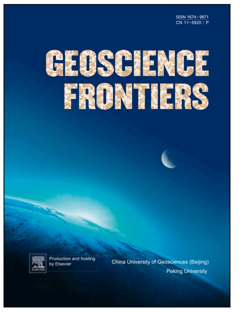

Reintegrating nanogranitoid inclusion composition to reconstruct the prograde history of melt-depleted rocks

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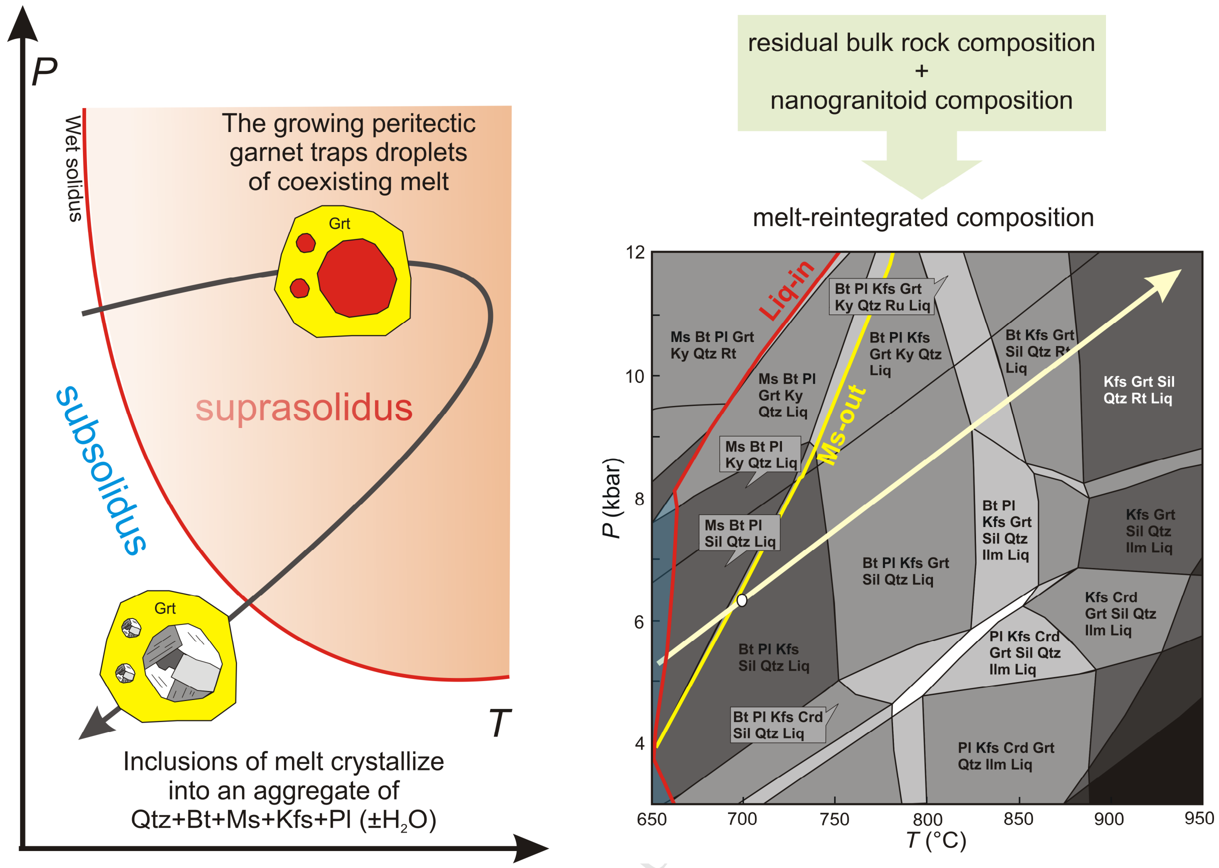

P
T
Wet solidus
The growing peritectic garnet traps droplets of coexisting melt
Grt
suprasolidus
subsolidus
Inclusions of melt crystallize into an aggregate of Qtz+Bt+Ms+Kfs+Pl (±H2O)
residual bulk rock composition + nanogranitoid composition
melt-reintegrated composition
P (kbar)
T (°C)
Liq-in
Ms-out
Ms Bt Pl Grt Ky Qtz Rt
Bt Pl Kfs Grt Ky Qtz Ru Liq
Bt Pl Kfs Grt Ky Qtz Liq
Ms Bt Pl Grt Ky Qtz Liq
Ms Bt Pl Ky Qtz Liq
Ms Bt Pl Sil Qtz Liq
Bt Kfs Grt Sil Qtz Rt Liq
Kfs Grt Sil Qtz Rt Liq
Bt Pl Kfs Grt Sil Qtz Ilm Liq
Bt Pl Kfs Grt Sil Qtz Liq
Kfs Grt Sil Qtz Ilm Liq
Kfs Crd Grt Sil Qtz Ilm Liq
Bt Pl Kfs Sil Qtz Liq
Pl Kfs Crd Grt Sil Qtz Ilm Liq
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Pl Kfs Crd Grt Qtz Ilm Liq

