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(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

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1	P-T Alpine metamorphic evolution for the Monte Rosa Nappe along the
2	Piedmont Zone boundary (Gressoney Valley, NW Alps)
3	
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13	Abstract. The pseudosection modelling of two chemical systems (both metabasic and metapelitic)
14	allowed to reconstruct the exhumation PT path followed by the southern slope of the Monte Rosa
15	Nappe (Upper Gressoney Valley) during the Alpine orogenesis. The metamorphic evolution of the
16	polymetamorphic basement complex from the Monte Rosa Nappe is marked by texturally distinct
17	mineral assemblages, defining four Alpine metamorphic stages (M1, M2, M3 and M4) developed
18	under different PT conditions. In particular, well preserved eclogitic boudins (M1 and M2
19	assemblages) were investigated to reconstruct the HP history related to the subduction event, while
20	re-equilibrated metapelites allowed to infer the PT conditions attained during the development of
21	the regional foliation (M3 and M4 assemblages). The HP event (M1) occurred at 550-570 °C and
22	24-27 kbar and is characterized by the assemblage $Omp + Grt + Lws + Phe + Qtz + Gln \pm Tlc$ in the
23	eclogites. The M2 metamorphic stage consists of the assemblage Omp + Grt + Barr + Zo + Phe +
24	Pg + Qtz and developed at 590-630 °C and 14.5-16.5 kbar suggesting a T increasing during
25	decompression. After a further decompressional stage associated with a T decrease, the M3 tectono-
26	metamorphic event developed syn-kinematically with the main regional foliation S_1 . It is marked by
27	the assemblage Phe + Pg + Grt + Chl + Ab/Olig + Hbl + Qtz + Rt/Ilm \pm Bt in metapelites and by
28	Cam (blue-green) + Chl + Ab + Bt + Qtz + Rt in the re-equilibrated metabasite boudins. It
29	developed during increasing T (from 550 to ca. 600°C) and P (from 7 to 9 kbar). Finally, the M4
30	assemblage grew as rim over the M3 minerals or overgrew the S_1 regional foliation (albite
31	porphyroblasts overgrowing the S_1 foliation already defined by albite) and therefore can be
32	considered as the final stage of the M3 tectono-metamorphic event. From this data a different P-T
33	path is proposed for the Monte Rosa Nappe compared to previous works. In particular, it shows a
34	post-eclogitic decompression trajectory up to 7 kbar, followed by a P-T increase that can be related

to multiple burial-exhumation cycles during alpine orogenesis, as recently reported in literature for
other Alpine units.

Keywords: Alpine metamorphism, pseudosection, PT path, Monte Rosa Nappe, Western Italian Alps.

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1. Introduction

The axial portion of the Western Italian Alps (Austroalpine and Penninic Domains) represents a fossil subduction complex developed during the Alpine orogenic cycle. In the last twenty years, many geological transects (e.g. Pognante *et al.* 1987; Inger and Ramsbotham, 1997; Bucher *et al.*, 2004; Keller *et al.*, 2005) have improved our knowledge of the structural and metamorphic framework of the Western Alps. In the last years, numerous Authors, based on thermodynamic models, reported the P-T conditions reached during the metamorphic peak of the subduction event for the Gran Paradiso (Le Bayon *et al.*, 2006; Gabudianu *et al.*, 2009; Gasco *et al.*, 2010) and the Dora Maira (Chopin, 1984; Chopin *et al.*, 1991; Castelli *et al.*, 2007; Gasco *et al.*, in press) Massifs. Instead, for the Monte Rosa Nappe no recently reconstruction of P-T paths by means of the analysis of phase equilibria is performed, with exception of the Mg-riched metapelites system of whiteschist (Le Bayon *et al.*, 2000; 2006). For this reason, an apparent disagreement currently exist between P-T conditions reported for the Monte Rosa Nappe and the other Internal Crystalline Massifs (Gran Paradiso and Dora-Maira), despite their common Alpine tectono-metamorphic evolution.

This work aims to reconstruct the exhumation PT path of the Monte Rosa Nappe based on the pseudosection approach. The PEPLEX thermodynamic model of Connolly (1990) was applied to selected metabasic and metapelitic rocks in order to estimate the PT conditions attained during the eclogitic peak metamorphic event and to better constrain the PT path followed during the exhumation. Two different chemical systems have been investigated because of their tendency to register different stage of the metamorphic evolution. Generally, the basic system preserves very well the HP climax while the pelitic one records the last stages of the tectonometamorphic evolution. The studied rocks contain well preserved evidence of different high pressure stages that allowed to reconstruct the early-Alpine subduction event for the Monte Rosa Nappe. Phase diagrams modelling has also permitted to reconstruct the exhumation portion of the Alpine PT path on the base of the garnet growth zoning and on the chemical composition and micro-structural relationships with other minerals.

- **3 2.** Geological setting
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The Monte Rosa Nappe, together with the Dora Maira and the Gran Paradiso Massifs, represent continental basement Nappes of the inner Penninic Domain (e.g. Schmid *et al.*, 2004) in the Western Italian Alps, and are characterized by the occurrence of high pressure (HP) and in the case of Dora Maira Massif ultra-high pressure (UHP) metamorphic assemblages. They are known as the Internal Crystalline Massifs (

12 The Monte Rosa Nappe (Bearth, 1952; Dal Piaz, 2001 for a review; consists of pre-13 Alpine basement composed of a high-grade (biotite + sillimanite + k-feldspar assemblages and 14 cordierite anatexites) paragneisses complex characterized by the occurence of anatectic melts, 15 which was transformed into garnet-micaschists during the Alpine event (Dal Piaz, 2001). A 16 composite Late Paleozoic batolith with granite to granodiorite composition intruded the 17 paragneisses in the Late Carboniferous (310-330 Ma; Hunziker., 1970; Frey et al., 1976; Engi et al., 18 2001), while Permian ages (260-270 Ma; Lange et al., 2000; Engi et al., 2001) have been attributed 19 to late magmatic stages. The whole nappe is characterized by low-strain domains which preserves 20 intrusive relationships between the granitoids and the high-grade pre-alpine complex, and by high-21 strain domains in which the Alpine structural and metamorphic imprint is well developed (Dal Piaz, 22 1964, 1966, 1971;). Horizons rich of mafic boudins and marbles are present at different structural 23 levels within the metapelites and are known as Furgg Zone s.s. (Bearth, 1952, 1954) in the northern 24 part of the Nappe and southern Furgg Zone (Dal Piaz, 1964, 1966) on the Italian side. While the 25 southern Furgg Zone is considered as a pre-Permian metamorphic complex (Dal Piaz, 2001), the 26 interpretation of the Furgg Zone s.s. is very contrasting: Froitzheim (2001), Liati et al. (2001) and 27 Kramer (2002) considered it as a Mesozoic tectonic mélange while Jaboyedoff et al. (1996) and 28 Keller and Schmid (2001) suggested that it is an highly deformed stratigraphic sequence of Permo-29 Triassic cover and continental basement, intruded by post-Triassic mafic dykes. The post-Variscan 30 cover of the Monte Rosa is represented by Late-Carboniferous-Permian and Mesozoic sequences 31 mainly preserved in the external parts of the Nappe (Gornergrat Zone) or included in the Furgg 32 Zone s.s. (Jaboyedoff et al., 1996; Escher et al., 1997). High pressure relics referred to the Alpine 33 event consist of eclogite boudins and phengite-garnet-kyanite assemblages within the paragneisses,

and of phengite-talc-chloritoid-chlorite-kyanite-quartz schists (whiteschist) along shear zones
 within the orthogneisses (Dal Piaz and Lombardo, 1986).

