



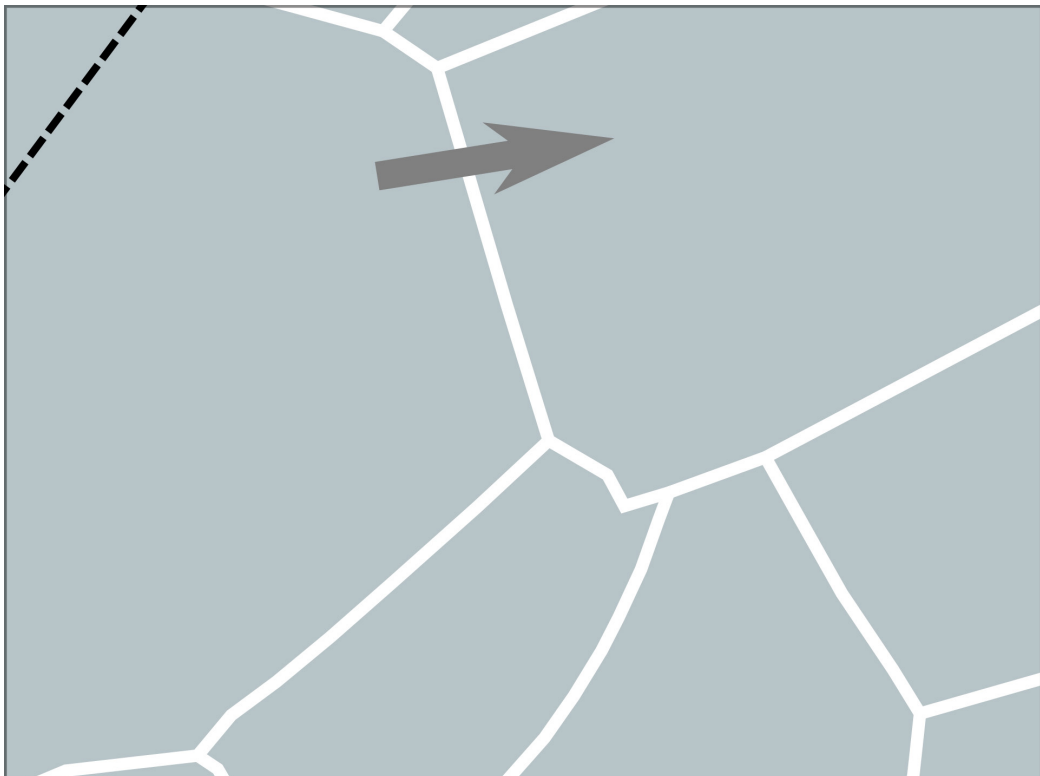
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Blueschist- or eclogite-facies? Re-assessing the peak P-T conditions of the Pinerolo Unit (Western Alps)

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Abstract

The Dora-Maira Massif of the Western Alps is one of the world's most famous locations for the study of (Ultra-) High-Pressure metamorphism. The Pinerolo Unit of the Dora-Maira Massif, the deepest unit exposed in the Western Alps, is overshadowed by the higher-pressure units overlying it, and the seldom studied unit has historically been estimated to have reached epidote-amphibolite-facies to blueschist-facies conditions. In the northern Dora-Maira Massif, no P-T estimates have been made for the Pinerolo Unit. By contrast, a recent study in its southern sector constrained its peak P-T conditions at 20-23 kbar and 500-515°C, i.e. in the eclogite facies. In the light of the new estimate, this study aims to re-assess the peak P-T conditions experienced by the northern sector of the Pinerolo Unit by petrographic examination and thermodynamic modelling. A result corroborating the new P-T estimate obtained in the southern part of this Unit would shed new light on the metamorphic history of the Pinerolo Unit and its role in the subduction of the Briançonnais microcontinent. On the other hand, a significantly lower-P estimate for the northern Pinerolo Unit would indicate the existence of two different units with the same name. To constrain the peak P-T conditions, thermodynamic modelling based on an internally consistent dataset and modern solution models were used in concert with petrographic and microprobe analysis. The results of this study show that the Pinerolo Unit experienced two deformational stages, initial garnet crystallisation and growth occurred at 18-20 kbar and 480-495°C, progressing to peak P-T conditions for the Pinerolo Unit at 18-20 kbar and 505-525°C. The results of this study in the northern sector of the Pinerolo Unit are in agreement with the recent investigation of the P-T evolution in its southern sector. This new P-T estimate extends the assessment of eclogite-facies metamorphism to the Pinerolo Unit as a whole.

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1. Introduction

Continental subduction is a fascinating subject; the buoyancy of continental crust typically prevents significant crustal portions to disappear into the mantle, but before the momentum of a continental collision has been stopped, immense amounts of continental crust may have been sucked down (Ingalls *et al.*, 2016). When slices of crust trapped by subduction are exhumed from the depths, their history may be gleaned. The exhumation mechanism of subducted crust in continental collisions is debated, but the fact that there are occurrences of deeply subducted continental crust exposed in the Himalayas (e.g. Wang *et al.*, 2021), remnants of the Variscan orogeny (Závada *et al.*, 2021), the Eo-Alpine Alps (e.g. Chopin *et al.*, 1991; Groppo *et al.*, 2019), the Caledonides (Majka *et al.*, 2014; Klonowska *et al.*, 2017) and the Altaids (Sobolev & Shatsky, 1990) indicate that it's not a unique or rare phenomenon. One major problem of explaining the occurrence of (Ultra-) High-Pressure (HP/UHP) rocks at surface levels is the high speed of exhumation needed to prevent overprinting of the HP-UHP assemblages (e.g. Duchêne *et al.*, 1996).

As crustal extension or erosion alone is not likely to produce the observed exhumation rates, various models have been proposed, such as extrusion through channel flow due to rheological differences (e.g. Grujic *et al.*, 1996; Godin *et al.*, 2006, and references therein), extensional events enabling buoyancy-driven extrusion without significant erosion (Malusà *et al.*, 2011) and exhumation of an extrusion wedge through faulting and thrusting of the bounding units in a convergent setting (Ring & Glodny, 2010). There are also suggestions that some occurrences of HP-UHP metamorphism may be the result of tectonic overpressure, where the apparent exhumation rate is deemed unrealistic for deep subduction (e.g. Schmalholz *et al.*, 2014; Schenker *et al.*, 2015). In the exhumation process, deeply subducted units may be juxtaposed above lower-P units as part of the nappe stack formation (e.g. Brueckner & Van Roermund, 2007; Manzotti *et al.*, 2015a), a concept which caused great debate and satirical cartoons in the late 19th century but now is accepted as fact (Gee & Kumpulainen, 1980).

To describe the degree and type of metamorphism, i.e. pressure and temperature conditions (Eskola, 1915), the concept of metamorphic facies is used as a convenient label that is not too narrow or wide in definition. The different metamorphic facies are characterised by distinct mineral assemblages that developed in metabasalts (e.g. Winter, 2021) (Fig. 1). Metamorphic facies indicative of relatively high pressures are the blueschist and eclogite facies. In metabasalts, the blueschist facies is associated with the development of glaucophane-lawsonite, whereas a garnet-omphacite assemblage is indicative of eclogite-facies metamorphism (e.g. Liou *et al.*, 2012). The concept of metamorphic facies is frequently extended to other types of rocks (e.g. metapelites), even if the typical mineral assemblages observed in metabasalt do not develop in these rocks. Though this can be tricky, overall it provides a first hint of the P-T conditions registered by a rock.

The Western Alps are well suited for the study of HP-UHP metamorphism as large sections have experienced blueschist – eclogite-facies metamorphism, with UHP assemblages in parts of the Dora-Maira Massif (e.g. Chopin *et al.*, 1991; Bousquet *et al.*, 2012a). The Pinerolo Unit in the Dora-Maira Massif is made of monocyclic graphite-bearing mica-schist, conglomerates and orthogneiss (Compagnoni *et al.*, 2004) and is interpreted as the lowermost tectonic unit exposed in the Western Alps (e.g. Beltrando *et al.*, 2010). The Pinerolo Unit has long been thought to have experienced blueschist-facies metamorphism (Vialon, 1966, Avigad *et al.*, 2003), though P-T estimates were quite uncertain. A recent petrological investigation of a sample collected in the southern sector of this Unit (Groppo *et al.*, 2019)

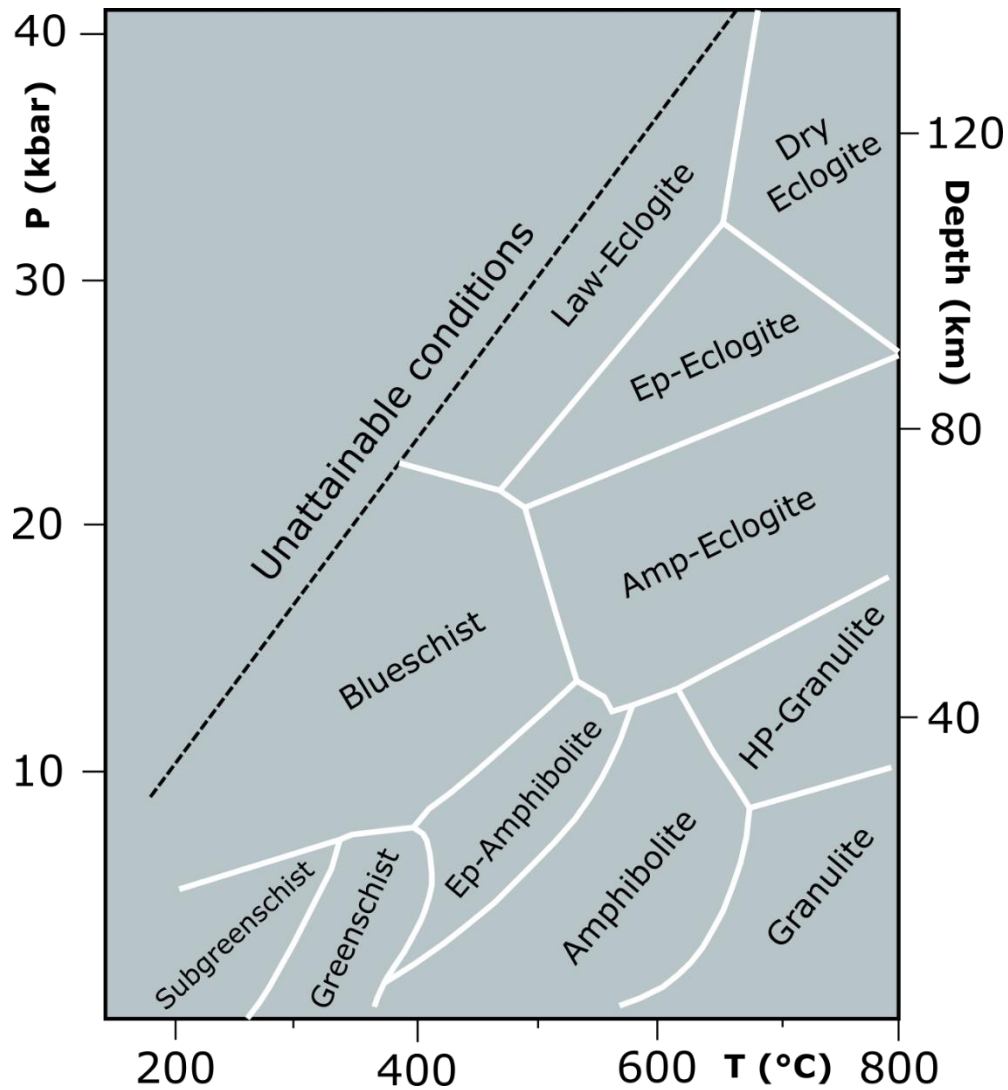


Fig. 1. Sketch of metamorphic facies as presented by Liou & Zhang (2003). Prefixes describe subdivisions of facies, HP = High-Pressure, Amp = Amphibole, Ep = Epidote, Law = Lawsonite.

proposed new peak-P conditions at 20-23 kbar and 500-515°C, suggesting that previous P-T estimates underestimated the peak pressures reached by this Unit during the Alpine subduction. The new peak P-T conditions proposed by Groppo *et al.* (2019) for the Pinerolo Unit fall in the P-T range typical of the eclogite facies.

In the northern sector of the Pinerolo Unit there are no petrological studies that constrain the peak P-T conditions. Few studies have been conducted so far, providing only a petrographic description of the lithologies constituting this Unit (Vialon, 1966, Wheeler, 1991).

This study aims to (i) re-assess the peak P-T conditions (blueschist or eclogite?) of the northern Pinerolo Unit through a detailed petrological investigation, (ii) examine previous estimates and (iii) discuss the tectonic implications of potential differing results between the northern and southern sectors.

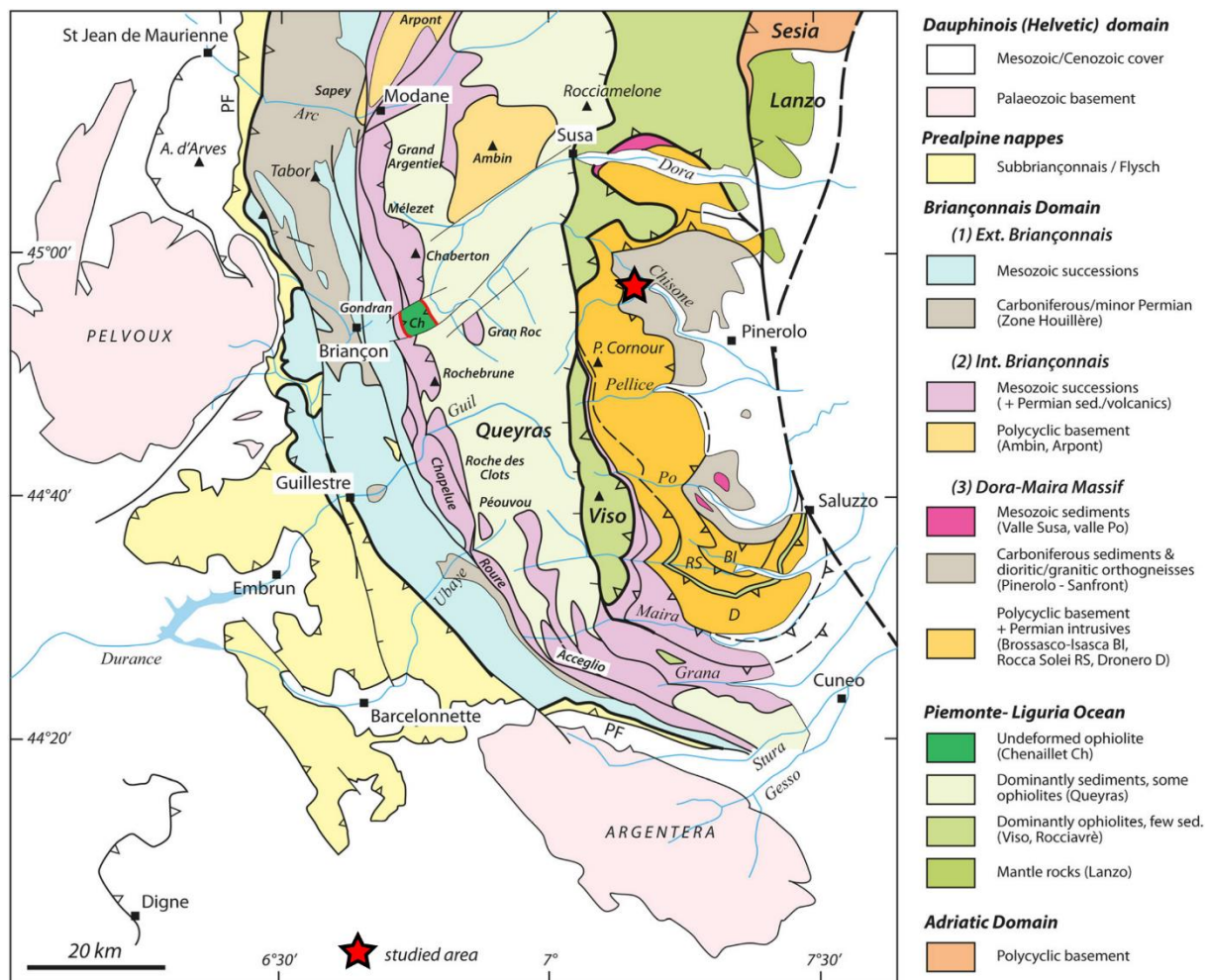


Fig. 2. Simplified map of tectonic units in the Western Alps including the studied area (modified after Ballèvre *et al.*, 2020).

2. Geological setting

The Western Alps are part of the Alpine orogeny, consisting of stacked and deformed nappes (e.g. Bousquet *et al.*, 2012b) (Fig. 2). The cause of the orogeny was, simply put, convergence of the Eurasian and Adriatic plates, but in fact the collision involved multiple microcontinents and oceanic regions caught between the larger plates at the closing of the Tethys Ocean (e.g. Dewey *et al.*, 1973; Stampfli *et al.*, 1998; Schmid *et al.*, 2004). Remnants the Briançonnais microcontinent, once a part of the European plate margin which experienced rifting at the breakup of Pangaea, make up a large portion of the Western Alps (Handy *et al.*, 2010; Ballèvre *et al.*, 2020 and references therein; Manzotti & Ballèvre, In press).

Evidence of deep continental subduction during the subsequent convergence can be seen in parts of the Briançonnais domain, such as in the Dora-Maira Massif where coesite has been found in eclogite-facies units (Chopin *et al.*, 1991; Schertl & O'Brien, 2013). The Dora-Maira Massif is famous for its HP-UHP metamorphism both in the blueschist- and eclogite-facies zones and has long been a reference site for UHP mineral assemblages (e.g. Groppo *et al.*, 2019). There are numerous HP-UHP units in the massif, both mono- and polymetamorphic, with an eclogite-facies Piemonte-Ligurian meta-ophiolite bounding the massif to the west (Ballèvre *et al.*, 2020).

