Into the structure of the Permian deep continental crust

Multiscale reconstruction of migmatization in the Valpelline Series (Dent Blanche Tectonic System, Western Italian Alps)

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INTRODUCTION

The deep continental crust is the lowest part of the crust above the lithospheric mantle, mainly composed of rocks associated with partial melting, such as migmatites and granulites (Bohlen, 1987; Hacker et al., 2015). In extensional geodynamic frameworks, lithospheric thinning causes asthenospheric upwelling, enhancing partial melting of the lithospheric mantle and deep crust. In these contexts, deformation plays a fundamental role in melanosome-leucosome differentiation by facilitating the movement and segregation of melt within the crust. Foliation and shear zones provide pathways for melt migration, which allow melt to move and accumulate into discrete leucosome bands, reacting with the host rock, enhancing the differentiation of the crust.

During the Permian, the Variscan lithosphere was affected by extension due to the Pangea breakup, followed by the Tethys opening. Among the preserved Permian basements across the Alps, the Valpelline Series in the Dent Blanche Tectonic System in the Western Alps represents an exceptionally preserved exposure of granulite and migmatite, showing high-temperature structures and mineral assemblages despite being involved in the subsequent Alpine collision (Manzotti & Zucali, 2013). This contribution provides a multiscale description that focuses on understanding the effects of deformation and metamorphism in shaping the deep continental crust structure of the Valpelline Series during the Permian time.

GEOLOGICAL SETTING

The Valpelline Series lies in the Dent Blanche Tectonic System of the Western Italian Alps, which is a continental klippe belonging to the Adriatic paleomargin and overlying the oceanic units of the Liguro-Piemonte ocean (Fig. 1a). Together with the neighbouring Arolla Series it has been involved in Alpine subduction-collision events (Compagnoni et al., 1977; Manzotti et al., 2014), still preserving pre-Alpine amphibolite- to granulite-facies mineral assemblages and structures (Manzotti & Zucali, 2013) or magmatic textures like those within the Arolla Series Permian granitoids (Baletti et al., 2012). The Valpelline Series is a deep continental crust section composed of migmatitic gneiss, amphibolites and marbles enclosing lenses of mafic granulites, crosscutted by different systems of pegmatitic dykes (Manzotti & Zucali, 2013; Caso et al., 2024a, b). The regional foliation S_2 in the Valpelline Series is related to the partial melting of both metapelites and amphibolites and is folded and locally transposed at different scales, developing a sillimanite-rich foliation S_3. The pressure (*P*) – temperature (*T*) conditions of partial melting and regional foliation development are 810±40°C and 0.7±0.01 GPa (Manzotti & Zucali, 2013). Metamorphism and partial melting of the Valpelline Series are Permian in age (Kunz et al., 2018) and are related to the crustal thinning and magmatism during the Pangea breakup (Lardeaux & Spalla, 1991).

RESULTS

Rock types of the deep continental crust

The Valpelline Series is mostly made of migmatitic gneiss (pink colour in Fig. 1b) whose outcrops can extend up to hundreds of metres and host the regional structures (S_2 foliation traces in Fig. 1b). Migmatitic gneiss are made of a stromatic structure made of dark-coloured layers (melanosomes) consisting of biotite, sillimanite and garnet and light-coloured layers (leucosomes) of plagioclase, K-feldspar and quartz (Fig. 2a). Leucosomes, assumed to represent the melt, highlight folds with different geometries. In localised outcrops, migmatitic gneiss contains cordierite or orthopyroxene along with garnet. Sillimanite-gneiss occurs as centimetric to hectometric domains that overprint the pervasive foliation of migmatitic gneiss. They show a foliation extremely rich in sillimanite (and locally biotite) wrapping garnet and, when present, cordierite porphyroblast (Fig. 2b). Leucosomes in sillimanite-gneiss are thinner, discontinuous and locally even absent. Felsic granulite

