 3law = gr + 3mctd + 3q + 3H <sub>2</sub> O
2) alm + 3law = gr + 3fctd + 3g + 3H <sub>2</sub> O	2) $alm + 3law = gr + 3fctd + 3g + 3H_2O$

alm + 3law = gr + 3fctd + 3q + 3H<sub>2</sub>O
 fcel + 2fctd = mu + alm + 2H<sub>2</sub>O

4) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law

Phe(10.9)-Grt(2.25)-Ctd(2.49)-Lws-Qz-H<sub>2</sub>O

py + 3law = gr + 3mctd + 3q + 3H<sub>2</sub>O
 alm + 3law = gr + 3fctd + 3q + 3H<sub>2</sub>O
 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law

#### Sample DM1281 (BIU)

Phe(12.2)-Grt(6.3)-Ctd(5.7)-Ky-Coe-H<sub>2</sub>O 1)  $3fctd + 2coe = alm + 2ky + 3H_2O$ 2) 3mu + py + 4coe = 3cel + 4ky3) 3cel + alm = 3fcel + py

Phe(6.88)-Grt(6.32)-Ctd(6.36)-Ky-Coe-H<sub>2</sub>O

1)  $3fctd + 2coe = alm + 2ky + 3H_2O$ 

2) 3mu + py + 4coe = 3cel + 4ky

3) 3cel + alm = 3fcel + py

#### Phe(1.18)-Grt(9.1)-Ctd(2.40)-Lws-Qz-H<sub>2</sub>O

1)  $py + 3law = gr + 3mctd + 3q + 3H_2O$ 

- 2)  $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law

3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law

4) 15cel + 2gr + 12fctd + 6q = 3mu + 12fcel + 5py + 6law

Phe(12.1)-Grt(6b.1)-Ctd(6.49)-Ky-Coe-H<sub>2</sub>O

1)  $3fctd + 2coe = alm + 2ky + 3H_2O$ 

2) 3mu + py + 4coe = 3cel + 4ky

3) 3cel + alm = 3fcel + py

Phe(8.3)-Grt(10.13)-Ctd(6.33)-Ky-Coe-H<sub>2</sub>O

1)  $3fctd + 2coe = alm + 2ky + 3H_2O$ 

2)  $pa = ky + jd + H_2O$ 

3) 3mu + py + 4coe = 3cel + 4ky

4) 3cel + alm = 3fcel + py

### Table SM7b. Independent set of reactions modelled by AvPT and used to estimate P-T conditions

Sample DM1504 (RSU)	
Phe(2.34)-Grt(2.2)-Ctd(2.35)-Gln(2.52)-Jd(2.44)-Lws-Qz-H <sub>2</sub> O	Phe(6.21)-Grt(2.26)-Ctd(4.4)-Gln(2.52)-Jd(2.44)-Lws-Qz-H <sub>2</sub> O
1) py + 3law = gr + 3mctd + 3q + 3H <sub>2</sub> O	1) py + 3law = gr + 3mctd + 3q + 3H <sub>2</sub> O
2) alm + 3law = gr + 3fctd + 3q + 3H <sub>2</sub> O	2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
3) cel + 2mctd = mu + py + $2H_2O$	3) cel + 2mctd = mu + py + 2H <sub>2</sub> O
4) 3mctd + 2jd + 2q = 2pa + py + H <sub>2</sub> O	4) fcel + 2fctd = mu + alm + $2H_2O$
5) fcel + 2fctd = mu + alm + $2H_2O$	5) 12fcel + py + 4mctd + 8jd + 4q = 5mu + 7cel + 4fgl
6) 3pa + fgl = 3fctd + 5jd + 4q + H <sub>2</sub> O	
7) 27mu + 9cel + 4spss + 12fgl + 12law = 36fcel + 24pa + 3py +	
4gr + 12mnctd	
Phe(6.16)-Grt(1.19)-Ctd(6.8)-Gln(2.52)-Jd(2.44)-Lws-Qz-H <sub>2</sub> O	Phe(6.3)-Grt(2.1)-Ctd(2.32)-Gln(2.52)-Jd(2.44)-Lws-Qz-H <sub>2</sub> O
1) $py + 3law = gr + 3mctd + 3q + 3H_2O$	1) py + 3law = gr + 3mctd + 3q + 3H <sub>2</sub> O
2) alm + 3law = gr + 3fctd + 3q + 3H <sub>2</sub> O	2) alm + 3law = gr + 3fctd + 3q + 3H <sub>2</sub> O
3) cel + 2mctd = mu + py + $2H_2O$	3) cel + 2mctd = mu + py + $2H_2O$
4) 3mctd + 2jd + 2q = 2pa + py + H <sub>2</sub> O	4) $3mctd + 2jd + 2q = 2pa + py + H_2O$
5) fcel + 2fctd = mu + alm + $2H_2O$	5) fcel + 2fctd = mu + alm + 2H <sub>2</sub> O
6) 6fcel + 2pa + py + 2jd = 3mu + 3cel + 2fgl	6) 3pa + fgl = 3fctd + 5jd + 4q + H <sub>2</sub> O
	7) 6fcel + 2pa + py + gr + 2acm = 3mu + 3cel + andr + 2fgl
Sample DM1565 (DSU)	
Phe(5.12)-Grt(3.15)-Ctd(2.3)-Lws-Qz-H₂O	Phe(5.6)-Grt(3.11)-Ctd(2.32)-Lws-Qz-H2O
1) py + 3law = gr + 3mctd + 3q + 3H <sub>2</sub> O	1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$	2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law	3) 3cel + 2gr + 12fctd + 6q = 3mu + py + 4alm + 6law
Phe(3.6)-Grt(7.1)-Ctd(2.25)-Lws-Qz-H <sub>2</sub> O	