Reintegrating nanogranitoid inclusion composition to reconstruct the prograde history of melt-depleted rocks

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Abstract

A recent fascinating development in the study of high-grade metamorphic basements is represented by the finding of tiny inclusions of crystallized melt (nanogranitoid inclusions) hosted in peritectic phases of migmatites and granulites. These inclusions have the potential to provide the primary composition of crustal melts at the source. A novel use of the recently-published nanogranitoid compositional database is presented here. Using granulites from the world-renowned Ivrea Zone (NW Italy) on which the original melt-reintegration approach has been previously applied, it is shown that reintegrating melt inclusion compositions from the published database into residual rock compositions can be a further useful method to reconstruct a plausible prograde history of melt-depleted rocks. This reconstruction is fundamental to investigate the tectonothermal history of geological terranes.

Keywords: nanogranitoids, melt-reintegration, granulite, high-temperature metamorphism

1. Introduction

The deep continental crust has been ubiquitously affected by partial melting from Archean to present day in different geodynamic settings (Nehring et al., 2009; Sawyer et al., 2011). Loss of melt is a notoriously widespread process in crustal partially-melted rocks (Powell, 1983; White and Powell, 2002; Brown, 2007; Korhonen et al., 2010; Yakymchuk and Brown, 2014) and melt migration to upper crustal levels results in the formation of anatectic granites, leading to the geochemical differentiation of the Earth's crust (Brown and Rushmer, 2006). It follows that the study of melt-depleted rocks from the deep crust (residual migmatites and granulites) is key to understanding and characterizing the main processes that have promoted the chemical evolution of our planet (e.g. White and Powell, 2002; Guenrina and Sawyer, 2003; Morfin et al., 2013; Korhonen et al., 2015; Weinberg and Hasalovà, 2015).

In the framework of natural crustal melts, a recent important advance is the finding of small crystallized melt inclusions (nanogranitoids) hosted in peritectic phases of migmatites and granulites (Fig. 1; Cesare et al., 2009, 2015; Ferrero et al., 2012; Bartoli et al., 2013a). When microstructurally, experimentally and microchemically investigated following precise procedures and protocols (Bartoli et al., 2013b; Cesare et al., 2015), these small data repositories can provide the primary composition of crustal melts at the source (Acosta-Vigil et al., 2010; Bartoli et al., 2014, 2016a; Ferrero et al., 2016a). The study and characterization of nanogranitods have allowed significant advances in our understanding of crustal anatexis, such as a better comprehension of the melting mechanismsup to extreme UHP-UHT conditions (Acosta-Vigil et al., 2010, 2016; Bartoli et al., 2014, 2016a; Cesare et al., 2015; Ferrero et al., 2015, 2016a; Stepanov et al., 2016; Deng et al., 2017).

A geochemical database based on more than 600 nanogranitoid compositions has been recently constructed: it comprises melt inclusions formed at conditions varying from 670 to 950 °C and 4 to 27 kbar, and found in metapelitic,metapsammitic and metagranitoid migmatites, and granulites (Cesare et al., 2015; Bartoli et al., 2016a). This dataset has been successfully used to track the processes involved in the chemical evolution of felsic magmas (e.g., fractional crystallization, cumulus phenomena, entrainment of peritectic phases, restiteunmixing; see Bartoli et al., 2016b). Experimental and modeling studies often refer to nanogranitoid compositions to complement and/or validate their inferences/results (e.g., Gao et al., 2016; Garcia-Arias and Stevens, 2017). Notably, Stepanov and Hermann (2013) used melt inclusion compositions from anatectic rocks to discuss an important and actively debated geochemical issue in the geological community such as the "missing Nb paradox".

In this contribution an additional and novel use of the nanogranitoid compositional database is presented. Using granulites from the world-renowned Ivrea Zone (NW Italy) as an example, it is shown that reintegrating melt inclusion compositions from the published database into residual rock compositions can be considered a further useful method to reconstruct a plausible prograde history (melting conditions and reactions, and melt productivity) of melt-depleted rocks by means of phase equilibria modeling.