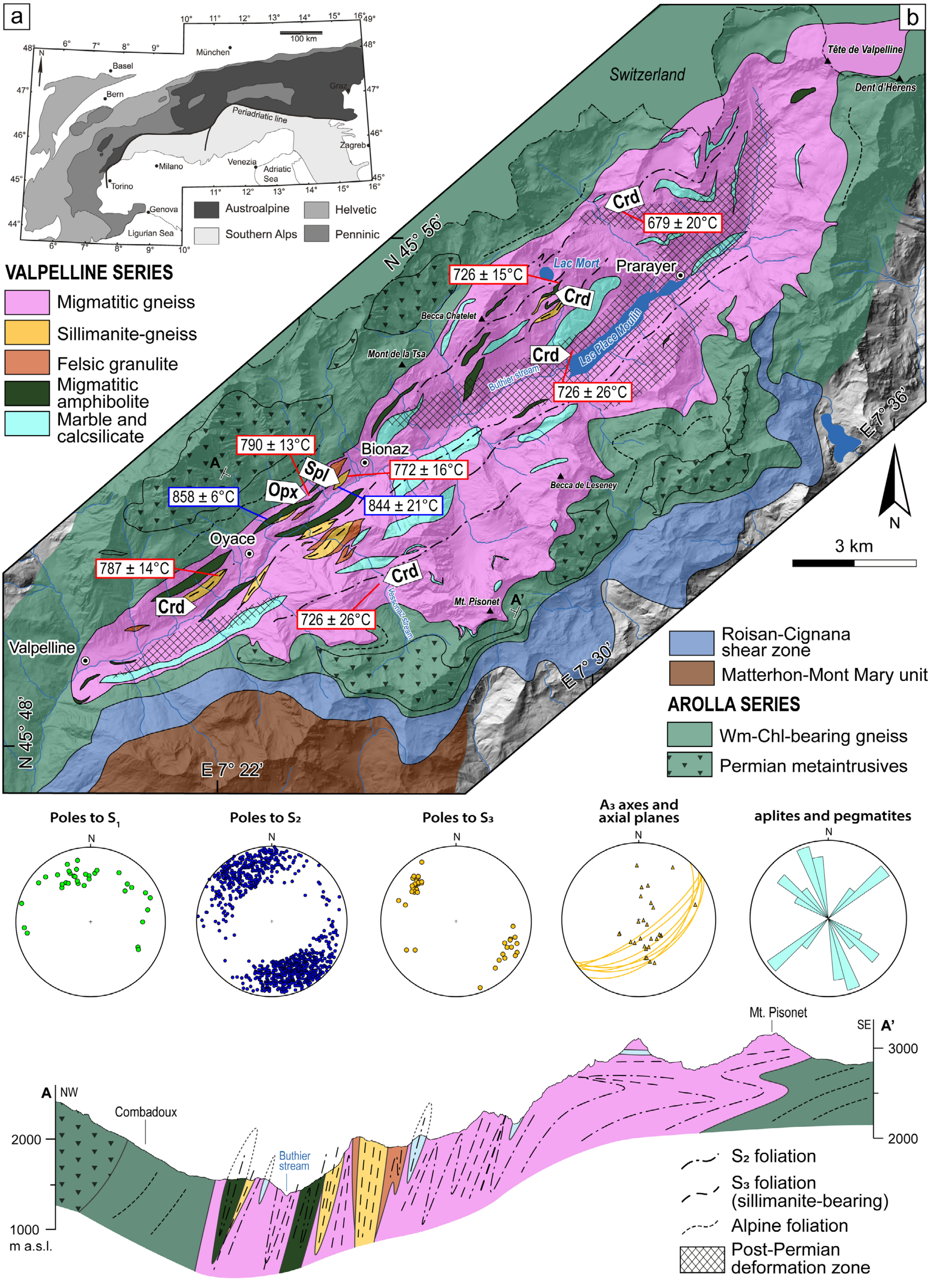

Figure 1 ***a)*** *Tectonic sketch map of the Alps.* ***b)*** *Geological maps of the Valpelline and Arolla Series with temperatures estimations, stereoplots of the main structural elements and geological cross section on the bottom (modified after Caso et al., 2024a).*