The eclogite facies metamorphic conditions have been estimated with classical thermobarometry giving ca 16 kbar & 500°C (Chopin and Monié, 1984), 10 ± 2 kbar and 500 ± 50 °C (Dal Piaz and Lombardo, 1986; Borghi *et al.*,1996) and 13-20 kbar and 535-620 °C (Ferrando, 2002; Ferrando *et al.*, 2002) in the southern part of the Nappe.

7 Lapen et al. (2007) reported similar results (P > 13 kbar and 480-570 °C obtained with 8 classical thermobarometry) for quartz-phengite-carbonate-rutile veins crosscutting eclogite boudins, 9 within the southern Furgg Zone. These veins were dated by U/Pb geochronology on rutile giving a 10 minimum age of 42.6 ± 0.6 Ma for the eclogite facies event (Lapen *et al.*, 2007). In the central and 11 the northeastern part of the Nappe, Engi et al. (2001) reported an age of 36 ± 6 (Th/U/Pb on 12 monazite with most of the accurate ages at 32-38 Ma) for an high pressure stage during exhumation 13 at 9-12 kbar for T data grouping at 580-620 °C and 730-755 °C, without any correlation with the 14 regional gradient. A late-Alpine thermal overprinting is evidenced by monazite ages at 25-27 Ma 15 (Engi et al., 2001). The Alpine peak-pressure conditions estimated with the pseudosection approach 16 for talc-chloritoid-phengite-quartz whiteschist gave 25 kbar and 580 °C (Le Bayon et al. 2000) and 17 24 ± 3 kbar and 505 ± 30 °C followed by decompression to 8 ± 3 kbar and 475 ± 30 °C (Le Bayon 18 et al. 2006).

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20 3. Tectonic setting

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New detailed mapping at the 1:10000 scale was performed along the southern border of the Monte Rosa Nappe along the watershed between Gressoney and Ayas Valley and allowed to reconstruct its structural setting (Gasco and Gattiglio, 2011). A simplified map of the study area is reported in performed in the deepest outcropping the Monte Rosa Nappe which is geometrically overlain, at the regional scale, by the Zermatt-Saas Unit.

27 The Monte Rosa Nappe mainly consists of a polymetamorphic complex including medium 28 to coarse-grained garnet micaschists with the following main assemblage: Qtz + Wm + Chl + Ab +29 Grt (abbreviations of minerals are given according to Kretz, 1983 with the of by Bucher and Frey, 2002). The garnet micaschists show many intercalations of metabasite boudins which locally 30 are arranged along layers parallel to the regional foliation (1), 3, a) and minor layers of meta-31 32 intrusives comprising orthogneisses and aplitic dykes. Metabasites consist of well-preserved 33 eclogites and re-equilibrated epidote-albite amphibolites. Other intercalations within the garnet 34 micaschists are represented by albite micaschists poor of garnet and by fine-grained graphitebearing micaschists. Both albite and graphite micaschists show transitional contact towards the garnet micaschists (Fig. 3b) and are considered to be stratigraphic intercalations within an heterogeneous pre-Alpine basement. Locally Bt + Grt rich dark nodules in a light quartz-feldspatic matrix were observed and were interpreted as stretched restitic portion of a partial melting process of pre-Alpine age (Fig. 3c).

6 The Zermatt-Saas Unit consists of a stack of tectonic slices comprising ultrabasic and basic 7 rocks rarely overlain by a thin stratigraphic cover. The ultramafic rocks consist of foliated 8 serpentinites that locally show thin layers (max 50-60 cm thick) of meta-rodingites (Fig. 3d) and 9 boudins of eclogites, while the metabasites comprise medium to coarse-grained Mg-Al 10 metagabbros, epidote-albite amphibolites and eclogites interpreted as Fe-Ti metagabbros or 11 metabasalts. Eclogites consists of coherent bodies 100 m long and of boudins (20 cm to 5 m) within 12 reequilibrated epidote-albite amphibolites. The Mesozoic cover sequence is scarce in the study area 13 and mainly consists of by garnet calcschists interposed with impure marbles and by subordinate 14 micaschists and greenstones (layered Ab + Chl + Act + Ep schists interpreted as submarine 15 volcanics). The tectonic contact between Monte Rosa d the Zermatt-Saas in marked by mylonitic 16 micaschists with S-C structures with a foliation defined by $Chl + Wm + Qtz + Grt + Hbl + Rt \pm Ab$ and by rare serpentinite lenses and Chl-Act schists derived from the metabasites or serpentinites. 17 The mylonitic foliation in the caschists shows almost the same assemblage which define the 18 19 S_1 foliation. The deformation zone is always in the range of 1-10 m thick and no eclogite facies assemblage has been observed along the contact. 20

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22 4. Petrography and mineral chemistry

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24 In order to constrain the metamorphic evolution of the southern border of the Monte Rosa 25 Nappe, about thirty samples (micaschists and metabasites) were studied. **L**field study and petrographic investigation of selected samples, reveal that generally metapel with a well 26 27 developed regional foliation registered the recauilibration stage, while the eclogite facies assemblages are better preserved in the metabasite **F**oudins. Two samples have been selected (Fig. 28 29 2) for pseudosection modelling: a preserved eclogite boudin (GR5) and a pervasively LP retrajectory during the 30 equilibrated micaschist (GR3), in order to reconstruct the entire 31 exhumation.

On the basis of micro-structural relationships and mineral chemistry data four Alpine metamorphic stages have been distinguished (Fig. 4): i) the peak-pressure metamorphic event (M1); ii) a first decompressional event (M2) 1 metamorphic event (M3) responsible for the development of the main regional foliation under upper

2 greenschist to amphibolite facies Finally, a static re-equilibration occurred under
3 amphibolite facies conditions (M4).

4 Minerals were analyzed with a Cambridge Stereoscan 360 SEM equipped with an EDS 5 Energy 200 and a Pentafet detector (Oxford Instruments). The operating conditions were 15 kV 6 accelerating voltage and 60 s counting time. Mineral formulae were recalculated assuming all 7 ept for clino-pyroxenes and amphiboles, for which rectangle calculated measured FeO as 8 according to Linsdley and Anderson (1983) and according to the IMA-97 (Leake et al., 1997) 9 recommendation, respectively. Garnet real alculated on the basis of 12 oxygens, white mica on the basis of 11 oxygens, feldspar on the basis of 8 oxygens, chlorite on the basis of 28 oxygens, and 10 1.1119*FeO. Representative mineral epidote on the basis of 25 oxygens and assuming 11 compositions of the selected samples are given in Tables T and 2. Abbreviations of minerals are 12 13 given according to Kretz (1983) with the update of Bucher and Frey (2002).

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15 4.1. Monte Rosa metabasites

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The metabasites hosted within the garnet-micaschists of the Monte Rosa Nappe show different dimension from 10 cm to 5 m length and are represented by boudins enveloped by the S_1 regional foliation in the micas sts (Fig. 3.a). Often, these boudins are good shear sense indicators and generally preserve a foliation (pre-S1) (Fig. 5a) defined by eclogite facies assemblages (M1 assemblage: Omp + Grt + Phe + Gln + Qtz + Rt). Eclogites are partly re-equilibrated and developed a foliation defined by Cam (blue-green) + Chl + Bt + Wm + Ab + Spn + Qtz (M3 assemblage).

