

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

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

This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1718942> since 2019-12-11T15:27:34Z

Published version:

DOI:10.1127/ejm/2019/0031-2860

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

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--

Manuscript Number:	ejm190006R1
Article Type:	Research paper
Full Title:	What's in the sandwich? New P-T constraints for the (U)HP nappe stack of southern Dora-Maira Massif (Western Alps)
Short Title:	Prograde P-T evolution of (U)HP units in the southern DMM
Corresponding Author:	Chiara Groppo University of Torino Torino, ITALY
Corresponding Author E-Mail:	chiara.groppo@unito.it
Order of Authors:	Chiara Groppo Simona Ferrando Manuele Gilio Serena Botta Francesco Nosenzo Gianni Balestro Andrea Festa Franco Rolfo
Abstract:	<p>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 (500-520°C, 20-24 kbar), and followed the same prograde path, suggesting similar burial mechanisms. The UHP BIU followed an early prograde evolution similar to that of the other eclogitic units of the southern DMM tectonic “sandwich”. The attainment of UHP peak conditions occurred through an earlier steep, almost isothermal increase in pressure and a later increase in temperature. The DSU is the only unit of the southern DMM nappe stack that did not experience eclogite-facies metamorphism (peak metamorphism at blueschist-facies conditions: 450-470 °C, 17-18 kbar) and it is separated from the eclogitic units by a shear zone (the Valmala Shear Zone), whose interpretation requires further studies. These new data represent the inescapable starting point for any conceptual model aiming for a deeper understanding of the subduction/exhumation processes of UHP</p>

	continental units.
Keywords:	(U)HP metamorphism; southern Dora-Maira Massif; peak P-T conditions; prograde evolution; P-T pseudosections
Manuscript Region of Origin:	ITALY
Requested Editor:	Patrick Cordier, Editor-in-Chief
Additional Information:	
Question	Response
Author Comments:	
Response to Reviewers:	<p>Dear Editor, the two reviewers and your own constructive comments have been carefully considered in order to improve the revised version of our manuscript. Please, find in the "ANSWERS TO EDITOR AND REVIEWERS".pdf file how and where the editor + reviewers comments have been incorporated in the manuscript. We hope that the manuscript now meets your approval for publication in European Journal of Mineralogy.</p> <p>With best regards, Chiara Groppo and co-authors</p>

1 **Cover Page**

2

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

5

6

7 Running title

8 **Prograde P-T evolution of (U)HP units in the southern DMM**

9

10 **Detailed plan of the article:**

11 1. Introduction

12 2. Geological setting

13 3. Methods

14 3.1 Micro-X-ray fluorescence (μ -XRF) maps

15 3.2 Mineral chemistry

16 3.3 Pseudosection modelling

17 3.4 Optimal thermobarometry

18 4. Petrography and mineral chemistry

19 4.1 Sample DM 1485 (PU)

20 4.2 Sample DM1667c (SCU)

21 4.3 Sample DM1281 (BIU)

22 4.4 Sample DM1504 (RSU)

23 4.5 Sample DM1565 (DSU)

24 5. Resulting P-T evolution

25 5.1 Sample DM1485 (PU)

26 5.2 Sample DM1667c (SCU)

27 5.3 Sample DM1281 (BIU)

28 5.4 Sample DM1504 (RSU)

29 5.5 Sample DM1565 (DSU)

30 6. Discussion

31 6.1 New constraints on the prograde evolution of the tectonic units in the southern DMM

32 6.1.1 Prograde evolution of the HP units bounding the UHP BIU

33 6.1.2 Prograde P-T path revised for the UHP BIU

34 6.2 Implications for the geodynamic interpretation of the southern DMM

35 Acknowledgements

36 References

37 Figure captions

38

39 **Corresponding author:**

40 Chiara Groppo

41 Dept. of Earth Sciences, University of Torino

42 Via Valperga Caluso, 35, 10125 Torino (Italy)

43 chiara.groppo@unito.it

44 Tel. +39/0116705106

45 Fax: +39/0116705128

46 **Title Page**

47

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

50

51

52

53

54 Chiara Groppo^{1,2,*}, Simona Ferrando¹, Manuele Gilio¹, Serena Botta¹, Francesco Nosenzo¹, Gianni
55 Balestro¹, Andrea Festa¹, Franco Rolfo^{1,2}

56

57

58 ¹Department of Earth Sciences, University of Torino, via Valperga Caluso 35, 10125 Torino, Italy

59 ²CNR-IGG, via Valperga Caluso 35, 10125 Torino, Italy

60 *Corresponding author: chiara.groppo@unito.it

61

62 **Abstract**

63 The Brossasco-Isasca Unit (BIU) of the southern Dora-Maira Massif (DMM), Western Alps, is one of the most
64 studied ultra-high pressure (UHP) units in the world. However, the interpretation of UHP metamorphism in
65 the BIU is still a highly debated and challenging issue. The structural and tectonometamorphic setting of the
66 southern DMM is described in the literature as a tectonic “sandwich”, with the UHP unit in the middle,
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.

89
90 **Key-words**

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

93

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; Schmalholz *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
111 after the discovery of coesite in the BIU. Decades later, the alternative idea of tectonic overpressure
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
118 the top of the tectonometamorphic package (Fig. 1). In contrast to the well-constrained P-T evolution of the
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
134 to five samples (one for each unit). Concerning the HP units bounding the UHP BIU, our results confirm peak-
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

140 in continental crust; however, further studies are needed in order to understand if (and how) the studied
141 units shared part of their prograde evolution at HP to UHP conditions or if (and how) they were coupled
142 during exhumation.

143

144 **2. Geological setting**

145 The Dora-Maira Massif (DMM) in the Western Alps, represents part of the subducted-exhumed European
146 continental margin (*e.g.*, Michard *et al.*, 1996). It is now stacked in the Alpine orogenic wedge (Lardeaux *et al.*,
147 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
150 Permian igneous bodies (*e.g.*, Vialon, 1966; Henry, 1990; Chopin *et al.*, 1991; Michard *et al.*, 1993, 1995;
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 &
164 Hermann, 2001; Hermann, 2003; Ferraris *et al.*, 2005; Di Vincenzo *et al.*, 2006; Castelli *et al.*, 2007; Groppo
165 *et al.*, 2007a; Ferrando *et al.*, 2009; Gauthiez-Putallaz *et al.*, 2016); (iv) the Rocca Solei Unit, lithologically
166 similar to the BIU and the SCU, experienced Alpine peak P-T conditions at quartz-eclogite facies conditions
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 al.*,
173 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
183 the Department of Earth Sciences, University of Torino. Operating conditions were: 100 ms counting time,
184 40 kV accelerating voltage, and a probe current of 900 μ A. A spatial resolution of about 65 μ m in both x and

185 y directions was used. Quantitative modal amounts of each mineral phase were obtained by processing the
186 maps with the software Petromod (Cossio *et al.*, 2002). For each sample, the processed X-ray maps are
187 reported in Fig. 2. Additional microstructural details, at greater magnification, are given in Figs. 3-5. Mineral
188 abbreviations are after Whitney & Evans (2010), except white mica (Wm) and phengite (Phe).
189

190 **3.2 Mineral chemistry**

191 The rock-forming minerals were analyzed with a Jeol JSMIT300LV Scanning Electron Microscope at the
192 Department of Earth Sciences, University of Torino. The instrument was equipped with an energy dispersive
193 spectrometry (EDS) Energy 200 system and an SDD X-Act3 detector (Oxford Inca Energy). Operating
194 conditions were: 50 s counting time, 15 kV accelerating voltage, spot size 2 μm . SEM-EDS quantitative data
195 were acquired and processed using the Microanalysis Suite Issue 12, INCA Suite version 4.01; natural mineral
196 standards were used to calibrate the raw data; the $\phi\rho\rho Z$ correction (Pouchou & Pichoir, 1988) was applied.
197 Tables SM1 and SM2-SM6, freely available online as Supplementary Material linked to this article on the GSW
198 website of the journal, <https://pubs.geoscienceworld.org/eurljmin/>, summarize the compositional variations
199 (Table SM1) and the representative chemical compositions for the main minerals in each sample; Figs. 6-7
200 and SM1 show the composition of garnet and phengite. For practical purposes, the term phengite is used in
201 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**

205 The pseudosection modeling approach was applied to each metapelite sample, excluding DM1565. Bulk-rock
206 composition of each sample (Table 1) was calculated by combining estimated mineral modes with mineral
207 chemistry (see above). Determination of an effective bulk composition for sample DM1565 (DSU) was
208 problematic because: (i) the fine-grained nature of Alpine Grt₂ hampered its correct quantification from
209 micro-XRF maps; (ii) the presence of pre-Alpine garnet porphyroblasts (Grt₁), that should be subtracted from
210 the bulk-composition effectively reacting during Alpine metamorphism, makes the conventional bulk-rock
211 analysis (*e.g.*, XRF or ICP-MS) not suitable.

212 For each considered sample, three P-T isochemical phase diagrams have been calculated (*i.e.*, a total
213 of 12 pseudosections) considering the fractionation effects on the bulk-composition due to the growth of
214 zoned garnet porphyroblasts. Each pseudosection was used to model: (i) P-T conditions for garnet core
215 growth (measured bulk-composition: MBC), (ii) P-T conditions for garnet mantle growth (MBC minus garnet
216 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-Na₂O-
218 K₂O-CaO-FeO-MgO-Al₂O₃-SiO₂-TiO₂-Fe₂O₃-H₂O), except for sample DM1281 (BIU), for which Fe³⁺ was
219 neglected, because Fe³⁺-rich oxides are absent and the amount of Fe³⁺ in the analyzed minerals is very low.
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 H₂O 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 H₂O ($a_{\text{H}_2\text{O}}=1$), but a reduced $a_{\text{H}_2\text{O}}=0.4$ was considered in the pseudosection that
227 models the garnet rim growth in DM1281 (BIU) because experimental and fluid inclusions studies (Sharp *et al.*,
228 1993; Hermann, 2003; Ferrando *et al.*, 2009) demonstrated that, at the UHP peak, the activity of H₂O was
229 strongly reduced by the abundance of dissolved species.

230

231 **3.4 Optimal thermobarometry**

232 The THERMOCALC “Average PT” (AvPT) method (*i.e.*, “Optimal thermobarometry”: Powell & Holland, 1994)
233 was applied to all the samples. THERMOCALC v3.40 and the Holland & Powell (2011) dataset (ds62) were
234 used. Activity-composition relationships were calculated using the software AX. The method was applied to
235 the peak assemblage for all the samples, except sample DM1281 (BIU), for which it was applied to the late
236 prograde assemblage (see Section 4.3). Used sets of mineral compositions and of independent reactions are
237 given in Tables SM2-SM7. AvPT results are discussed in terms of weighted means (*i.e.*, values with smaller
238 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)**

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

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

253 Phengite defines the S_m and rarely occurs, in association with paragonite and relict chloritoid, in
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_m , 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_m and it is thus interpreted as a retrograde phase.

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

265

266 **4.2 Sample DM1667c (SCU)**

267 This garnet-bearing phengitic micaschist has a strongly heterogeneous grain size. It shows a mm-thick banded
268 structure, with continuous medium- to coarse-grained phengite-rich layers alternating with fine- to medium-
269 grained discontinuous quartz-rich layers (Fig. 2). It consists of white mica (mostly phengite: 42%), garnet
270 (30%), quartz (18%) and minor chloritoid (1%). Retrograde chlorite (7%), epidote (1%), minor biotite, and
271 accessory magnetite, rutile, ilmenite, tourmaline and apatite also occur. The main foliation (S_m) is defined by
272 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 μm) and discontinuous outer rim
282 slightly enriched in Mn has been interpreted as due to local retrograde re-equilibration.

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

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

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

297

298 **4.3 Sample DM1281 (BIU)**

299 This sample consists of white mica (mostly phengite, 41%), quartz (24%), garnet (21%), kyanite (10%), jadeite
300 (3%) and minor chloritoid, staurolite and chlorite (Fig. 2). Albite and pyrophyllite are retrograde phases,
301 whereas rutile, tourmaline and apatite are the main accessory minerals. The grain size is markedly
302 heterogeneous, with pluri-mm garnet and kyanite porphyroblasts set in a fine-grained matrix mostly
303 consisting of phengite and quartz (Fig. 2). The main schistosity (S_m) is defined by mm-thick, continuous
304 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_m . 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).
312 Monocrystalline inclusions in garnet mantle are represented by pseudomorphs after jadeite and glaucophane
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).

316 Phengite defines the S_m and is locally included in garnet rim. Retrograde muscovite is scarce and its
317 occurrence is limited to the pseudomorphs after jadeite and glaucophane. A few prograde muscovite flakes
318 are preserved in the polymineralic inclusions within garnet core. Paragonite is common in the polymineralic
319 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)
321 porphyroblasts enveloped by the main foliation (Fig. 4b); ii) smaller idioblasts in equilibrium with the S_m (Fig.
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.

328 Chloritoid, chlorite and staurolite only occur in the fine-grained polymineralic inclusions within garnet
329 core and mantle (Fig. 4d,e). Chlorite is a prograde phase and the X_{Mg} of the chlorite included in garnet mantle
330 is higher than that of the chlorite included in garnet core (Table SM1). Chloritoid is generally associated with
331 paragonite and chlorite. Staurolite is only present as inclusion in both garnet core and mantle, where it mostly
332 occurs in association with kyanite, paragonite and chlorite, more rarely with chloritoid. Microstructural
333 relationships clearly show that staurolite grew at the expense of kyanite, often preserved as rounded relics
334 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)

338 This fine- to coarse-grained, garnet-bearing phengitic micaschist consists of white mica (mostly phengite, 49
339 % and paragonite, 6%), quartz (20%), chloritoid (12%) and garnet (8%) (Fig. 2), with minor amounts of
340 glaucophane and jadeite (almost completely replaced by retrograde phases). Retrograde chlorite (3%),
341 epidote (1%) and biotite, and accessory rutile, ilmenite, magnetite and apatite also occur. The main foliation
342 (S_m) is defined by mm- to pluri-mm -thick, continuous, micaceous layers alternated with mm-thick,
343 discontinuous, quartzitic layers. Relics of an earlier S_{m-1} schistosity are locally preserved in microlithons and
344 are defined by the alignment of white mica.

345 Mm- to pluri-mm -sized garnet porphyroblasts are partially enveloped by the S_m , 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.

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

361 Epidote, chlorite, albite and biotite are retrograde phases. Epidote within garnet occurs in tabular-
362 shaped aggregates, in association with quartz and white micas, interpreted as deriving from former lawsonite
363 (Fig. 5c). In the matrix, it forms few fine-grained idioblasts, often with an allanitic core. Aggregates of chlorite
364 statically overgrows the S_m and replaces garnet along fractures and at the rim. Its rim is locally replaced by
365 biotite. Albite occurs as replacement of jadeite and glaucophane.