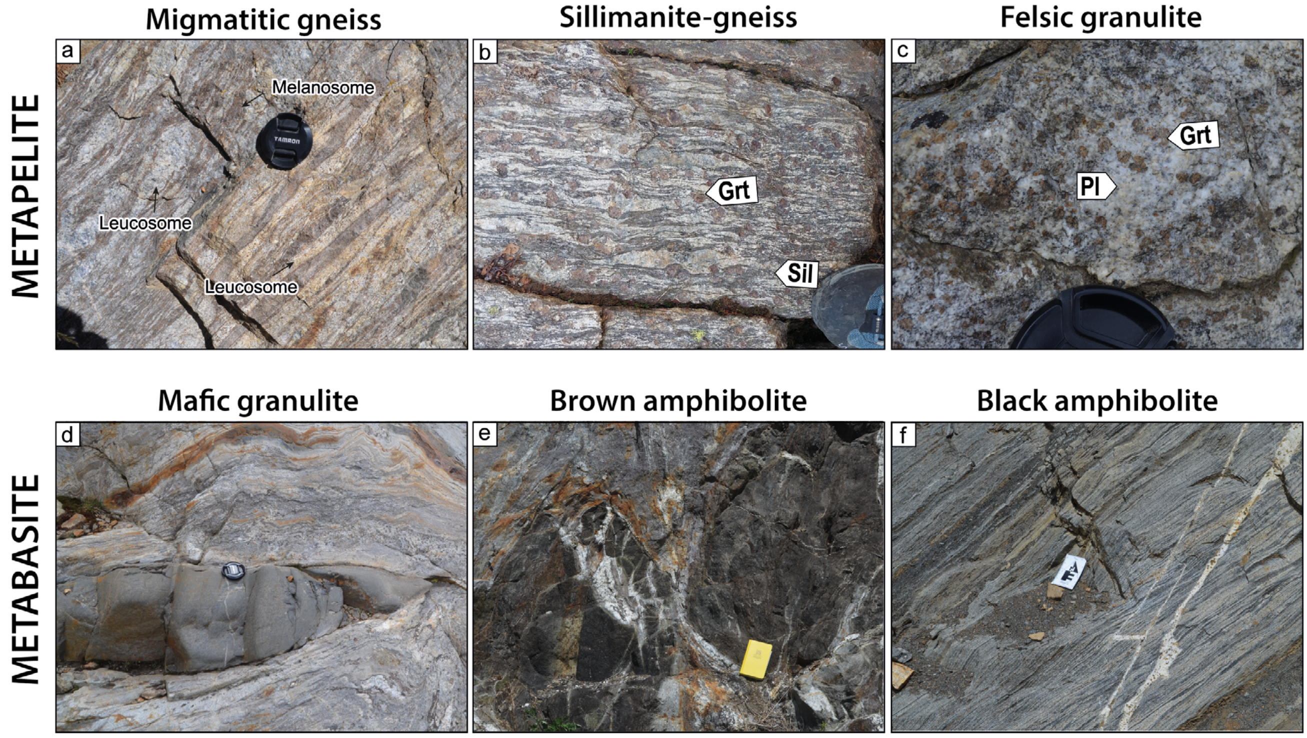

Figure 2 ***a)*** *Migmatitic gneiss outcrop with leucosome and melanosome layers indicated.* ***b)*** *Sillimanite-gneiss made of Sil-rich layer wrapping around large Grt porphyroblasts (mineral abbreviations after Warr, 2021).* ***c)*** *Felsic granulite with a granoblastic structure made of Pl and Grt.* ***d)*** *Lense of mafic granulite within migmatitic gneiss.* ***e)*** *Lenses of brown amphibolite within migmatitic gneiss.* ***f)*** *Outcrop of black amphibolite whose foliation is cut by a pegmatite.*