24

26

32 (Figs. 5b). Zoisite grains are coarse grained (500 μ m) and have inclusions of Grt + Omp (Fig. 33 5c, ggesting that it grew after the M1 assemblage. Further re-equilibration during decompression 34 is testified by the growth of barroisite (Barr) rim around Gln at the expense of Omp (Figs. 5d),

^{25 4.1.1.} Sample GR5

suggesting that Barr developed during the M2 event (Barr + Zo + Pg). The last re-equilibration
 stage consist of Czo/Ep neoblasts on Zo (Fig. 5c), rare Ab at the expense of Phe and Spn around Rt
 (M3 event: Czo/Ep + Ab + Spn).

- 4
- 5 Garnet

6 Garnet crystals show max 200 μ m dimensions and have inclusions (max 25 μ m in size; Fig. 7 5e) of abundant Omp + Qtz + Barr + Czo/Ep and rare Gln + Phe + Pg + Chl probably representing 8 in part a relic prograde assemblage. Grt is zoned from core to rim with rather constant Alm, 9 increasing Prp, decreasing Sps and first increasing and then decreasing Grs content. Thus, three 10 different composition can be distinguished (Fig. 6a): the core with Alm₅₆₋₆₁Grs₂₉₋₃₃Prp₄₋₆Sps₄₋₈ 11 composition, the mantle with Alm₅₆₋₅₉Grs₃₅₋₃₈Prp₅₋₆Sps₀₋₁ composition and finally the rim with 12 Alm₅₇₋₆₁Grs₂₇₋₃₁Prp₁₀₋₁₂Sps₀₋₁ composition.

13

14 *Omphacite*

Omphacite is fine grained (max 100 μ m) and is generally recrystallized in sub-grains. It shows slightly increasing Jd content from core (0.38-0.40) to rim (0.46-0.49) (Figs. 5f and 6b) and locally preserves relic cores with lower Jd content (min X_{Jd} 0.26). X_{Mg}(Fe²⁺) is rather constant between 0.77-0.87 (X_{Mg} is 0.74-0.84 assuming all Fe²⁺) without any correlation with X_{Jd}, while the Acm content is homogeneous and lower than 5 mol. %. Omp is also included in the Grt mantle and rim (Fig. 5e) and shows the same composition as the omphacite in the rock matrix (0.33-0.45 X_{Jd}; 0.70-0.78 X_{Mg} assuming all

22

23 White mica

White mica has 250-300 μ m dimensions and consists mainly of oriented phengite which defines a relict foliation and of rare Pg always associated to Zo. Phe shows decreasing Si content (Fig. 6c) from core (max 3.65 Si a.p.f.u.) to rim (min 3.31 Si a.p.f.u.). The zoning of phengite is not continuous showing a gap between 3.49-3.53 Si a.p.f.u. X_{Mg} decreases from core (0.82-0.88) to rim (0.64-0.68) while X_{Na} increases towards the rim up to 0.11.

29

30 Amphibole

31 Amphibole consists of a blue Gln core/mantle with a thin rim (50-100 μ m thick) of green 32 Barr (Fig. 6d). It has up to 1 mm length and shows PDO defining the relict foliation (pre-S₁), 33 however its dimensions and the textural relationships with Grt and Omp suggest that Gln continues 34 to grow after the relict foliation mainly at the expense of Omp. Gln has the composition 0.00-0.20

1 Al[IV] a.p.f.u., 1.65-1.80 Al[VI] a.p.f.u., 1.60-1.75 Na[B] a.p.f.u., 0.00-0.10 Na[A] a.p.f.u. with 2 decreasing XMg from core (0.77-0.80) towards the Gln rim (0.64-0.67). The Barr rim is slightly 3 zoned towards the outer rim, with increasing Al[IV] (from 0.55 to 0.95 a.p.f.u.), rather constant Al[VI] (0.95-1.15 a.p.f.u) and Na[B] (0.55-0.75 a.p.f.u.), increasing Na[A] (from 0.30 to 0.49 4 5 a.p.f.u. with up to 0.07 K[A] a.p.f.u.;) and decreasing XMg from 0.70 to 0.60. Locally the rim of 6 Barr shows $[Na + K]A \ge 0.50$ and is edenite/katophorite in composition (Fig. 6d), but this 7 classification strongly depends on the assumption that all measured FeO was ferrous. The interface 8 between Gln and Barr is very irregular (Fig. 5d) indicating that Gln, after being grown along the HP 9 foliation, was resorbed before the growth of the Ca-Amph. Amphibole shows inclusions of Grt 10 which is partially resorbed when in contact both with Gln and Barr (Fig. 5d) suggesting that Gln 11 rim was not in equilibrium with the Grt rim and that Gln grew again after the M1 assemblage. Barr 12 mainly grew at the expense of Omp + Gln + Grt.

13

14 Epidote

Epidote is in low amount and can be texturally distinguished into three generations: the first is included in Grt and has 0.14-0.45 **mathefred** a.p.f.u. and is interpreted as a prograde relic (Zo); the second is coarser and sub-idiomorphic with low birefringence (Zo with less than 0.19 **mathefred** a.p.f.u.) and grew in aggregates with Pg, the third (Clzo) shows higher birefringence, is idiomorphic and small grained and grows at the expense of Zo. The third generation is zoned showing increasing Fe3+ from core to rim (0.33-0.54 **mathefred** a.p.f.u.).

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22 4.2. Monte Rosa metapelites

23

The Alpine metamorphic evolution of the Monte Rosa metapelites is mainly characterized by two metamorphic events representing the development of the main regional foliation S_1 (M3 event) and a late re-equilibration developed under static conditions (M4 event) respectively. The S_1 regional foliation is defined by the M3 assemblage Phe + Pg + Grt II+ ChII + Ab/Olig + Qtz + Rt/IIm while the late static assemblage M4 consists of Ms + Pg + ChIII + Olig + Qtz + Bt + IIm (Fig. Furthermore, in the study area a few samples preserved a pre- S_1 foliation probably related to the HE retamorphism because of the high Si a.p.f.u. content of the relict phengite cores.

31 A representative \mathbf{x} valuate the metamorphic evolution 32 of the southern side of the Monte Rosa Nappe in the Gressoney Valley. The sample shows a well 33 developed S₁ foliation, \mathbf{x} foliation, \mathbf

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4.2.1. Sample GR3

Sample GR3 is a medium to coarse-grained micaschist characterized by the bimodal distribution of garnet. The coarse-grained garnet (GrtI) is xenomorphic, has up to 3 mm dimensions and is partly enveloped by the main foliation (S_1), while the matrix garnet (GrtII) shows smaller dimensions (1-1.5 mm in diameter) and is in textural equilibrium with the minerals defining the regional foliation (S_1). A pre- S_1 foliation (Fig.7a) is preserved within isoclinal to rootless fold hinges and is defined by Phe + Pg + Rt. The high Si content of phengite cores suggest that pre- S_1 could represent an HP foliation, associated to the M1-M2 metamorphic stages.