1)  $py + 3law = gr + 3mctd + 3q + 3H_2O$ 

2) alm + 3law = gr + 3fctd + 3q +  $3H_2O$ 

3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law

$\Sigma$ prod	Residuals
4.544	0.604
4.006	-0.604
0.936	-0.574
0.012	0.012
0.564	0.274
0.018	0.010
1.055	0.055
	Σprod 4.544 4.006 0.936 0.012 0.564 0.018 1.055

 $0.264 \text{ Chl} + 3.496 \text{ Ky} + 0.123 \text{ Grt}_{c} = 1.000 \text{ St}$ 

#### 0.263 Chl + 3.712 Ky + 0.064 Grt<sub>c</sub> = 1.000 St

	Reactants			Products			
Phases	Chl 11.34	Ky 11.32	Grtc 11.6	St 11.34	$\Sigma$ react	$\Sigma$ prod	Residuals
coeff	-0.263	-3.712	-0.064	1.000			
SiO <sub>2</sub>	2.71	1.00	2.90	4.11	-4.110	4.610	0.500
Al <sub>2</sub> O <sub>3</sub>	1.56	1.00	1.00	4.69	-4.685	4.185	-0.500
FeO	2.43	0.00	2.19	1.27	-1.270	0.779	-0.491
MnO	0.00	0.00	0.10	0.00	0.000	0.006	0.006
MgO	1.75	0.00	0.54	0.26	-0.260	0.494	0.234
CaO	0.00	0.00	0.16	0.00	0.000	0.010	0.010
H <sub>2</sub> O	4.00	0.00	0.00	1.00	-1.000	1.052	0.052

#### $0.211 \text{ Chl} + 3.620 \text{ Ky} + 0.131 \text{ Grt}_{M} = 1.000 \text{ St}$

Rea	ctants			Products			
Phases	Chl 6.52	Ky 6.53	Grt <sub>M</sub> 6.21	St 6.50	$\Sigma$ react	$\Sigma$ prod	Residuals
coeff	-0.211	-3.620	-0.131	1.000			
SiO <sub>2</sub>	2.77	1.00	2.99	4.04	-4.040	4.598	0.558
$AI_2O_3$	1.33	1.00	1.00	4.59	-4.590	4.032	-0.558
FeO	1.56	0.00	2.05	1.23	-1.230	0.599	-0.631
MnO	0.00	0.00	0.08	0.00	0.000	0.010	0.010
MgO	3.01	0.00	0.67	0.46	-0.460	0.724	0.264
CaO	0.00	0.00	0.17	0.00	0.000	0.022	0.022
H <sub>2</sub> O	4.00	0.00	0.00	1.00	-1.000	0.846	-0.154

Reactions were balanced using the least-squares method. Stoichiometric coefficients and compositions are expressed in moles.  $\Sigma$  react: overall composition of the reactants;  $\Sigma$  prod: overall composition of the products; *Residuals:* residual vector from the method of least squares (molar bulk composition of the product - molar bulk composition of the reactants).