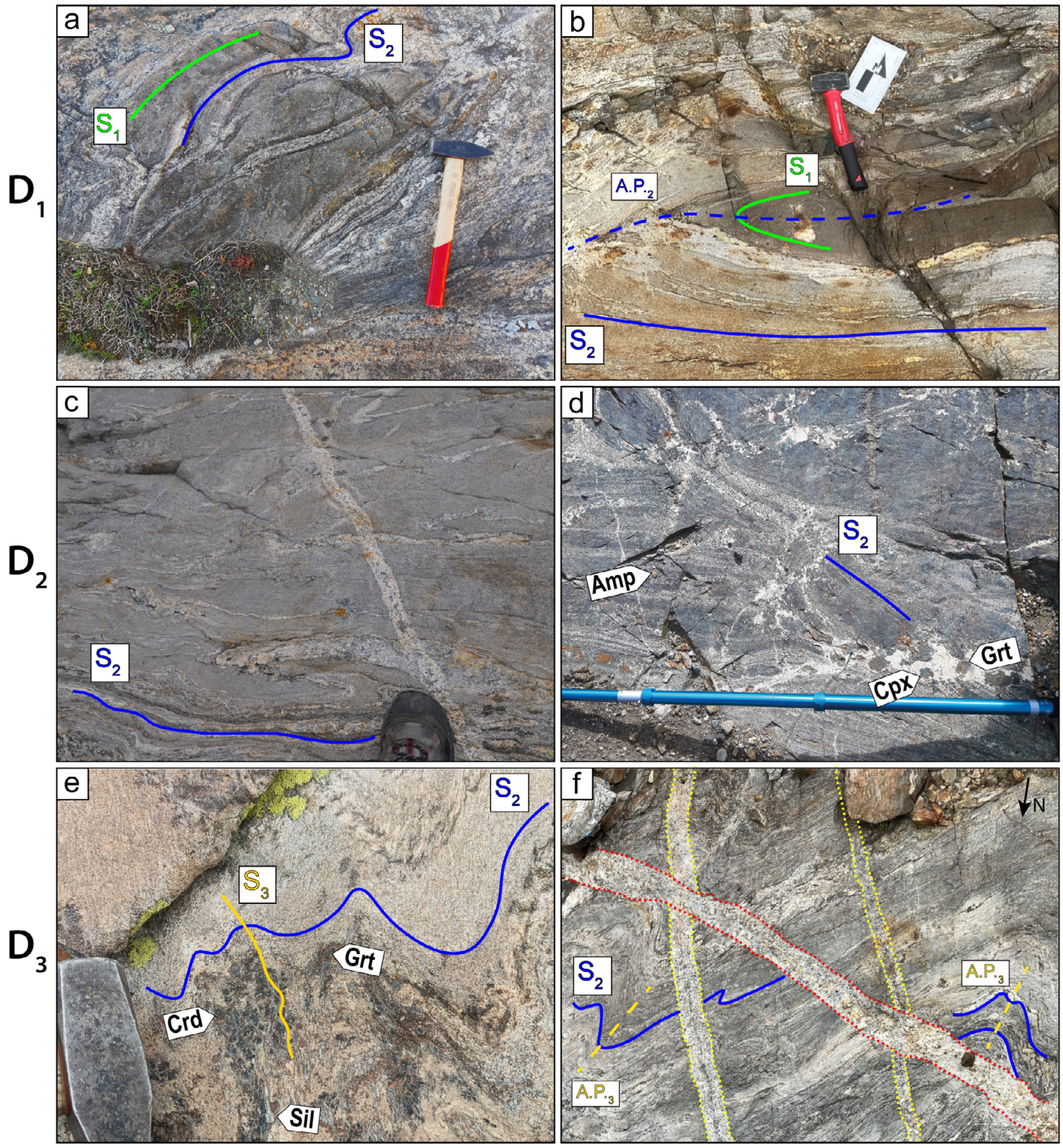

Figure 3 ***a)*** *Mafic granulite lenses hosting* S_1 *foliation, wrapped by the* S_2 *pervasive in migmatitic gneiss.* ***b)*** *Folded brown amphibolite layer withi Crd-migmatitic gneiss, highlighting the* S_1 *foliation.* ***c)*** S_2 *foliation in Crd-migmatitic gneiss cut by leucosomes and pegmatite.* ***d)*** S_2 *in black amphibolite made of dark-green amphibole; the* S_2 *fabric is cut by Pl+Cpx+Grt leucosomes.* ***e)*** D_3 *folds in Crd-migmatitic gneiss with* S_3 *axial plane foliation made of Sil, wrapping Crd and Grt porphyroblasts.* ***f)*** D_3 *folds in migmatitic gneiss crosscut by two different systems of pegmatitic dykes.*

occurs as lenses and layers within migmatitic gneiss. It displays garnet, plagioclase and quartz with granoblastic texture (Fig. 2c).