366 Rutile mostly occurs as inclusion in garnet, whereas it is pervasively replaced by ilmenite in the
367 matrix. Retrograde magnetite is fine-grained and widespread in the matrix, and it is strongly oxidized. Apatite
368 occurs as relatively large grains both in the matrix and included in garnet.

369

370 **4.5 Sample DM1565 (DSU)**

371 This garnet-bearing phengitic micaschist consists of white mica (mostly phengite, 54% and paragonite, 8%),
372 quartz (26%), garnet (5%) and chloritoid (3%) (Fig. 2). Retrograde chlorite (3%) and biotite and accessory
373 rutile, ilmenite and tourmaline also occur. The main schistosity (S_m) is defined by pluri-mm thick, continuous,
374 micaceous layers alternating with mm-thick quartzitic layers. Large (pluri-mm) garnet porphyroblasts are
375 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_m , interpreted as amphibolite-facies Variscan garnets (Grt_1); (ii)
379 small (ca. 100 μm) idioblasts in equilibrium with S_m and a thin and discontinuous corona around
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_2
383 idioblasts are also zoned and include very fine-grained quartz (Fig. 6e and Table SM1).

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

390 Retrograde chlorite occurs as large flakes statically overgrowing the S_m and partially replacing garnet
391 at the rim and along fractures. Biotite is limited to late and discontinuous shear bands crosscutting the main
392 foliation. Accessory ilmenite is included in pre-Alpine garnet (Grt_1) and is rimmed by rutile, if it communicates
393 with the external matrix through fractures. In the matrix, rutile is rimmed by ilmenite.

394

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 $T < 550-600^\circ C$, 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.

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

412

413 **5.1 Sample DM1485 (PU)**

414 The observed prograde and peak assemblage (Qz + Phe + Grt + Chl + Cld + Rt + Ilm) is not modeled in the P-T
415 region of interest because chloritoid is always predicted to be stable with a Na-rich phase (either paragonite
416 or glaucophane), which was not observed in the studied sample. However, the occurrence of large oligoclase
417 porphyroblasts in the matrix statically overgrowing the main foliation suggests that one or more Na-rich
418 phases (e.g. glaucophane, paragonite) was likely stable in the prograde and peak assemblages and it is not
419 preserved. The glaucophane/paragonite-bearing assemblage (Qz + Phe + Grt + Chl + Cld + Gln/Pg + Rt + Ilm)
420 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 ($Sps_5Prp_6Grs_8Alm_{80}$) 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 ($Sps_{2.5}Prp_8Grs_{7.5}Alm_{81}$) and of its inclusions of chloritoid ($X_{Mg}=0.15$) 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 ± 7 °C, 19.0 ± 0.7 kbar (Table 2), consistent with the results of pseudosection modeling (Fig. 8c).

431

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_C + Chl + Cld + Ep + Rt + Ilm) and late prograde (Qz + Phe + Grt_M + Cld ± Chl ±
437 Ep/Lws + Rt + Ilm) 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 ($Sps_5Prp_{3.5}Grs_{26}Alm_{65}$) and its inclusions of phengite
441 ($Si=3.34-3.46$ a.p.f.u.) (Fig. 9a); (ii) late prograde P-T conditions are constrained at 480-490°C, 19-21 kbar
442 using the compositions of garnet mantle ($Sps_{2.5}Prp_5Grs_{24}Alm_{68}$) and of its inclusions of chloritoid ($X_{Mg}=0.20$)
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.

445 The observed peak assemblage (Qz + Phe + Grt_R + Cld + Lws + Rt + Ilm) is modeled by a relatively small
446 quadri-variant field at 450-520°, 22-27 kbar. The intersection of compositional isopleths for garnet rim
447 ($Sps_{0.8}Prp_{10}Grs_{18}Alm_{74}$) and its inclusions of chloritoid ($X_{Mg}=0.20$) and phengite ($Si=3.36-3.43$ a.p.f.u.) defines
448 peak P-T conditions at 500-520°C, 21-24 kbar (Fig. 9c). The AvPT approach applied to four different sets of
449 mineral compositions gives peak P-T conditions of 512 ± 8 °C, 21.9 ± 0.9 kbar (Table 2), consistent with the
450 results of pseudosection modeling (Fig. 9c).

451

452 **5.3 Sample DM1281 (BIU)**

453 Garnet core and its inclusions define the early prograde assemblage (Qz + Phe + Grt_C + Cld + Pg + Chl + Rt).
454 Staurolite is not considered as part of this assemblage due to its supposed retrograde nature (see
455 microstructural relationships presented in Section 4.3). This assemblage is modeled by a quadri-variant field
456 at 450-570°C, 10-18 kbar. The best fit between observed and modeled garnet (Sps_{6.5}Prp₁₂Grs₆Alm₇₄),
457 chloritoid (X_{Mg}=0.25) and chlorite (X_{Mg}=0.62) compositions constrains P-T conditions for the growth of garnet
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}Prp₁₉Grs₂Alm₇₆) 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).

474 The peak assemblage (Coe + Phe + Grt_R + Ky + Jd + Rt) is modelled by a large penta-variant field at T
475 > 530°C and P > 25 kbar. Although garnet (Sps_{1.7}Prp₂₆Grs_{3.5}Alm₆₈) compositional isopleths are far apart, their
476 intersection with phengite (Si = 3.45-3.49 a.p.f.u.) isopleths allows constraining peak P-T conditions at 660-
477 730°C and 38-43 kbar (Fig. 10c), consistent with the peak P-T conditions proposed in previous papers and
478 based on other lithologies (*i.e.*, pyrope-bearing whiteschists, eclogites, marbles; see review in Ferrando *et al.*,
479 2017). The AvPT approach applied on the peak assemblage did not converge to a result, because its
480 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 (Sps₉Prp_{8.5}Grs₁₆Alm₆₇), of its chloritoid inclusions (X_{Mg}=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 (Sps₆Prp_{9.5}Grs₂₀Alm₆₄), of its chloritoid inclusions (X_{Mg}=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}Prp₉Grs_{18.5}Alm₆₈), 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 ± 8 °C,
493 20.3 ± 0.6 kbar (Table 2), consistent with pseudosection results (Fig. 11c).

494

495 **5.5 Sample DM1565 (DSU)**

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

499 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 (Nosengo,
501 2018). The AvPT results point to peak P-T conditions of 452 ± 8 °C, 17.2 ± 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**

505 *6.1.1 Prograde evolution of the HP units bounding the UHP BIU*

506 The prograde P-T evolution inferred for the four units bounding the UHP BIU is summarized below:

- 507 - The PU experienced a prograde evolution starting in the lawsonite-blueschist facies and reaching peak
508 conditions in the eclogite-facies (500-515°C, 20-23 kbar; Fig. 12a). Peak-T conditions are similar to those
509 estimated by Avigad *et al.* (2003) (*i.e.*, 530 °C) using multi-equilibrium thermobarometry applied on
510 garnet-bearing metapelites from the same structural position. However, peak-P conditions are
511 significantly higher than the 14-16 kbar estimated by the same authors (Fig. 12a).
512
- 513 - The P-T prograde path inferred for the SCU and RSU is remarkably similar to that constrained for the PU,
514 with eclogite-facies peak P-T conditions at 500-520°C, 20-24 kbar (Fig. 12b, d). The estimated peak-P
515 conditions are significantly higher than those (500-550°C, 15 kbar) constrained by Chopin *et al.* (1991)
516 and Compagnoni & Rolfo (2003), whereas peak-T are in agreement with literature data (Fig. 12b, d).
517
- 518 - In contrast to the other units, the DSU did not experience eclogitic metamorphism. Estimated peak
519 conditions (450-470 °C, 17-18 kbar) point to lawsonite-blueschist facies conditions (Fig. 12e); peak-T are
520 similar to those reported by Chopin *et al.* (1991) (500°C, 10-12 kbar), but pressures are significantly higher
521 (Fig. 12e).

522 Overall, our new data for the HP units bounding the UHP one substantially confirm peak-T already
523 estimated more than 25 years ago, but point to a significant increase of peak-P estimates ($\Delta P = 5-10$ kbar).
524 This is the same trend already followed in the definition of peak P-T conditions for the UHP BIU, that were
525 initially estimated to be at about 30 kbar (*e.g.*, Chopin *et al.*, 1991; Compagnoni *et al.*, 1995) and progressively
526 increased (35 kbar: *e.g.*, Compagnoni & Rolfo, 2003) up to 40-43 kbar (*e.g.*, Hermann, 2003; Castelli *et al.*,
527 2007; Groppo *et al.*, 2007a; Ferrando *et al.*, 2009, 2017), in parallel with the progressive improvement of
528 thermodynamic modeling approaches that extended the limits of conventional thermobarometry.

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

544 & Hirajima (2001) interpreted the coexistence of chloritoid, kyanite, staurolite and chlorite in the
545 polymineralic inclusions hosted within garnet cores as evidence that the BIU prograde trajectory passed close
546 to the invariant point involving $\text{Cld} + \text{Ky} + \text{St} + \text{Chl}$, located around 600°C, 15 kbar. This was considered as a
547 pinning point for the BIU prograde path for more than 25 years, resulting in a steep prograde trajectory
548 located at temperatures significantly higher than the peak-T conditions estimated at that time for the
549 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: $\text{Chl} + \text{Ky} + \text{Grt} = \text{St}$ (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⁻¹, 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
598 through an earlier almost isothermal increase in pressure ($\Delta P=8-10$ kbar) along a significantly lower T/P
599 gradient (ca. $3^{\circ}\text{C kbar}^{-1}$) and a later increase in temperature ($\Delta T=150-170$ °C) along a medium T/P gradient
600 (ca. $15^{\circ}\text{C kbar}^{-1}$). 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.

604 (3) the DSU is the only unit of the southern DMM tectonic “sandwich” that, according to our results, did not
605 experience eclogite-facies metamorphism. It is worth noting that, on the field, the DSU is separated from
606 the eclogitic units by a hundreds of metres thick shear zone (tectonic *mélange sensu* Festa *et al.*, 2019),
607 which includes slices of meta-ophiolite (Valmala Shear Zone: Nosenzo, 2018). The detailed description
608 and interpretation of this shear zone is beyond the aim of this paper and further studies are necessary
609 to understand its role in decoupling the southern DMM during subduction and/or in driving exhumation
610 of related (U)HP units.

611

612 **Acknowledgements**

613 Roberto Compagnoni introduced most of us to the fascinating southern Dora-Maira Massif and to the beauty
614 and challenges of metamorphic petrology. R. Compagnoni, R. Turello and T. Hirajima collected sample
615 DM1281 studied in this paper. Two anonymous reviewers provided constructive comments which
616 significantly improved the manuscript; the Guest Editor is warmly thanked for its several constructive
617 remarks and its meticulous editorial handling. This research was funded by University of Torino, Ricerca
618 Locale, ex-60% 2016, 2017 funds: FERS_RILO_17_01 (SF), FESA_RILO_17_01 (AF), GROC_RILO_17_01 (CG),
619 ROLF_RILO_16_01 (FR), and by the Italian Ministry of University and Research, PRIN 2015: 2015EC9PJ5 (GB).

620

621 **References**

622

- 623 Avigad, D., Chopin, C., Le Bayon R. (2003): Thrusting and extension in the southern Dora-Maira ultra-high
624 pressure massif (Western Alps): view from below the coesite-bearing unit. *J. Geol.*, **111**, 57–70.
- 625 Balestro, G., Cadoppi, P., Di Martino, L., Sacchi, R. (1995): Il settore meridionale del Massiccio Dora-Maira
626 (Valli Maira e Varaita): inquadramento, carta geologica e guida a un'escursione. Rapporti Alpi-Appennino
627 e guida alle escursioni. *Accademia Nazionale delle Scienze*, **14**, 501–529.
- 628 Balestro, G., Festa, A., Borghi, A., Castelli, D., Gattiglio, M., Tartarotti, P. (2018): Role of Late Jurassic intra-
629 oceanic structural inheritance in the Alpine tectonic evolution of the Monviso meta-ophiolite Complex
630 (Western Alps). *Geol. Magaz.*, **155** (2), 233-249.
- 631 Biino, G. & Compagnoni R. (1992): Very high pressure metamorphism of the Brossasco coronite metagranite,
632 southern Dora-Maira Massif, Western Alps. *Schweiz. Mineral. Petrogr. Mitt.*, **72**, 347–363.
- 633 Botta, S. (2015): Studio geologico-petrografico dell'Unità di Rocca Solei, Massiccio Dora-Maira meridionale
634 (Alpi Occidentali). Unpublished MSc Thesis, Univ. Torino, Italy, 245 pp.
- 635 Burov, E., Francois, T., Yamato, P., Wolf, S. (2014): Mechanisms of continental subduction and exhumation
636 of HP and UHP rocks. *Gondw. Res.*, **25**, 464–493.
- 637 Butler, J.P., Beaumont, C., Jamieson, R.A. (2013): The Alps 1: a working geodynamic model for burial and
638 exhumation of (ultra)high-pressure rocks in Alpine-type orogens. *Earth Planet. Sci. Lett.*, **377–378**, 114–
639 131.
- 640 Castelli, D., Rolfo, F., Groppo, C., Compagnoni, R. (2007): Impure marbles from the UHP Brossasco-Isasca Unit
641 (Dora-Maira Massif, Western Alps): evidence for Alpine equilibration in the diamond stability field and
642 evaluation of the X(CO₂) fluid evolution. *J. metamorphic Geol.*, **25**, 587–603.
- 643 Chemenda, A.I., Mattauer, M., Mattavieille, J., Bokun, A.N. (1995): A mechanism for syn-collisional rock
644 exhumation and associated normal faulting: results from physical modelling. *Earth Planet. Sci. Lett.* **132**,
645 225–232.
- 646 Chopin, C. (1984): Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and
647 some consequences. *Contrib. Mineral. Petrol.*, **86**, 107–118.
- 648 — (2003): Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. *Earth Planet. Sci.*
649 *Lett.*, **212**, 1–14.
- 650 Chopin, C., Henry, C. Michard, A. (1991): Geology and petrology of the coesite-bearing terrain, Dora Maira
651 Massif, Western Alps. *Eur. J. Mineral.*, **3**, 263–291.
- 652 Compagnoni, R. & Hirajima, T. (2001): Superzoned garnets in the coesite-bearing Brossasco-Isasca Unit, Dora-
653 Maira massif, western Alps, and the origin of the whiteschists. *Lithos*, **57**, 219–236.
- 654 Compagnoni, R. & Rolfo, F. (1999): Characteristics of UHP pelites, gneisses and other unusual rocks.
655 *International Geology Review*, **41**, 552-570.
- 656 —, — (2003): Ultrahigh-pressure units in the Western Alps. *in: "Ultrahigh-pressure metamorphism"*, D.A.
657 Carswell & R. Compagnoni, eds, *EMU Notes in Mineralogy*, **5**, 13–49.
- 658 Compagnoni, R., Hirajima, T., Chopin, C. (1995): Ultra-high pressure metamorphic rocks in the Western Alps.
659 *in: "Ultrahigh Pressure Metamorphism"*, R.G. Coleman & X. Wang, eds., Cambridge University Press, 206–
660 243.
- 661 Compagnoni, R., Rolfo, F., Groppo, C., Hirajima, T., Turello R. (2004): Mapping of Alpine rocks characterized
662 by "HP" to "UHP" metamorphic overprint in the southern Dora-Maira Massif (Western Alps). *in: "Mapping*
663 *Geology in Italy"*, G. Pasquare & C. Venturini, eds., APAT, Dipartimento Difesa del Suolo, Servizio Geologico
664 d'Italia, Roma 2004 (2006), **Map 34**, 287–294, Printed by S.EL.CA., Firenze.
- 665 Compagnoni, R., Rolfo, F., Groppo, C., Hirajima, T., Turello R. (2012): Geologic map of the UHP Brossasco-
666 Isasca Unit (Western Alps). *J. Maps*, **8/4**, 465–472.