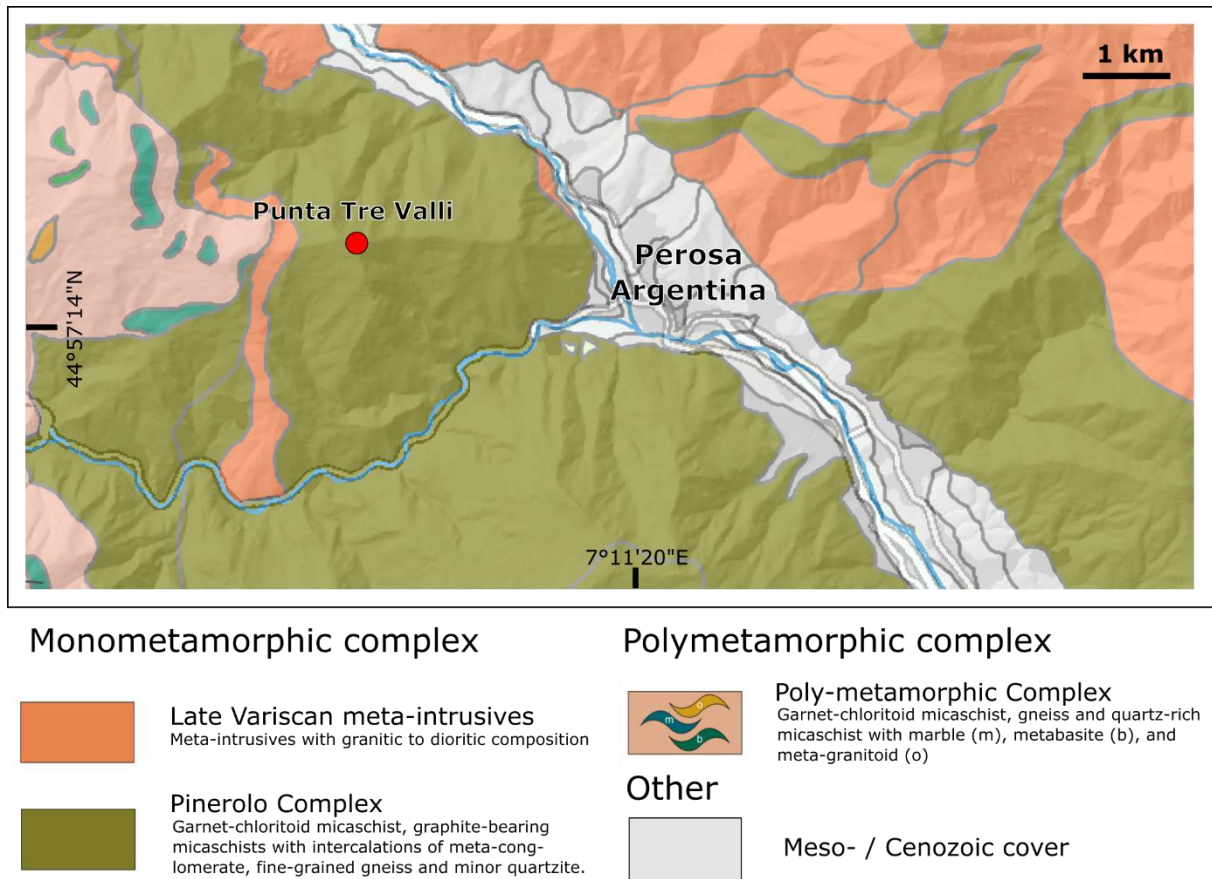


Fig. 3. Geological units surrounding Perosa Argentina village. The studied sample is collected in the area of Punta Tre Valli. Modified after Piana *et al.* (2017).

The Pinerolo Unit of the Dora-Maira is described as the deepest unit exposed in the Western Alps (Avigad *et al.*, 2003; Beltrando *et al.*, 2010), and is a monometamorphic unit consisting of metasediments and orthogneiss (Compagnoni *et al.*, 2004). The Carboniferous terrigenous metasedimentary complex is likely related to the lithologically similar Zone Houillère, which consists of weakly deformed and metamorphosed Carboniferous sediments (Sandrone *et al.*, 1993; Manzotti *et al.*, 2016). The Pinerolo Unit consists of metaconglomerate (Vialon, 1966; Petrocchia & Iaccarino, 2021), graphite-bearing metapelite (Gasco *et al.*, 2011) and granitic to dioritic intrusions of Middle Carboniferous to Lower Permian age (Bussy & Cadoppi, 1996), now occurring as orthogneiss. The provenance of the sediments is uncertain but is thought to have been the Variscan basement rocks, as the maximum depositional age is constrained at around 330 Ma (Manzotti *et al.*, 2016). This study concerns the metasediments in the northern sector (Fig. 3) and comparisons to their counterparts in the southern sector and other related units; thus only the metasedimentary complex is discussed when referring to the Pinerolo Unit, unless otherwise noted.

In relation to the Zone Houillère, Ballèvre *et al.* (2020) place the Pinerolo Unit basin distally from the European margin on the Briançonnais microcontinent; during the Alpine orogeny the Zone Houillère detached from the Briançonnais basement and was thrust shallowly towards the north-west while the Pinerolo Unit was buried deeply to at least blueschist-facies conditions in the orogenic wedge. The Pinerolo Unit is also considered to be likened to the Money unit in the Gran Paradiso Massif, a graphite-bearing mica-schist overthrust by the eclogite-facies Gran Paradiso Unit (Manzotti *et al.*, 2015a),

though this is thought to have originated in a separate basin or at the fringe of the Zone Houillère (Manzotti *et al.*, 2015b).

In the southern Dora-Maira Massif, P-T estimates for the Pinerolo Unit range from epidote-amphibolite-facies at 8-10 kbar and 400-500°C (Avigad *et al.*, 2003) to eclogite-facies at 20-23 kbar and 500-515°C (Groppo *et al.*, 2019).

The Pinerolo Unit in the southern sector of the Dora-Maira Massif is overlain by several units. The quartz-eclogite-facies San Chiaffredo and Rocca Solei Units have similar lithologies, consisting of monometamorphic orthogneisses, meta-granitoids, and polymetamorphic mica-schists (Compagnoni *et al.*, 2004). Both bound the coesite-bearing unit, the Rocca Solei above and the San Chiaffredo in contact with the Pinerolo Unit below (Compagnoni & Rolfo, 2003). The Brossasca-Isasca Unit also consists of monometamorphic gneisses and meta-granitoids and polymetamorphic mica-schists, though these have reached coesite-eclogite-facies metamorphism at 30 kbar and 700-750°C (Chopin *et al.*, 1991) or up to 40-43 kbar and 730°C (Groppo *et al.*, 2019). All units above the Pinerolo Unit contain small lenses of eclogite (Compagnoni *et al.*, 2004).

In the northern part of the massif, the Pinerolo Unit is only overlain by the quartz-eclogite-facies polymetamorphic Muret Unit. The latter consists of lithologies similar to the ones constituting the Rocca Solei and San Chiaffredo Units (Nosenzo *et al.*, 2022). No P-T conditions have been estimated so far in the northern sector of the Pinerolo Unit.

Table 1. Representative mineral analysis (for muscovite see section “white mica”). $X_{Mg} = Mg/(Mg + Fe)$ (chl); $X_{Ca} = Ca/(Ca+Na+K)$ (ab); $X_{Na} = Na/(Ca+Na+K)$ (ab); $X_K = K/(Ca+Na+K)$ (ab); $X_{Fe} = Fe/(Fe + Mg)$ (g).

DataSet/Point	13 / 1.	16 / 1.	30 / 1.	40 / 1.	2 / 1.	11 / 1.	DataSet/Point	b60 / 19.	b60 / 35.	b60 / 39.	b59 / 50.	b59 / 3.
Mineral	pl	pl	chl	chl	ilm	ilm	Mineral	g	g	g	g	g
							Position	Garnet 1 mantle	Garnet 1 rim	Garnet 2 core	Garnet 2 mantle	Garnet 2 rim
SiO ₂	63.54	64.05	24.46	24.90	0.04	0.00	SiO ₂	36.51	36.96	36.88	37.00	36.81
TiO ₂	0.01	0.00	0.09	0.12	52.78	53.56	TiO ₂	0.12	0.03	0.07	0.11	0.08
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.00	0.00	Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	22.18	21.95	21.95	20.92	0.02	0.03	Al ₂ O ₃	21.14	21.12	20.99	21.02	21.14
FeO	0.08	0.05	29.36	29.19	45.73	45.84	FeO	33.03	34.45	30.16	32.30	33.82
MnO	0.00	0.00	0.06	0.11	0.99	1.00	MnO	2.67	2.05	4.89	2.58	1.76
NiO	0.03	0.02	0.04	0.08	0.00	0.07	NiO	0.02	0.00	0.00	0.01	0.00
MgO	0.04	0.00	11.58	12.01	0.06	0.04	MgO	0.91	1.01	0.96	0.97	1.03
CaO	3.54	3.22	0.03	0.00	0.01	0.01	CaO	6.12	5.22	6.12	6.59	5.82
Na ₂ O	9.41	9.66	0.00	0.00	0.00	0.00	Na ₂ O	0.05	0.00	0.12	0.00	0.00
K ₂ O	0.09	0.08	0.00	0.01	0.00	0.02	K ₂ O	0.00	0.00	0.00	0.00	0.03
Total	98.93	99.04	87.57	87.35	99.64	100.58	Total	100.57	100.84	100.18	100.58	100.49
Oxygen	8.00	8.00	14.00	14.00	3.00	3.00	Oxygen	12.00	12.00	12.00	12.00	12.00
Si	2.83	2.85	2.64	2.69	0.00	0.00	Si	2.94	2.97	2.97	2.97	2.96
Ti	0.00	0.00	0.01	0.01	1.00	1.01	Ti	0.01	0.00	0.00	0.01	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	Cr	0.00	0.00	0.00	0.00	0.00
Al	1.17	1.15	2.79	2.67	0.00	0.00	Al	2.00	2.00	1.99	1.99	2.01
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	Fe ³⁺	0.11	0.05	0.07	0.05	0.06
Fe ²⁺	0.00	0.00	2.65	2.64	0.97	0.96	Fe ²⁺	2.11	2.26	1.96	2.12	2.22
Mn	0.00	0.00	0.01	0.01	0.02	0.02	Mn	0.18	0.14	0.33	0.18	0.12
Ni	0.00	0.00	0.00	0.01	0.00	0.00	Ni	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	1.86	1.94	0.00	0.00	Mg	0.11	0.12	0.12	0.12	0.12
Ca	0.17	0.15	0.00	0.00	0.00	0.00	Ca	0.53	0.45	0.53	0.57	0.50
Na	0.81	0.83	0.00	0.00	0.00	0.00	Na	0.01	0.00	0.02	0.00	0.00
K	0.01	0.00	0.00	0.00	0.00	0.00	K	0.00	0.00	0.00	0.00	0.00
X _{Mg}			0.41	0.42			X _{Fe}	0.95	0.95	0.94	0.95	0.95
X _{Ca}	0.17	0.15					alm	0.72	0.76	0.67	0.71	0.75
X _{Na}	0.82	0.84					pyr	0.04	0.04	0.04	0.04	0.04
X _K	0.01	0.00					spss	0.06	0.05	0.11	0.06	0.04
							grs	0.18	0.15	0.18	0.19	0.17

3. Methods

3.1 Petrographic investigation

A thin section of the sample was prepared to allow petrographic examination for determination of mineral assemblage. Thin section was prepared by Thin Section Lab in Nancy (thinsectionlab.com). The thin section was prepared to 30 μm thickness and polished.

3.2 Microprobe analysis

Microsonde Ouest (Brest, France) carried out microprobe analysis of minerals. Analyses were made with a Cameca SX100 electron microprobe operating in the wavelength dispersive mode. Operating conditions for spot analyses were set to 15 keV accelerating voltage, 20 nA beam current and 10 s counting time on the peak (spot size = 1 μm). ϕ (ρZ) matrix correction was applied based on Pouchou & Pichoir (1985). Standards were natural albite (Na, Si), orthoclase (K), corundum (Al), wollastonite (Ca), forsterite (Mg), MnTiO₃ (Mn, Ti), andradite (Fe). BSE and X-ray element maps have been elaborated with the software SX100. Further classification of microprobe analysis sites was performed through inspection of back-scattered electron images. Composition of representative minerals are shown in Table 1. Mineral abbreviations follow Holland & Powell (1998) except pyrope (abbreviated pyr).

3.3 Bulk rock chemistry

XRF sample preparation and analyses were performed at the PetroTectonics analytical facility at Stockholm University. A representative volume of a crushed specimen was fused into a glass chip by fusion of di-lithium tetraborate and crushed rock powder in a 5:2 ratio.

3.4 Thermodynamic modelling

In order to estimate the peak P-T conditions reached by the Pinerolo Unit, a P-T pseudosection has been calculated, using the bulk rock composition obtained by XRF. The software used is Theriak-Domino (de Capitani & Brown, 1987; de Capitani & Petrakakis, 2010) together with the internally consistent dataset tcds55 (Holland & Powell, 1998) converted for use in Theriak-Domino by D.K. Tinkham (2012, <https://dtinkham.net/peq.html>). The pseudosection, solid solution isopleths and mineral modes were calculated in the range 400-600°C and 5-25 kbar.

Phase diagrams were calculated in the MnO-Na₂O-K₂O-CaO-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂-Fe₂O₃ system (MnNCKFMASHTO). Solution models used were garnet, biotite, ilmenite, hematite (White et al., 2005), amphibole (Diener & Powell, 2012), carpholite (Wei & Powell, 2004), clinopyroxene (Diener & Powell, 2012), chlorite (Le Bayon et al., 2006; based on Holland et al., 1998), chloritoid (Mahar et al., 1997; White et al., 2000), muscovite (Coggon & Holland, 2002), plagioclase (Holland & Powell, 2003), epidote (Holland & Powell, 1998), magnetite (White et al., 2000). Fluid was considered in excess and pure H₂O. The amount of Ca in the bulk composition was corrected for apatite using the amount of phosphorous. Fe₂O₃ was recalculated to FeO and an arbitrary small amount of Fe₂O₃ (5%). In the diagram, all sodic amphiboles have been marked as 'gl', as in Manzotti et al. (2020). Clinopyroxene is labelled cpx regardless of composition.

In addition to the pseudosection, Si p.f.u. isopleths were calculated for muscovite within the range 3 – 3.6 p.f.u. with increments of 0.05 p.f.u.. Mol.% isopleths were calculated for the garnet endmember, within enough margin to allow analysis of compositional evolution. Garnet endmember isopleths were calculated with increments of 5 mol.%, and additional calculations with increments of 2 for spessartine

and almandine. Garnet and chloritoid mode isopleths were calculated within the range 0 – 20 vol.% and increments of 2 vol.%.

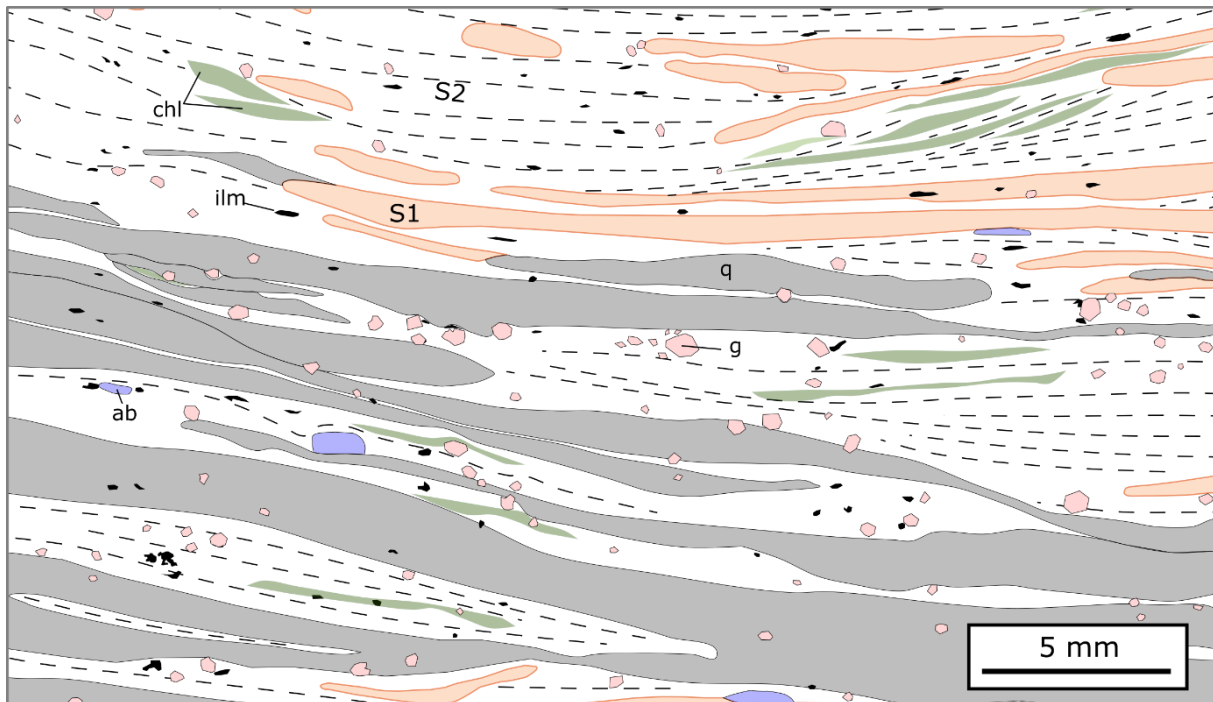


Fig. 4: Simplified structural sketch of thin section. White S2 domains are dominated by white mica and chlorite, striped lines mark S2 foliation. S1 microlithons principally contain folded white mica. Grey quartz bands contain thin white mica and chlorite films between quartz layers.

4. Results

4.1 Sample description

The sample is a fine-grained light grey mica-schist with anastomosing quartz bands (Fig. 4), collected in the area of the Punta Tre Valli, north-west of Perosa Argentina village. It consists of quartz (40 %), white mica (35-40 %), chlorite (15 %), garnet (3 %), ilmenite (1-2 %), graphite (1 %), albite (1 %) and accessory epidote (<1 %), rutile (<1 %), apatite (<1%) and zircon (<1 %).

At the mesoscale, the trend of the foliation observed in the sample is consistent with the main regional foliation of the Pinerolo Unit. Two main domains can be identified by hand lens, a mica-rich and a quartz-rich.

At the microscale, further observations can be made. The argillaceous domain is dominated by fine-grained white mica that define a pervasive foliation, wrapping around garnet porphyroblasts. Microlithons of white mica show folding of relict foliation. Garnets in the sample, 200-800 μm , contain quartz, rutile, apatite and zircon inclusions and show slight chlorite replacement. Chlorite is abundant, mostly oriented parallel to the main pervasive foliation, but also occur in sites with random orientation and as replacement of garnet. The quartz-rich domain shows anastomosing quartz bands separated by thin films of white mica and chlorite. Graphite and ilmenite grains are abundant in the matrix and are oriented parallel to the pervasive foliation. Rare albite porphyroblasts also occur.

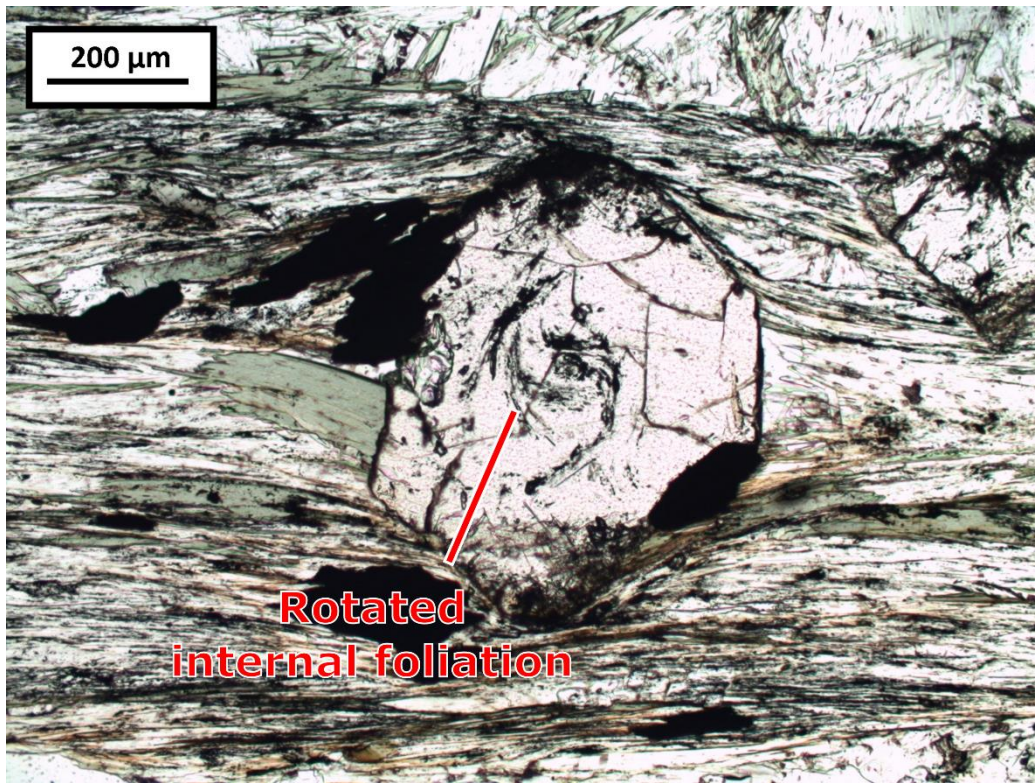


Fig. 5. Thin section micrograph of garnet porphyroblast with rotated internal foliation marked by graphite (PPL).