Metabasite in the Valpelline Series comprises mafic granulite and brown amphibolite cropping out as metric lenses or boudins (Fig. 2d, e) and black amphibolite cropping out as hectometric outcrops (Fig. 2f). Mafic granulite has a granoblastic structure made of orthopyroxene, plagioclase, amphibole and locally biotite. Brown amphibolite is made of brown hornblende and plagioclase, marking a foliation. Black amphibolites are banded, with alternating levels of dark-green amphibole and whiteish plagioclase-rich levels. Their main fabric is locally crosscut by leucosomes made of plagioclase, garnet and clinopyroxene.

Structural evolution

The deformation evolution of the Valpelline Series related to the migmatization history can be summarised in three deformation stages: D_1, D_2 and D_3 recognised at meso- and microscale.

The D_1 stage is testified by the S_1 foliation, which is localised in the metric boudins of mafic granulite and brown amphibolite. This foliation has various orientations to the regional S_2 foliation and elongation of main lithological boundaries (see stereonets in Fig. 1b). In most cases, the S_1 is geometrically discordant to the long axis of the boudins and to the penetrative foliation that wraps them (Fig. 3a). At microscale, the S_1 is marked by Amp I + Pl I + Cpx I + Opx I in mafic granulites and brown amphibolites (Fig. 4a, b). In metapelites, there is no clear evidence of S_1 but rounded inclusions of Bt I, Pl I and Qz I within peritectic Grt/Crd or Opx and relict Bt I and Sil I may be attributed to this stage (Fig. 4c).

During the D_2 the S_1 is folded (Fig. 3b), and the main regional foliation S_2 develops. The S_2 and the lithological boundaries tend to strike NE–SW and dip vertically toward NW or SE (see stereonets in Fig. 1b). The S_2 is pervasive in migmatitic gneiss and black amphibolite (Figs. 3c, d). In migmatitic gneiss, S_2 is marked by leucosome-melanosome alternation (Fig. 3c). At microscale, the S_2 is marked by Bt II + Grt + Opx in + Qz II Opx-migmatitic gneiss and by Bt II + Sil II + Qz II + Pl II + Grt + Crd in Crd-migmatitic gneiss (Fig. 4d, e). In black amphibolite is marked by the isorientation of Amp II and Pl II. Locally, the Pl-rich levels contain Grt and Cpx interpreted as peritectic phases (Fig. 4f).