Bartoli (2017) has recently reviewed the different melt-reintegration approaches proposed in the literature. Whereas that manuscript provides a description and a comparative study of different procedures, in this contribution the utility of the published nanogranitoiddatabaseis illustrated in the framework of phase equilibria modeling of residual (melt-depleted) rocks.

Rocks from the Ivrea Zone have been chosen for three main reasons: (i) they represent a well-known and -studied anatecticterrane from amphibolite- to granulite-facies conditions (Schmid and Wood, 1976; Zingg, 1980; Bea and Montero, 1999; Redler et al., 2012, 2013; Ewing et al., 2015); (ii) here, the melt-reintegration approach originally proposed by White et al. (2004) has been previously applied (Redler et al., 2013) and, therefore, a comparison between the two different methods can be done; and (iii) the precise protolith composition of these rocks is well-knownallowing one to validate/invalidate the obtained results (Bartoli, 2017).

2. Geological setting

The Ivrea Zone (southern Alps of northwest Italy) is considered to represent a complete Permian mid to lower crustal section (Schmid, 1993; Barboza and Bergantz, 2000). It comprises two main units: the Kinzigite Formation and the Mafic Complex (Quick et al., 2003). The Kinzigite Formation consists of a sequence of amphibolite to granulite facies rocks. The latter are associated with widespread anatexis, producing highly residual rocks (Schnetger, 1994; Redler et al., 2012, 2013). Metapelites are volumetrically dominant and are interlayered with metabasic rocks and minor calcsilicate rocks and marbles (Schmid, 1993; Redler et al., 2012; Kunz et al., 2014). Regional amphibolite to granulite facies metamorphism has been dated at c. 316Ma (U–Pb ages of zircon; Ewing et al., 2013). The reader may refer to Redler et al. (2012, 2013) and Kunz et al. (2014) for a detailed petrographic description of rocks across the entire Kinzigite Formation.

The sample selected for this study comes from the Val Strona di Omegnawhich represents a section through amphibolite to granulite facies rocks (Fig. S1).Redler et al. (2012) modeledthe stability fields for the inferred peak phase assemblages in different samples across the Val Strona di Omegna. These authors demonstrated that the sample set definesa continuous increase in pressure and temperature. The obtainedmetamorphic gradient extends from conditions of 3.5–6.5 kbar at ~650 °C to 10–12 kbar at > 900°C (Redler et al., 2012). Similar peak temperatures (900–930 °C) for the highest-grade rocks were obtained by zirconium-in-rutile thermometry (Ewing et al., 2013).

3. Phase equilibria modeling

Phase equilibria modeling represents a key methodology to study the tectonothermal history of geological terranes (White et al., 2007, 2017; Palin et al., 2016a, b). A widespread method to reconstruct the prograde history of melt-depleted rocks by means of phase equilibria modeling consists of (i) the addition of a certain amount of melt, whose composition is calculated at a given pressure and temperature, into the residual composition and (ii) performing phase equilibria modeling of the new model composition (White et al., 2004). Bartoli (2017) demonstrated that highly residual (SiO_2< 55 wt.%) compositions may affect somehow the feasibility of the melt-reintegration approach. Indeed, for these bulk rock compositions, the reintegration of a certain amount of melt up to the appearance of a H_2O-saturated solidus at the pressure of interest (i.e., the appearance ofwet solidus has been generally used to determine the amount of melt to add back) does not guarantee the restoration of a reliable protolith composition, and the subsequent phase equilibria modeling of this model protolith may provide significant underestimations of melt productivity.

To avoid this drawback, the residual granulite IZ070 characterized by ~59 wt.% of SiO_2 was selected for this study from the bulk rock compositions previously modeled by Redler et al. (2013). Because these authors applied the original melt-reintegration method,it is possible to compare the results obtained by the two different melt-reintegration procedures.Granulite IZ070 was collected in the highest-grade zone of Val Strona di Omegna (Fig. S1). The peak mineral assemblageis composed of quartz, K-feldspar, garnet, sillimanite, ilmenite and rutile, and it is predicted to be stable at >850 °C, 8–12 kbar (Redler et al., 2012, 2013).

Phase diagrams have been constructed using the Perple_X software (Connolly, 2009) with the thermodynamic database of Holland and Powell (1998, as revised in 2003). The chemical system Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2 (NCKFMASHT) was selected. Ferric iron was ignored because its abundance in melt inclusions was not determined. Manganese was excluded because it has little effect on garnet-bearing equilibria at high-grade conditions (Redler et al., 2013). The solution model used are: melt from White et al. (2007), garnet from Holland and Powell (1998), biotite from Tajčmanová et al. (2009), white mica from Coggon and Holland (2002), plagioclase from Newton et al. (1980) and K-feldsparfrom Thompson and Hovis (1979). An ideal model was used for cordierite and ilmenite.