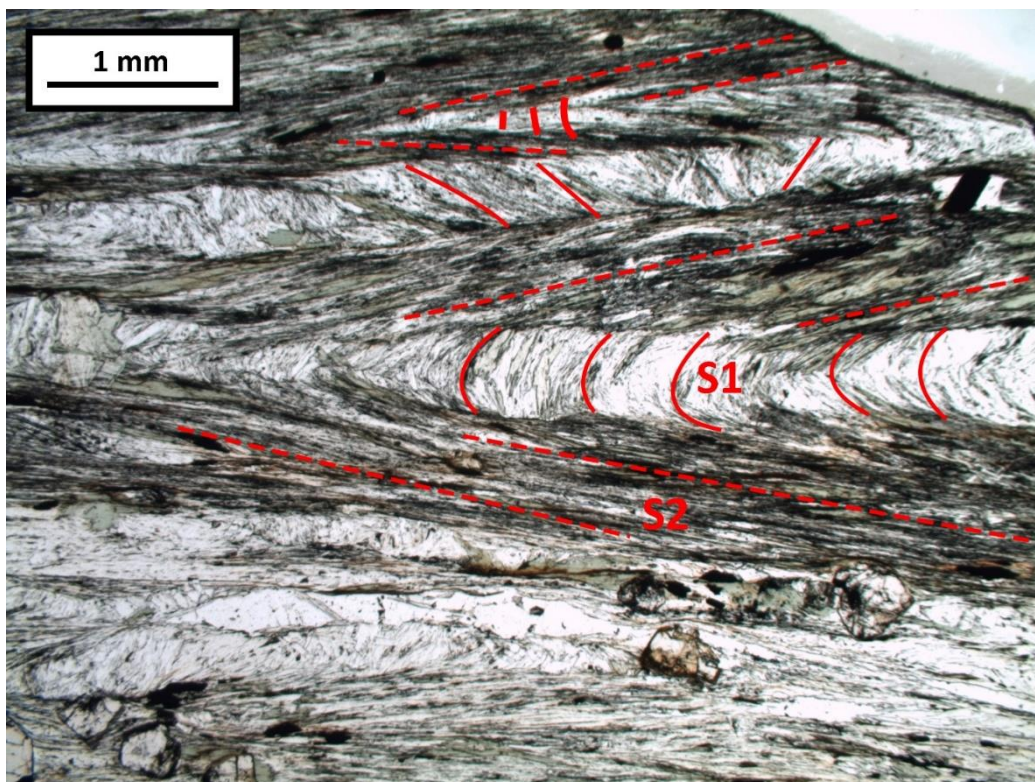


Figure 6: Thin section micrograph of S1 and S2 foliation (PPL). Crenulation cleavage is visible, indicating realignment of the S1 foliation during stage 2.

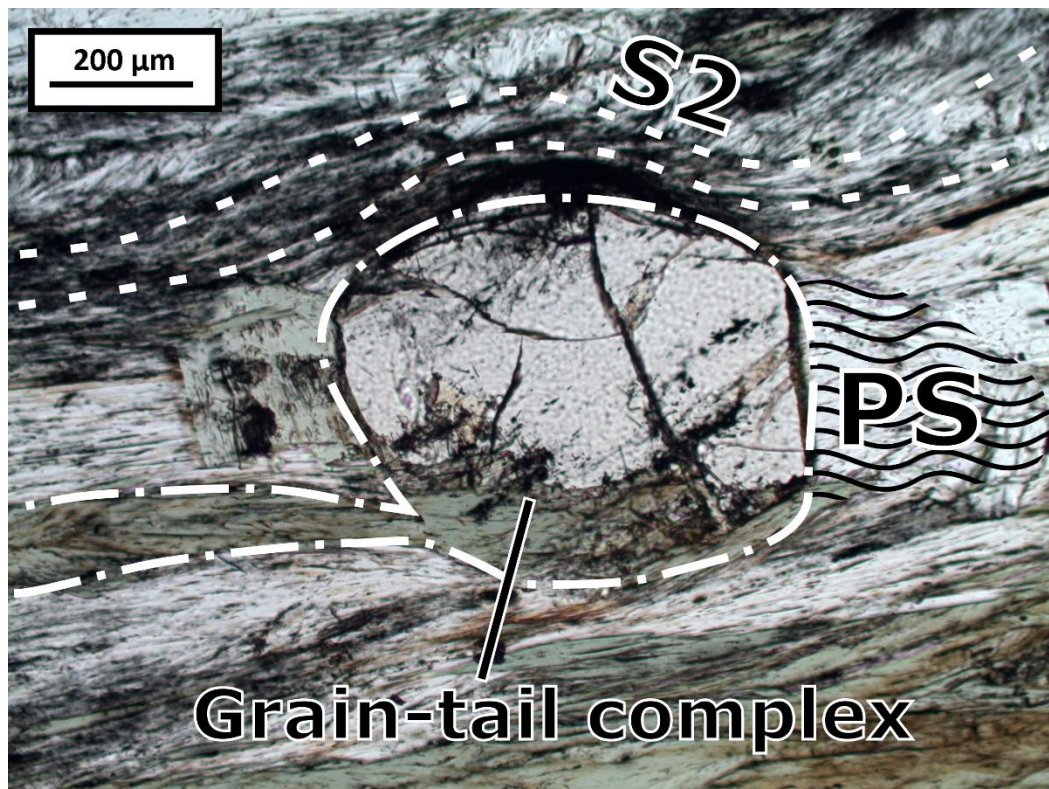


Fig. 7. Thin section micrograph of garnet-chlorite grain-tail complex with partial chlorite replacement (PPL). S2 foliation wraps around the garnet, and a pressure shadow (PS) is visible on either side, unoriented muscovite on the right (area marked with wavy lines) and unoriented chlorite on the left.

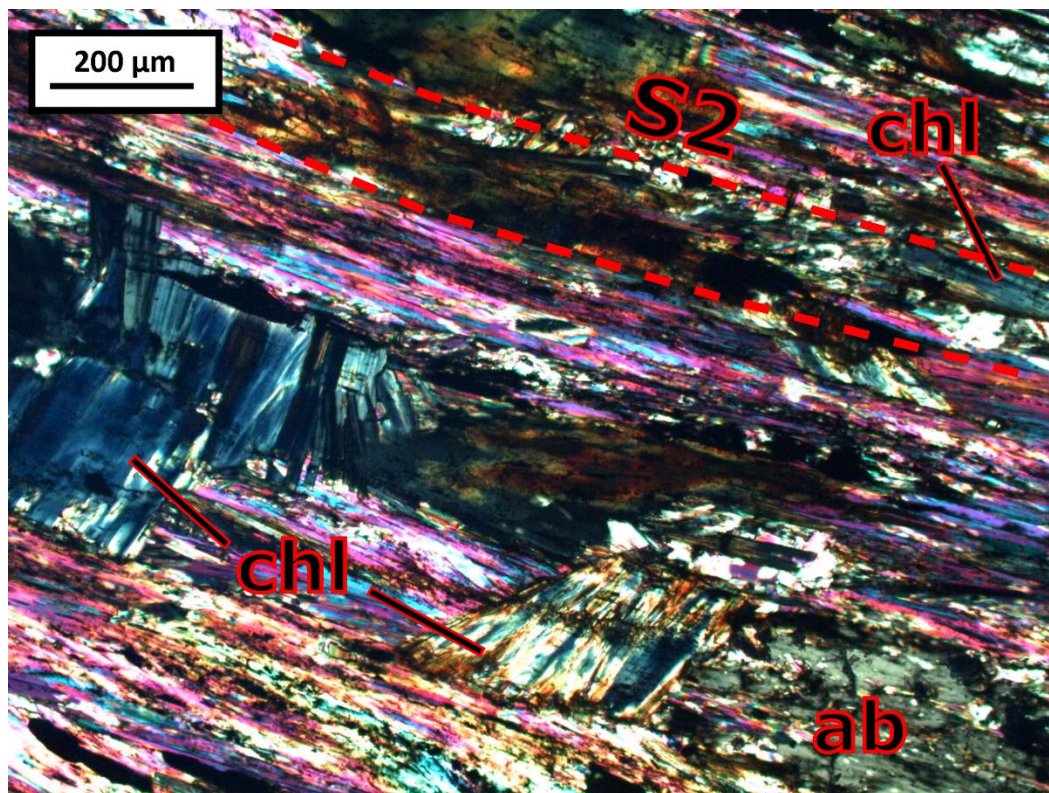


Fig. 8. Thin section micrograph of chlorite crystals oriented parallel to S2 (upper right) and unoriented chlorite crystals (lower left), here in close association with albite (XPL).

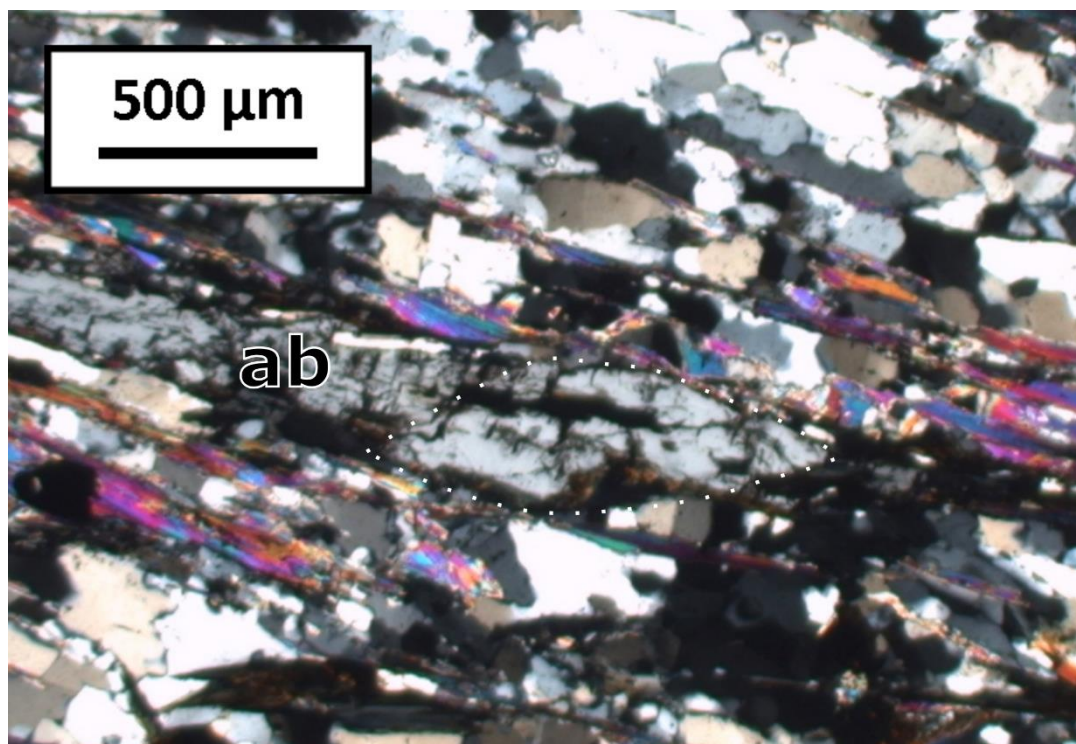


Fig. 9. Thin section micrograph of likely glaucophane pseudomorphed by albite (XPL). The pseudomorphed glaucophane crystal is outlined with white dots.

4.2 Deformation and metamorphism relations

The original sedimentary bedding is not observed in the sample and is interpreted to have been overprinted by subsequent metamorphism.

The early metamorphic history (stage 1) involves the growth of garnet cores and its mineral inclusions. Identified inclusions are zircon, rutile, graphite, apatite and quartz. Graphite inclusions in one garnet crystal (Fig. 5) define a rotated internal foliation. Garnet growth and rotation of the internal foliation is likely syn-kinematic with stage 1. Relicts of S1 foliation can be seen in microlithons of folded white mica, interpreted to also relate to stage 1 based on Si content per formula unit (p.f.u.) content of muscovite (see section “white mica” for further details). The folding of S1 and its relation to crenulation cleavage is visible (Fig. 6), but the original orientation of S1 cannot be determined.

The pervasive foliation, S2, is interpreted to have developed during stage 2. It is marked by the preferred orientation of white mica, chlorite, graphite, ilmenite and albite. Quartz domains are also oriented parallel to S2 in anastomosing bands separated by thin films of white mica and chlorite. S2 wraps around garnet and albite grains, with pressure shadows frequently formed around the grains. Grain-tail complexes do not give an obvious sense of shear (Fig. 7), and in-depth analysis of the deformation structures falls outside the scope of this study. An internal foliation defined by graphite inclusions is locally observed in albite porphyroblasts. It displays the same orientation as the matrix foliation S2, indicating albite crystallisation during or after stage 2. Microlithons of S1 domains follow S2, with indications of crenulation. Chlorite crystals are mostly oriented parallel to S2, though sites of randomly oriented chlorite are observed (Fig. 8), both in S1 and S2 domains. These large unoriented chlorite crystals and the rare albite porphyroblasts are possible pseudomorphs after glaucophane, sometimes indicated by crystal form (Fig. 9).

Gentle folding of S2 visible in the sample may reflect deformation during or after stage 2.

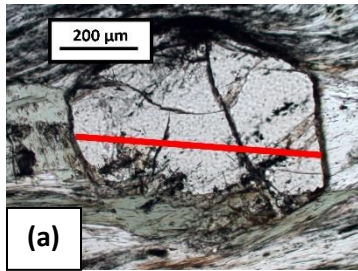


Fig. 10. Profile across garnet 1. (a) Thin section micrograph showing the path of the profile (PPL). (b) Compositional profile of garnet 1.

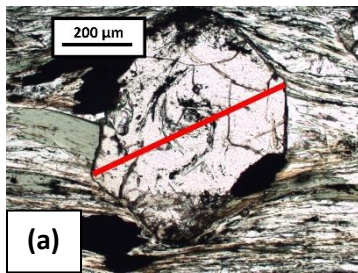
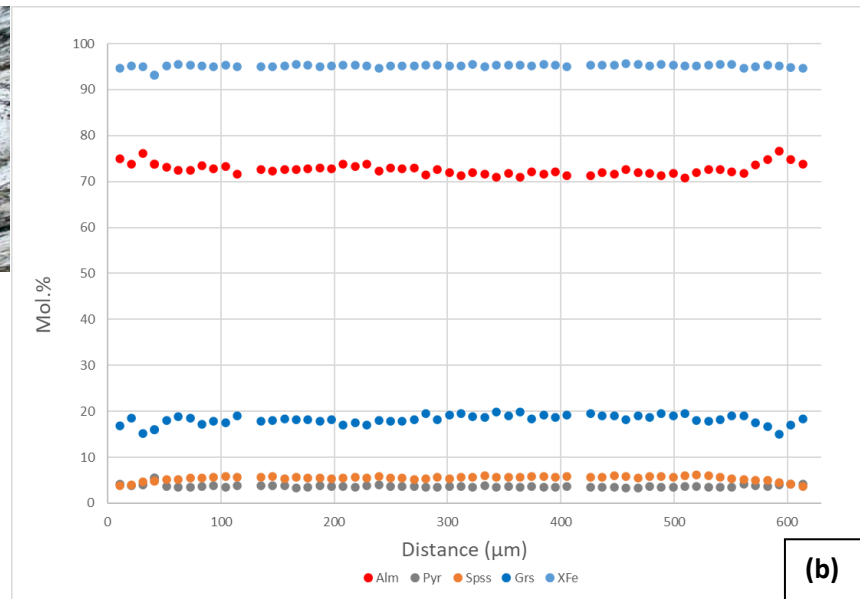
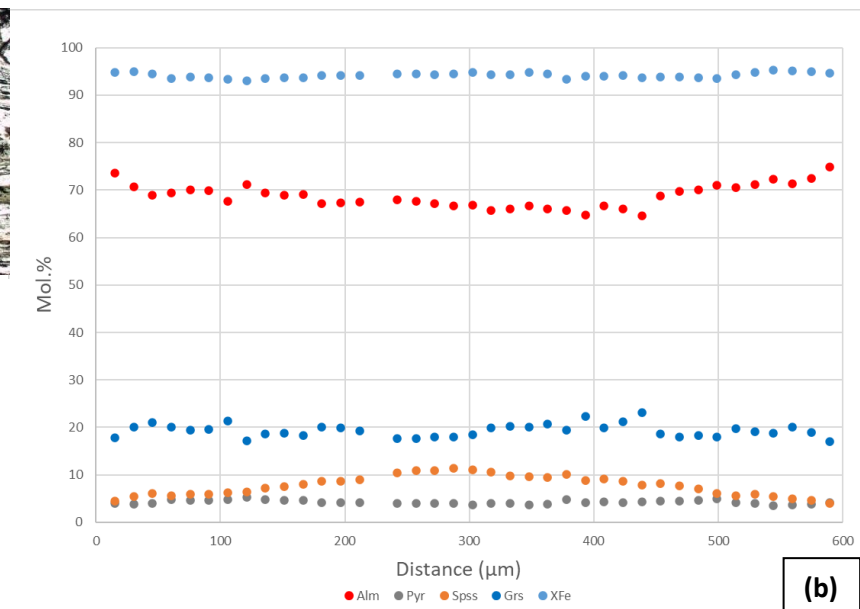


Fig. 11. Profile across garnet 2. (a) Thin section micrograph showing the path of the profile (PPL). (b) Compositional profile of garnet 1.



4.3 Garnet analysis

Garnets appear throughout the sample, size ranging between 200 μm and 800 μm. They are slightly more abundant in association with quartz, white mica and chlorite compared to the mica-chlorite domain. Common inclusions are rutile, zircon, quartz and graphite. Garnets are euhedral to subhedral and typically display some degree of chlorite replacement or rim. Brown coloration in PPL is interpreted as oxidized chlorite.

Microprobe profiles across two garnet crystals show compositional evolution during growth. Garnet 1 (Fig. 10) is almandine rich, ranging from 71 mol.% in the core to a maximum of 77 mol.% towards the rim. Grossular decreases from 19 mol.% in the core to 15 mol.% towards the rim. Spessartine decreases (from 6 mol.% to 4 mol.%) and pyrope increases modestly (4 mol.% to 5 mol.%) from core to rim. Increase in almandine content is balanced by decrease in grossular. Almandine and grossular content fluctuate slightly (within 3 mol.% units) in the garnet core, with clear compositional change only

occurring within 60 μm of the rim. Curiously, the outermost data points in the rim show a reversal of almandine and grossular content, approaching the same composition as the core.