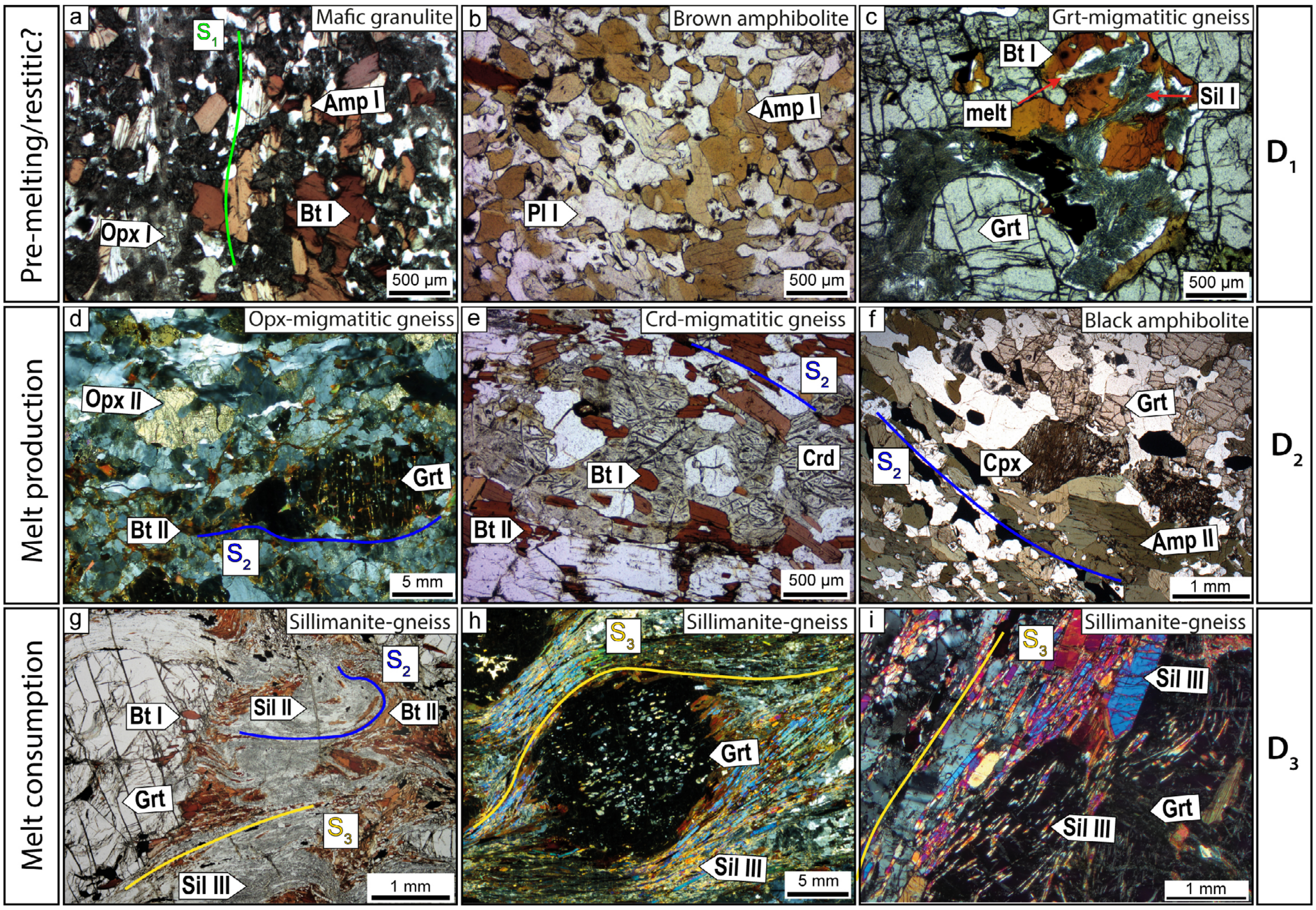

***Figure 4 a)** Opx I, Bt I and Amp I in mafic granulite boudin (XPL: crossed-polarised light). **b)** Amp I and Pl I in brown amphibolite (PPL: plane-polarised light). **c)** Relict deformed Bt I and fibrous Sil I reacting to produce melt and Grt II in migmatitic gneiss (PPL). **d)** Microscale view of Opx and Grt porphyroblasts marking S_2 foliation in Opx-migmatitic gneiss (XPL). **e)** Rounded Bt I blasts included in Crd in a migmatitic gneiss and Bt II marking S_2 foliation (PPL). **f)** S_2 foliation in black amphibolite marked by Amp II + Cpx + Grt (PPL). **g)** S_2 microfold preserved within microlithon in sillimanite-gneiss, whose limbs are parallel to S_3 foliation marked by Sil III and Bt III (PPL). **h)** Sillimanite-gneiss whose foliation is defined by prismatic Sil III blasts wrapping around centimetric Grt porphyroblasts (XPL). **i)** Garnet rim with fine-grained needles of sillimanite marking an internal foliation in continuity with respect to the external one (XPL).*

During the D_3, the S_3 is deformed and folded in different ways. In migmatitic gneiss, the folds affecting S_2, highlighted by leucosomes, are mainly close to open and only locally isoclinal. In domains where the folding is more intense, the S_2 is transposed and overprinted by the Sil-rich axial plane S_3 foliation (Fig. 3e), which wraps around Grt and Crd (Fig. 4g, h, i). Locally, at microscale in sillimanite-gneiss is still possible to observe in microlithons the overprinting relationships between S_2 and S_3, where S_2 is preserved as relict microfolds marked by Sil II and Bt II (Fig. 4g). Peritectic garnet, grown during D_2, locally continues to grow also during D_3 stage, as testified by thin garnet rims with an internal foliation made of Sil III needles parallel the external S_3 (Fig. 4i).

These domains of high-strain D_3-related deformation correspond to sillimanite-gneiss, domains that can range from the cm- up to hectometric scale, where leucosomes are deformed and sometimes completely transposed.

Temperature and pressure estimations

The *P-T* conditions related to the D_1-D_2-D_3 stages have been retrieved by combining different geothermobarometers on metapelites and metabasite of the Valpelline Series.