The regional foliation S_1 is defined by Phe + Pg + GrtII + ChII + Ab/Olig + Qtz + Rt/Ilm (M3 assemblage) and is partially overprinted by a late static assemblage M4 consisting of Olig + Ilm + ChIII + Ms + Pg + Qtz + Ilm. The presence of rare Hbl partially replaced by fine grained Chl + Qtz \pm Olig aggregates along the S_1 foliation (Fig. 7b) is interpreted as part of a previous assemblage (M2).

18

19 Garnet

20 Garnet occurs as multistage xenomorphic coarse grains (GrtI) with up to 3 mm dimensions 21 and as widespread idiomorphic grains with max 1-1.5 mm in diameter (GrtII). The coarse garnet 22 preserves a **core** showing fractures filled by a Grs-rich garnet (indicated by white arrows in 23 Fig. 7c). GrtI is overgrown by a new garnet generation (GrtII) grown as smaller grains in the rock 24 matrix (Fig. 7c). GrtI is unzoned with the Alm₈₀₋₈₅Grs₂₋₄Prp₇₋₉Sps₄₋₈ composition, while the fractures 25 are filled by a grossular rich garnet with Alm₆₆₋₆₉Grs₁₈₋₂₃Prp₄₋₆Sps₆₋₈ composition. GrtII instead is 26 slightly zoned (Fig. 8a-b-c) with the Alm₆₉₋₇₆Grs₁₃₋₁₉Prp₄₋₆Sps₅₋₆ composition at the core (similar to 27 the garnet filling the fractures of GrtI), the Alm₇₉₋₈₁Grs₇₋₁₀Prp₉₋₁₁Sps₁₋₃ composition at the mantle 28 and the Alm₇₇₋₈₀Grs₃₋₄Prp₁₆₋₁₉ composition at the rim. XMg increases from core (0.07-0.08) to rim 29 (0.16-0.18). GrtI shows inclusions of Qtz, while GrtII includes Qtz, Rt and locally Rt rimmed by 30 Ilm.

31

32 White mica

White mica consists of Phe and minor Pg which define the main foliation S_1 and the relict foliation pre- S_1 . Phe is zoned with decreasing Si content (Fig 8d) from core (max 3.46 a.p.f.u) to rim (3.28-3.30 Si a.p.f.u.), with up 0.06-0.12 Na a.p.f.u. XMg does not show a good correlation
with the Si content probably because of the presence of small amount of Fe³⁺ and roughly decreases
from 0.75 to 0.63. The rim of Phe is overgrown by a late generation of white mica represented by
Ms with 3.14-3.23 Si a.p.f.u and an XMg of 0.52-0.62 (Fig. 8d). Both phengite and paragonite show
small inclusions of rutile.

6

7 Other minerals

8 Two generations of chlorite can be texturally distinguished: ChlI is medium-grained and is 9 in lenses along the S₁ foliation while ChlII is fine-grained and is associated to Qtz or overgrew ChlI. 10 ChlII + Qtz aggregates are interpreted as pseudomorphs after hornblende (Fig. 7d-e-f). Both ChlI

11 and ChlII

(Fig. 8e). Bo generations locally show fine grained Bt interlayer along the cleavage but it was not possible to acquire quantitative analyses because of its small dimensions. Plagioclase consists mainly of oligoclase with up to 0.25 XAn which locally preserve an albite core. Plagioclase locally shows a PDO defining the S_1 foliation and the rim instead grew after Phe, suggesting it is stable both during M3 and M4; ilmenite grew at the expense of Rt and has up to 1 wt. % of MnO.

17Hornblende (Figs. 7e-f and 8f) is partly preserved and has 0.70-1.45 Al^[IV] a.p.f.u. 0.85-1.1018Al^[VI] a.p.f.u, and 0.15-0.40 Na^[B] a.p.f.u., 0.12-0.42 Na^[A] a.p.f.u. and 0.51-0.62 XMg, and is19replaced by Qtz + Chl (0.49-0.51 XMg) \pm Olig (0.72-0.74 XAb).

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22 23

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Metamorphic conditions for the polymetamorphic Complex of the Monte Rosa Nappe in the Gressoney-Ayas Valleys have been reconstructed

25 invitational interaction in the interaction of the eclogite (GR5) and the metapelite
26 (GR3) samples described above. All pseudosections have been calculated with PERPLE_X
27 (Connolly, 1990; Connolly and Petrini, 2002) using the thermodynamic database of Holland and
28 Powell (1998, 2004 upgrade).

All pseudosections have been calculated assuming all FeO as ferrous, and H_2O saturated conditions with a pure H_2O fluid-phase ($aH_2O = 1$). This is a realistic assumption for the studied samples since they contains abundant hydrous phases and because of the absence of primary carbonates and sulphurs. The following solid solution models have been used:

clino-pyroxene (Green et al., 2007), amphibole (Dale et al.,

34 20 , feldspar (Holland and Rell, 2003; or Furman and Lindsley, 1988), paragonite (

and Froese, 1975), phengite-muscovite (Holland, 2002), chlorite, chloritoid, staurolite and
carpholite (Holland and Powell, 1996,

]	
ļ	In a
	pseudosections, minimum initial and small letters indicate pure phases
	All calculated pseudosections consist of di-, tree-, quad-, penta-, six-variant fields which ar
	represented in white (di-variant) and with progressively darker grey hues.
	The bulk rock composition for the studied samples (Table 3) has been established by the
	XRF method at the Vancouver laboratories of the ALS Chemex. The location of the studied
	samples is reported in Fig. 2.
	5.1 Results for pseudosection modelling of GR5 (eclogite)
	The M1 assemblage (Grt + Omp + Phe + Qtz + Lws + $Rt \pm Gln$) represent the peak-pressure
	event and was modelled in the PT range of 13-29 kbar and of 350-700 °C with
ļ	Two pseudosections were calculated, the first (I) with SiO2 saturated conditions as
	justified by the presence of Qtz inclusions in Grt and the second (II) with SiO ₂ saturated condition
	and constraining a second s
	In pseudo I (Fig. 9a) the Grt compositional isopleths cross only at the Grt rim in the
	Omp + Grt + Tlc + Phe + Lws + Qtz ± Gln at 555-565 °C and 25-27 kbar (Fig. 9b). No Tlc was
	observed in the sample and the reason for the unmatched composition for garnet core and mantle
	could be the SiO2-H2O saturated conditions or the modelled composition of Gln which is too Fe
	rich (0.15-0.55 XMg; Fig. 9c) relative to the XMg measured (0.65-0.80). The SiO ₂ saturation
	condition is constrained by abundant Qtz inclusions in garnet and by low amount of Qtz in the
	matrix. Since the H_2O content in the rock at the PT conditions of Grt rim (1.0-3.0 wt. %; Fig. 9d) i
	a reasonable one and since the compositional discrepancy between calculated and modelled Gln i
	very large, pseudosection II was calculated constraining the XMg of Gln to values ≥ 0.60 .
	Pseudosection II (Fig. 10a) is contoured for Alm-Grs-Prp isopleths from garnet core (Alm ₅₆
	(1Grs20.22Prp4.6) to rim (Alm57.61Grs27.22Prp10.12) compositions (Fig. 10b), for XJd and XMg it

³³₆₁Grs₂₉₋₃₃Prp₄₋₆) to rim (Alm₅₇₋₆₁Grs₂₇₋₃₂Prp₁₀₋₁₂) compositions (Fig. 10b), for XJd and XMg in
 ³⁴ omphacite (Fig. 10c), for Si a.p.f.u. in phengite and for Na^[B], Al^[IV] and XMg in Ca-amphibole (Fig.