Garnet 2 (Fig. 11) shows a similar composition as garnet 1, but with a more apparent evolution from core to rim. Almandine content is around 67 mol.% in the core and increases to 75 mol.% near the rim. Grossular content is 18 mol.% in the core, increases slightly in the mantle and finally decreases to 17 mol.% near the rim. Spessartine shows a maximum in the centre of the core at 11 mol.% and decreases to 4 mol.% near the rim while pyrope shows no distinct change, hovering around 4 mol.% to 6 mol.%. Variance in almandine is mainly balanced by grossular, with the increase at the rim also balanced by decrease in spessartine.

The clear signs of compositional evolution in garnet 2 compared to garnet 1 indicates that the profile across garnet 1 may not have analysed the true core of the crystal, but instead a homogenous section of the mantle. The anomalous two outermost points on each side of garnet 1 may be caused by retro-grade evolution or diffusion, while the points 60 – 30 μm from the rim closely follow the rimward evolution of garnet 2. As peak P-T modelling will rely partly on garnet rim composition, the anomalous points are not considered when the rim composition of garnet 1 is referred to.

Mineral Structural position	mu (20 / 1) S1	mu (48 / 1) S1	mu (5 / 1) S2	mu (46 / 1) S2	mu (45 / 1) S2	mu (b3 / 1) Pressure Shadow	mu (b6 / 1) Pressure Shadow
SiO ₂	50.10	50.07	50.24	49.35	48.26	46.96	46.23
TiO ₂	0.25	0.21	0.17	0.25	0.22	0.28	0.16
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Al ₂ O ₃	28.47	27.70	27.17	28.49	30.46	34.42	35.34
FeO	2.84	3.01	3.10	2.86	2.26	1.80	1.56
MnO	0.00	0.00	0.02	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.04	0.02	0.03	0.00	0.00
MgO	2.52	2.74	2.83	2.34	1.85	1.01	0.81
CaO	0.01	0.00	0.01	0.00	0.00	0.04	0.00
Na ₂ O	0.38	0.35	0.31	0.34	0.42	1.06	0.85
K ₂ O	10.03	10.46	9.99	9.98	9.78	9.46	9.75
Total	94.60	94.54	93.87	93.63	93.30	95.03	94.72
Composition per formula unit (on the basis of 11 anhydrous oxygen)							
Si	3.36	3.38	3.40	3.35	3.28	3.12	3.09
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.25	2.20	2.17	2.28	2.44	2.70	2.78
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.16	0.17	0.18	0.16	0.13	0.10	0.09
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.25	0.28	0.29	0.24	0.19	0.10	0.08
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.05	0.05	0.04	0.04	0.06	0.14	0.11
K	0.86	0.90	0.86	0.86	0.85	0.80	0.83
Tetrahedral Al	0.64	0.62	0.60	0.65	0.72	0.88	0.91
Octahedral Al	1.62	1.58	1.58	1.63	1.71	1.82	1.87
$\Sigma(\text{Mg,Fe})$	0.41	0.45	0.46	0.40	0.32	0.20	0.17
$\Sigma(\text{K,Na})$	0.91	0.95	0.90	0.91	0.90	0.94	0.94
1 - (K+Na)	0.09	0.05	0.10	0.09	0.10	0.06	0.06
X _{Na}	0.05	0.05	0.05	0.05	0.06	0.15	0.12

Table 2. Representative mineral analysis of muscovite crystals. $X_{\text{Na}} = \text{Na}/(\text{Na} + \text{K})$.

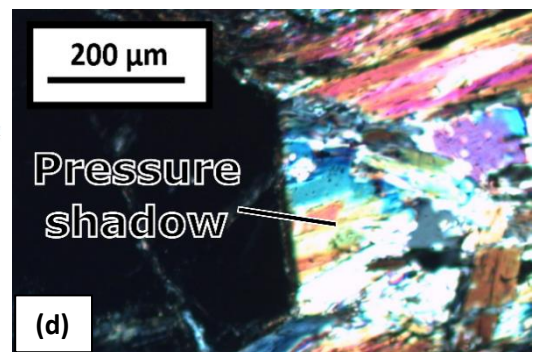
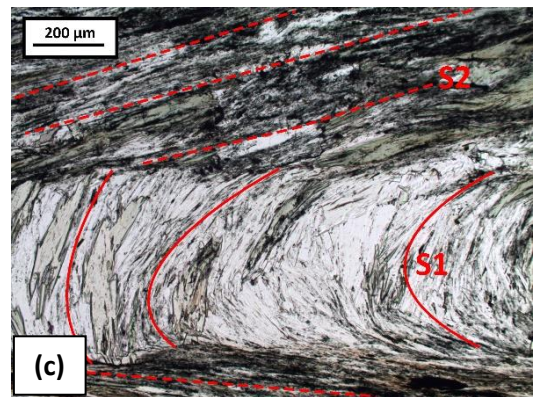
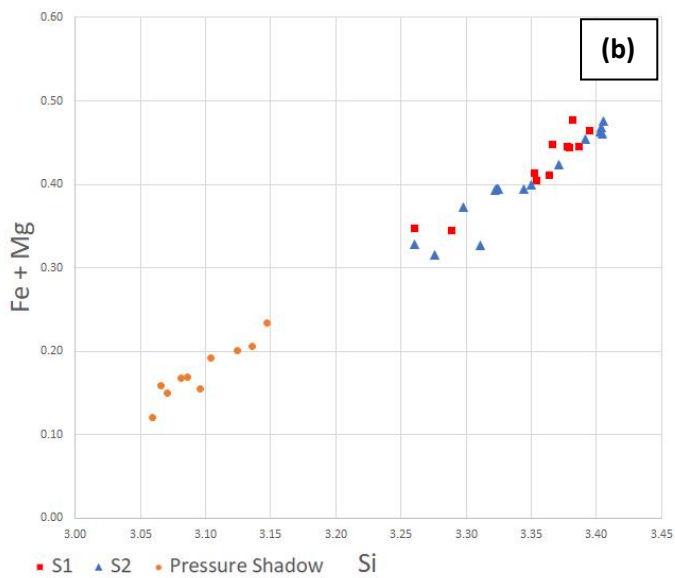
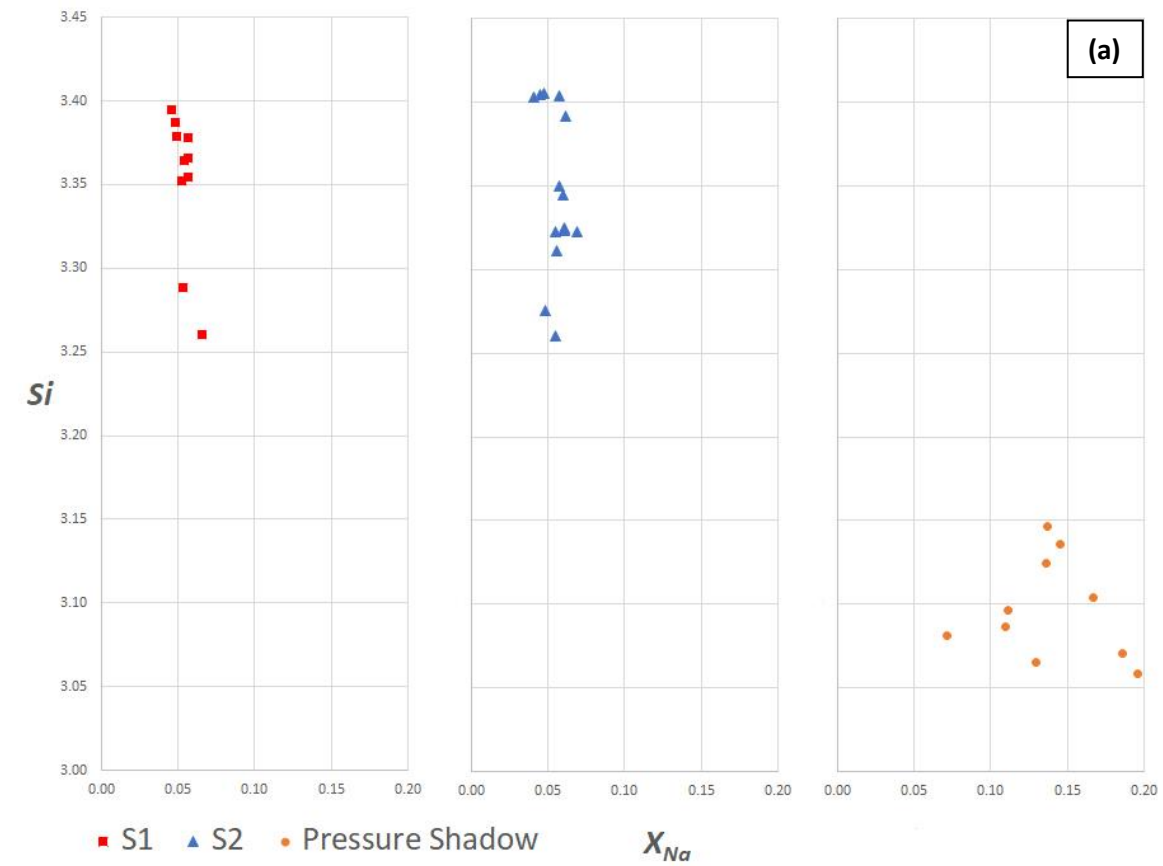


Fig. 12. Compositional spread and structural positions of muscovite. (a, b) Diagram of muscovite composition p.f.u. Muscovite marking S1 and S2 show markedly higher Si content and corresponding Al^{3+} substitution by Fe^{2+} and Mg^{2+} . $X_{Na} = Na/(Na + K)$. (c, d) Thin section micrographs showing the structural positions of muscovite.

4.4 White mica analysis

After quartz, white mica makes up the bulk of the matrix. S1 foliation is marked by folded white mica in microlithons. White mica also marks S2 foliation and appear as randomly oriented crystals in the pressure shadows of garnets. White mica marking S1 and S2 are identified as phengitic muscovite with $X_{Na} = 0.05-0.07$. Due to the lack of formal definition of the term phengite and the complete solid solution with celadonite, phengitic muscovite will only be referred to as muscovite. White mica in pressure shadows is also identified as muscovite, though with a lower silica content and higher sodium range than either S1 or S2 muscovite (Fig. 12).

S1 muscovite grains show a high Si content p.f.u. with the majority of samples grouped between 3.35 p.f.u. and 3.39 p.f.u.. A few outliers ($n=2$) show slightly lower Si substitution (3.25 p.f.u. and 3.30 p.f.u.). Muscovite marking the S2 foliation cover a larger compositional range than S1 muscovite (3.25 p.f.u. - 3.41 p.f.u.) and are quite evenly spread out over the range. Muscovites marking both S1 and S2 show a high degree of (Mg,Fe) substitution in octahedral sites, (Mg,Fe) content ranging from 0.29 p.f.u. to 0.48 p.f.u., increasing linearly with Si content (Fig. 12).

Muscovite in pressure shadows has no preferred orientation and are compositionally different from muscovite marking S1 and S2, with Si content ranging from 3.06 p.f.u. to 3.15 p.f.u.. There is a greater compositional variety in the K-Na spectrum; X_{Na} ranges from 0.08 to 0.20. (Mg,Fe) content ranges from 0.12 p.f.u. to 0.23 p.f.u., increasing linearly with Si content.

Mineral	M1 + D1	M2+D2	M3 (+D3?)
q	Inclusions in garnet, relict foliation	Pervasive foliation, strain shadows	Unoriented crystals, possible gentle folding
mu			
g			
chl			
ilm			
graphite			
ru			
ab			

Table 3. Mineral growth and deformation relationships of the observed assemblage. The presence of a third deformational stage is uncertain; gentle folding of S2 is observed in the sample, but the cause may also be attributed to stage 2.

4.5 Sample and mineral summary

To sum up, three structural and metamorphic stages are identified in the studied sample (Table 3):

- Stage 1, characterised by the mineral assemblage garnet-muscovite-quartz-graphite-rutile and the development of S1 foliation.
- Stage 2, characterised by the mineral assemblage muscovite-quartz-chlorite- albite-ilmenite-graphite and the development of S2 foliation.
- Stage 3, characterized by the mineral assemblage muscovite-chlorite-albite-ilmenite, the growth of unoriented crystals, and possible gentle folding.

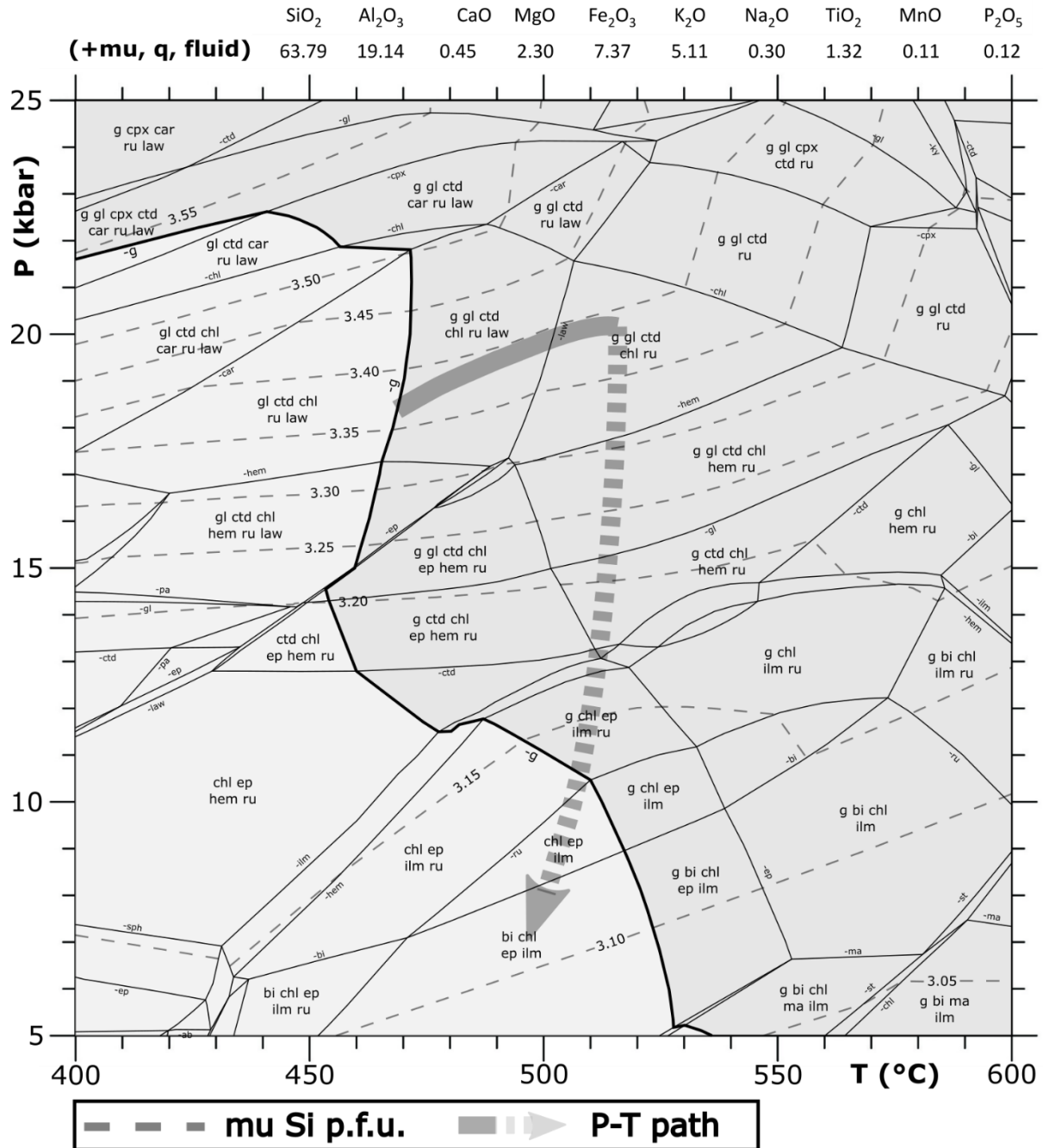


Fig. 13. P-T pseudosection calculated using the bulk rock composition, displayed in wt.%. The assemblages in unlabelled fields may be deduced from assemblages in neighbouring fields. The full line of the P-T path represents the estimate of prograde and peak P-T conditions, the striped line represents an imagined exhumation path based on other HP-UHP units in the Alps (e.g. Liou & Zhang, 2003; Beltrando *et al.*, 2010; Malusà *et al.*, 2011; Manzotti *et al.*, 2015a) and the observed assemblage. No constraints have been calculated for the exhumation path.

4.6 Thermodynamic modelling

To constrain the peak P-T conditions of the Pinerolo Unit, a P-T pseudosection was calculated using the bulk rock composition of the sample and calculated within the range 400-600°C and 5-25 kbar (Fig. 13). A large pressure range was chosen to accommodate the possibility of high-pressure assemblages. The reaction line denoting the appearance of garnet has been made thicker and the garnet-containing

fields darker to easily distinguish the field of analysis. Given the small size and modal amount of garnet in the studied sample, no fractionation of the bulk rock composition has been done.

To constrain the peak P-T conditions, the garnet composition measured in the studied sample was compared to the modelled garnet composition (i.e. endmember isopleths) (Fig. 14). Initial garnet crystallization and growth is inferred to have occurred at 480-495°C and 18-20 kbar (Fig. 15). Garnet core composition of garnet 2 (alm = 67 mol.%, grs = 18 mol.%, spss = 11 mol.%, pyr = 4 mol.%) corresponds well to the calculated isopleths. The garnet core composition is comprised in the field g-gl-ctd-chl-ru-law (+q, mu, fluid) and falls within the range of the measured S1 muscovite Si p.f.u. (3.35 – 3.40 p.f.u. Garnet 1 shows little evolution between core and mantle, which likely is due to the garnet being cut farther from the core than garnet 2. The core and mantle of the profile of garnet 1 is therefore interpreted to only represent the crystal's mantle.