- 667 Connolly (1990): Multivariable phase diagrams: an algorithm based on generalized thermodynamics. *Am. J.*
668 *Sci.*, **290**, 666–718.
- 669 — (2005): Computation of phase equilibria by linear programming: A tool for geodynamic modeling and its
670 application to subduction zone decarbonation. *Earth Planet. Sci. Lett.*, **236**, 524–541.
- 671 — (2009): The geodynamic equation of state: what and how. *Geochem. Geophys. Geosyst.*, **10**, Q10014.
- 672 Cossio, R., Borghi, A., Ruffini, R. (2002): Quantitative modal determination of geological samples based on X-
673 ray multielemental map acquisition. *Microsc. Microanal.*, **8**, 139–149.
- 674 Di Vincenzo, G., Tonarini, S., Lombardo, B., Castelli, D., Ottolini, L. (2006): Comparison of ⁴⁰Ar–³⁹Ar and Rb–Sr
675 data on phengites from the UHP Brossasco-Isasca Unit (Dora Maira Massif, Italy): Implications for dating
676 white mica. *J. Petrol.*, **47**, 1439–1465.
- 677 Ferrando, S., Frezzotti, M.L., Petrelli, M., Compagnoni, R. (2009): Metasomatism of continental crust during
678 subduction: the UHP white schists from the southern Dora-Maira Massif (Italian Western Alps). *J.*
679 *metamorphic Geol.*, **27**, 739–756.
- 680 Ferrando, S., Groppo, C., Frezzotti, M.L., Castelli, D., Proyer, A. (2017): Dissolving dolomite in a stable UHP
681 mineral assemblage: evidence from Cal-Dol marbles of the Dora-Maira Massif (Italian Western Alps). *Am.*
682 *Mineral.*, **102**, 42–60.
- 683 Ferraris, C., Castelli, D., Lombardo, B. (2005): SEM/TEM-AEM characterization of micro- and nano-scale
684 zonation in phengite from a UHP Dora-Maira marble: Petrologic significance of armoured Si-rich domains.
685 *Eur. J. Mineral.*, **17**, 453–464.
- 686 Festa, A., Pini, G.A., Ogata, K., Dilek, Y. (2019): Diagnostic features and field-criteria in recognition of tectonic,
687 sedimentary and diapiric mélanges in orogenic belts and exhumed subduction-accretion complexes.
688 *Gondw. Res.*, **online version**, <https://doi.org/10.1016/j.gr.2019.01.003>.
- 689 Ford, M., Duchéne, S., Gasquet, D., Vanderhaeghe, O. (2006): Two-phase orogenic convergence in the
690 external and internal SW Alps. *J. Geol. Soc.*, **163**, 815–826.
- 691 Fuhrman, M.L. & Lindsley, D.H. (1988): Ternary-Feldspar Modeling and Thermometry. *Am. Mineral.*, **73**, 201–
692 215.
- 693 Gauthiez-Putallaz, L., Rubatto, D., Hermann, J. (2016): Dating prograde fluid pulses during subduction by in
694 situ U–Pb and oxygen isotope analysis. *Contrib. Mineral. Petrol.*, **171**, article 15, 20 pp.
- 695 Gerya, T. (2015): Tectonic overpressure and underpressure in lithospheric tectonics and metamorphism. *J.*
696 *metamorphic Geol.*, **33**, 785–800.
- 697 Gerya, T. & Stöckhert, B. (2006): Two-dimensional numerical modeling of tectonic and metamorphic histories
698 at active continental margins. *Int. J. Earth Sci. (Geol. Rundsch.)*, **95**, 250–274.
- 699 Godard, G. (2009): Two orogenic cycles in eclogite-facies gneisses of the Southern Armorican Massif (France).
700 *Eur. J. Mineral.*, **21**, 1173–1190.
- 701 Green, E.C.R., Holland, T.J.B., Powell, R. (2007): An order–disorder model for omphacitic pyroxenes in the
702 system jadeite–diopside–hedenbergite–acmite, with applications to eclogite rocks. *Am. Mineral.*, **92**,
703 1181–1189.
- 704 Green, E.C.R., White, R.W., Diener, J.F.A., Powell, R., Holland, T.J.B., Palin, R.M. (2016): Activity–composition
705 relations for the calculation of partial melting equilibria in metabasic rocks. *J. metamorphic Geol.*, **34**, 845–
706 869.
- 707 Groppo, C. (2002): Studio geologico-petrografico della terminazione nord-occidentale dell’Unita Brossasco-
708 Isasca in facies eclogitica a coesite, Massiccio Dora-Maira (Alpi Occidentali). Unpublished M.Sc. Thesis,
709 Univ. Torino, Italy, 175 pp.
- 710 Groppo, C., Castelli, D., Compagnoni, R. (2006): Late chloritoid-staurolite assemblage in a garnet-kyanite
711 bearing metapelite from the UHP Brossasco-Isasca Unit (Dora-Maira Massif, Western Alps): new
712 petrological constraints for a portion of the P-T decompressional path. *in*: “Ultrahigh-pressure

- 713 metamorphism: Deep continental subduction”, B.H. Hacker, W.C. McClelland & J.G. Liou J.G., eds., GSA
714 Special Paper, **403**, 127–138.
- 715 Groppo, C., Castelli, D., Rolfo, F. (2007b): HT, Pre-Alpine relics in a spinel-bearing dolomite marble from the
716 UHP Brossasco-Isasca Unit (Dora-Maira Massif, western Alps). *Per. Mineral.*, **76**, 155–168.
- 717 Groppo, C., Lombardo, B., Castelli, D., Compagnoni, R. (2007a): Exhumation history of the UHPM Brossasco-
718 Isasca Unit, Dora-Maira Massif, as inferred from a phengite-amphibole eclogite. *Int. Geol. Rev.*, **49**, 142–
719 168.
- 720 Guiraud, M., Holland, T.J.B., Powell R. (1990): Calculated mineral equilibria in the greenschist-blueschist-
721 eclogite facies in Na₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O: methods, results and geological applications. *Contrib.*
722 *Mineral. Petrol.*, **104**, 85–98.
- 723 Henry, C. (1990): L’unité à coesite du massif Dora-Maira dans son cadre pétrologique et structurale (Alpes
724 Occidentales, Italie). Thèse Doctorat., Université Paris 6, 149 pp.
- 725 Henry, C., Michard, A., Chopin, C. (1993) : Geometry and structural evolution of ultra-high pressure and high
726 pressure rocks from the Dora-Maira massif, western Alps, Italy. *J. Struct. Geol.*, **15**, 965–981.
- 727 Hermann, J. (2003): Experimental evidence for diamond-facies metamorphism in the Dora-Maira massif.
728 *Lithos*, **70**, 163–182.
- 729 Holland, T.J.B. & Powell, R. (1998): An internally consistent thermodynamic dataset for phases of petrological
730 interest. *J. metamorphic Geol.*, **16**, 309–343.
- 731 —, — (2011): An improved and extended internally consistent thermodynamic dataset for phases of
732 petrological interest, involving a new equation of state for solids. *J. metamorphic Geol.*, **29**, 333–383.
- 733 Lardeaux, J., Schwartz, S., Tricart, P., Paul, A., Guillot, S., Béthoux, N., Masson, F. (2006): A crustal-scale cross-
734 section of the south-western Alps combining geophysical and geological imagery. *Terra Nova*, **18** (6), 412–
735 422.
- 736 Li, Z., Gerya, T.V., Burg, J.P. (2010). Influence of tectonic overpressure on P-T paths of HP–UHP rocks in
737 continental collision zones: thermomechanical modelling. *J. metamorphic Geol.*, **28**, 227–247.
- 738 Liou, J.G. & Zhang, R.Y. (2002): Ultrahigh-pressure metamorphic rocks. Ency Phys Sci Tech (Third Edition). 17,
739 Academia Press, 227–244.
- 740 Manzotti, P., Pitra, P., Langlade, J., Ballèvre, M. (2015): Constraining P-T conditions during thrusting of a
741 higher pressure unit over a lower pressure one (Gran Paradiso, Western Alps). *J. metamorphic Geol.*, **33**,
742 981–1002.
- 743 Manzotti, P., Ballèvre, M., Poujol, M. (2016): Detrital zircon geochronology in the Dora Maira and Zone
744 Houillère: A record of sediment travel paths in the Carboniferous. *Terra Nova*, **28**, 279–288.
- 745 Matsumoto, N. & Hirajima, T. (2000): Garnet in pelitic schists from a quartz-eclogite unit of the southern
746 Dora-Maira massif, Western Alps. *Schweiz. Mineral. Petrol. Mitt.*, **80**, 53–62.
- 747 Manzotti, P., Bosse, V., Pitra, P., Robyr, M., Schiavi, F., Ballèvre, M. (2018): Exhumation rates in the Gran
748 Paradiso (Western Alps) constrained by in situ U-Th-Pb dating of accessory phases (monazite, allanite and
749 xenotime). *Contrib. Mineral. Petrol.*, **173**, 24.
- 750 Michard, A., Chopin, C., Henry, C. (1993): Compression versus extension in the exhumation of the Dora-Maira
751 coesite-bearing unit, Western Alps. *Tectonophysics*, **221**, 173–193.
- 752 Michard, A., Henry, C., Chopin, C. (1995): Structures in UHPM rocks: a case study from the Alps. in: “Ultrahigh
753 Pressure Metamorphism”, R.G. Coleman & X. Wang, eds., Cambridge University Press, 132-158.
- 754 Michard, A., Goffe, B., Chopin, C., Henry, C. (1996): Did the Western Alps develop through an Oman-type
755 stage? The geotectonic setting of high-pressure metamorphism in two contrasting Tethyan transects. *Ecl.*
756 *Geol. Helv.*, **89**, 43– 80.
- 757 Nosenzo (2018): Studio geologico-strutturale e metamorfico del massiccio Dora-Maira meridionale in
758 Valmala (Valle Varaita, Alpi Occidentali). Unpublished M.Sc. Thesis, Univ. Torino, Italy, 187 pp.

- 759 Nowlan, E.U., Schertl, H.P., Schreyer, W. (2000): Garnet–omphacite–phengite thermobarometry of eclogites
760 from the coesite-bearing unit of the southern Dora-Maira Massif, Western Alps. *Lithos*, **52**, 197–214.
- 761 Pouchou, J.L. & Pichoir, F. (1988): Determination of mass absorption coefficients for soft X-rays by use of the
762 electron microprobe. Microbeam Analysis. San Francisco Press, San Francisco, 319–324 p.
- 763 Powell, R. & Holland, T.J.B. (1994): Optimal geothermometry and geobarometry. *Am. Mineral.*, **79**, 120–133.
- 764 Proyer, A. (2003): Metamorphism of pelites in NKFMAH - a new petrogenetic grid with implications for the
765 preservation of high pressure mineral assemblages during exhumation. *J. metamorphic Geol.*, **21**, 493–
766 509.
- 767 Reuber, G., Kaus, B.J.P., Schmalholz, S.M., White, R.W. (2016): Nonlithostatic pressure during subduction and
768 collision and the formation of (ultra)high-pressure rocks. *Geology*, **44**, 343–346.
- 769 Rubatto, D. & Hermann, J. (2001): Exhumation as fast as subduction? *Geology*, **29**, 3–6.
- 770 Sandrone R., Cadoppi P., Sacchi R., Vialon P. (1993): The Dora-Maira Massif. in: “Pre-Mesozoic Geology in the
771 Alps”, J.F. von Raumer & F. Neubauer, eds., Springer-Verlag, 317–325.
- 772 Schenker, F.L., Schmalholz, S.M., Moulas, E., Pleuger, J., Baumgartner, L.P., Podladchikov, Y., Vrijmoed, J.,
773 Buchs, N., Müntener O. (2015): Current challenges for explaining (ultra)high-pressure tectonism in the
774 Pennine domain of the Central and Western Alps. *J. metamorphic Geol.*, **33**, 869–886.
- 775 Schertl, H.P. & O’Brien, P.J. (2013): Continental Crust at Mantle Depths: Key Minerals and Microstructures.
776 *Elements*, **9**, 261–266.
- 777 Schertl, H.P., Schreyer, W., Chopin, C. (1991): The pyrope-coesite rocks and their country rocks at Parigi, Dora
778 Maira Massif, Western Alps: detailed petrography, mineral chemistry and P-T path. *Contrib. Mineral.
779 Petrol.*, **108**, 1–21.
- 780 Schmalholz, S.M. & Duretz, T. (2015): Shear zone and nappe formation by thermal softening, related stress
781 and temperature evolution, and application to the Alps *J. metamorphic Geol.*, **33**, 887–908.
- 782 Schmalholz, S.M., Duretz, T., Schenker, F.L., Podladchikov, Y.Y. (2014): Kinematics and dynamics of tectonic
783 nappes: 2-D numerical modelling and implications for high and ultrahigh pressure tectonism in the
784 Western Alps. *Tectonophysics*, **631**, 160–175.
- 785 Sharp, Z.D., Essene, E.J., Hunziker, J.C. (1993): Stable isotope geochemistry and phase equilibria of coesite-
786 bearing whiteschists, Dora Maira Massif, western Alps. *Contrib. Mineral. Petrol.*, **114**, 1–12.
- 787 Smith, D.C. (1984): Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature*,
788 **310**, 641–644.
- 789 Smye, A.J., Greenwood, L.V., Holland, T.J.B. (2010): Garnet–chloritoid–kyanite assemblages: eclogite facies
790 indicators of subduction constraints in orogenic belts. *J. metamorphic Geol.*, **28**, 753–768.
- 791 Solarino, S., Malusà, M.G., Eva, E., Guillot, S., Paul, A., Schwartz, S., Zhao, L., Aubert, C., Dumont, T., Pondrelli,
792 S., Salimbeni, S., Wang, Q., Xu, X., Zheng, T., Zhu, R. (2018): Mantle wedge exhumation beneath the Dora-
793 Maira (U)HP dome unravelled by local earthquake tomography (Western Alps). *Lithos*, **296–299**, 623–636.
- 794 Stöckhert, B. & Gerya, T.V. (2005): Pre-collisional high pressure metamorphism and nappe tectonics at active
795 continental margins: a numerical simulation. *Terra Nova*, **17**, 102–110.
- 796 Turello, R. (1993): Studio geologico e petrografico dell’area tra Martiniana (Valle Po) e Brossasco (Valle
797 Varaita) - Massiccio Dora-Maira meridionale. Unpublished M.Sc. Thesis, Univ. Torino, Italy, 238 pp.
- 798 Vialon, P. (1966): Etude géologique du Massif Cristallin Dora-Maira, Alpes Cottiennes internes, Italie. PhD
799 Tesis, Univ. Grenoble, Travaux du Lab. Géol. Fac. Sci. Grenoble, Memoir 4, 193 pp
- 800 Wei, C.J. & Powell, R. (2004): Calculated phase relations in high-pressure metapelites in the system NKFMAH
801 (Na₂O-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O). *J. Petrol.*, **45**, 183–202.
- 802 —, — (2006): Calculated phase relations in the system NCKFMASH (Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O)
803 for high-pressure metapelites. *J. Petrol.*, **47**, 385–408.