Temperatures have been obtained using the Zr-in-rutile (Tomkins et al., 2007) and the Ti-in-biotite (Henry et al., 2005) thermometers on metapelites and the Ti-in-amphibole thermometer (Liao et al., 2021) applied on black and brown amphibolites. Since the Zr-in-rutile thermometer is P-dependent, a value of 0.7 GPa has been used as input for the calculations (value from Manzotti & Zucali, 2013). We have analysed rutile crystals from different microstructural positions, like those included within garnet or marking S_2 or S_3 fabrics. Rutile from sillimanite-gneiss yielded temperatures ranging from 691 to 818°C, while Grt-migmatite gneiss temperatures vary between 683 and 773°C (Fig. 5a). In felsic granulite, temperatures range between 667 and 843°C (Fig. 5a). The Ti-in-Bt thermometer has been applied to biotites from three different microstructural domains (Bt I, Bt II and Bt III). Temperatures from Grt-bearing migmatitic gneiss range from 676 and 784°C. There is a slight difference in temperatures between Opx- and Crd-migmatitic gneiss: in the former, temperatures range from 750 to 810°C, while in the latter are lower, from 654 to 789°C. Temperatures from sillimanite-gneiss range from 721 and 812°C (Fig. 5b).

The Ti-in-amphibole thermometer yielded higher temperatures with respect to those from metapelite: *i)* in brown amphibolite (Amp I marking the S_1), they range from 750 to 900°C, *ii)* in black amphibolites (Amp II marking S_2) temperatures are between 746 and 880°C with two main clusters at 767 ± 19°C and 844 ± 21°C (Fig. 5c).

Pressures have been obtained applying two geobarometers, *i.e.*, the Grt–Crd (Bhattacharya, 1986) and the Pl–Amp barometer (Molina et al., 2015). Pressures from Crd-migmatitic gneiss are at 0.55-0.58 GPa (orange ellipse in Fig. 5d) while those from black-amphibolite are much higher. Obtained *P* ranges between 0.8 ± 0.08 GPa (at 767°C) and 1.1 ± 0.10 GPa (at 879°C; green ellipse in Fig. 5d).