10d). The garnet core isopleths cross at 495-525 °C and 21-24 kbar and the rim at 550-570 °C and
 24-27 kbar. Along this path (black arrow in Fig. 10b) the sequence of the metamorphic assemblages
 is Gln + Lws, Cam + Gln + Lws, Tlc + Cam + Gln + Lws, Tlc + Gln + Lws, Tlc + Lws (with Grt +

4 Omp + Phe + Qtz in excess).

- 8 Along the inferred PT path, the Grt core is in equilibrium with a Di-rich Cpx (0.15-0.25 XJd) which 9 is quickly replaced or overgrown by a Jd- rich Omp (0.30-0.45 XJd) in equilibrium with the garnet rim (Fig. 10c). Therefore along this path garnet was in equilibrium with omphacite showing 0.15-10 11 0.45 XJd and XMg 0.55-0.75 (Fig. 10c), and phengite with max 3.70 Si a.p.f.u. (Fig. 10c). The 12 calculated compositions agree with the measured one except for the presence of a Jd poor pyroxene 13 generation (XJd < 0.25) with an intermediate XMg value (0.55-0.60) which has not been observed 14 and which was probably resorbed during the growth of Omp. The max XJd and XMg in the Na-Ca 15 pyroxene are reached during a first decompression stage (XJd = 0.46 and XMg = 0.80-0.81) at 575-16 600 °C and 21-22 kbar in the Omp + Grt + Phe + Cam + Qtz \pm Gln stability field (black arrow in 17 Fig. 10c).
- The path A **perform** ear-isothermal decompression trough the Gln stability field towards the Barr stability field, while path B represents a decompressional heating outside of the Gln stability field. Path A better represents textural relationships observed in the studied sample as Gln continued to grow after the M1 assemblage and then was resorbed before Barr growth. In the calculated pseudosection (Fig. 10), Barr should be in equilibrium with Omp (XJd 0.45-0.46; XMg 0.60-0.70) while in our sample Barr grew at the rim of Gln and at the expense of Omp (XJd 0.46-0.49; XMg 0.75-0.84).
- The second decompression step is constrained by the composition of Barr (0.55-0.95 $Al^{[IV]}$; 0.55-0.75 Na^[B]; 0.60-0.70 XMg) and by the Si content of the Phe rim (min 3.30 Si a.p.f.u.) and developed at 580-630 °C and 14.5-16.5 kbar in the Grt + Omp + Phe + Cam + Zo + Qtz stability field (Fig. 10d).
- All the previous observations and because of the great uncertainties in the amphibole solution model suggest that the PT conditions inferred for the exhumation path have to be treated with caution.
- 32

garnet rim contours cross at 550-565 °C and 23.5-26 kbar mainly in the Grt + Omp + Phe + lws + Qtz ± Tlc field at slightly lower P compared to the unfractionated composition. The Tlc amount in equilibrium with the Grt rim (Fig. 10f) is 7-9 vol. % and the Omp composition shows 0.47 XJd and 0.80-0.82 XMg on decompression similarly to Fig. 10c. This mean that the change in the effective bulk composition reacting during prograde metamorphism does not influence as much the minerals composition.

The

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9 5.2. Results for pseudosection modelling of GR3 (metapelite)

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- 11 5.2.1. PT conditions for GrtI generation
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13 GrtI generation represent the relic of a metamorphic event older than the M3 assemblage. 14 Since there is no other relic mineral and the only inclusions in GrtI consist of Qtz + Ilm, the PT 15 condition of equilibration for GrtI are poorly constrained and are only based according to its 16 composition (Alm₈₀₋₈₆Grs₂₋₅Prp₇₋₉). In the pseudosection of Fig. 11 no intersection has been 17 identified at high pressure, therefore GrtI cannot be related to the Alpine eclogite facies event 18 (M1/M2 assemblages) as already suggested by Ilm inclusions. Instead, the GrtI isopleths intersect at 19 550-575 °C and 4-6 kbar conditions in the Bt + Chl + Grt + Pl + Phe (Ms) + Qtz \pm Pg \pm St field. 20 Therefore, GrtI generation can be considered as a pre-Alpine relic belonging to the Variscan 21 orogenesis. These PT conditions are a minimum estimation of the pre-Alpine event since GrtI is 22 strongly resorbed and fractured.

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24 5.2.2. PT conditions for GrtII generation

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26 The M3 (Phe + Pg + Grt II + ChII + Ab/Olig + Qtz) and M4 assemblages (Ms + Pg + ChIII 27 + Olig + Qtz + Bt) were modelled in the PT window 5-15 kbar and 500-650 °C with Qtz + Ms/Phe 28 in excess (Fig. 12a). Since the Gln has revealed a problem in pseudosection modelling of sample 29 GR5 and since there is no evidence of former presence of this mineral in this sample where the only amphibole is relict Hbl, the Gln and Act solution models were rejected from calculations. This 30 31 means that the HP portion of the pseudosection could be metastable relative to Gln. The relative 32 bulk rock composition (2.98 MnO, 1.03 CaO, 37.24 FeO, 2.02 MgO, 20.21 Al₂O₃, in wt. %) has been calculated, according to the method of Gaidies *et al.* (2006), fractionati 33 34 of the average composition of GrtI.

1 The pseudosection is contoured for Alm, Grs, Prp isopleths for the GrtII core (Alm₆₉₋₇₆Grs₁₂₋ 2 ₁₈Prp₅₋₇) (Fig. 12b), mantle (Alm₇₉₋₈₁Grs₇₋₁₀Prp₉₋₁₁) and rim (Alm₇₇₋₈₀Grs₃₋₄Prp₁₆₋₁₉) compositions 3 (Fig. 12c); while in Fig 12d the Si isopleths in phengite, XMg in chlorite and XAn in plagioclase 4 are reported. The resulting PT path according to the garnet growth zoning represented by GrtII core 5 to mantle compositional zoning, suggests a near isobaric prograde event from 550 to 600 °C at 6.5-6 7.5 kbar (Fig. 12d) within the Bt stability field. In particular, the mantle composition of GrtII is 7 stable with Bt (max 3-4 vol. %) + Chl (XMg 0.46-0.52) + Pl (XAn < 0.30) + Ms (3.15-3.10 Si 8 a.p.f.u.) + Pg + Qtz.

9

fractionation of Si-rich Phe could displace the Bt-in towards higher T or cover reduce its vol. % 11 amount. GrtII rim should be stable with 4-5 vol. % St, with up to 11-14 % Bt, with andesine (XAn 12 13 > 0.30) and in absence of Chl. In this case all the Chl should be interpreted as pseudomorph after St 14 + Bt but since ChlI define the regional foliation it seems unlikely. However, we cannot exclude that 15 ChlII represents pseudomorphs after former Bt during retrogression. The absence of obvious 16 pseudomorphs after St together with the XMg of Chl (0.46-0.52) constrain the maximum PT 17 conditions for the M3 event at *ca* 600 °C and 7.5 kbar where the rock should contain less than 4 vol. 18 % of Bt.

Indeed, the

In this case, the GrtII rim composition does not reflect M3 peak conditions. This should be related to a later diffusion process and the M3 event should represent a re-heating of max 40 °C during the development of the regional foliation, while the M4 event developed immediately after the peak T during retrogression as suggested by the composition of ChIII which developed also at the expense of GrtII.