804 White, R.W., Powell, R., Holland, T.J.B., Johnson, T.E., Green, E.C.R. (2014): New mineral activity–composition
805 relations for thermodynamic calculations in metapelitic systems. *J. metamorphic Geol.*, **32**, 261–286.
806 Whitney, D.L. & Evans, B.W. (2010): Abbreviations for names of rock-forming minerals. *Am. Mineral.*, **95**,
807 185–187.
808 Yamato, P., Burov, E., Agard, P., Le Pourhiet, L., Jolivet, L. (2008): HP-UHP exhumation during slow continental
809 subduction: self-consistent thermodynamically and thermomechanically coupled model with application
810 to the Western Alps. *Earth Planet. Sci. Lett.*, **271**, 63–74.
811

812 **Figure captions**

813 **Fig. 1** – Simplified geological map (a) of the southern Dora-Maira Massif around the UHP Brossasco-Isasca
814 Unit (modified from Compagnoni *et al.*, 2012, and with unpublished data from Botta, 2015, and Nosenzo,
815 2018). Sample locations are shown by black stars both in the map and cross sections. The Polymetamorphic
816 and Monometamorphic Complexes in the SCU, BIU, RSU and DSU refer to a Variscan amphibolite-facies
817 metamorphic basement and to Permian igneous bodies, respectively, each of which reworked during Alpine
818 metamorphism. The insets (b, c) show the location of the southern DMM in north-west Italy (b) and within a
819 simplified tectonic sketch-map of the Western Alps (c).

820
821 **Fig. 2** – Processed micro-XRF maps of the studied metapelites. For sample DM1565 (DSU), Grt_c and Grt_M refer
822 to pre-Alpine Grt₁ porphyroblasts, whereas Alpine Grt₂ idioblasts in the matrix are reported as Grt_R. Dark-
823 grey to black domains are holes in the thin sections (*i.e.*, pixels not assigned to mineral phases).

824
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).

833
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 (Ky₁)
838 enveloped by the main foliation. Small idioblasts of Ky₂ are in equilibrium with the S_m. (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 ± 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).

847
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 (Grt₁)
855 enveloped by the main foliation. (e) Top: small Alpine garnet idioblasts (Grt₂) in equilibrium with the main
856 foliation defined by phengite; bottom: Grt₂ forming a discontinuous rim around Grt₁. (f) Large aggregate of

857 fine-grained chloritoid enveloped by the S_m and interpreted as a pseudomorph after pre-Alpine staurolite.
858 (a, b, c, d, e: PPL; f and insets in a, d: XPL; inset in b: BSE).

859

860 **Fig. 6** – Garnet compositions plotted in the Prp-Alm-(Grs+Sps) diagram. The zoning trend for each sample is
861 highlighted by the arrow. Samples are grouped according to their bulk-composition (*i.e.*, Ca-poor vs. Ca-rich
862 metapelites). For sample DM1565, only compositions of Alpine Grt₂ are plotted.

863

864 **Fig. 7** – Potassic white mica compositions plotted in the Si vs. Fe²⁺ + Mg (a.p.f.u.) diagram. Compositions of
865 micas defining the S_m are distinguished from those included in garnet and from the late flakes overgrowing
866 the S_m . Samples are grouped according to their bulk-composition (*i.e.*, oxidized vs. not oxidized). The dashed
867 line represents the ideal celadonic substitution. Note that point analyses for samples DM1485 (PU),
868 DM1667c (SCU) and DM1504 (RSU) plot slightly above the line of ideal celadonite substitution, thus
869 suggesting that these white micas contain some Fe³⁺.

870

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

878

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

880

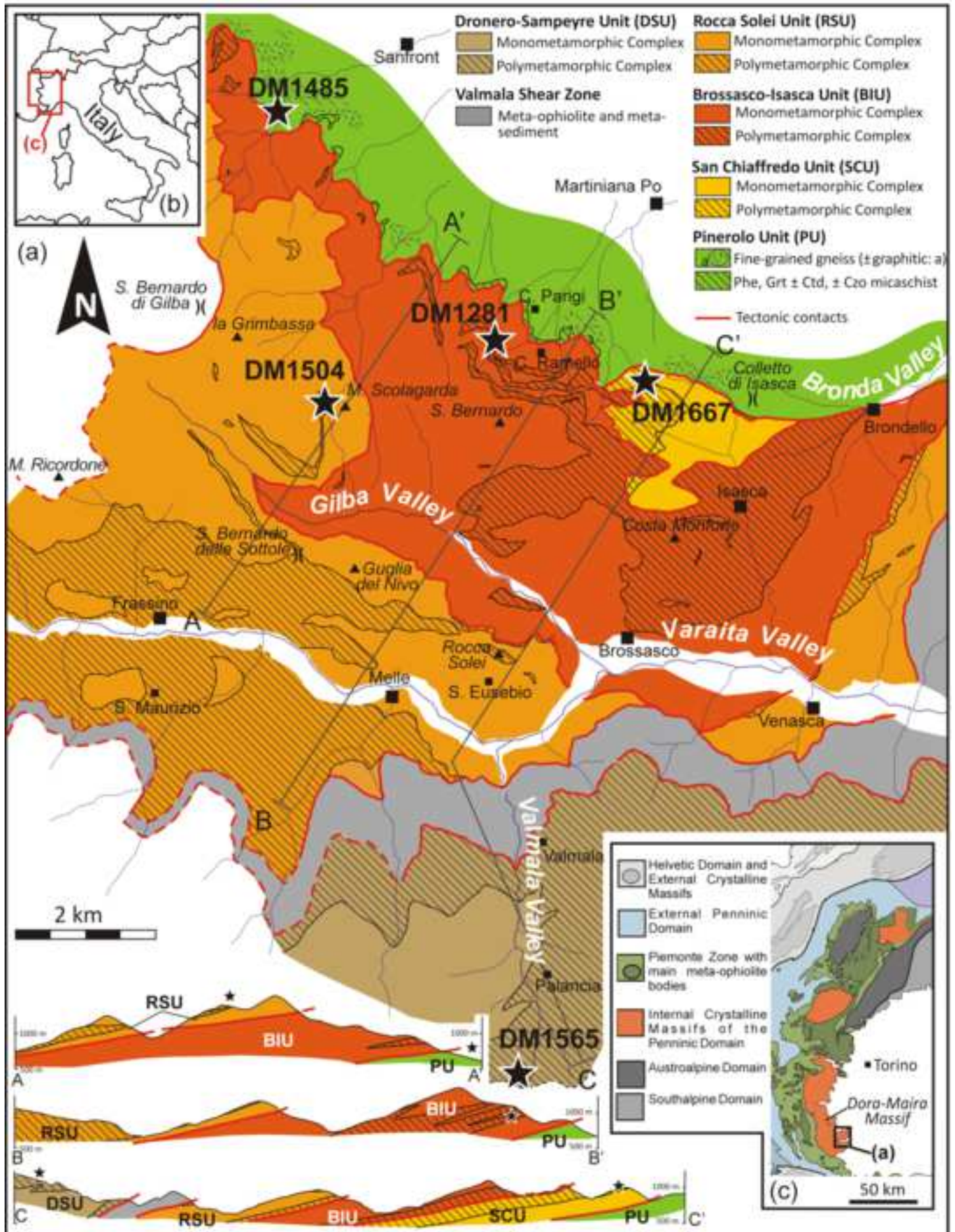
881 **Fig. 10** – P-T pseudosections modeled for sample DM1281 (BIU). (a), (b), (c) and all the symbols as in Fig. 8;
882 the inset in (b) clarifies the mineral assemblages stable in the narrow fields modelled in the central part of
883 the pseudosection. Note that the scale is different from that in Fig. 8, 9 and 11, that pseudosection in (c) has
884 been calculated at $a_{H_2O}=0.4$, and that AvPT data in (b) refer to late prograde P-T conditions.