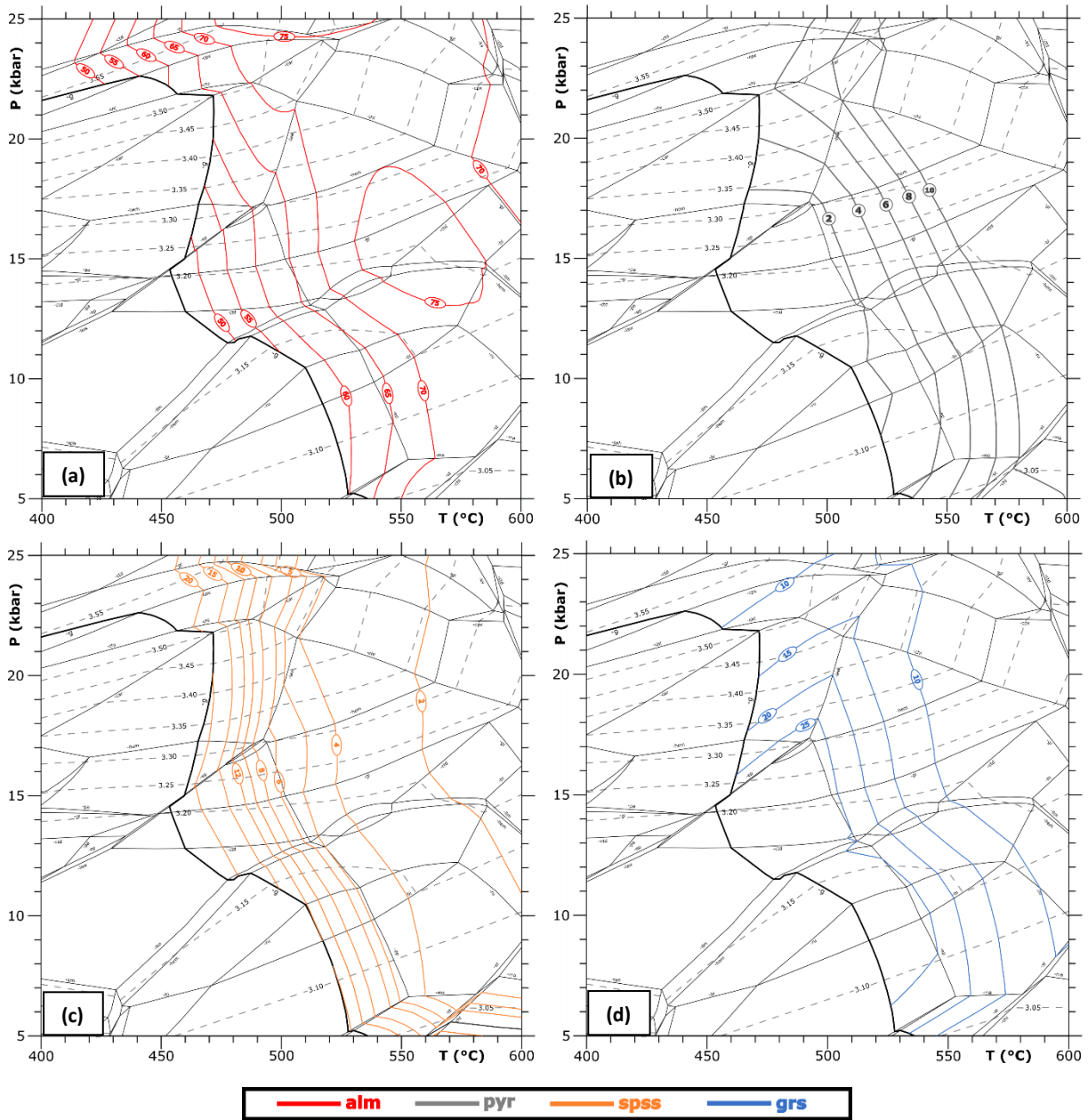


Fig. 14. P-T pseudosection with garnet composition isopleths (mol.%) of (a) almandine, (b) pyrope, (c) spessartine, (d) grossular. Assemblages are removed for clarity.

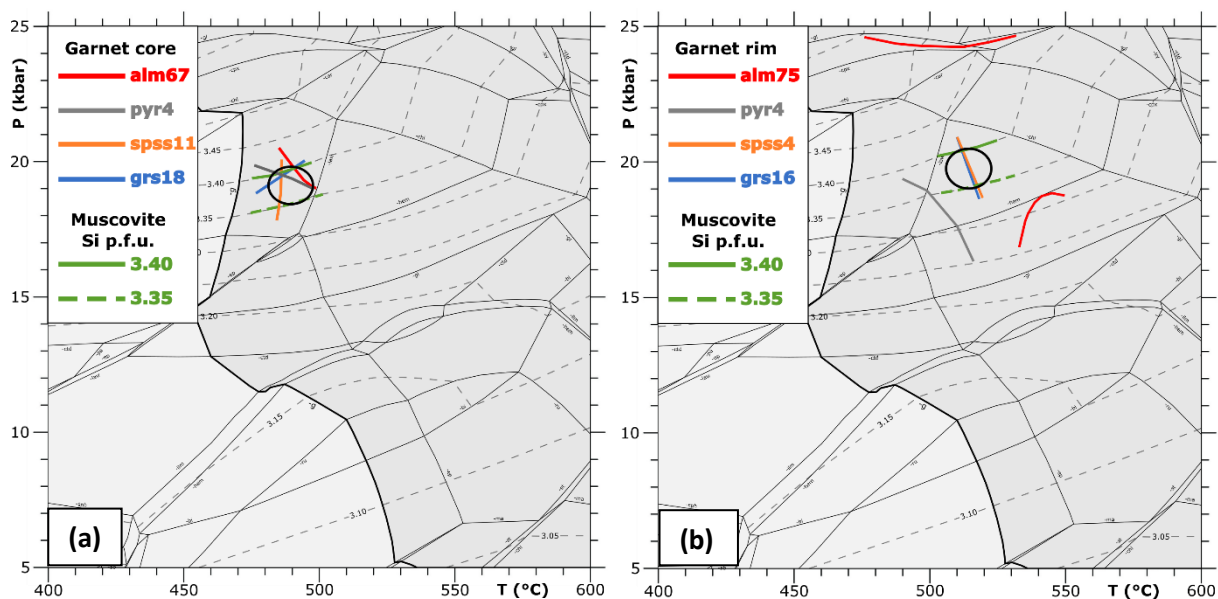


Fig. 15. P-T pseudosection showing analysed muscovite and garnet composition correlated to calculated compositional isopleths. (a) Garnet core, representing prograde conditions and (b) garnet rim, representing peak P-T conditions. Assemblages are removed for clarity. Ellipses mark the area of P-T conditions constrained by garnet composition and muscovite Si p.f.u..

The garnet peak P-T conditions likely occurred at 505 – 525°C and 18-20 kbar (Fig. 15), where spessartine and, importantly, grossular of garnet 1 & 2 mean rim composition (alm = 75 mol.%, grs = 16%, spss = 4 mol.%, pyr = 4 mol.%) correspond to garnet composition isopleths, which also falls within the range of S1 muscovite Si p.f.u. (3.35-3.40). The low diffusion rate of grossular makes this endmember an important proxy when determining peak P-T conditions (e.g. Schwandt *et al.*, 1996). In the area of inferred peak P-T conditions, lawsonite disappears from the assemblage with increased temperature, leading to the drop in grossular content and leaving the assemblage g-gl-ctd-chl-ru (+q, mu, fluid). Abundant rutile and quartz inclusions in garnet cores and mantles can be observed in the thin section.

In the studied sample, the observed mineral assemblage developed during stage 1 is garnet-chlorite-rutile-quartz-muscovite-glaucophane (the latter consistently pseudomorphed by chlorite and albite). The predicted assemblage at peak P-T conditions is garnet-chlorite-chloritoid-rutile-quartz-muscovite-glaucophane±lawsonite. Lawsonite and chloritoid are not observed in the studied sample.

This requires an explanation. No lawsonite or chloritoid can be observed as garnet inclusions, but given the low mode of garnet, as well as glaucophane and lawsonite at peak P-T conditions, this is not surprising. Rutile can be observed as inclusions in garnet and seems otherwise to have been replaced by ilmenite. A grid of point calculations in the peak P-T range (Table 4) reveals that lawsonite mode lies between 0 and 0.2 mol.%. Lawsonite was likely consumed by garnet growth as the lawsonite-out reaction line was crossed. This is supported by the relatively high grossular content in the analysed garnets. The calculated chloritoid modes indicate that this mineral is relatively abundant at peak P-T conditions, in the range of 6.7-10.4 mol.%. At these P-T conditions, chlorite is also present. During retrogression (i.e. decreasing P) the chlorite modal amount increases whereas chloritoid abundance rapidly decreases. Chloritoid then disappears at ~13-14 kbar (Fig. 16). This trend may suggest that during retrogression chloritoid was progressively and completely replaced by chlorite. In the studied sample, glaucophane pseudomorphs have been observed. Calculated glaucophane mode is between 2 and 2.6 mol.%. The glaucophane predicted at peak P-T conditions, which also contains significant amounts of Fe- and Mg-amphibole, is present at such a low mode that consumption and replacement by retrograde Na-containing phases is highly plausible. Some Na may have been fractionated into unoriented

mica, which shows higher X_{Na} than S1 and S2 muscovite, and the presence of albite ($\sim Ab_{84}, An_{15}, Kfs_1$) in the sample indicates that some other sodic phase was present above the albite stability field.

P-T conditions		Mineral mode					
P	T	g	chl	ctd	gl	law	ru
18	500	2.35	5.60	7.64	2.12	0.00	0.89
19	500	2.50	4.09	9.00	2.39	0.00	0.90
20	500	2.41	2.69	10.37	2.63	0.21	0.90
18	510	2.82	5.41	7.29	2.05	0.00	0.89
19	510	3.02	3.89	8.59	2.31	0.00	0.90
20	510	3.25	2.34	9.91	2.55	0.00	0.90
18	520	3.46	5.11	6.86	1.97	0.00	0.89
19	520	3.72	3.59	8.10	2.23	0.00	0.90
20	520	4.01	2.02	9.35	2.47	0.00	0.90

Table 4. Calculations of mineral mode for selected minerals in the range of inferred peak P-T conditions. Isothermal points are listed in groups, isobaric points are highlighted in the same colour.

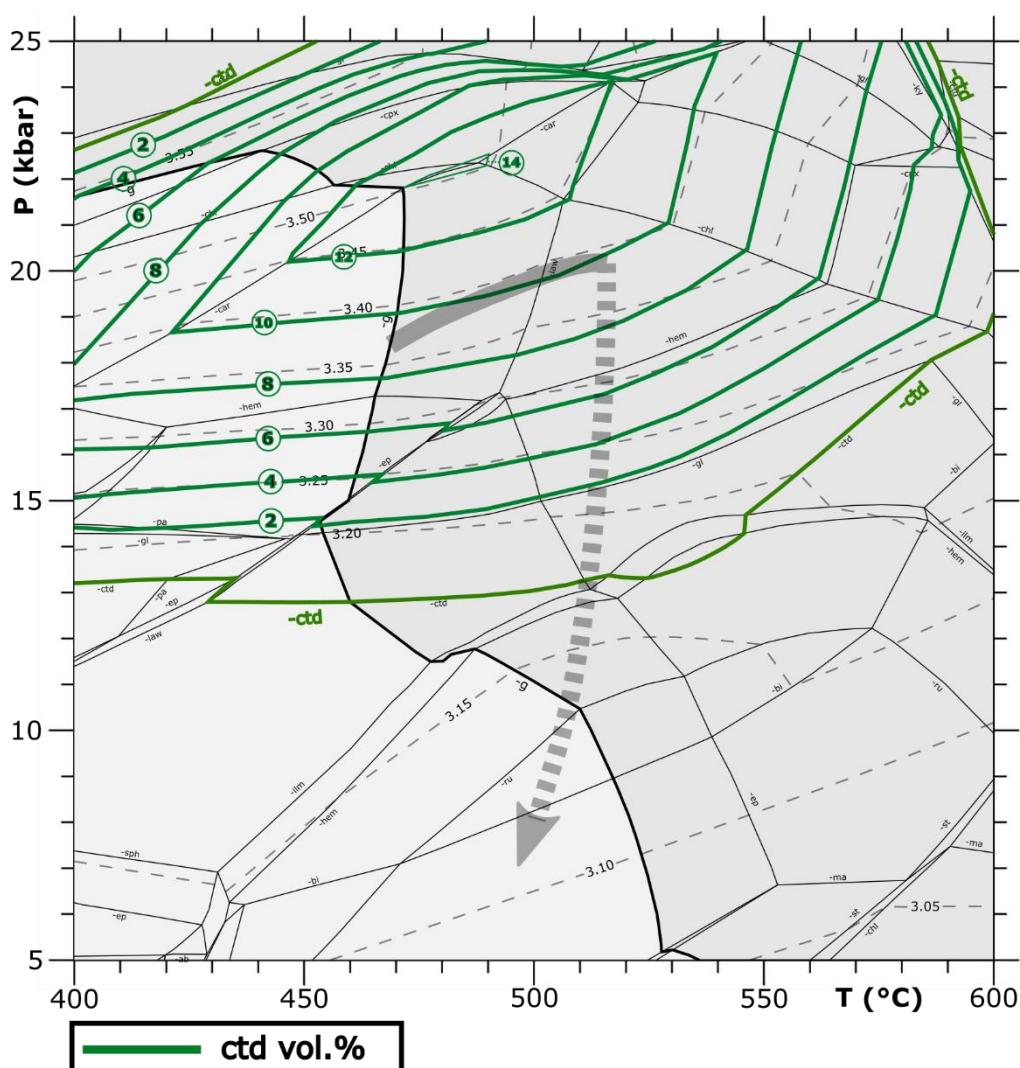


Fig. 16. P-T pseudosection showing chloritoid mode isopleths. Calculated for bulk composition and excess fluid, chloritoid disappears at ~ 13 -14 kbar along the imagined retrograde path. Assemblages are removed for clarity

5. Discussion

In summary, the prograde and peak P-T path of the northern Pinerolo Unit developed at blueschist-facies up to eclogite-facies conditions. Peak P-T conditions are 18-20 kbar and 505-525°C (Fig. 13)

5.1 Prograde and peak P-T conditions

The prograde evolution of the studied sample is well constrained by the comparison of measured garnet core composition (i.e. initial garnet growth) and the modelled garnet endmember isopleths, as well as by the Si content of muscovite marking the S1 foliation which likely formed contemporaneously with garnet growth. Peak P-T conditions are likewise well constrained, as the modal abundance of garnet is low and the proposed peak P-T conditions occur with a likely isobaric increase in T from initial growth conditions. Though dehydration and garnet fractionation may alter the assemblage stability fields (e.g. Dragovic *et al.*, 2012), the effect is considered small enough to not significantly alter the peak P-T estimate. The slightly variable but consistent grossular amount in the garnet core and mantle indicates the 20 mol.% grossular isopleth was followed quite closely in the prograde path, until a drop in grossular content near the rim likely shows that the lawsonite stability field was exited.

5.2 Exhumation history

High-pressure metamorphic units may reach peak-T conditions during peak-P conditions, making a hairpin curve in P-T space (e.g. Dragovic *et al.*, 2012; Klonowska *et al.*, 2017), or during exhumation (e.g. Liou & Zhang, 2003). As most HP-UHP units in the Alps reached peak P and T simultaneously (e.g. Liou & Zhang, 2003; Beltrando *et al.*, 2010; Malusà *et al.*, 2011), this is may be the case for the Pinerolo Unit as well.

A detailed reconstruction of the retrograde evolution will require further modelling with a fixed H₂O content (e.g. Manzotti *et al.*, 2018), a task that is out of scope of this study. Due to dehydration after peak metamorphism and bulk matrix composition changes due to garnet fractionation, thermodynamic modelling with a recalculated bulk composition is needed (e.g. Marmo *et al.*, 2002). However, some preliminary conclusions about retrograde reactions can be drawn based on petrographic observations.

For instance, white mica with significantly lower Si p.f.u. (3.06 – 3.15) than muscovite marking S1 and S2 and without a preferred orientation grew in the matrix. S2 muscovite shows a spread in Si p.f.u. which indicates that realignment of muscovite grains occurred during stage 2. Further analysis of the zoning of grains in the S2 fabric is needed to reveal more about muscovite re-equilibration and change in orientation.

Chlorite is interpreted to mainly have formed by decomposition of chloritoid during exhumation and is largely aligned with S2 foliation. Chlorite also occurs in pressure shadows and, curiously, as large unoriented crystals in both S1 and S2 fabric. As most chlorite is oriented along S2, it is likely that chlorite growth occurred syn-kinematically. The retrograde phases ilmenite and albite are also oriented parallel to S2.

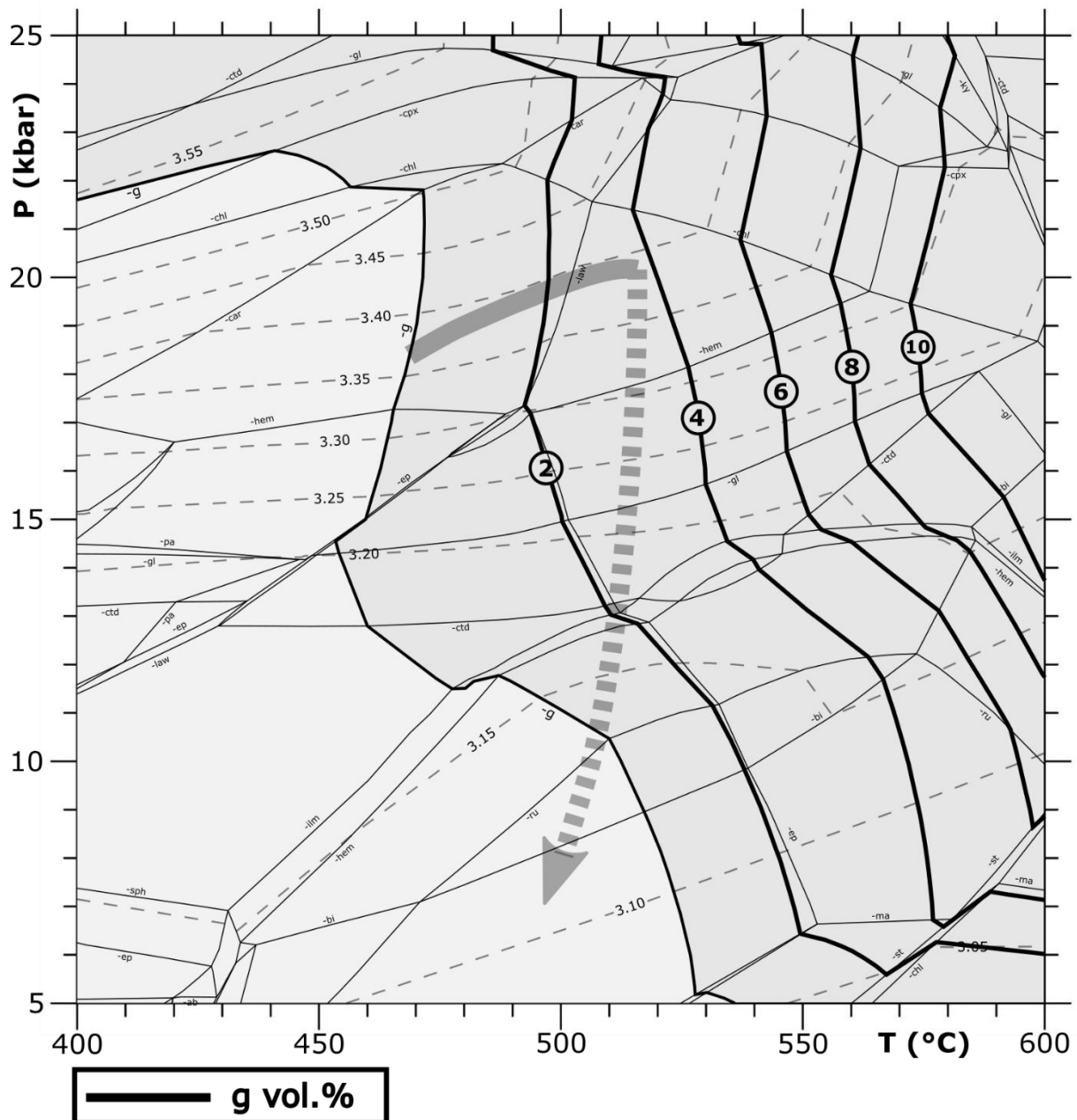


Fig. 17. P-T pseudosection showing garnet mode isopleths. Garnet mode at peak P-T conditions corresponds to the observed assemblage. The wide stability field of garnet is typical of MnO-containing systems (White *et al.*, 2014). Assemblages are removed for clarity.