Finally, the presence of Hbl partially destabilizated in Chl + Qtz \pm Olig (see Figs. 7e-f) is compatible with the dashed decompressional path reported in Fig. 12d and should represent a pre-S₁ relic phase related to the M2 decompressional assemblage.

27 Another pseudosection for GR3 metapelite was calculated using the feldspar solution model 28 of Furman and Lindsley (1988) to check the difference with the Holland and Powell (2003) model 29 which slightly seems to overestimate the Ca content in plagioclase. The use of this solution model 30 changes the pseudosection topology shifting the Bt-in reaction towards higher T (compare Figs. 12a 31 and 13a). The intersection of Grt contours for the core composition constrain its stability at 545-555 32 °C and 7-7.5 kbar in the biotite-out stability field (Fig. 13b). The GrtII mantle contours cross at 33 580-595 °C and 8.5-9 kbar always in the Chl + Phe + Pg + Pl + Grt + Qtz field assemblage, while 34 the rim should be in equilibrium also with Bt (max 3 vol. %) at 610-620 °C and 8.5-9 kbar (Fig. 13c). If the ChIII should be partly interpreted as pseudomorph after former Bt during retrogression
 these PT conditions are likely, otherwise the Tmax in constrained to *ca* 590°C by the Chl
 composition. The resulting PT path differs from the previous one because the prograde trajectory is
 slightly compressional instead of isobaric.

The use of different feldspar solution model does not change as much the PT conditions for the M3 assemblage and the contours intersection of garnet and chlorite but the Furman and Lindsley (1988) model justifies in a better way the equilibrium assemblage identified in this sample and the plagioclase composition, probably also because the CaO content in the rock composition is very low (0.30 wt.%).

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11 6. Discussion

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In Fig. 14 the complete Alpine P–T path inferred for the southern side of the Monte Rosa Nappe in the Gressoney valley is reported. All the curves representing the geothermal gradients were calculated assuming an average density of 2.95 kg/dm³ for an heterogeneous subducted crust for P > 10 kbar (Bousquet *et al.*, 1997). At lower P where the average density is less (2.70-2.80 kg/dm³) the curves lay at slightly lower pressures without significant changes because of the close spacing of the geothermal gradients.

25 The eclogitic boudins on the south western part of the Monte Rosa Nappe registered peak pressure 26 conditions which occurred at 550-570 °C and 24-27 kbar and are characterized by the assemblage $Omp + Grt + Lws + Phe + Qtz + Gln + Rt \pm Tlc$ (inferred from pseudesection modelling) while the 27 28 only HP relic found in metapelites is Phe with high Si content (3.45-3.50 a.p.f.u.). The inferred PT 29 conditions for the M1 event are similar to previous estimations on whiteschists which yield 505 \pm 30 30 °C and 24 kbar (Le Bayon et al., 2006) while P is significantly higher compared to values 31 reported in the southern part of the nappe by Chopin & Monié (1984) (17 kbar and 500 °C), Dal 32 Piaz and Lombardo, (1986) and Borghi *et al.*, (1996) (10 ± 2 kbar and 500 ± 50 °C) and by Lapen et al. (2007) in the Furgg Zone (P > 13 kbar and 480-570 °C). 33

higher (ca 60°) than those reported in literature and similar to that recently inferred for the HP event
in the Gran Paradiso Massif (Gabudianu et al., 2009; Gasco et al., 2010).

3

4 The M2 metamorphic stage consists of the assemblage Omp + Grt + Amph + Zo + Phe + Pg5 + Qtz + Rt in the eclogites. This event can be divided in two successive decompressional stages. 6 The first developed in the Gln-Cam stability field at 575 – 600 °C and 21-22 kbar, wile the second 7 step occurred at 590-630 °C and 14.5-16.5 kbar suggesting a T increase during decompression. The 8 presence of this heating stage during decompression at still HP conditions is mainly related to the 9 amphibole composition: being aware of the many uncertainties in this solution model (Dale et al., 2005), these PT conditions have to be treated with caution. If these PT conditions of re-equilibration 10 11 at HP were true, the garnet and omphacite preserved in the rock are metastable in composition 12 relative to Barr. However, similar rocks were studied by Zhang et al., (2009) in the Western Dabie 13 Mountain (Central China) and the PT path reconstructed for the Monte Rosa eclogites is very 14 similar to that proposed by these authors. The presence or absence of this decompressional heating 15 (Fig. 14) does not influence the average exhumation rates but clearly have different meanings: indeed such an heating event at a depth of 50-60 km during exhumation could be linked to the slab 16 17 breakoff model (Davies and Von Blanckenburg, 1995) and to the ascent of astenospheric mantle 18 and could explain the almost complete overprinting of the M1 assemblage in the metapelites. 19 Taking into account the inaccuracy of the amphibole solution model and supposing that Barr 20 represent a local equilibrium, an alternative post-peak trajectory is represented by the dashed line of 21 Fig. 14.

22 The subsequent M3 tectono-metamorphic event developed syn-kinematically respect to the 23 main regional foliation S_1 and is characterized by the assemblage Phe + Pg + Grt + Chl + Ab/Olig + 24 Hbl + Qtz + Ilm in metapelites and by Cam (blue-green) + Chl + Ab + Bt + Qtz + Pg + Phe + Clzo 25 in the re-equilibrated metabasite boudins. It developed during increasing T from 550 to ca. 600°C at 26 7 - 9 kbar. The maximum T reached depends mainly on the interpretation of the Chl (see Fig 13). If 27 Chl can be partly interpreted as pseudomorph after Bt the maximum T reached is otherwise is 590° C. Since in the studied metapelites Bt is present in low amoun = he first 28 29 hypothesis is more reliable. These PT estimation are different from that of Le Bayon et al. (2006) 30 who reported for the decompressional event associated to the regional foliation in the whiteschists T 31 of 475 ± 30 °C and P of 8 kbar. Other PT data for the retrograde event are reported for the central 32 eastern portion of the Monte Rosa Nappe where rocks reached T range from 580 to 750 °C at 9-12 33 kbar (Engi et al., 2001).

1 7. Conclusions

2

3 The pseudosection modelling of two chemical systems (both metabasites and metapelites) allowed to reconstruct a portion of the PT path followed by the southern Monte Rosa Nappe during 4 5 the Alpine orogenesis (Upper Gressoney Valley). In particular, well preserved eclogite facies rocks 6 (M1 and M2 assemblages) were investigated to reconstruct the HP history related to the subduction 7 event, while re-equilibrated metapelites allowed to infer the PT conditions attained during the 8 development of the exhumation regional foliation (M3 to M4 assemblages). The metamorphic 9 evolution of the basement complex from the Monte Rosa Nappe is marked by texturally distinct mineral assemblages, defining four Alpine metamorphic stages (M1, M2, M3 and M4) developed 10 11 under different PT conditions. The M1 and M3 tectono-metamorphic stages are related to the 12 development of the pre- S_1 and S_1 foliations, respectively.