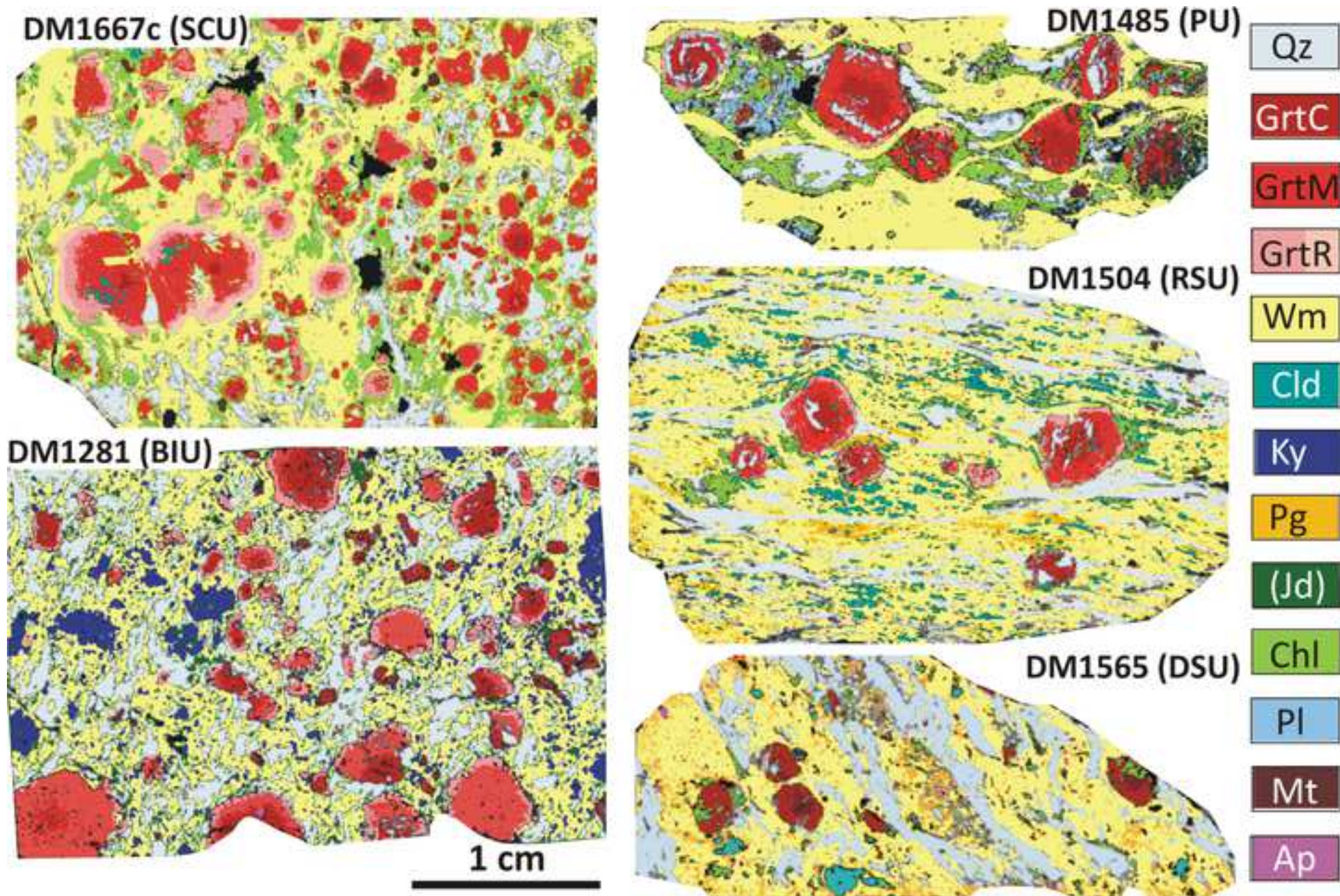
885

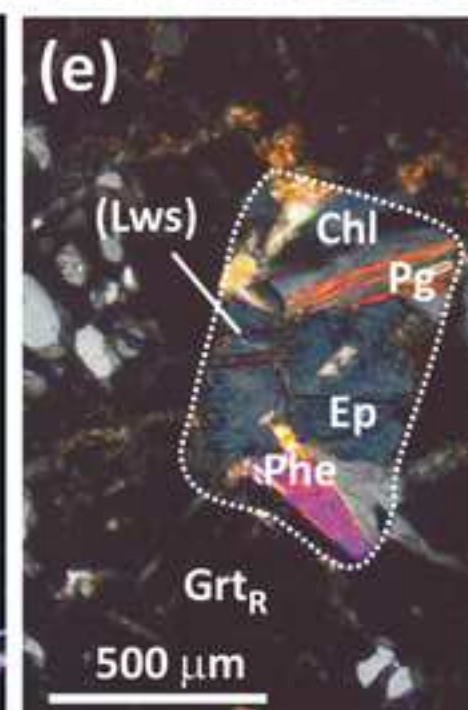
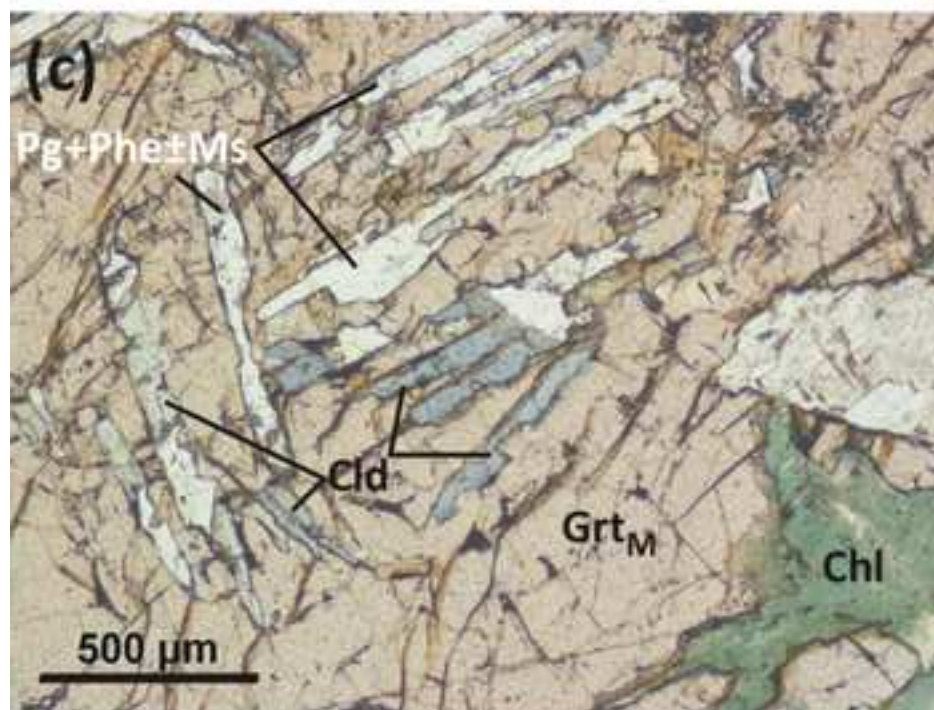
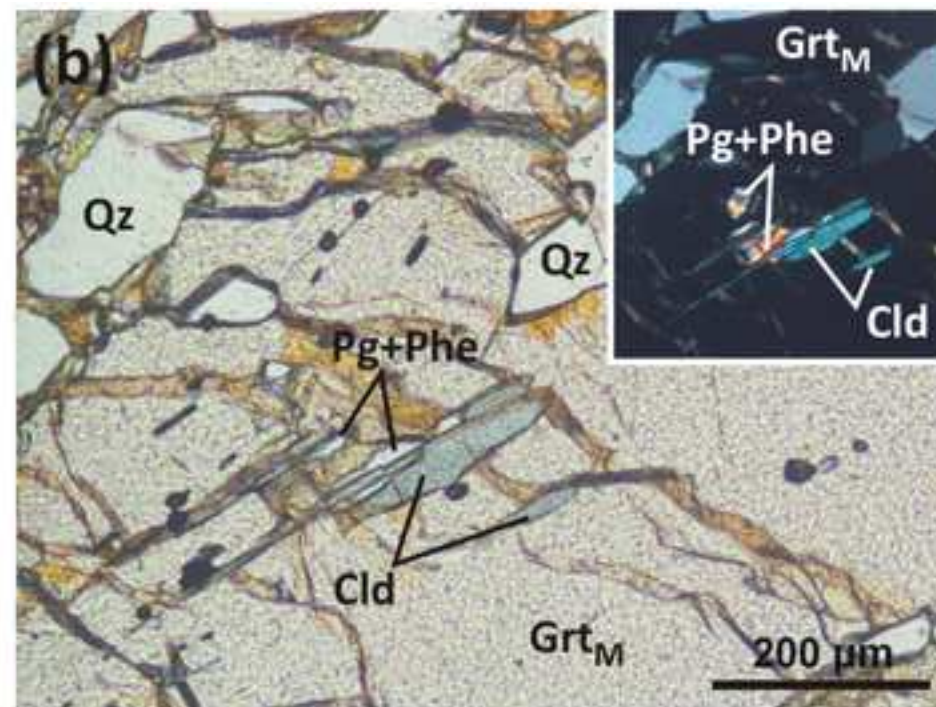
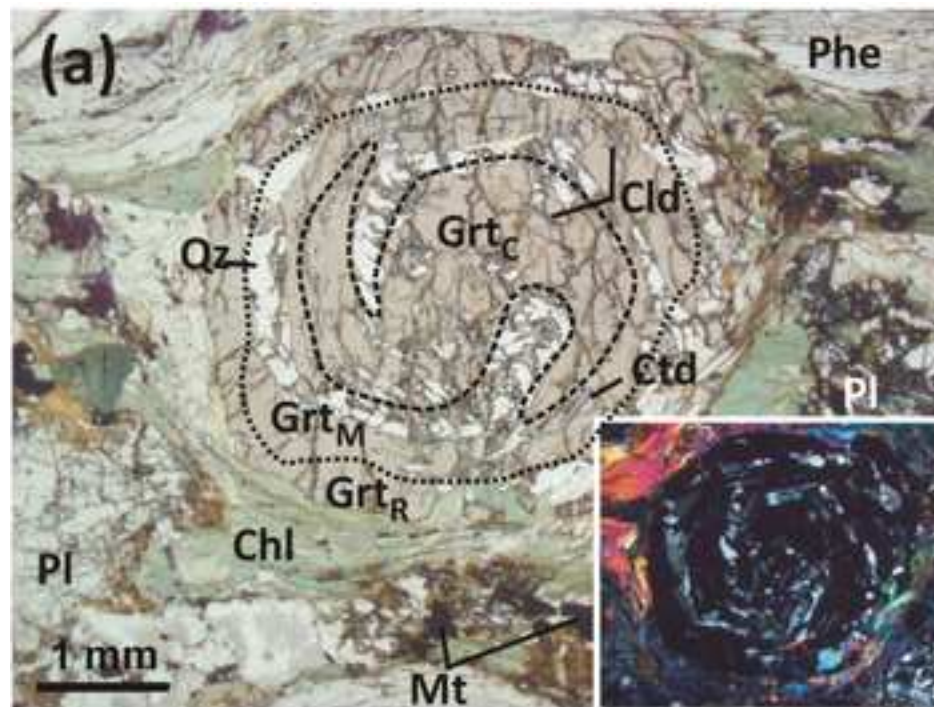
886 **Fig. 11** – P-T pseudosections modeled for sample DM1504 (RSU). (a), (b), (c) and all the symbols as in Fig. 8.

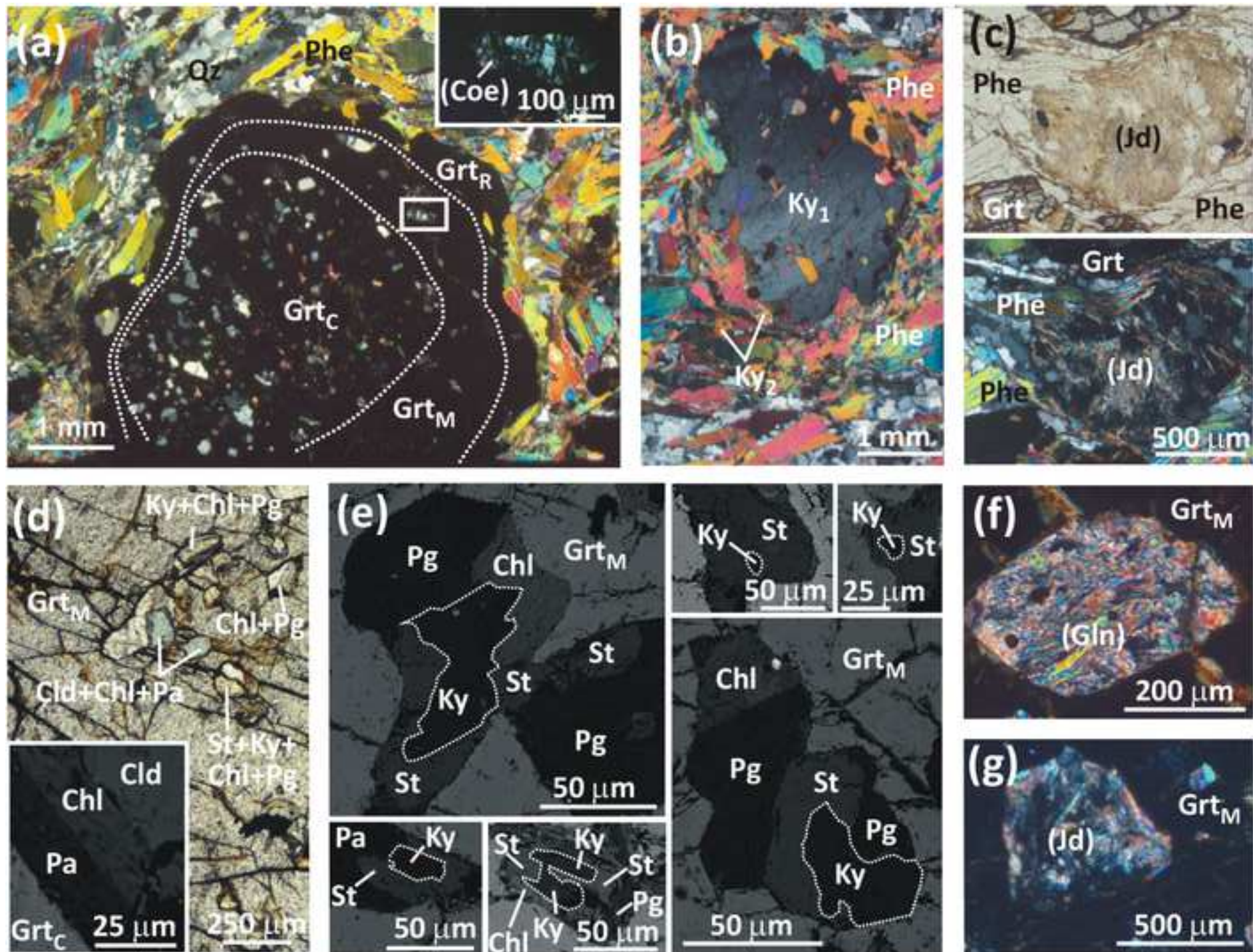
887

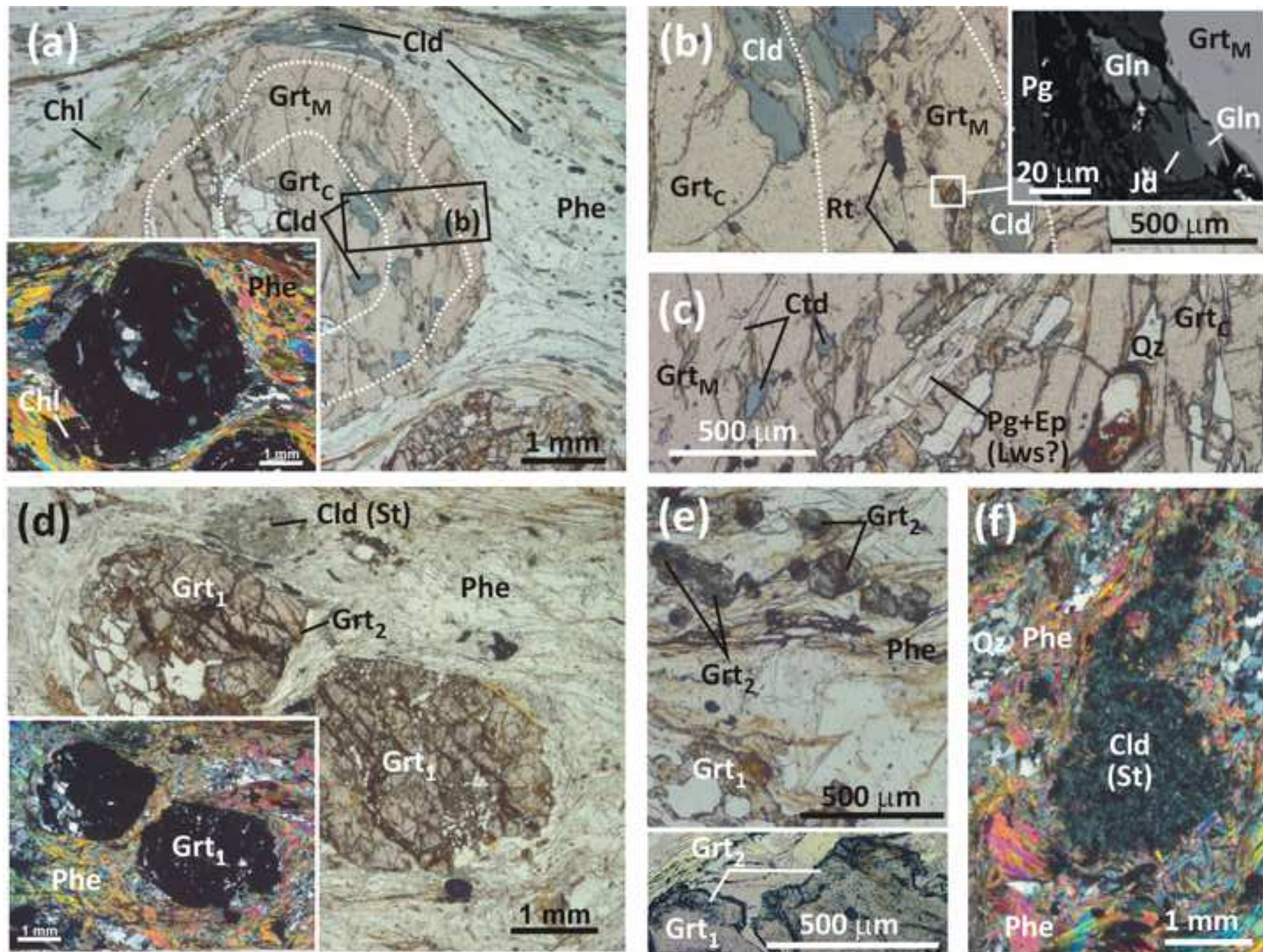
888 **Fig. 12** – (a-e) P-T grids showing the prograde trajectories for the Pinerolo Unit (a), San Chiaffredo Unit (b),
889 Brossasco-Isasca Unit (c), Rocca Solei Unit (d) and Dronero-Sampeyre Unit (e) as inferred in this study,
890 compared to peak P-T conditions derived from the literature (PU: Avigad *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.