Chlorite also appears as reaction rims on garnet. The preservation of well-formed garnets despite the low modal abundance is likely attributed to the wide stability field of garnets in MnO-containing systems, even at 0.1 wt.% MnO (Symmes & Ferry, 1992; White *et al.*, 2014) (Fig. 17). Some decomposition and chlorite replacement are observed, indicating partial re-equilibration outside the garnet stability field. As observed for units of the Dora-Maira Massif (e.g. Malusà *et al.*, 2011), exhumation to shallow depths was likely fast, and dehydration after peak metamorphism might have prevented retrograde reactions to completely consume garnets.

Biotite was expected in the sample, but either retrograde reactions halted before the biotite line was passed or the formation of biotite was impeded by the slow re-equilibration rate of phengitic muscovite (Massonne & Schreyer, 1987). Brown coloured grains in the sample are interpreted as oxidised chlorite, based on habit, optical properties, and often close association with unoxidized chlorite (Fig.

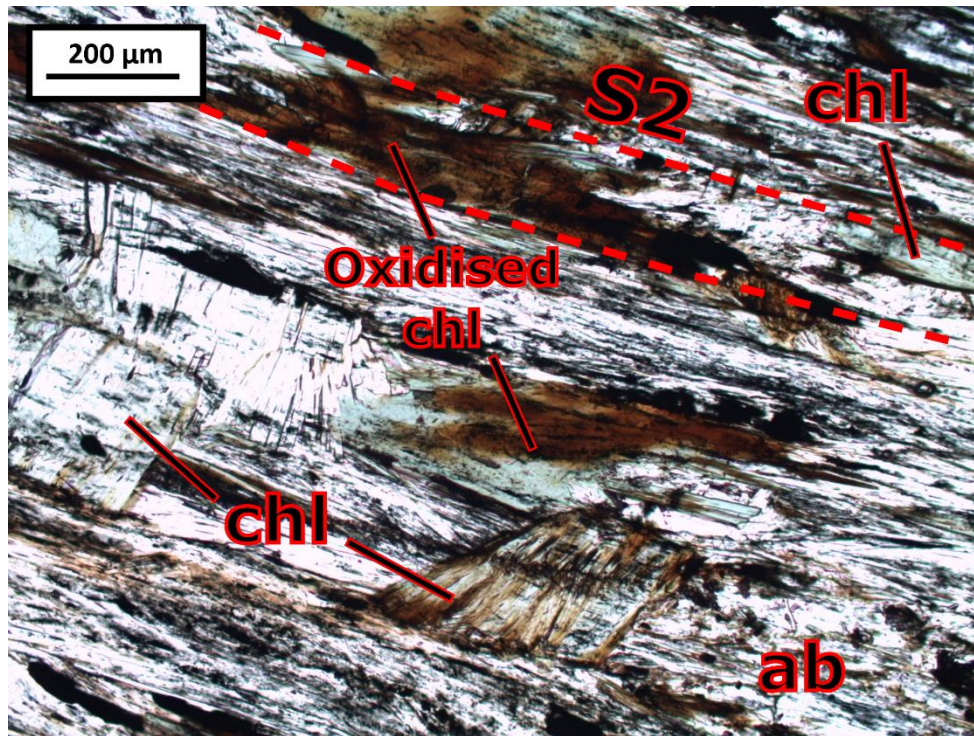


Fig. 18. Thin section micrograph of oxidised chlorite, showing its continuity with unaltered chlorite (PPL).

18). This identification may prove inaccurate, but the estimated change in observed chlorite mode would not contradict the assessment of peak-P assemblage decomposition.

Based on the calculated P-T pseudosection, the observed assemblage was expected to include epidote. Some small grains are tentatively identified as epidote, but further analysis is needed for accurate identification.

5.3 Deformational history.

Structural analysis of the sample points to a deformational history involving two stages. The Pinerolo Unit was subducted to significant depth in the collision of the European and Adriatic plates (e.g. Ballèvre *et al.*, 2020; Manzotti & Ballèvre, in press). This study corroborates the estimate by Groppo *et al.* (2019) that the Pinerolo unit was dragged down to sufficient depths for eclogite-facies metamorphism during stage 1, though the northern part of the unit is estimated to have experienced slightly lower pressure. Deformation during the prograde path can be glimpsed in the rotation of the internal foliation of a garnet. As garnet growth is estimated to have started at pressures close to peak P, rotation of the graphite foliation reflects deformation during subduction, which likely also caused the S1 foliation. The accuracy of the interpretation of shear cannot be gauged, another garnet shows graphite accumulation during growth without evidence of shearing, with graphite outlining what seems like zoning in the garnet (Fig. 19).

The pervasive foliation evolved by reworking the S1 fabric during stage 2, the exhumation of the Pinerolo Unit. This may have involved both realignment of existing grains and recrystallization, indicated by the large spread of silica content in muscovite marking S2. The decreasing silica content points to exhumation as the cause of deformation, and there is ample evidence that shearing occurred during this period. Grain-tail complexes are abundant but ambiguous or even contradictory indicators to sense of shear. The difficulty of correctly deducing strain from lineation and fabric shear indicators (e.g. Grasemann *et al.*, 2019) prevents any detailed analysis of the deformational history inside the

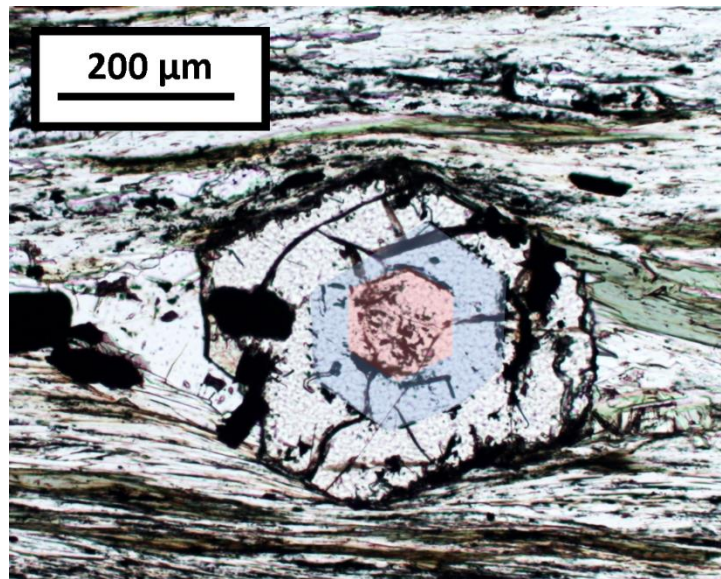


Fig. 19. Thin section micrograph of garnet with apparent zoning marked by graphite (PPL). Zoning demarcation is highlighted by blue and red fields.

scope of this study. Further structural analysis of the sample and the Pinerolo Unit as a whole is likely to reveal more details.

5.4 Comparison with previous studies

The P-T estimate put forth in this study disputes some previous claims of the metamorphic history of the Pinerolo Unit. There are no thorough investigations of the peak metamorphic conditions of the northern sector of the Pinerolo Unit using a petrological approach with thermodynamic modelling, and the proposed blueschist-facies classification is based on observations of mineral assemblages with rare glaucophane (Vialon, 1966). Prior to the examination of the whole HP-UHP package of the southern Dora Maira Massif by Groppo *et al.* (2019), studies of the southern Pinerolo Unit were also lacking.

Chopin *et al.* (1991) estimate peak-P conditions of the Pinerolo Unit to, or less than, 8-10 kbar and 500°C, a peak T corresponding to the approximate T at peak P in this study, but pressures 10 kbar lower. The authors focus on the more obvious UHP units, and little information is given about the Pinerolo Unit sample(s) and analysis.

A more in-depth investigation into the Pinerolo Unit is provided by Avigad *et al.* (2003), but it seems likely that they describe one of the polymetamorphic units bounding the Brossasco-Isasca Unit or the coesite-bearing unit itself instead. Large garnets show two separate growth stages with inclusions, among them staurolite, in the core that correspond to garnets in the Brossasco-Isasca Unit (Chopin *et al.*, 1991; Compagnoni *et al.*, 1995). P-T estimates of the garnet core indicated amphibolite-facies metamorphism, like other polymetamorphic units originating in the Variscan orogeny (e.g. Nosenzo *et al.*, 2022). Some mica-schists are described as kyanite-bearing with kyanite wrapping around garnets, also corresponding to descriptions of the Brossasco-Isasca Unit (Chopin *et al.*, 1991; Groppo *et al.*, 2019). With a variety of methods, Avigad *et al.* (2003) reach a peak P-T estimate of 14-16 kbar and 400-500°C for what may or may not be the Pinerolo Unit, though the pressure estimate is cited as 6-8 kbar for the Pinerolo Unit mica-schist in other studies (Compagnoni & Rolfo, 2003; Gasco *et al.*, 2011).

The latest comprehensive study of the (U)HP nappes of the southern Dora-Maira by Groppo *et al.* (2019) investigated one mica-schist sample from the Pinerolo Unit collected close to the contact with the UHP Brossasco-Isasca Unit. Their P-T estimate is slightly higher (i.e. 20-23 kbar and 500-515°C) than the one obtained by this study (i.e. 18-20 kbar and 505-525°C) (Fig. 20). Though the description

corresponds with possible assemblages in the Pinerolo Unit (Vialon, 1966; Manzotti *et al.*, 2016) and the related Money Unit (Manzotti *et al.*, 2015a), the high garnet mode and growth history together with the absence of diagnostic graphite raise the possibility that these authors, too, may have investigated a polymetamorphic unit (i.e. the San Chiaffredo Unit). It is of course also highly possible that a differing bulk composition may have allowed continued garnet growth during exhumation, and the absence of graphite is not a sufficient criterion to rule out that the analysed sample belongs to the Pinerolo Unit. Another possibility is that the southern sector of the unit could share provenance with the northern sector, but separation during subduction caused different metamorphic histories. Further mapping and analysis are needed to assess the continuity of the Pinerolo Unit.

The Money Unit in the Gran Paradiso Massif is lithologically similar to the Pinerolo Unit and is estimated to have experienced similar though slightly lower P, 16-18 kbar, but higher T, 510-540°C (Manzotti *et al.*, 2015a). Their relationship during sedimentation and subduction however is unknown.

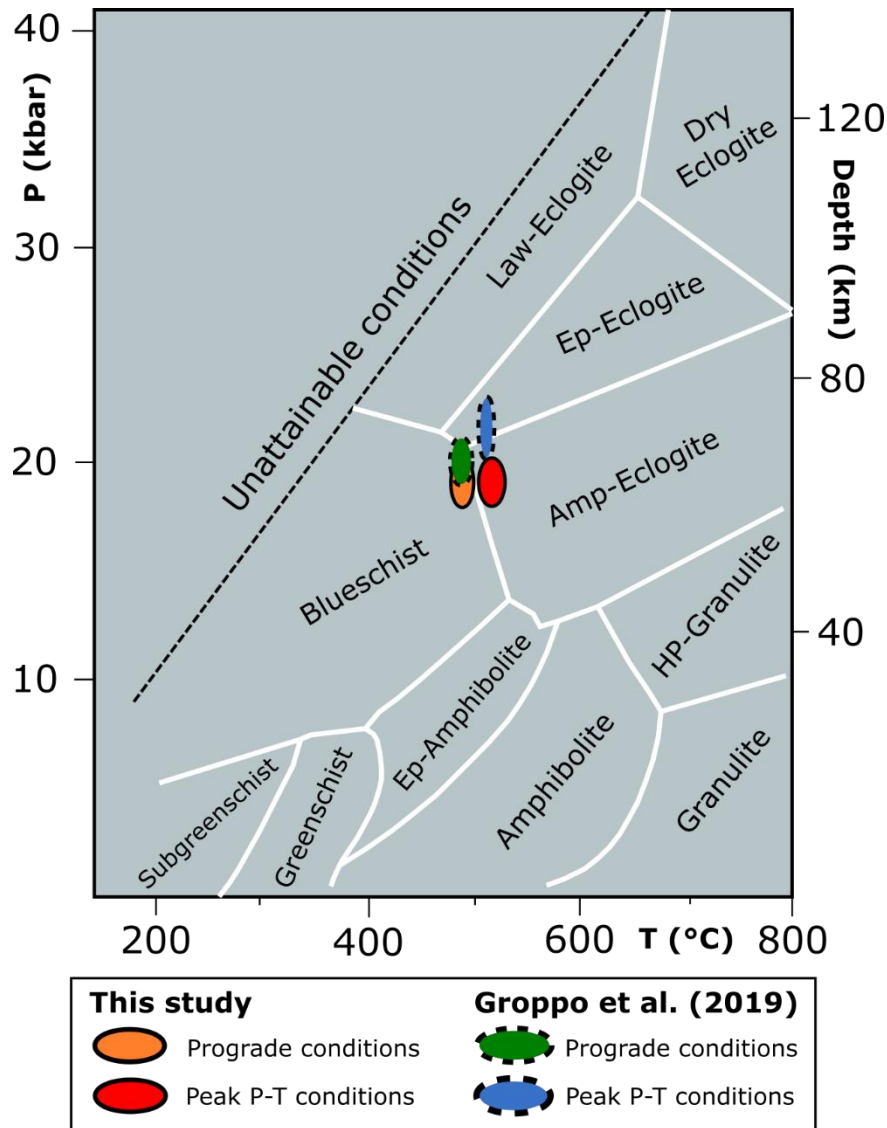


Fig. 20. Comparison of prograde and peak P-T condition estimates by this study (480-495°C, 18-20 kbar and 505-525°C, 18-20 kbar, respectively) and Groppo et al. (2019) (480-495°C, 19-21 kbar and 500-515°C, 20-23 kbar, respectively). Metamorphic facies fields are drawn as presented by Liou & Zhang (2003).

6. Conclusions

The use of modern thermodynamic modelling software and solution models allows more accurate assessments of P-T conditions than what was previously possible. The Pinerolo Unit has historically been labelled as a blueschist-facies unit, based on observations of glaucophane in the northern sector. In the last decades, studies of the Pinerolo Unit underlying the coesite-bearing Brossasco-Isasca Unit have variously concluded that it reached epidote-amphibolite-facies to blueschist-facies metamorphism, until Groppo *et al.* (2019) estimated a significantly higher peak P for the unit.

This study provides new constraints for the Pinerolo Unit, exploring a sample collected in its northern sector. Petrological observations and thermodynamic modelling constrains the prograde and peak P-T conditions at 18-20 kbar and 480-495°C and 18-20 kbar and 505-525°C, respectively. After peak P-T, conditions are significantly less well constrained and further modelling is needed to describe the retrograde path. This new estimate extends the assessment of eclogite-facies metamorphism to the Pinerolo Unit as a whole.

7. Implications and future prospects

Despite limited thermodynamic modelling based on only one sample, this study provides compelling evidence that the Pinerolo Unit as a whole may have experienced deep subduction and high pressures, extending the assessment of eclogite-facies metamorphism (Groppo *et al.*, 2019) to the northern sector of the unit.

An important conclusion drawn based on the new P-T estimate: the Pinerolo Unit was subducted deeper than previously thought. A more thorough investigation is needed to provide robust constraints on the metamorphic and structural history of this Unit:

- Thermodynamic modelling based on samples from different localities in the northern Pinerolo Unit could corroborate or dispute the peak P-T estimate.
- Elastic geothermobarometric analysis of quartz and zircon inclusions in garnet can help constrain pressure at time of inclusion (e.g. Gilio *et al.*, 2021).
- Further analysis is needed to reconstruct and constrain retrogression history. Modelling using bulk compositions compensated for garnet fractionation limited fluid content would give a precise view of the retrograde path.
- Integration with further analysis of the southern Pinerolo Unit could allow a comprehensive description of the Pinerolo Unit as a whole.

At a regional scale, further questions need to be addressed:

- How closely does the Money Unit relate to the Pinerolo Unit? While the similar lithology and structural history hints at a close relationship (Manzotti *et al.*, 2015a; Manzotti *et al.*, 2016), what were their geographical and stratigraphical positions on the Briançonnais microcontinent? Are they outcroppings of a larger continuous unit or do they have separate histories?
- In the northern Dora-Maira Massif, the Pinerolo Unit is overlain by a single eclogite-facies polymetamorphic unit (e.g. Gasco *et al.*, 2011; Nosenzo *et al.*, 2022), while in the southern part of the massif it is overlain by the famous UHP Brossasco-Isasca Unit and related units. What is the relationship between the overlying unit(s) in the northern and southern part of the massif?