13 The reconstructed PT path (Fig. 14) shows a clockwise trajectory characterized by a 14 prograde stage along a 6-7 °C/km geothermal gradient up to the eclogitic peak pressure (M1 stage). 15 The exhumation path is linked to a slightly decompressional heating (ca. 40 °C and 10 kbar) up to the development of the second stage of the M2 metamorphic event. Further exhumation is 16 17 accompanied to cooling down to 540-550 °C and 7-9 kbar implying an exhumation of 25 km (7-8 18 kbar) linked to a T decrease. Afterwards, rocks followed a slightly compressional (from 7 to 9 kbar) 19 trajectory associated to an increase in T (from 550 to 600 °C) accompanied to the development of 20 the main regional foliation. During this event the apparent geothermal gradient range between 15 21 and 20 °C/km. Further exhumation was related to major cooling up to shallow crustal levels.

In Fig. 14 is also reported the trajectory proposed by Borghi *et al.*,
(1996). It shows similar shape respect to inferred path presented in this work, bat placed at lower P-T conditions.

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Moreover, the reconstructed trajectory is marked by a late thermal pulse accompanied by a limited burial stage. Recently, evidence of burial–exhumation cycles that took place during a single orogeny have been reported by Beltrando *et al.* (2007) in the Piedmont Zone, in the area located between the Gran Paradiso massif and the Aosta Valley. Based on geochronological data reported in literature, the HP stage has been dated at 42-43 Ma by Lapen *et al.* (2007) while the reequilibration stage range from 32 to 38 Ma (Engi *et al.*, 2001) in the central to eastern Monte Rosa.

11 12	
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14	Figure captions
15	
16	Fig. 1. a) Simplified tectonic map of the Western Italian Alps (modified after Schmid <i>et al.</i> , 2004).
17	The black box is enlarged in b); b) simplified geological map of the Monte Rosa Massif and
18	surrounding units (redrawn by Dal Piaz and Lombardo, 1986; Steck et al., 1999; Pleuger et al.,
19	2005). The dashed box shows the study area on the south side of the Monte Rosa Massif.
20	
21	Fig. 2. Simplified geological map of the study area showing the position of the studied samples. For
22	a detailed geological map see Gasco and Gattiglio (2011).
23	
24	Fig. 3. Main rock types of the study area: a) eclogite boudins within the garnet-micaschists; b)
25	transitional contact marked by intercalations (black arrows) between garnet-micaschists and albite-
26	micaschists just below the tectonic contact with the Zermatt-Saas metabasites; c) Bt + Grt rich dark

nodules in a light quartz-feldspatic matrix interpreted as meta-anatexites of pre-Alpine age; d)
 stretched meta-rodingites layers within the serpentinites.

3

4 Fig. 4. Mineral abundances and relationships between the metamorphic evolution and the
5 deformation stages of the studied samples.

6

7 Fig. 5. Microstructures of sample GR5: a) well preserved eclogite with a pre-S1 foliation mainly 8 defined by PDO of Phe and of Rt aggregates. Omp is partly recrystallized in subgrains and Gln has 9 up to 1 mm size and shows a Barr rim; b) Pg + Zo association overgrowing the pre-S1 foliation 10 interpreted as lozenge-shaped pseudomorph after Lws (highlighted by the red dotted line). Back-11 scattered images of eclogite GR5: c) Zo + Pg aggregate interpreted as pseudomorphs after Lws. 12 Coarse Zo has inclusions of Grt + Omp and is overgrown by late Czo; d) Gln with a Barr rim 13 overgrowing the M1 assemblage (mainly Grt + Omp). Barr also developed at the expense of Omp; 14 e) Qtz + Czo/Ep + Barr + Omp inclusions in Grt; f) zoned Omp showing increasing Jd content from 15 core (brighter) to rim (darker).

16

Fig. 6. Minerals chemistry of sample GR5. a) chemical zoning rim-to-rim profile of garnet; b) chemical composition of omphacite showing increasing Jd content from core to rim; c) composition of white micas showing decreasing Si content from core to rim; d) chemical composition of amphibole showing a glaucophane core and a barroisite/katophorite rim.

21

Fig. 7. Thin section images: a) D_1 fold in Monte Rosa micaschists preserving a pre-S₁ foliation; b) relict Hbl grains parly replaced by Chl +Qtz along the S₁ foliation. Back-scattered images of micaschist GR3: c) xenomorphic GrtI overgrown by GrtII which developed in the matrix too. The inset enhance a fracture (between arrows) in GrtI healed by GrtII. The A-A' line shows the core-torim profile of Fig. 8a; d) Qtz + Chl aggregate interpreted as pseudomorphs after Hbl; e) relict Hbl
 partly replaced by Qtz + Chl + Olig; f) particular of e).

3

Fig. 8. Minerals chemistry of sample GR3. a) chemical zoning core-to-rim profile of a garnet porphyroclast consisting of GrtI core overgrown by a GrtII rim; b) core-to-rim profile of a matrix GrtII showing a Grs-rich core similar in composition to the garnet filling the fractures of GrtI; c) chemical composition of garnet with arrow from core to rim of GrtII; d) chemical composition of white mica consisting of Pg, Ms and Phe with decreasing Si content from core to rim; e) chemical composition of the two chlorite generations; f) chemical composition of hornblende relict.

10

Fig. 9. a) PT pseudosection I for GR5 calculated with H₂O and SiO₂ saturated conditions for the composition reported in Table 3 (column A); b) contours for Alm, Grs and Prp showing that only the rim composition is stable; c) XMg in Gln; e) H₂O content in wt. %.

14

15 Fig. 10. a) PT pseudosection II for GR5 calculated with the same conditions of Fig. 9 and 16 constraining the XMg of Gln to values ≥ 0.60 ; b) contours intersection for core and rim 17 compositions of garnet. c) XJd and XMg contours for omphacite constraining the first exhumation step to 570-590 °C and 21-22 kbar. XJd increases quickly from 0.25 to 0.45 (0.30, 0.35 and 0.40 18 XJd curves are not represented for simplicity); d) Si content in phengite and XMg, Al^[IV] and Na^[B] 19 20 in amphibole constraining the development of Barr to 13-15 kbar and max 610 °C; e) Grt rim isopleths intersection after fractionation of garnet core-mantle using the composition of column B 21 22 of Table 3; f) Omp composition after fractionation of the Grt core-mantle.

23

Fig. 11. a) PT pseudosection for GrtI growth conditions of sample GR3 calculated for the
composition of column C of Table 3; b) Grs, Pyr and Alm contours intersection for GrtI.

Fig. 12. a) PT pseudosection for GrtII and M3 assemblage growth conditions of sample GR3 using
 the composition in column D reported in Table 3; b) Grs, Pyr, Alm and Sps contours intersection
 for GrtII core; c) Grs, Pyr and Alm contours intersection for GrtII mantle and rim; d) Si content in
 phengite, XMg in Chl and XAn in plagioclase.

5

Fig. 13. a) PT pseudosection for GrtII and M3 assemblage growth conditions of sample GR3 using
the feldspar solution model of Furman and Lindsley (1988) using the unfractionated composition of
column D in Table 3; b) Grs, Pyr, Alm and Sps contours intersection for GrtII core c) Grs, Pyr and
Alm contours intersection for GrtII mantle and rim; d) Si content in phengite, XMg in Chl and XAn
in plagioclase.

11

Fig. 14. Alpine PT path reconstructed for the southern Monte Rosa Massif according to the results obtained from eclogite and metapelite samples. The PT paths of Borghi *et al.*, (1996) and Le Bayon *et al.* (2006) has been reported for comparison. The depth is calculated on the basis of an average density of 2.95 kgr/dm³ for subducted crust.