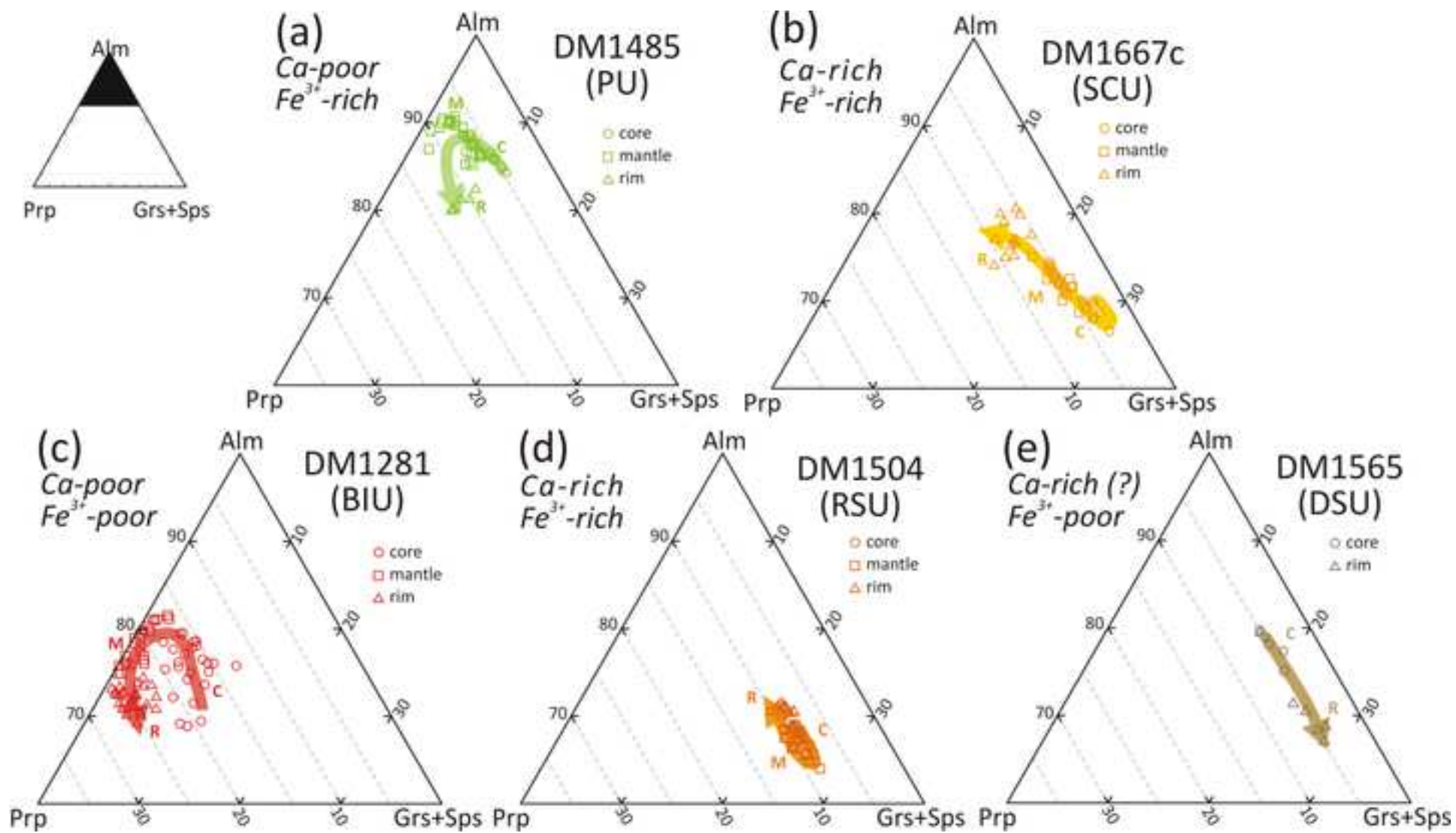


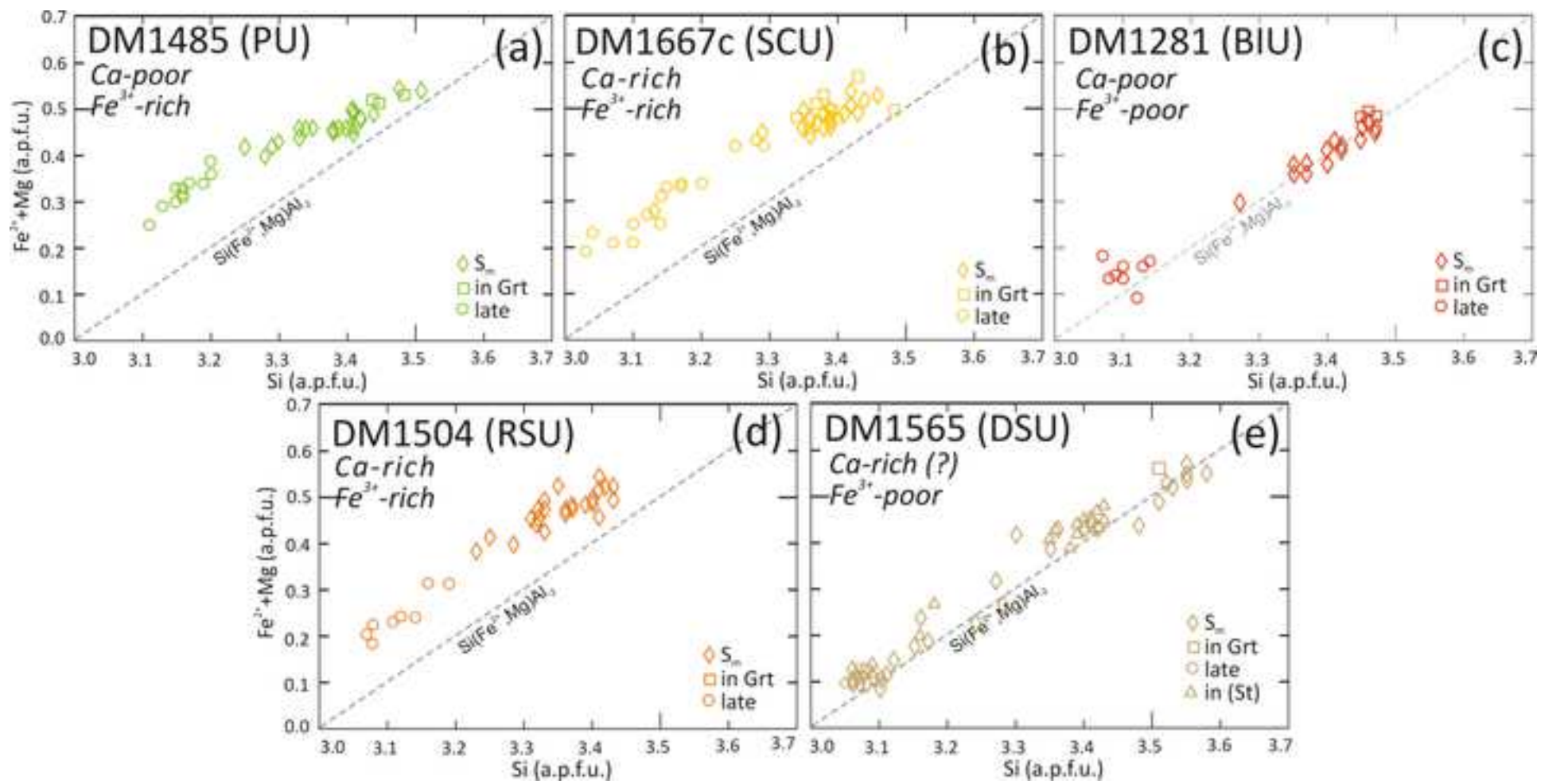


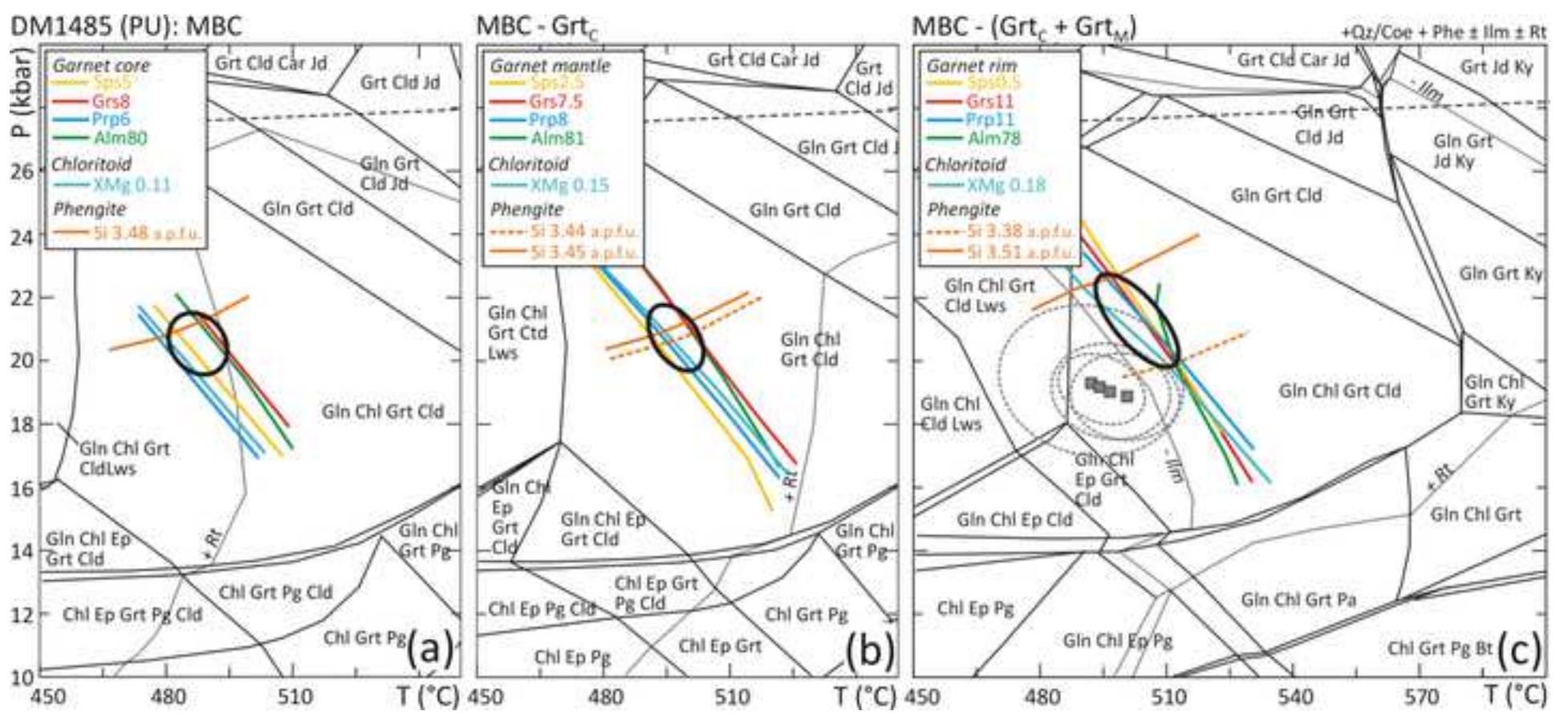




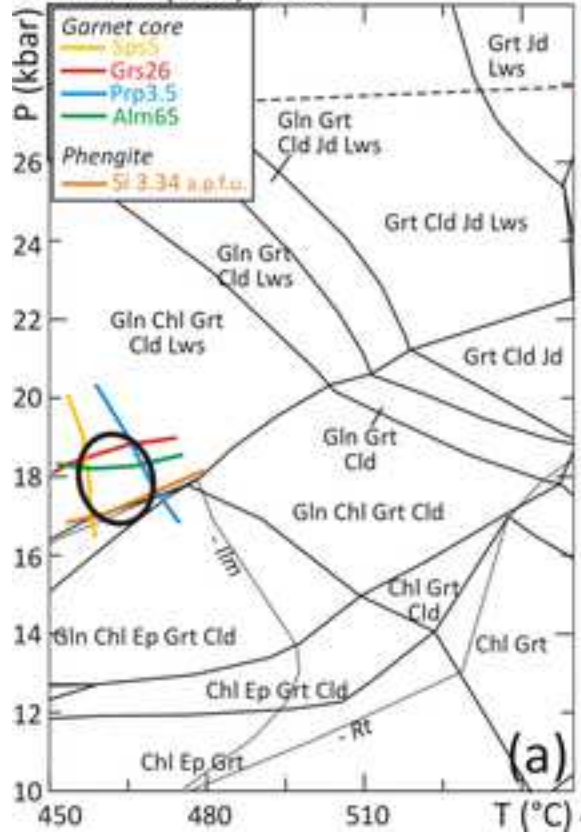




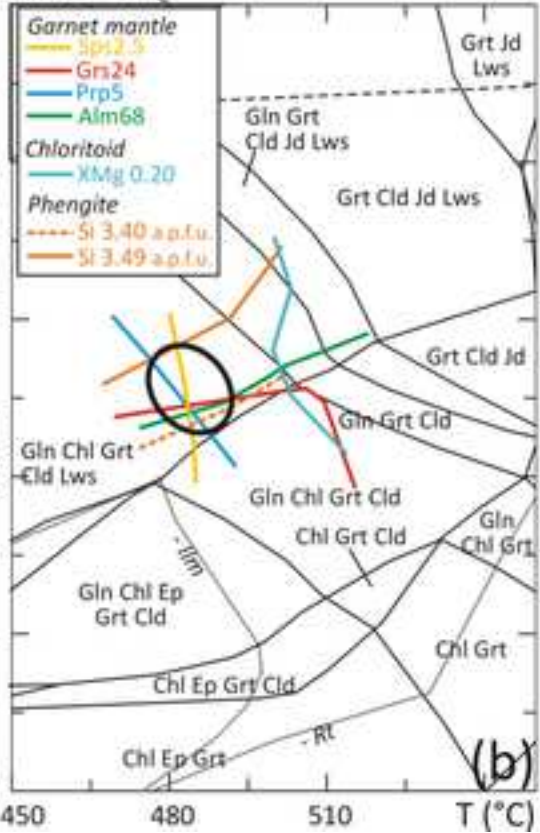




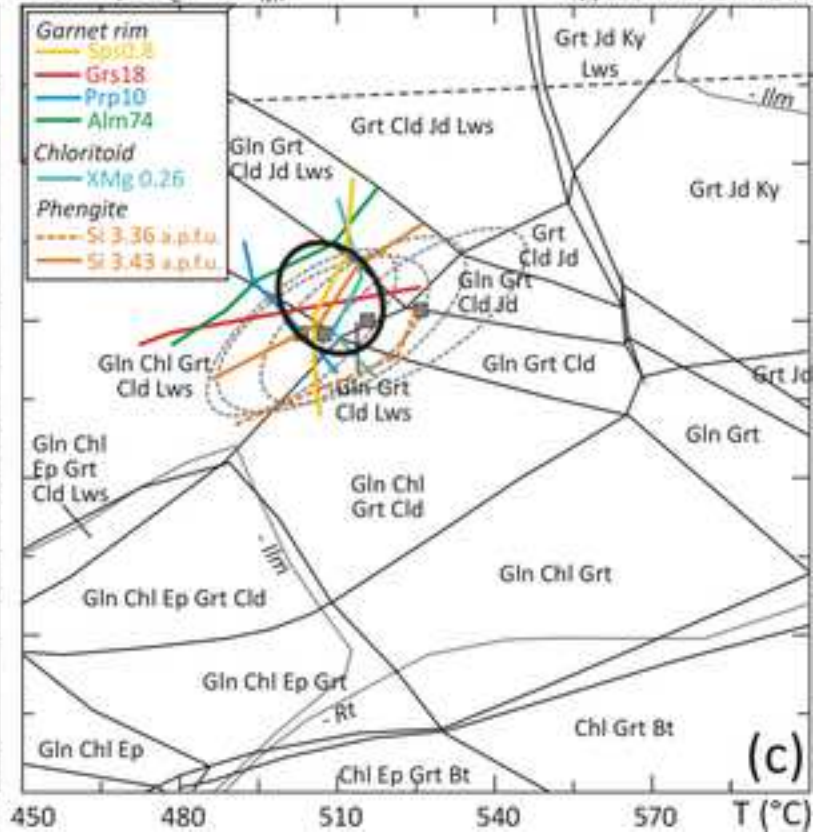
DM1667c (SCU): MBC



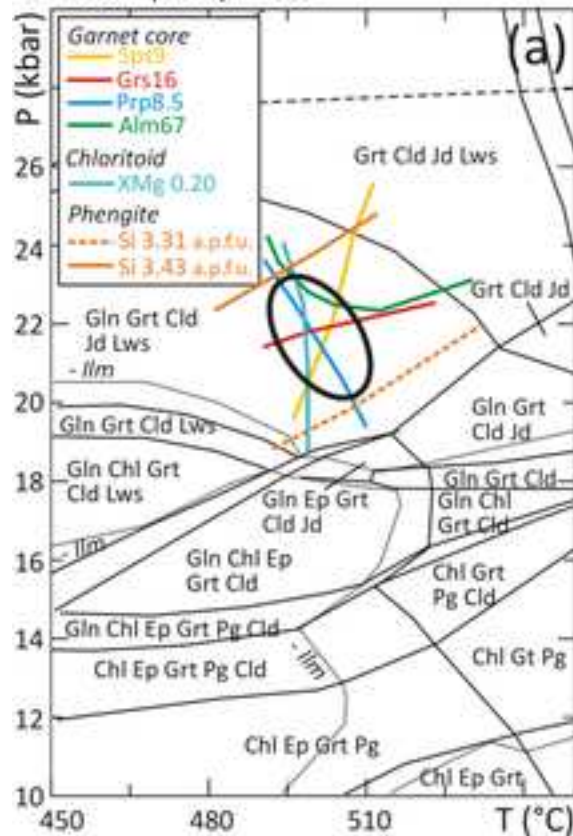
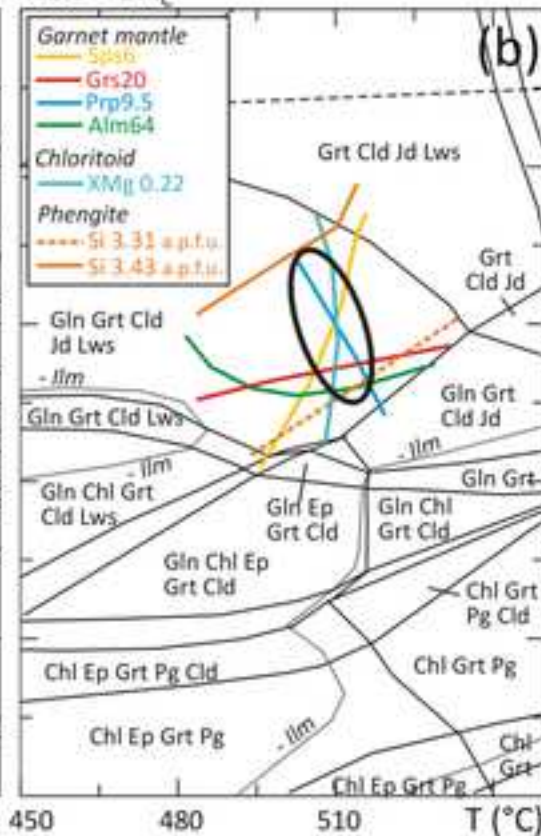
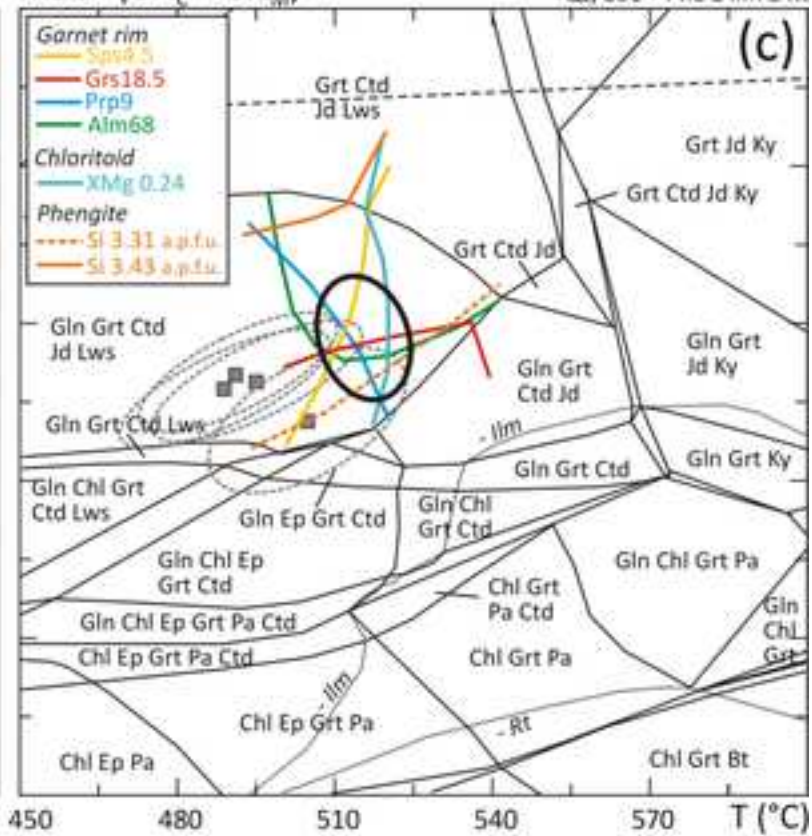
MBC - Grt_c



MBC - (Grt_c + Grt_M)



DM1504 (RSU): MBC

MBC - Grt_CMBC - (Grt_C + Grt_M)

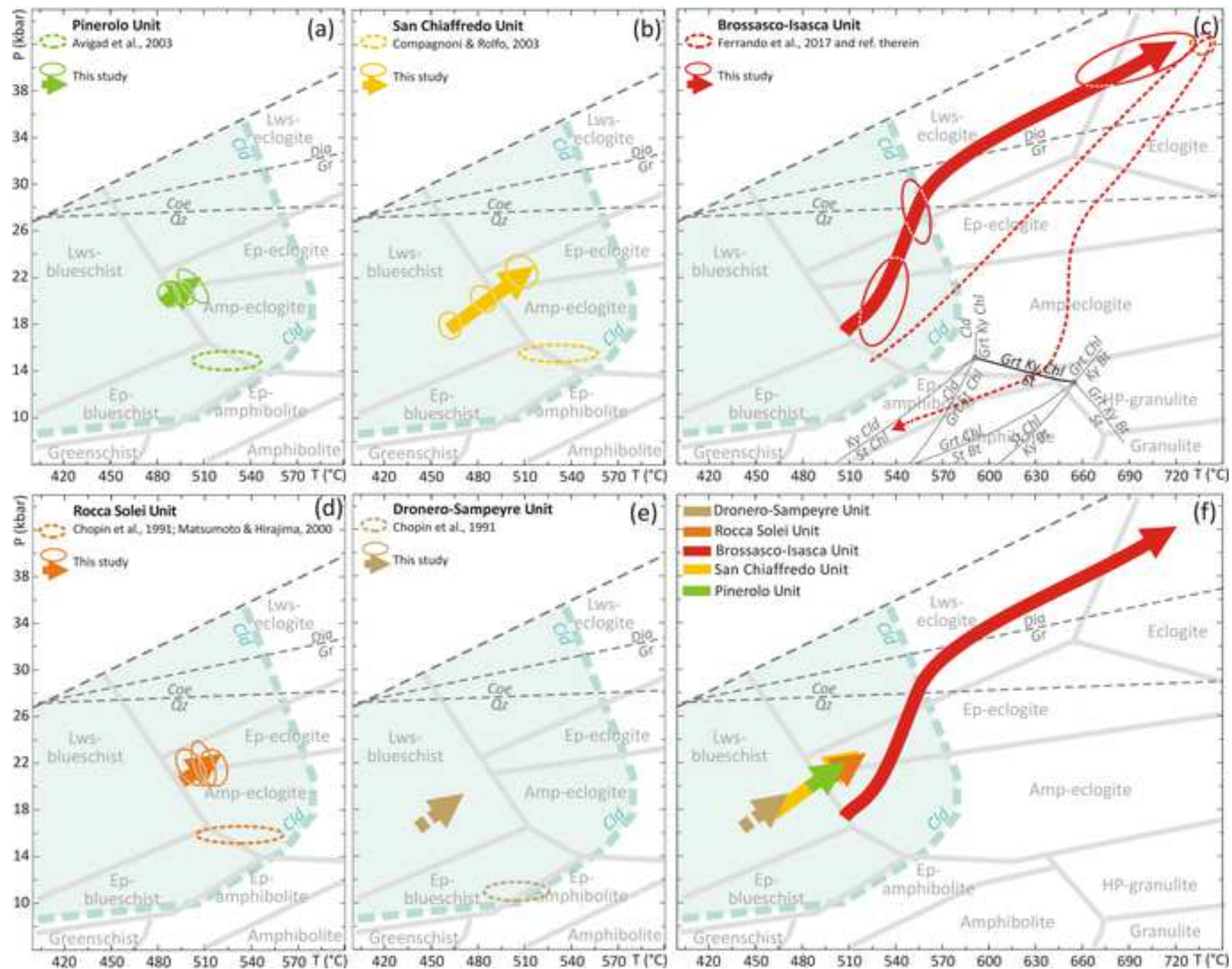


Table 1. Effective bulk-compositions (mol%) of the studied metapelites

Sample	DM1485 (PU)			DM1667c (SCU)			DM1281 (BIU)			DM1504 (RSU)		
	MBC	MBC-Grt _c	MBC-(Grt _c +Grt _R)	MBC	MBC-Grt _c	MBC-(Grt _c +Grt _R)	MBC	MBC-Grt _c	MBC-(Grt _c +Grt _R)	MBC	MBC-Grt _c	MBC-(Grt _c +Grt _R)
SiO ₂	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 ₂	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 ₂ O ₃	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 ₂ O ₃	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 ₂ 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 ₂ 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

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.

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

Sample	Assemblage (+Qz/Coe* + H ₂ O)	Phe a.p.f.u.	Si XMg	Grt XMg	Ctd XMg	Chl XMg	average T (°C)	error (σ) T (°C)	average P (kbar)	error (σ) P (kbar)	σfit	N° of reactions
DM1485 (PU)	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	
	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	
	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	
	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	