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Appendix A. Mineral analysis

Table A1. Mineral analysis of muscovite. $X_{Na} = Na/(Na + K)$

DataSet/Point	5 / 1.	6 / 1.	7 / 1.	9 / 1.	10 / 1.	17 / 1.	20 / 1.	21 / 1.	22 / 1.	23 / 1.	24 / 1.	25 / 1.	36 / 1.	38 / 1.
Mineral	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu
Structural position	S2	S2	S2	S2	S2	S2	S1	S1	S1	S1	S1	S1	S1	S1
SiO ₂	50.24	50.41	50.24	48.22	50.46	48.69	50.10	49.90	49.74	50.06	48.64	49.50	48.13	49.44
TiO ₂	0.17	0.21	0.20	0.31	0.15	0.25	0.25	0.22	0.21	0.20	0.28	0.29	0.27	0.21
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Al ₂ O ₃	27.17	27.13	27.10	30.62	27.33	29.74	28.47	28.54	27.60	27.03	30.00	27.68	30.25	28.36
FeO	3.10	3.22	3.26	2.43	3.28	2.17	2.84	2.95	2.88	2.99	2.63	3.18	2.82	2.77
MnO	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.04	0.02	0.00
NiO	0.04	0.00	0.00	0.02	0.01	0.06	0.00	0.06	0.00	0.02	0.00	0.00	0.07	0.00
MgO	2.83	2.92	2.76	1.89	2.82	2.01	2.52	2.47	2.77	2.92	1.94	2.63	1.86	2.45
CaO	0.01	0.00	0.00	0.02	0.03	0.03	0.01	0.05	0.00	0.18	0.02	0.00	0.01	0.00
Na ₂ O	0.31	0.33	0.29	0.38	0.38	0.39	0.38	0.37	0.34	0.33	0.37	0.40	0.48	0.33
K ₂ O	9.99	10.00	10.33	10.00	9.80	9.62	10.03	10.20	10.12	10.39	10.15	10.00	10.26	10.20
Total	93.87	94.21	94.18	93.89	94.25	92.97	94.60	94.79	93.66	94.11	94.03	93.73	94.18	93.76
Composition per formula unit (on the basis of 11 anhydrous oxygen)														
Si	3.40	3.41	3.40	3.26	3.40	3.31	3.36	3.35	3.38	3.39	3.29	3.37	3.26	3.35
Ti	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr	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	2.17	2.16	2.16	2.44	2.17	2.38	2.25	2.26	2.21	2.16	2.39	2.22	2.42	2.27
Fe ³⁺	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
Fe ²⁺	0.18	0.18	0.18	0.14	0.18	0.12	0.16	0.17	0.16	0.17	0.15	0.18	0.16	0.16
Mn	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
Ni	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
Mg	0.29	0.29	0.28	0.19	0.28	0.20	0.25	0.25	0.28	0.29	0.20	0.27	0.19	0.25
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Na	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.05	0.06	0.04
K	0.86	0.86	0.89	0.86	0.84	0.83	0.86	0.87	0.88	0.90	0.88	0.87	0.89	0.88
Tetrahedral Al	0.60	0.59	0.60	0.74	0.60	0.69	0.64	0.65	0.62	0.61	0.71	0.63	0.74	0.65
Octahedral Al	1.58	1.57	1.57	1.70	1.58	1.70	1.62	1.61	1.59	1.56	1.68	1.58	1.68	1.62
Σ(Mg,Fe)	0.46	0.48	0.46	0.33	0.47	0.33	0.41	0.41	0.44	0.46	0.34	0.45	0.35	0.40
Σ(K,Na)	0.90	0.90	0.93	0.91	0.89	0.89	0.91	0.92	0.92	0.94	0.92	0.92	0.95	0.93
1 - (K+Na)	0.10	0.10	0.07	0.09	0.11	0.11	0.09	0.08	0.08	0.06	0.08	0.08	0.05	0.07
X _{Na}	0.05	0.05	0.04	0.05	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.07	0.05

Table A2. Mineral analysis of muscovite. $X_{Na} = Na/(Na + K)$

DataSet/Point	39 / 1.	44 / 1.	45 / 1.	46 / 1.	47 / 1.	48 / 1.	49 / 1.	51 / 1.	52 / 1.	53 / 1.	54 / 1.	55 / 1.
Mineral	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu
Structural position	S1	S2	S2	S2	S2	S1	S1	S2	S2	S2	S2	S2
SiO ₂	50.34	50.22	48.26	49.35	49.63	50.07	50.51	49.00	47.73	49.45	50.52	50.63
TiO ₂	0.23	0.23	0.22	0.25	0.28	0.21	0.19	0.30	0.28	0.28	0.15	0.20
Cr ₂ O ₃	0.00	0.00	0.01	0.01	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.00
Al ₂ O ₃	27.82	27.38	30.46	28.49	28.79	27.70	27.68	30.08	31.70	30.16	27.66	27.97
FeO	3.14	3.17	2.26	2.86	2.82	3.01	3.42	2.62	2.55	2.30	3.17	2.94
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.03	0.02	0.00	0.00	0.03	0.00	0.01	0.02	0.00	0.04
MgO	2.68	2.74	1.85	2.34	2.35	2.74	2.86	2.06	1.55	1.91	2.87	2.67
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.03	0.00
Na ₂ O	0.39	0.40	0.42	0.34	0.40	0.35	0.40	0.43	0.52	0.38	0.30	0.33
K ₂ O	9.84	10.27	9.78	9.98	9.96	10.46	10.20	9.85	10.08	10.00	10.04	10.04
Total	94.45	94.40	93.30	93.63	94.27	94.54	95.30	94.42	94.42	94.50	94.75	94.83
Composition per formula unit (on the basis of 11 anhydrous oxygen)												
Si	3.39	3.39	3.28	3.35	3.34	3.38	3.38	3.32	3.32	3.32	3.32	3.32
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr	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	2.21	2.18	2.44	2.28	2.29	2.20	2.18	2.31	2.31	2.31	2.31	2.31
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.18	0.18	0.13	0.16	0.16	0.17	0.19	0.16	0.16	0.16	0.16	0.16
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.27	0.28	0.19	0.24	0.24	0.28	0.29	0.23	0.23	0.23	0.23	0.23
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.05	0.05	0.06	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06
K	0.84	0.88	0.85	0.86	0.86	0.90	0.87	0.87	0.87	0.87	0.87	0.87
Tetrahedral Al	0.61	0.61	0.72	0.65	0.66	0.62	0.62	0.68	0.68	0.68	0.68	0.68
Octahedral Al	1.59	1.57	1.71	1.63	1.63	1.58	1.57	1.63	1.64	1.64	1.64	1.64
Σ(Mg,Fe)	0.45	0.45	0.32	0.40	0.39	0.45	0.48	0.39	0.39	0.39	0.39	0.39
Σ(K,Na)	0.90	0.94	0.90	0.91	0.91	0.95	0.92	0.93	0.93	0.93	0.93	0.93
1 - (K+Na)	0.10	0.06	0.10	0.09	0.09	0.05	0.08	0.07	0.07	0.07	0.07	0.07
X _{Na}	0.06	0.06	0.06	0.05	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06

Table A3. Mineral analysis of muscovite. $X_{Na} = Na/(Na + K)$

DataSet/Point	56 / 1.	57 / 1.	58 / 1.	59 / 1.	b1 / 1.	b2 / 1.	b3 / 1.	b4 / 1.	b5 / 1.	b6 / 1.	b7 / 1.	b8 / 1.
Mineral	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu	mu
Structural position	S2	S2	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow	Pressure Shadow
SiO ₂	49.72	49.21	46.16	46.88	45.88	45.89	46.96	46.90	46.15	46.23	46.54	45.84
TiO ₂	0.21	0.29	0.23	0.26	0.17	0.19	0.28	0.19	0.20	0.16	0.17	0.34
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Al ₂ O ₃	27.92	29.89	35.92	33.98	36.11	35.49	34.42	33.37	34.93	35.34	34.79	35.10
FeO	3.01	2.93	1.62	1.89	1.26	1.58	1.80	2.15	1.47	1.56	1.85	1.66
MnO	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.03	0.00	0.00	0.03	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
MgO	2.50	2.09	0.69	1.00	0.51	0.61	1.01	1.13	0.73	0.81	0.90	0.75
CaO	0.00	0.01	0.00	0.02	0.00	0.00	0.04	0.01	0.04	0.00	0.04	0.02
Na ₂ O	0.39	0.49	1.00	1.12	1.51	1.43	1.06	1.05	0.86	0.85	1.29	0.55
K ₂ O	10.13	10.01	9.55	9.40	9.18	9.27	9.46	9.94	10.06	9.75	9.25	9.96
Total	93.93	94.93	95.18	94.58	94.62	94.50	95.03	94.75	94.43	94.72	94.85	94.21
Composition per formula unit (on the basis of 11 anhydrous oxygen)												
Si	3.37	3.30	3.07	3.14	3.06	3.07	3.12	3.15	3.10	3.09	3.10	3.08
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Cr	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	2.23	2.36	2.81	2.68	2.84	2.80	2.70	2.64	2.76	2.78	2.73	2.78
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.17	0.16	0.09	0.11	0.07	0.09	0.10	0.12	0.08	0.09	0.10	0.09
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.25	0.21	0.07	0.10	0.05	0.06	0.10	0.11	0.07	0.08	0.09	0.07
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.05	0.06	0.13	0.14	0.20	0.19	0.14	0.14	0.11	0.11	0.17	0.07
K	0.88	0.86	0.81	0.80	0.78	0.79	0.80	0.85	0.86	0.83	0.79	0.85
Tetrahedral Al	0.63	0.70	0.93	0.86	0.94	0.93	0.88	0.85	0.90	0.91	0.90	0.92
Octahedral Al	1.60	1.66	1.88	1.82	1.90	1.87	1.82	1.79	1.86	1.87	1.84	1.86
Σ(Mg,Fe)	0.42	0.37	0.16	0.21	0.12	0.15	0.20	0.23	0.16	0.17	0.19	0.17
Σ(K,Na)	0.93	0.92	0.94	0.95	0.98	0.98	0.94	0.99	0.97	0.94	0.95	0.93
1 - (K+Na)	0.07	0.08	0.06	0.05	0.02	0.02	0.06	0.01	0.03	0.06	0.05	0.07
X _{Na}	0.05	0.07	0.14	0.15	0.20	0.19	0.15	0.14	0.11	0.12	0.17	0.08

Table A4. Mineral analysis of chlorite. $X_{Mg} = Mg/(Mg + Fe)$

DataSet/Point	26 / 1.	27 / 1.	28 / 1.	29 / 1.	30 / 1.	31 / 1.	32 / 1.	33 / 1.	34 / 1.	35 / 1.	40 / 1.
Mineral	chl	chl	chl	chl	chl	chl	chl	chl	chl	chl	chl
SiO ₂	24.73	24.74	24.67	24.55	24.46	24.74	24.84	25.57	24.83	24.46	24.90
TiO ₂	0.06	0.09	0.09	0.09	0.09	0.07	0.11	0.10	0.11	0.03	0.12
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
Al ₂ O ₃	21.18	21.59	21.11	21.67	21.95	21.45	21.18	22.57	21.36	21.51	20.92
FeO	29.51	29.13	29.35	29.87	29.36	29.81	28.76	29.22	29.73	29.89	29.19
MnO	0.12	0.10	0.09	0.12	0.06	0.14	0.13	0.19	0.08	0.12	0.11
NiO	0.06	0.02	0.01	0.03	0.04	0.02	0.07	0.00	0.01	0.01	0.08
MgO	11.89	11.77	11.91	11.77	11.58	11.64	11.63	11.28	11.94	11.63	12.01
CaO	0.00	0.00	0.02	0.01	0.03	0.02	0.03	0.01	0.02	0.02	0.00
Na ₂ O	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.01	0.01	0.00	0.01	0.00	0.01	0.02	0.27	0.00	0.00	0.01
Total	87.57	87.44	87.27	88.14	87.57	87.90	86.79	89.21	88.08	87.68	87.35
Composition per formula unit (on the basis of 14 oxygen)											
Si	2.67	2.67	2.67	2.64	2.64	2.67	2.70	2.70	2.67	2.64	2.69
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.70	2.74	2.70	2.75	2.79	2.72	2.71	2.80	2.70	2.74	2.67
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	2.67	2.63	2.66	2.68	2.65	2.69	2.61	2.58	2.67	2.70	2.64
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Ni	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Mg	1.92	1.89	1.92	1.89	1.86	1.87	1.88	1.77	1.91	1.88	1.94
Ca	0.00	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	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
X_{Mg}	0.42	0.42	0.42	0.41	0.41	0.41	0.42	0.41	0.42	0.41	0.42

Table A5. Mineral analysis of chlorite. $X_{Mg} = Mg/(Mg + Fe)$

DataSet/Point	41 / 1 .	42 / 1 .	43 / 1 .	b9 / 1 .	b10 / 1 .	b11 / 1 .	b12 / 1 .	b15 / 1 .	b16 / 1 .	b17 / 1 .	b18 / 1 .
Mineral	chl	chl	chl	chl	chl	chl	chl	chl	chl	chl	chl
SiO2	24.94	24.91	25.05	24.21	23.98	24.10	24.06	25.33	24.59	23.91	23.92
TiO2	0.07	0.11	0.07	0.04	0.07	0.06	0.05	0.08	0.06	0.09	0.10
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Al2O3	21.11	20.94	21.24	22.19	22.70	22.52	22.05	21.16	22.39	22.32	21.83
FeO	29.19	29.45	29.35	30.20	29.74	30.12	30.66	29.81	29.41	30.17	30.44
MnO	0.13	0.12	0.10	0.14	0.10	0.09	0.09	0.13	0.07	0.08	0.13
NiO	0.02	0.13	0.04	0.05	0.02	0.08	0.01	0.04	0.01	0.12	0.03
MgO	11.98	11.94	11.92	11.02	10.80	11.03	10.67	11.73	10.89	11.06	10.93
CaO	0.04	0.03	0.01	0.00	0.05	0.03	0.04	0.02	0.01	0.01	0.08
Na2O	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.00
K2O	0.03	0.03	0.01	0.01	0.00	0.01	0.00	0.00	0.20	0.01	0.02
Total	87.52	87.65	87.80	87.85	87.48	88.05	87.64	88.28	87.67	87.77	87.48
Composition per formula unit (on the basis of 14 oxygen)											
Si	2.69	2.69	2.69	2.62	2.60	2.60	2.61	2.71	2.65	2.59	2.60
Ti	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.68	2.67	2.69	2.83	2.90	2.86	2.82	2.67	2.84	2.85	2.80
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	2.63	2.66	2.64	2.73	2.69	2.71	2.78	2.67	2.65	2.73	2.77
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ni	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Mg	1.93	1.92	1.91	1.78	1.74	1.77	1.73	1.87	1.75	1.78	1.77
Ca	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Na	0.00	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	0.03	0.00	0.00
X_{Mg}	0.42	0.42	0.42	0.39	0.39	0.39	0.38	0.41	0.40	0.40	0.39

Table A6. Mineral analysis of plagioclase and ilmenite. $X_{Ca} = Ca/(Ca+Na+K)$ (pl); $X_{Na} = Na/(Ca+Na+K)$ (pl); $X_K = K/(Ca+Na+K)$ (pl).

DataSet/Point	13 / 1 .	15 / 1 .	16 / 1 .	18 / 1 .	19 / 1 .	DataSet/P	1 / 1 .	2 / 1 .	3 / 1 .	4 / 1 .	11 / 1 .	12 / 1 .
Mineral	pl	pl	pl	pl	pl	Mineral	ilm	ilm	ilm	ilm	ilm	ilm
SiO ₂	63.54	63.99	64.05	64.41	63.89	SiO ₂	0.03	0.04	0.00	0.79	0.00	0.06
TiO ₂	0.01	0.04	0.00	0.01	0.05	TiO ₂	52.56	52.78	53.70	50.81	53.56	53.28
Cr ₂ O ₃	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
Al ₂ O ₃	22.18	22.22	21.95	22.22	22.76	Al ₂ O ₃	0.01	0.02	0.04	1.36	0.03	0.00
FeO	0.08	0.04	0.05	0.05	0.03	FeO	45.72	45.73	45.35	44.93	45.84	45.14
MnO	0.00	0.00	0.00	0.00	0.00	MnO	0.99	0.99	0.99	0.93	1.00	0.88
NiO	0.03	0.00	0.02	0.00	0.03	NiO	0.01	0.00	0.03	0.06	0.07	0.00
MgO	0.04	0.02	0.00	0.04	0.00	MgO	0.07	0.06	0.08	0.12	0.04	0.09
CaO	3.54	3.48	3.22	3.34	4.00	CaO	0.02	0.01	0.01	0.03	0.01	0.03
Na ₂ O	9.41	9.68	9.66	9.60	9.34	Na ₂ O	0.04	0.00	0.00	0.04	0.00	0.00
K ₂ O	0.09	0.10	0.08	0.08	0.08	K ₂ O	0.06	0.00	0.01	0.04	0.02	0.00
Total	98.93	99.56	99.04	99.75	100.18	Total	99.52	99.64	100.20	99.11	100.58	99.48
Composition per formula unit (on the basis of 8 oxygen)												
Si	2.83	2.84	2.85	2.84	2.82	Si	0.00	0.00	0.00	0.02	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	Ti	1.00	1.00	1.01	0.96	1.01	1.01
Cr	0.00	0.00	0.00	0.00	0.00	Cr	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.17	1.16	1.15	1.16	1.18	Al	0.00	0.00	0.00	0.04	0.00	0.00
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.00	0.00	0.00	0.00	0.00	Fe ²⁺	0.97	0.97	0.95	0.95	0.96	0.95
Mn	0.00	0.00	0.00	0.00	0.00	Mn	0.02	0.02	0.02	0.02	0.02	0.02
Ni	0.00	0.00	0.00	0.00	0.00	Ni	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	Mg	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.17	0.17	0.15	0.16	0.19	Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.81	0.83	0.83	0.82	0.80	Na	0.00	0.00	0.00	0.00	0.00	0.00
K	0.01	0.01	0.00	0.00	0.00	K	0.00	0.00	0.00	0.00	0.00	0.00
Composition per formula unit (on the basis of 3 oxygen)												
X _{Ca}	0.17	0.16	0.15	0.16	0.19							
X _{Na}	0.82	0.83	0.84	0.83	0.81							
X _K	0.01	0.01	0.00	0.00	0.00							

Table A7. Mineral analysis of garnet 1. $X_{Fe} = Fe/(Mg + Fe)$

DataSet/Point	b59/1.	b59/2.	b59/3.	b59/5.	b59/6.	b59/7.	b59/8.	b59/9.	b59/10.	b59/11.	b59/13.	b59/14.	b59/15.	b59/16.	b59/17.	b59/18.	b59/19.	b59/20.	b59/21.
Mineral	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g
SiO ₂	36.96	36.73	36.96	36.64	36.57	36.70	36.74	36.89	36.82	36.90	37.02	36.62	36.94	37.35	36.83	36.53	36.80	36.87	36.66
TiO ₂	0.07	0.08	0.03	0.10	0.07	0.11	0.10	0.10	0.10	0.09	0.08	0.07	0.11	0.08	0.09	0.12	0.12	0.11	0.10
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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	21.41	21.17	21.12	21.04	20.87	21.29	21.01	20.86	20.79	21.19	20.94	20.95	21.15	21.09	21.13	21.05	21.21	20.86	20.93
FeO	33.64	33.59	34.45	33.60	33.19	33.14	33.63	33.11	33.31	33.16	33.36	33.29	33.08	33.42	33.36	33.11	33.34	33.50	33.17
MnO	1.69	1.73	2.05	2.23	2.21	2.38	2.38	2.45	2.49	2.45	2.46	2.49	2.36	2.50	2.40	2.38	2.35	2.38	2.46
NiO	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.04	0.00	0.07	0.00	0.05	0.07	0.02	0.00	0.01	0.00
MgO	1.05	0.94	1.01	0.91	0.85	0.87	0.92	0.93	0.87	0.94	0.95	0.95	0.93	0.85	0.87	0.93	0.91	0.91	0.87
CaO	5.84	6.35	5.22	6.14	6.42	6.35	5.90	6.12	5.99	6.55	6.16	6.17	6.33	6.35	6.25	6.06	6.26	5.89	6.00
Na ₂ O	0.00	0.00	0.00	0.04	0.03	0.03	0.05	0.07	0.06	0.00	0.04	0.01	0.00	0.01	0.01	0.04	0.01	0.01	0.02
K ₂ O	0.01	0.00	0.00	0.01	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	0.00
Total	100.68	100.60	100.84	100.75	100.28	100.86	100.73	100.52	100.42	101.31	101.01	100.63	100.89	101.71	101.01	100.23	101.01	100.55	100.21
Composition per formula unit (on the basis of 12 oxygen)																			
Si	2.97	2.95	2.97	2.94	2.95	2.94	2.95	2.97	2.97	2.95	2.97	2.95	2.96	2.97	2.95	2.95	2.95	2.97	2.96
Ti	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Cr	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	0.00	0.00	0.00	0.00	0.00
Al	2.03	2.01	2.00	1.99	1.99	2.01	1.99	1.98	1.98	1.99	1.98	1.99	2.00	1.98	2.00	2.00	2.00	1.98	1.99
Fe ³⁺	0.03	0.08	0.05	0.11	0.11	0.09	0.10	0.08	0.08	0.10	0.09	0.11	0.06	0.06	0.09	0.09	0.09	0.06	0.07
Fe ²⁺	2.23	2.18	2.26	2.14	2.13	2.13	2.16	2.15	2.17	2.11	2.15	2.13	2.15	2.16	2.15	2.14	2.15	2.19	2.17
Mn	0.11	0.12	0.14	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.16	0.16	0.16	0.16	0.17
Ni	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	0.00	0.00	0.00	0.00	0.00
Mg	0.13	0.11	0.12	0.11	0.10	0.10	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.10	0.10	0.11	0.11	0.11	0.10
Ca	0.50	0.55	0.45	0.53	0.56	0.55	0.51	0.53	0.52	0.56	0.53	0.53	0.54	0.54	0.54	0.52	0.54	0.51	0.52
Na	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X _{Fe}	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96	0.95	0.95	0.95	0.95	0.95
alm	0.75	0.74	0.76	0.73	0.73	0.72	0.73	0.73	0.73	0.72	0.73	0.72	0.73	0.73	0.73	0.73	0.73	0.74	0.73
pyr	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
spss	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.06	0.05	0.05	0.06
grs	0.17	0.18	0.15	0.18	0.19	0.19	0.17	0.18	0.17	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.18