16

17 Table 1. Selected microprobe analyses for eclogite GR5 from the southern border of the Monte18 Rosa Massif.

19

Table 2. Selected microprobe analyses for metapelite GR3 from the southern border of the Monte
Rosa Massif.

22

Table 3. Chemical composition used to calculate the different pseudosection for the studiedsamples.



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Figure 3 Click here to download high resolution image



Figure 4 Click here to download high resolution image

		modal amount (vol. %)	pre-Alpine	prograde	$pre-S_1 = S_{HP}$ M1	- M2	S ₁ M3	- M4
5 - eclogite	Omp	45-50						
	Grt	25-30						
	Phe	- 5						
	Pg	_ \5						
	Lws	?						
	Ep	< 5		-Zo-		Zo	ezo	
	Gln	10-15						
GR	Cam	5-10				-Barr-	Kat	
	Ab	< 1						
	Qtz	< 1		-				
	Rt	1-5				1		
	Spn	< 1						
	Grt	5-10		<u>.</u>				
	Phe/Ms	45.50						
ite	Pg	43-30					2	
GR3 - metapeli	Hbl	< 5				-		
	Pl	5-10					Ab	——————————————————————————————————————
	Chl	5-10					<u> </u>	— II
	Bt	< 1						
	Qtz	30-35		-				
	Rt	< 1						
	Ilm	< 1						



Figure 6 Click here to download high resolution image



















	G	rt*	Omp**		Wm*			Am*		Zo***	Czo***
Analysis	gr200c	gr190r	omple	omp12r	wm14c	wm7r	wm116	am98c	am93r	zo27	ep20
Position	core	rim	core	rim	core	rim		core	rim		
5	11.00624	1410000 -	nice-o	600 m m m m	Phe	Phe	Pg	Gln	Barr		
SiO ₂	37,40	37,43	55,71	56,35	54,89	51,08	48,61	59,24	49,64	39,69	39,14
TiO ₂	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cr ₂ O ₃	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	20,90	21,11	8,81	11,12	22,76	27,71	39,57	11,40	11,80	31,31	27,29
FeOtot	27,12	28,64	4,91	3,11	1,52	2,11	0,00	6,34	13,06	1,82	7,61
MnO	3,73	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
MgO	1,08	3,09	9,31	8,65	5,43	3,31	0,00	13,15	11,57	0,00	0,00
NiO	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
CaO	10,40	9,93	15,51	13,74	0,00	0,00	0,00	1,13	8,60	24,95	24,45
Na ₂ O	0,00	0,00	5,90	6,82	0,00	0,89	6,92	6,74	3,70	0,00	0,00
K ₂ O	0,00	0,00	0,00	0,00	11,52	10,50	0,84	0,00	0,32	0,00	0,00
Sum	100,63	100,20	100,15	99,79	96,12	95,60	95,94	98,00	98,69	97,77	98,49
Si	2,985	2,967	1,998	1,998	3,621	3,397	3,065	7,955	7,077	6,059	6,029
Ti	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Cr	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al	1,966	1,972	0,372	0,465	1,770	2,172	2,942	1,804	1,984	5,635	4,956
Fe ³⁺	0,000	0,000	0,042	0,007	0,000	0,000	0,000	0,000	0,000	0,233	0,980
Fe ²⁺	1,811	1,899	0,105	0,085	0,084	0,118	0,000	0,712	1,558	0,000	0,000
Mn	0,252	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mg	0,129	0,365	0,498	0,457	0,533	0,328	0,000	2,631	2,459	0,000	0,000
Ni	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ca	0,890	0,844	0,596	0,522	0,000	0,000	0,000	0,163	1,313	4,081	4,037
Na	0,000	0,000	0,410	0,469	0,000	0,115	0,846	1,755	1,023	0,000	0,000
ĸ	0,000	0,000	0,000	0,000	0,970	0,891	0,067	0,000	0,058	0,000	0,000
Sum	8,033	8,047	4,021	4,003	6,978	7,021	6,920	15,020	15,472	16,008	16,002

*assuming all ferrous iron; ** Fe3+ according to Lindsley & Anderson (1983); Fe3+ assuming Fe2O3 = FeO/0.9

		Grt*			W	n*		Chl*	Pl	Hbl*
Analysi	grt4c	grt64c	grt82r	wm34c	wm31r	wm50r	pgl	chl45c	pl43	am6
Position		core	rim	core	rim	rim				
	GrtI	GrtII	GrtII	Phe	Phe	Ms	Pg	Chl	Olig	Hbl
SiO ₂	36,59	37,14	38,14	52,08	50,58	49,22	48,11	26,45	65,84	48,26
TiO ₂	0,00	0,00	0,00	0,00	0,46	0,51	0,00	0,00	0,00	0,00
Cr ₂ O ₃	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Al ₂ O ₃	19,95	19,98	20,46	28,41	28,58	34,63	38,48	21,64	21,34	10,68
FeOtot	36,93	36,80	36,10	1,53	2,33	1,10	0,73	26,66	0,00	16,37
MnO	3,08	3,22	0,62	0,00	0,00	0,00	0,00	0,00	0,00	0,00
MgO	2,00	2,82	3,11	2,99	2,87	1,01	0,00	14,54	0,00	11,52
NiO	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
CaO	1,47	0,63	2,42	0,00	0,00	0,00	0,00	0,00	2,72	8,46
Na ₂ O	0,00	0,00	0,00	0,61	0,64	0,95	6,93	0,00	9,57	1,11
K ₂ O	0,00	0,00	0,00	10,65	10,50	9,94	0,95	0,00	0,00	0,24
Sum	100,02	100,59	100,85	96,27	95,96	97,36	95,20	89,29	99,47	96,64
Si	2,997	3,011	3,043	3,420	3,353	3,182	3,073	5,480	2,900	7,090
Ti	0,000	0,000	0,000	0,000	0,023	0,025	0,000	0,000	0,000	0,000
Cr	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al	1,927	1,910	1,924	2,199	2,233	2,639	2,898	5,286	1,108	1,850
Fe ³⁺	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fe ²⁺	2,529	2,496	2,409	0,084	0,129	0,059	0,039	4,620	0,000	2,011
Mn	0,214	0,221	0,042	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mg	0,244	0,341	0,369	0,293	0,284	0,098	0,000	4,491	0,000	2,522
Ni	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ca	0,129	0,055	0,207	0,000	0,000	0,000	0,000	0,000	0,817	1,332
Na	0,000	0,000	0,000	0,077	0,082	0,119	0,858	0,000	0,128	0,315
K	0,000	0,000	0,000	0,892	0,888	0,820	0,078	0,000	0,000	0,046
Sum	8,040	8.034	7,994	6.965	6.992	6,942	6.946	19,877	4,953	15,160



- Grt core										
=	XRF	& mantle	XRF	- GrtI core						
SiO ₂	48.15	50.22	64.76	65.31						
Al_2O_3	15.73	14.79	19.62	19.61						
FeO	11.61	8.68	6.64	6.05						
CaO	11.97	11.96	0.43	0.42						
MgO	6.38	7.28	2.11	2.11						
Na ₂ O	3.35	3.99	1.00	1.02						
K ₂ Õ	0.49	0.58	4.14	4.22						
М́nО	0.29	0.08	0.10	0.04						