	<i>weighted mean**</i>					496	7	19.0	0.7			
DM1667c (SCU)	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	
	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	
	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	
	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	
	<i>weighted mean**</i>					512	8	21.9	0.9			
DM1281 (BIU)	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	
	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	
	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	
	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	
	<i>weighted mean**</i>					557	5	27.4	0.4			
DM1504 (RSU)	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	
	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	
	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	
	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	
	<i>weighted mean**</i>					495	8	20.3	0.6			
DM1565 (DSU)	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	
	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	
	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	
	<i>weighted mean**</i>					452	8	17.2	0.8			

*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

Chiara Groppo, Simona Ferrando, Manuele Gilio, Serena Botta, Francesco Nosenzo, Gianni Balestro, Andrea Festa, Franco Rolfo

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 16th 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 amigdalaires” 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). Thèse Doctorat., Université Paris 6, 149 pp.

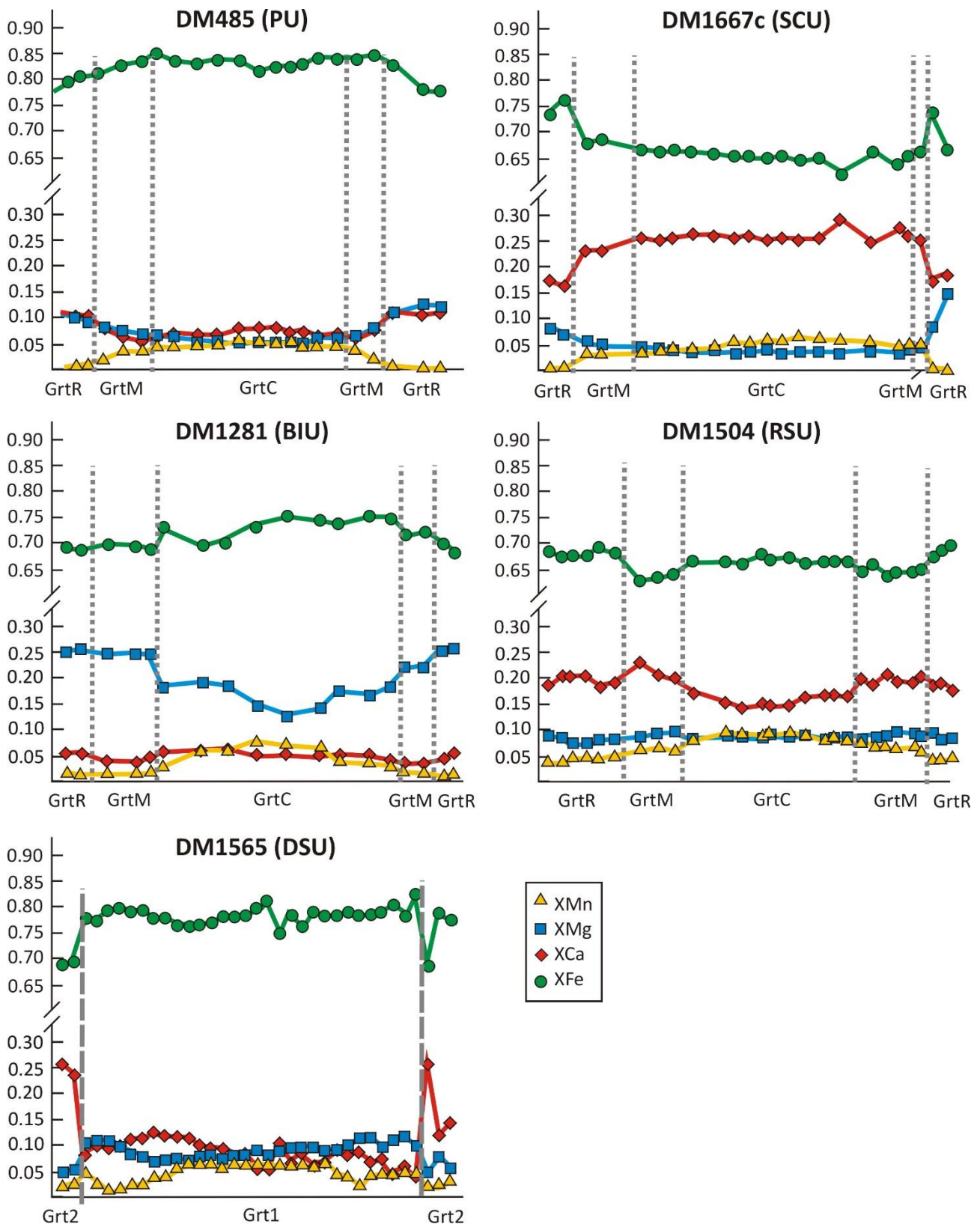


Fig. SM1 – Compositional profiles of garnet porphyroblasts from the investigated samples.