Table A8. Mineral analysis of garnet 1. $X_{Fe} = Fe/(Mg+Fe)$

DataSet/Point	b59 / 22 .	b59 / 23 .	b59 / 24 .	b59 / 25 .	b59 / 26 .	b59 / 27 .	b59 / 28 .	b59 / 29 .	b59 / 30 .	b59 / 31 .	b59 / 32 .	b59 / 33 .	b59 / 34 .	b59 / 35 .	b59 / 36 .	b59 / 37 .	b59 / 38 .	b59 / 39 .	b59 / 41 .
Mineral	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g
SiO ₂	36.86	36.69	36.70	36.88	37.03	36.64	36.86	36.61	36.52	36.89	36.92	37.14	36.73	37.03	36.57	37.11	38.07	36.82	36.95
TiO ₂	0.09	0.08	0.10	0.07	0.08	0.17	0.13	0.06	0.09	0.07	0.10	0.12	0.08	0.10	0.10	0.10	0.10	0.10	0.10
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	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Al ₂ O ₃	21.22	21.04	21.08	21.07	21.23	21.09	20.83	21.14	21.14	20.81	21.07	21.15	21.22	20.90	20.93	21.25	21.15	21.47	21.31
FeO	34.02	33.25	33.72	33.49	33.14	32.87	33.00	32.79	33.11	33.08	32.79	32.49	33.00	32.41	32.89	32.66	31.63	32.84	32.91
MnO	2.39	2.50	2.41	2.43	2.27	2.31	2.45	2.31	2.42	2.44	2.63	2.49	2.42	2.48	2.54	2.52	2.43	2.54	2.46
NiO	0.02	0.00	0.01	0.00	0.01	0.00	0.04	0.01	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.07	0.01	0.00	0.03
MgO	0.94	0.99	0.92	0.92	0.92	0.88	0.86	0.88	0.89	0.85	0.94	0.87	0.88	0.88	0.89	0.85	0.87	0.91	0.88
CaO	5.85	6.12	6.10	6.16	6.26	6.70	6.20	6.48	6.62	6.51	6.41	6.91	6.47	6.83	6.29	6.62	6.41	6.53	6.72
Na ₂ O	0.00	0.06	0.01	0.00	0.04	0.02	0.10	0.07	0.03	0.02	0.02	0.00	0.06	0.03	0.00	0.02	0.03	0.09	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.13	0.02	0.00
Total	101.39	100.73	101.06	101.02	100.97	100.68	100.47	100.38	100.84	100.68	100.87	101.17	100.91	100.67	100.23	101.20	100.85	101.33	101.36
Composition per formula unit (on the basis of 12 oxygen)																			
Si	2.95	2.95	2.94	2.96	2.97	2.94	2.97	2.95	2.93	2.97	2.96	2.97	2.94	2.97	2.95	2.96	3.05	2.93	2.95
Ti	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr	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	0.00	0.00	0.00	0.00	0.00
Al	2.00	1.99	1.99	1.99	2.00	2.00	1.98	2.01	2.00	1.97	1.99	1.99	2.00	1.98	1.99	2.00	1.99	2.02	2.00
Fe ³⁺	0.10	0.11	0.11	0.09	0.06	0.10	0.09	0.11	0.14	0.09	0.08	0.06	0.11	0.07	0.09	0.06	0.00	0.12	0.09
Fe ²⁺	2.18	2.12	2.15	2.16	2.16	2.11	2.14	2.10	2.08	2.13	2.12	2.11	2.10	2.11	2.13	2.12	2.12	2.07	2.11
Mn	0.16	0.17	0.16	0.17	0.15	0.16	0.17	0.16	0.16	0.17	0.18	0.17	0.16	0.17	0.17	0.17	0.16	0.17	0.17
Ni	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	0.00	0.00	0.00	0.00	0.00
Mg	0.11	0.12	0.11	0.11	0.11	0.11	0.10	0.11	0.11	0.10	0.11	0.10	0.11	0.11	0.11	0.10	0.10	0.11	0.10
Ca	0.50	0.53	0.52	0.53	0.54	0.58	0.54	0.56	0.57	0.56	0.55	0.59	0.56	0.59	0.54	0.57	0.55	0.56	0.57
Na	0.00	0.01	0.00	0.00	0.01	0.00	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
K	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	0.00	0.00	0.01	0.00	0.00
X _{Fe}	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
alm	0.74	0.72	0.73	0.73	0.73	0.72	0.73	0.72	0.71	0.72	0.72	0.71	0.72	0.71	0.72	0.72	0.72	0.71	0.71
pyr	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.04	0.04	0.04
spss	0.05	0.06	0.06	0.06	0.05	0.05	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
grs	0.17	0.18	0.18	0.18	0.18	0.20	0.18	0.19	0.19	0.19	0.19	0.20	0.19	0.20	0.18	0.19	0.19	0.19	0.19

Table A9. Mineral analysis of garnet 1. $X_{Fe} = Fe/(Mg+Fe)$

Mineral	b59/42 . g	b59/43 . g	b59/44 . g	b59/45 . g	b59/46 . g	b59/47 . g	b59/48 . g	b59/49 . g	b59/50 . g	b59/51 . g	b59/52 . g	b59/53 . g	b59/54 . g	b59/55 . g	b59/56 . g	b59/57 . g	b59/58 . g	b59/59 . g
SiO ₂	37.08	36.68	36.76	36.75	36.66	36.69	36.95	36.71	36.51	36.69	36.92	36.61	35.31	36.62	36.86	36.09	36.74	36.63
TiO ₂	0.13	0.07	0.09	0.08	0.09	0.12	0.07	0.15	0.12	0.05	0.07	0.11	0.07	0.08	0.07	0.05	0.05	0.05
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.01	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	20.82	20.95	20.73	21.09	20.98	21.27	21.06	20.86	21.14	20.95	21.16	21.10	20.43	21.15	21.04	20.46	21.04	20.99
FeO	33.01	32.67	33.23	32.96	32.95	32.54	32.73	32.99	33.03	32.90	32.95	33.20	31.64	33.72	34.06	34.15	34.46	33.89
MnO	2.46	2.60	2.51	2.42	2.52	2.51	2.49	2.60	2.67	2.58	2.45	2.34	2.11	2.16	2.14	1.89	1.79	1.57
NiO	0.05	0.06	0.03	0.00	0.00	0.05	0.02	0.03	0.02	0.00	0.04	0.00	0.00	0.00	0.07	0.00	0.00	0.00
MgO	0.88	0.85	0.83	0.83	0.89	0.84	0.87	0.89	0.91	0.86	0.86	0.85	0.95	0.95	0.89	0.96	1.01	1.03
CaO	6.54	6.48	6.24	6.55	6.38	6.69	6.53	6.70	6.12	6.11	6.27	6.51	6.16	5.98	5.72	5.04	5.84	6.27
Na ₂ O	0.04	0.00	0.00	0.01	0.04	0.00	0.05	0.03	0.05	0.04	0.02	0.01	0.08	0.00	0.01	0.03	0.01	0.03
K ₂ O	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.01
Total	101.01	100.38	100.42	100.69	100.51	100.71	100.77	100.98	100.57	100.18	100.74	100.73	96.91	100.66	100.85	98.66	100.95	100.49
Composition per formula unit (on the basis of 12 oxygen)																		
Si	2.97	2.96	2.97	2.95	2.95	2.95	2.96	2.94	2.94	2.96	2.97	2.94	2.94	2.95	2.96	2.97	2.95	2.95
Ti	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Cr	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	0.00	0.00	0.00	0.00
Al	1.97	1.99	1.97	2.00	1.99	2.01	1.99	1.97	2.00	1.99	2.00	2.00	2.01	2.00	1.99	1.98	1.99	1.99
Fe ³⁺	0.08	0.09	0.08	0.09	0.10	0.08	0.08	0.13	0.11	0.08	0.06	0.11	0.13	0.09	0.07	0.08	0.11	0.11
Fe ²⁺	2.13	2.12	2.16	2.13	2.11	2.10	2.12	2.08	2.11	2.15	2.15	2.12	2.07	2.17	2.21	2.27	2.20	2.17
Mn	0.17	0.18	0.17	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.17	0.16	0.15	0.15	0.15	0.13	0.12	0.11
Ni	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	0.00	0.00	0.00	0.00
Mg	0.10	0.10	0.10	0.10	0.11	0.10	0.10	0.11	0.11	0.10	0.10	0.10	0.12	0.11	0.11	0.12	0.12	0.12
Ca	0.56	0.56	0.54	0.56	0.55	0.58	0.56	0.58	0.53	0.53	0.54	0.56	0.55	0.52	0.49	0.44	0.50	0.54
Na	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01	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	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
X _{Fe}	0.95	0.95	0.96	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
alm	0.72	0.72	0.73	0.72	0.72	0.71	0.72	0.71	0.72	0.73	0.73	0.72	0.72	0.74	0.75	0.77	0.75	0.74
pyr	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04
spss	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04
grs	0.19	0.19	0.18	0.19	0.19	0.19	0.19	0.20	0.18	0.18	0.18	0.19	0.19	0.17	0.17	0.15	0.17	0.18

Table A10. Mineral analysis of garnet 2. $X_{Fe} = Fe/(Mg + Fe)$

DataSet/Point	b60/1.	b60/2.	b60/3.	b60/4.	b60/5.	b60/6.	b60/7.	b60/8.	b60/9.	b60/10.	b60/11.	b60/12.	b60/13.	b60/14.	b60/16.	b60/17.	b60/18.	b60/19.	b60/20.
Mineral	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g
SiO ₂	37.16	37.04	36.98	37.09	37.08	37.07	37.12	36.84	37.25	37.11	37.40	37.05	36.82	37.07	36.79	36.80	36.84	36.88	36.90
TiO ₂	0.13	0.10	0.07	0.06	0.06	0.09	0.13	0.14	0.14	0.12	0.08	0.09	0.05	0.13	0.08	0.07	0.07	0.07	0.03
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.01	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	21.16	21.00	21.11	20.97	21.32	21.24	21.19	20.82	21.22	20.85	21.43	21.09	21.23	21.26	21.01	21.19	21.26	20.99	21.02
FeO	33.58	31.84	31.88	31.82	31.96	31.55	31.33	29.03	31.64	31.47	31.61	31.08	30.40	30.39	31.24	30.55	30.49	30.16	29.97
MnO	1.98	2.34	2.64	2.38	2.55	2.57	2.75	2.61	3.14	3.31	3.49	3.76	3.75	3.93	4.49	4.66	4.71	4.89	4.75
NiO	0.04	0.04	0.00	0.03	0.00	0.00	0.00	0.04	0.00	0.01	0.04	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.02
MgO	1.00	0.91	0.98	1.16	1.14	1.16	1.18	1.21	1.21	1.16	1.17	1.05	1.02	1.05	0.98	0.96	0.99	0.96	0.88
CaO	6.19	6.76	7.24	6.74	6.73	6.79	7.40	5.46	6.47	6.52	6.35	6.91	6.84	6.68	6.02	5.99	6.11	6.12	6.24
Na ₂ O	0.00	0.23	0.05	0.30	0.03	0.00	0.02	0.24	0.02	0.03	0.05	0.03	0.03	0.01	0.08	0.11	0.09	0.12	0.15
K ₂ O	0.02	0.05	0.01	0.03	0.00	0.00	0.00	0.20	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	101.26	100.29	100.97	100.58	100.87	100.46	101.14	96.59	101.12	100.58	101.63	101.05	100.14	100.55	100.72	100.34	100.56	100.18	99.97
Composition per formula unit (on the basis of 12 oxygen)																			
Si	2.97	2.98	2.95	2.97	2.96	2.97	2.96	3.06	2.97	2.98	2.97	2.96	2.96	2.97	2.95	2.96	2.96	2.97	2.98
Ti	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Cr	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	0.00	0.00	0.00	0.00	0.00
Al	1.99	1.99	1.99	1.98	2.01	2.01	1.99	2.04	2.00	1.97	2.00	1.99	2.01	2.01	1.99	2.01	2.01	1.99	2.00
Fe ³⁺	0.06	0.09	0.10	0.14	0.06	0.03	0.09	0.00	0.05	0.06	0.06	0.09	0.06	0.03	0.11	0.07	0.08	0.07	0.06
Fe ²⁺	2.19	2.05	2.03	1.99	2.07	2.08	2.00	2.02	2.06	2.05	2.04	1.98	1.99	2.01	1.99	1.98	1.97	1.96	1.96
Mn	0.13	0.16	0.18	0.16	0.17	0.17	0.19	0.18	0.21	0.23	0.23	0.25	0.26	0.27	0.31	0.32	0.32	0.33	0.32
Ni	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	0.00	0.00	0.00	0.00	0.00
Mg	0.12	0.11	0.12	0.14	0.14	0.14	0.14	0.15	0.14	0.14	0.14	0.12	0.12	0.13	0.12	0.12	0.12	0.12	0.11
Ca	0.53	0.58	0.62	0.58	0.58	0.58	0.63	0.49	0.55	0.56	0.54	0.59	0.59	0.57	0.52	0.52	0.53	0.53	0.54
Na	0.00	0.04	0.01	0.05	0.00	0.00	0.00	0.04	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.01	0.02	0.02
K	0.00	0.01	0.00	0.00	0.00	0.00	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
X _{Fe}	0.95	0.95	0.95	0.94	0.94	0.94	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.95
alm	0.74	0.71	0.69	0.69	0.70	0.70	0.68	0.71	0.69	0.69	0.69	0.67	0.67	0.68	0.68	0.68	0.67	0.67	0.67
pyr	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
spss	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.08	0.08	0.09	0.09	0.09	0.10	0.11	0.11	0.11	0.11
grs	0.18	0.20	0.21	0.20	0.19	0.20	0.21	0.17	0.19	0.19	0.18	0.20	0.20	0.19	0.18	0.18	0.18	0.18	0.18

Table A11. Mineral analysis of garnet 2. $X_{Fe} = Fe/(Mg + Fe)$

Mineral	b60 / 21 .	b60 / 22 .	b60 / 23 .	b60 / 24 .	b60 / 25 .	b60 / 26 .	b60 / 27 .	b60 / 28 .	b60 / 29 .	b60 / 30 .	b60 / 31 .	b60 / 32 .	b60 / 33 .	b60 / 34 .	b60 / 35 .	b60 / 36 .	b60 / 37 .	b60 / 38 .	b60 / 39 .
SiO ₂	36.72	37.07	37.22	37.04	35.84	37.04	36.89	37.08	36.91	37.23	37.13	37.54	37.36	37.05	37.00	37.14	37.09	36.91	36.81
TiO ₂	0.07	0.07	0.09	0.10	0.06	0.06	0.07	0.06	0.06	0.07	0.08	0.08	0.05	0.07	0.11	0.07	0.06	0.11	0.08
Cr ₂ O ₃	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Al ₂ O ₃	21.23	21.25	21.20	21.06	20.22	21.30	21.02	21.28	21.25	20.80	21.36	21.66	21.18	21.01	21.02	21.20	21.16	21.19	21.14
FeO	30.27	29.90	29.87	30.36	29.60	29.70	30.67	30.69	29.84	32.01	31.73	32.05	32.45	32.01	32.30	32.94	33.09	33.13	33.82
MnO	4.53	4.24	4.22	4.14	4.09	3.86	3.98	3.77	3.42	3.59	3.39	3.10	2.65	2.45	2.58	2.36	2.20	2.05	1.76
NiO	0.00	0.00	0.00	0.07	0.01	0.01	0.01	0.06	0.06	0.00	0.04	0.06	0.00	0.00	0.01	0.05	0.06	0.00	0.00
MgO	0.96	0.98	0.91	0.95	1.10	1.03	1.05	1.01	1.08	1.11	1.13	1.17	1.23	1.05	0.97	0.89	0.90	0.95	1.03
CaO	6.80	6.97	6.91	7.09	6.28	7.72	6.87	7.26	7.97	6.42	6.20	6.34	6.30	6.81	6.59	6.51	6.94	6.52	5.82
Na ₂ O	0.06	0.07	0.08	0.06	0.26	0.02	0.00	0.08	0.00	0.08	0.04	0.07	0.00	0.02	0.00	0.01	0.00	0.01	0.00
K ₂ O	0.00	0.00	0.01	0.01	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03
Total	100.65	100.54	100.51	100.88	97.60	100.73	100.58	101.29	100.61	101.31	101.11	102.07	101.22	100.48	100.58	101.17	101.50	100.90	100.49
Composition per formula unit (on the basis of 12 oxygen)																			
Si	2.94	2.97	2.98	2.96	2.96	2.96	2.96	2.95	2.95	2.97	2.96	2.97	2.98	2.98	2.97	2.97	2.95	2.96	2.96
Ti	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00
Cr	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	0.00	0.00	0.00	0.00	0.00
Al	2.01	2.01	2.00	1.99	1.97	2.01	1.99	2.00	2.00	1.96	2.01	2.02	1.99	1.99	1.99	2.00	1.99	2.00	2.01
Fe ³⁺	0.11	0.05	0.03	0.09	0.17	0.07	0.08	0.11	0.09	0.11	0.06	0.05	0.04	0.06	0.05	0.06	0.10	0.07	0.06
Fe ²⁺	1.92	1.95	1.97	1.94	1.87	1.91	1.98	1.93	1.91	2.03	2.06	2.06	2.12	2.09	2.12	2.14	2.11	2.14	2.22
Mn	0.31	0.29	0.29	0.28	0.29	0.26	0.27	0.25	0.23	0.24	0.23	0.21	0.18	0.17	0.18	0.16	0.15	0.14	0.12
Ni	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	0.00	0.00	0.00	0.00	0.00
Mg	0.12	0.12	0.11	0.11	0.13	0.12	0.13	0.12	0.13	0.13	0.13	0.14	0.15	0.13	0.12	0.11	0.11	0.11	0.12
Ca	0.58	0.60	0.59	0.61	0.56	0.66	0.59	0.62	0.68	0.55	0.53	0.54	0.54	0.59	0.57	0.56	0.59	0.56	0.50
Na	0.01	0.01	0.01	0.01	0.04	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.01	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
X _{Fe}	0.94	0.94	0.95	0.94	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.95
alm	0.66	0.66	0.67	0.66	0.66	0.65	0.67	0.66	0.65	0.69	0.70	0.70	0.71	0.70	0.71	0.72	0.71	0.73	0.75
pyr	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04
spss	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.08	0.08	0.08	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04
grs	0.20	0.20	0.20	0.21	0.19	0.22	0.20	0.21	0.23	0.19	0.18	0.18	0.18	0.20	0.19	0.19	0.20	0.19	0.17