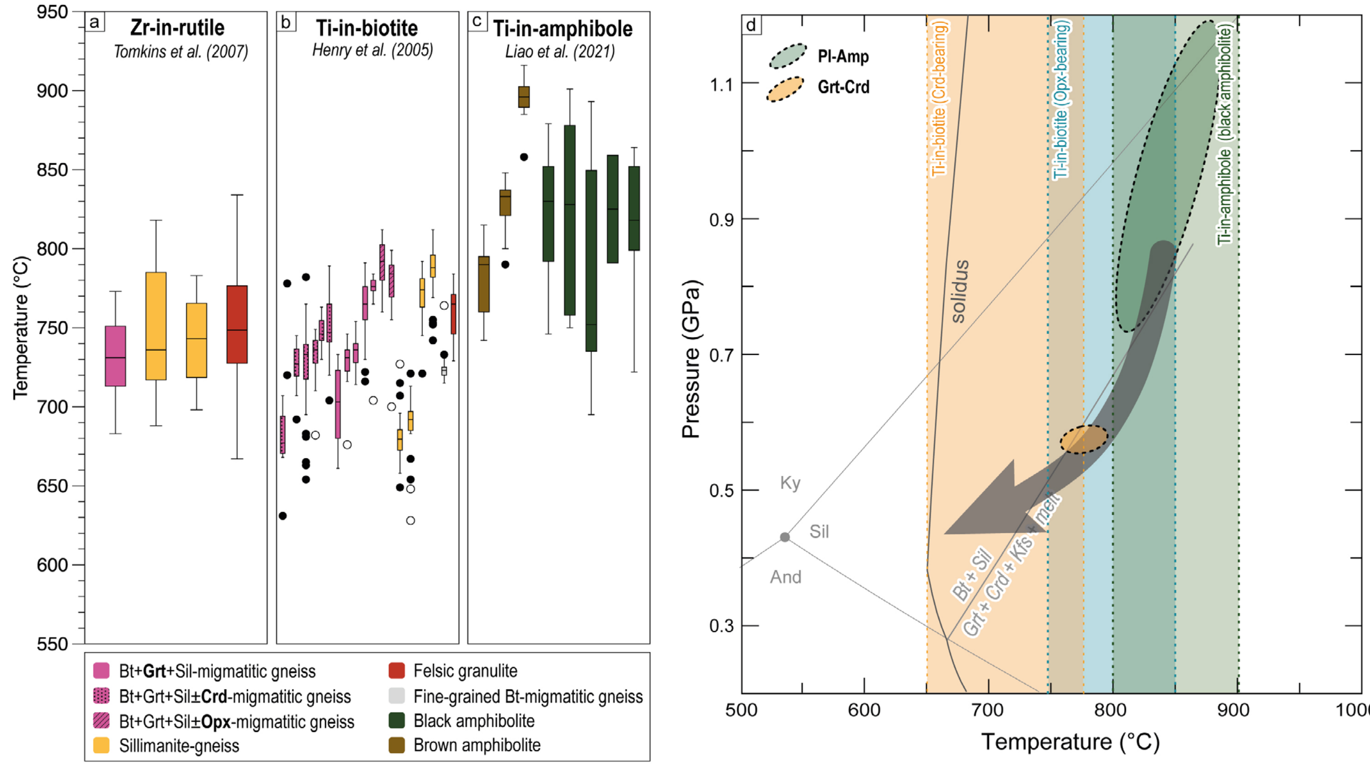

Figure 5 Summary of the T°C ranges of each analysed sample for different applied methods. ***a)*** *Zr-in-rutile thermometer of Tomkins et al. (2007).* ***b)*** *Ti-in-biotite thermometer of Henry et al. (2005).* ***c)*** *Ti-in-amphibole thermometer of Liao et al. (2021).* ***d)*** *Summary of the P-T conditions of the Valpelline Series (modified from Caso et al., 2024a).*

DISCUSSION AND FINAL REMARKS

The Valpelline Series represents a well-suited case study that exhibits diagnostic features and structures revealing information about different stages of the continental crust evolution and partial melting processes.

The oldest structures related to the D_1 stage are found in the mafic granulite and brown amphibolite meter-scale boudins, as an S_1 foliation. It is not easy to state whether these rocks have melted during this stage or not. However, the temperatures obtained, reaching ~850–900°C, may have been high enough to induce partial melting.

The regional S_2 foliation in the Valpelline Series is marked by leucosomes in migmatitic gneiss and locally in black amphibolite, testifying partial melting during the D_2. Temperatures obtained for this stage span from ~700 to ~900°C, with higher values in Opx-migmatitic gneiss (Ti-in-biotite; ~850°C) and black amphibolite (Ti-in-amphibole; ~800–900°C), agreeing with Bt-dehydration melting reaction (Fig. 5d). Temperatures are ~50–100°C lower in Crd-migmatitic gneiss than in Opx-migmatitic gneiss. Pressure estimates for the D_2 stage also change, being much higher in black amphibolite (up to 1.1 GPa) and lower in Crd-migmatitic gneiss (~0.58 GPa). Partial melting and S_2 development in migmatitic gneiss occurred at slightly different *P-T* conditions. Despite these differences in the *P-T* conditions, the presence of granulite-facies relicts related to the D_1 stage (mafic boudins with S_1 foliation) both in Opx- and Crd-bearing migmatites, and the common development of sillimanite-rich S_3, support that these portions were part of the same unit.

The S_3 foliation, marked by abundant sillimanite that wraps peritectic minerals as garnet and cordierite, can be the product of a back-reaction between peritectic phases and the melt that has migrated into these domains during D_3 stage deformation (Kriegsman & Alvarez-Valero, 2010). Moreover, *T* retrieved from biotite marking S_3 foliation in different samples across the valley yielded values from ~750 to 850°C, testifying that the conditions during this later stage were still at high temperature. The S_3 foliation can be used to trace the domains in which melt has migrated and reacted with the host rock during D_3 folding and axial plane foliation development.

The pervasive distribution of migmatite-bearing structures in the Valpelline Series rocks testifies that this unit was part of a km-scale migmatitic terrane involved in high-grade metamorphism during Permian lithospheric extension and asthenosphere rising, linked with abundant melt production.

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