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

DM1485 (PU)					DM1667c (SCU)					DM1281 (BIU)				
Garnet					Garnet					Garnet				
	Sps	Prp	Grs	Alm		Sps	Prp	Grs	Alm		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
Phengite					Phengite					Phengite				
	Si (a.p.f.u.)					Si (a.p.f.u.)					Si (a.p.f.u.)			
Sm	3.38-3.51				Sm	3.35-3.46				Sm	3.35-3.49			
in GrtC	3.48				in GrtC	3.34				in GrtR	3.45-3.47			
in GrtM	3.44-3.45				in GrtM	3.40-3.49				Chloritoid				
Chloritoid					Chloritoid					Chloritoid				
	XMg					XMg					XMg			
in GrtC	0.10-0.12				in GrtC/M	0.20-0.28				in GrtC/M	0.25-0.31			
in GrtM	0.13-0.16				in GrtR	0.25-0.28				Chlorite				
in GrtR	0.17-0.18				Chlorite					Chlorite				
Chlorite					Chlorite					Chlorite				
	XMg					XMg					XMg			
Sm	0.40-0.44				in GrtC/M	0.20-0.26				in GrtM	0.59-0.66			
late	0.37-0.38				late	0.37-0.42				in GrtC	0.33-0.50			
Biotite					Biotite					Staurolite				
	XMg					XPs					XMg			
late	0.38-0.40				in GrtC/M	0.50-0.84				in GrtC/M	0.15-0.25			
Biotite					Biotite					Biotite				
	XMg					XMg				Biotite				
late	0.35-0.42				late	0.32-0.46				Biotite				
Biotite					Biotite					Biotite				
	XMg					XMg				Biotite				
late	0.35-0.42				Biotite					Biotite				

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

DM1504 (RSU)					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
Chloritoid	XMg				GrtR	2-3	5-6	21-26	67-72
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				Chloritoid	XMg			
in GrtM	0.21-0.23				Sm; after St	0.13-0.18			
in GrtR	0.22-0.24				Chlorite	XMg			
Glaucophane	XMg	XNa			late	0.40-0.44			
in GrtM/R	0.38-0.42	0.91-0.94							
Jadeite	XJd	XAeg							
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 SM2a - Representative analyses of the main minerals in sample DM1485 (PU)

Analysis	White mica								Garnet					
	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 _c	In Grt _M	// S _m	// S _m	// S _m	// S _m	late	In Grt _M	Core	Mantle	Rim	Rim	Rim	Rim
SiO ₂	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 ₂	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 O ₃	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
Na ₂ O	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 ₂ 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 ⁺³	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 ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis Site	Chloritoid						Chlorite			
	1.28 Cl _d In Grt _c	1.46 Cl _d In Grt _M	1.49 Cl _d * In Grt _R	1.48 Cl _d * In Grt _R	2.29 Cl _d * In Grt _R	1.33 Cl _d * In Grt _R	4.7 Chl* // S _m	4.8 Chl* // S _m	4.9 Chl* // S _m	3.7 Chl* // S _m
SiO ₂	24.60	24.60	24.59	25.10	24.63	24.91	24.60	25.05	24.62	25.45
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	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
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ 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
Ti	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 ⁺³	0.06	0.09	0.11	0.03	0.06	0.06	0.00	0.00	0.00	0.00
Fe ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis	White mica								Garnet					
	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 _c	In Grt _M	In Grt _R	// S _m	// S _m	// S _m	// S _m	In Grt _M	Core	Mantle	Rim	Rim	Rim	Rim
SiO ₂	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 ₂	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
Al ₂ O 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 ₂ 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 ₂ 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 ⁺³	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 ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis Site	Chloritoid				Epidote		Chlorite	
	1.5 Cld* In Grt _R	2.52 Cld* In Grt _M	2.49 Cld* In Grt _M	2.40 Cld* In Grt _M	11.12 Ep In Grt _C	9.27 Ep In (Lws)	1.22 Chl In Grt _C	3.1 Chl late
SiO ₂	25.13	25.35	25.13	25.01	38.47	38.63	23.59	24.66
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O 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 ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ 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 ⁺³	0.08	0.04	0.01	0.02	0.70	0.40	0.04	0.00
Fe ⁺²	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
K	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		

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis Site	White mica							Garnet					
	12.2Phe* // S _m	12.1 Phe* // S _m	6.88 Phe* // S _m	8.3 Phe* // S _m	9.23 Phe In Grt _R	10.20 Ms In Grt _C	6.51 Pa In Grt _C	Grt 11.10 Core	6.3 Grt* Mantle	6b.1 Grt* Mantle	6.32 Grt* Mantle	10.13Grt* Mantle	6.1 Grt Rim
SiO ₂	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 ₂	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 ₂ O ₃	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
Na ₂ O	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 ₂ 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	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 ⁺³	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 ⁺²	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
K	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
XMg	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								0.75	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis Site	Chloritoid				Chlorite		Staurolite	
	5.7 Cld*	6.49 Cld*	6.36 Cld*	6.33 Cld*	6.52 Chl	10.24 Chl	6b.5 St	11.26 St
	In Grt _M	In Grt _M	In Grt _M	In Grt _M	In Grt _c	late	In Grt _c	In Grt _c
SiO ₂	25.88	25.58	25.75	25.54	27.56	24.03	30.70	29.57
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35
Al ₂ O ₃	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
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ 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 ⁺³	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis	White mica						Garnet					
	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 _R	// S _m	// S _m	In Cl _d	late	⊥ S _m	Core	Mantle	Rim	Rim	Rim	Rim
SiO ₂	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 ₂	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 O 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 ₂ 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 ₂ 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 ⁺³	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 ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis	Chloritoid							Jadeite	Glaucoephane
	7.9 Cl _d	1.22 Cl _d	1.20 Cl _d	6.8 Cl _d *	2.35 Cl _d *	4.4 Cl _d *	2.32 Cl _d *	2.44 J _d *	2.52 G _{ln} *
Site	Core	In Grt _c	In Grt _M	Rim	In Grt _R	In Grt _R	In Grt _R	In Grt _R	In Grt _R
SiO ₂	25.22	25.22	25.11	25.18	25.14	24.77	24.58	56.79	55.54
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O 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 ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.62	6.53
K ₂ 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 ⁺³	0.02	0.01	0.06	0.07	0.01	0.09	0.04	0.26	0.53
Fe ⁺²	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
Ca	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis Site	White mica						Pre-Alpine Garnet (Grt ₁)			Alpine Garnet (Grt ₂)			
	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*
	// S _m	// S _m	// S _m	ln (St)	Late	Late	Core	Mantle	Rim	Core	Rim	Rim	Rim
SiO ₂	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 ₂	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 ₂ O ₃	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 ₂ 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 ₂ 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 ⁺³	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 ⁺²	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
K	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

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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

Analysis	Chloritoid			Chlorite
	2.3 Cl _d *	2.32 Cl _d **	2.25 Cl _d	8.14 Chl
Site	ln (St)	ln (St)	ln (St)	Late
SiO ₂	25.07	24.94	25.16	24.97
TiO ₂	0.00	0.00	0.00	0.00
Al ₂ O 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 ₂ O	0.00	0.00	0.00	0.00
K ₂ 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 ⁺³	0.00	0.00	0.00	0.00
Fe ⁺²	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
Ca	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00
XMg	0.17	0.18	0.15	0.42

* Analysis used for AvPT calculations (see Table 2)

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

Fe³⁺ has been calculated by stoichiometry

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 ₂ O	Phe(2.31)-Grt(1.2)-Ctd(1.48)-Chl(4.8)-Qz-H ₂ O
1) ames + 2q = py + mctd + 3H ₂ O	1) ames + 2q = py + mctd + 3H ₂ O
2) 5alm + 5ames + 4q = 4py + 8mctd + 3daph	2) fctd + daph + 2q = 2alm + 5H ₂ O
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 ₂ O	Phe(6.6)-Grt(1.23)-Ctd(1.33)-Chl(3.7)-Qz-H ₂ O
1) ames + 2q = py + mctd + 3H ₂ O	1) ames + 2q = py + mctd + 3H ₂ O
2) fctd + daph + 2q = 2alm + 5H ₂ O	2) fctd + daph + 2q = 2alm + 5H ₂ O
3) 5alm + 5ames + 4q = 4py + 8mctd + 3daph	3) 3mctd + 3daph + 6q = py + 5alm + 15H ₂ O
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 ₂ O	Phe(10.1)-Grt(9.22)-Ctd(2.52)-Lws-Qz-H ₂ O
1) py + 3law = gr + 3mctd + 3q + 3H ₂ O	1) py + 3law = gr + 3mctd + 3q + 3H ₂ O
2) alm + 3law = gr + 3fctd + 3q + 3H ₂ O	2) alm + 3law = gr + 3fctd + 3q + 3H ₂ O
3) fcel + 2fctd = mu + alm + 2H ₂ O	3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law
4) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law	4) 15cel + 2gr + 12fctd + 6q = 3mu + 12fcel + 5py + 6law
Phe(10.9)-Grt(2.25)-Ctd(2.49)-Lws-Qz-H ₂ O	Phe(1.18)-Grt(9.1)-Ctd(2.40)-Lws-Qz-H ₂ O
1) py + 3law = gr + 3mctd + 3q + 3H ₂ O	1) py + 3law = gr + 3mctd + 3q + 3H ₂ O
2) alm + 3law = gr + 3fctd + 3q + 3H ₂ O	2) alm + 3law = gr + 3fctd + 3q + 3H ₂ O
3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law	3) 3cel + 2gr + 12mctd + 6q = 3mu + 5py + 6law
Sample DM1281 (BIU)	
Phe(12.2)-Grt(6.3)-Ctd(5.7)-Ky-Coe-H ₂ O	Phe(12.1)-Grt(6b.1)-Ctd(6.49)-Ky-Coe-H ₂ O
1) 3fctd + 2coe = alm + 2ky + 3H ₂ O	1) 3fctd + 2coe = alm + 2ky + 3H ₂ O
2) 3mu + py + 4coe = 3cel + 4ky	2) 3mu + py + 4coe = 3cel + 4ky
3) 3cel + alm = 3fcel + py	3) 3cel + alm = 3fcel + py
Phe(6.88)-Grt(6.32)-Ctd(6.36)-Ky-Coe-H ₂ O	Phe(8.3)-Grt(10.13)-Ctd(6.33)-Ky-Coe-H ₂ O
1) 3fctd + 2coe = alm + 2ky + 3H ₂ O	1) 3fctd + 2coe = alm + 2ky + 3H ₂ O
2) 3mu + py + 4coe = 3cel + 4ky	2) pa = ky + jd + H ₂ O
3) 3cel + alm = 3fcel + py	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-H₂O

- 1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
- 2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) $cel + 2mctd = mu + py + 2H_2O$
- 4) $3mctd + 2jd + 2q = 2pa + py + H_2O$
- 5) $fccl + 2fctd = mu + alm + 2H_2O$
- 6) $3pa + fgl = 3fctd + 5jd + 4q + H_2O$
- 7) $27mu + 9cel + 4spss + 12fgl + 12law = 36fccl + 24pa + 3py + 4gr + 12mnctd$

Phe(6.16)-Grt(1.19)-Ctd(6.8)-Gln(2.52)-Jd(2.44)-Lws-Qz-H₂O

- 1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
- 2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) $cel + 2mctd = mu + py + 2H_2O$
- 4) $3mctd + 2jd + 2q = 2pa + py + H_2O$
- 5) $fccl + 2fctd = mu + alm + 2H_2O$
- 6) $6fccl + 2pa + py + 2jd = 3mu + 3cel + 2fgl$

Phe(6.21)-Grt(2.26)-Ctd(4.4)-Gln(2.52)-Jd(2.44)-Lws-Qz-H₂O

- 1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
- 2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) $cel + 2mctd = mu + py + 2H_2O$
- 4) $fccl + 2fctd = mu + alm + 2H_2O$
- 5) $12fccl + py + 4mctd + 8jd + 4q = 5mu + 7cel + 4fgl$

Phe(6.3)-Grt(2.1)-Ctd(2.32)-Gln(2.52)-Jd(2.44)-Lws-Qz-H₂O

- 1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
- 2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) $cel + 2mctd = mu + py + 2H_2O$
- 4) $3mctd + 2jd + 2q = 2pa + py + H_2O$
- 5) $fccl + 2fctd = mu + alm + 2H_2O$
- 6) $3pa + fgl = 3fctd + 5jd + 4q + H_2O$
- 7) $6fccl + 2pa + py + gr + 2acm = 3mu + 3cel + andr + 2fgl$

Sample DM1565 (DSU)Phe(5.12)-Grt(3.15)-Ctd(2.3)-Lws-Qz-H₂O

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

Phe(3.6)-Grt(7.1)-Ctd(2.25)-Lws-Qz-H₂O

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

Phe(5.6)-Grt(3.11)-Ctd(2.32)-Lws-Qz-H₂O

- 1) $py + 3law = gr + 3mctd + 3q + 3H_2O$
- 2) $alm + 3law = gr + 3fctd + 3q + 3H_2O$
- 3) $3cel + 2gr + 12fctd + 6q = 3mu + py + 4alm + 6law$

Table SM8 - Mass balance of the staurolite-forming reactions

0.264 Chl + 3.496 Ky + 0.123 Grt_c = 1.000 St

	Reactants			Products			
Phases	Chl 6.68	Ky 6.66	Grt _c 6.15	St 6.67	Σreact	Σprod	Residuals
coeff	-0.264	3.496	-0.123	1.000			
SiO ₂	2.59	1.00	2.98	3.94	-3.940	4.544	0.604
Al ₂ O ₃	1.47	1.00	1.00	4.61	-4.610	4.006	-0.604
FeO	2.48	0.00	2.30	1.51	-1.510	0.936	-0.574
MnO	0.00	0.00	0.10	0.00	0.000	0.012	0.012
MgO	1.93	0.00	0.45	0.29	-0.290	0.564	0.274
CaO	0.00	0.00	0.14	0.01	-0.008	0.018	0.010
H ₂ O	4.00	0.00	0.00	1.00	-1.000	1.055	0.055

0.263 Chl + 3.712 Ky + 0.064 Grt_c = 1.000 St

	Reactants			Products			
Phases	Chl 11.34	Ky 11.32	Grt _c 11.6	St 11.34	Σreact	Σprod	Residuals
coeff	-0.263	-3.712	-0.064	1.000			
SiO ₂	2.71	1.00	2.90	4.11	-4.110	4.610	0.500
Al ₂ O ₃	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 ₂ O	4.00	0.00	0.00	1.00	-1.000	1.052	0.052

0.211 Chl + 3.620 Ky + 0.131 Grt_M = 1.000 St

	Reactants			Products			
Phases	Chl 6.52	Ky 6.53	Grt _M 6.21	St 6.50	Σreact	Σprod	Residuals
coeff	-0.211	-3.620	-0.131	1.000			
SiO ₂	2.77	1.00	2.99	4.04	-4.040	4.598	0.558
Al ₂ O 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 ₂ 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. Σ_{react} : overall composition of the reactants; Σ_{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).