The first *P*–*T* pseudosection was calculated using the estimated residual bulk composition (Fig. 2a). Therefore, this diagram is only valid for assessing the peak and post-peak history (White et al., 2004). The peak conditions (>900 °C, 10–12 kbar) inferred by Redler et al. (2012) correspond to a quadrivariant field in the high-*T* part of the diagram containing the phase assemblage Kfs–Grt–Sil–Qtz–Rt–Liq (Fig. 2a), in agreement with the petrography observation of sample IZ070. The absence of ilmeniteis likely due to the chosen Fe^{3+}-free chemical system (Dumond et al., 2015). Considering the proposed *P*–*T* evolution, the solidus is encountered at ~850 °C and ~9 kbar.

The main stages of melt production in Ivrea Zone granulites are expected to occur at ~650–700°C via muscovite breakdown and from ~750 to ~850 ° C via biotite breakdown (Redler et al., 2013). In applying melt-reintegration methodology some approximations, such as the number of melt-reintegration steps and the amount of melt to be added back at each step, are needed because it isimpossible to retrieve the real melt loss history of crustal rocks. In the case of Ivrea Zone rocks, three melt-reintegration steps (Fig. 2b–d) were performed along a schematic *P–T* path where an amount of melt, sufficient to promote melt drainage and loss, is expected to have been producedon the basis of field and petrographic observations, and phase equilibria constraints (Fig. 10 in Redler et al., 2013) –i.e., at ~700 °C and ~ 6 kbar where muscovite is likely to have been totally consumed in these rocks (i.e., at the likely maximum temperature at which muscovite-melting derived melts have been produced), and at 800 °C (during biotite dehydration melting) and at 850 °C, ~8–10 kbar (i.e., close to the Bt-out reaction). Melt inclusion compositions appropriate for these conditions were selected from the geochemical database published in Cesare et al. (2015) and Bartoli et al. (2016a). The *P–T*conditions of melt inclusion formation were determined by different methods (i.e., remelting experiments, phase equilibria modeling, classic thermobarometry, trace element thermometry) or by a combination of them (Cesare et al., 2015 and references therein). Because the composition of the source rock may exert a control on the composition of anatectic melts, nanogranitoids found in metapelitic rocks were selected for this study (Fig. S2).

The bulk compositions used to calculate pseudosections as well as the compositions of reintegrated melts and their inferred *P–T* conditions of formation are reported in Table 1. Melt inclusions formed at higher temperature generally show higher FeO, CaO and K_2O contents and lower H_2O amounts (Table 1).

At each melt-reintegration step, a certain amount of melt was added back until melt persisted to conditions appropriate for the next reintegration. For example, 27 wt.% melt formed at ~850 °C was added back to the residuum composition until solidus appeared at ~800 °C and ~8 kbar (Fig.2b). Then, 20 wt.% melt was reintegrated at 800 °C (Fig. 1c). In agreement with the melt-reintegration modeling performed by Redler et al. (2013) and the assumed *P–T*path, an amount of melt sufficient to produce a H_2O-saturated solidus at *T*<700 °C and at *P*~7kbarwas added back during the last melt-reintegration step at 700 °C (Fig.2d). Once melt-reintegration procedure has been completed, the most evident changes in the phase diagram topology are (i) the shift of the solidus to lower temperatures, (ii) the H_2O-saturated character of solidus curve at *P* <8 kbar, and (iii) the appearance of muscovite-bearing subsolidus and suprasolidus assemblages (Fig. 2).

The final model protolith composition (IZ070c) overlaps the composition of amphibolite-facies rocks which are considered to reflect the composition of the protoliths of granulite-facies rocks (Fig. 3). Therefore, the approach proposed in this study ensures the restoration of a reliable protolith composition.

4. Discussion

4.1. Comparison with the original melt-reintegration approach

In the original melt-reintegration method proposed by White et al. (2004), melt was added back at conditions of the original solidus calculated with the observed bulk composition until melt persisted to lower temperatures. The procedure was repeated so that the lower temperature boundary of each phase assemblage field involves the appearance of melt, until a free fluid was present beyond the solidus (Bartoli, 2017). Redler et al. (2013) applied this method to the melt-depleted rocks IZ070 and IZ020 from the granulite-facies and transition zones, respectively. Their model protolith composition for the highest grade rock (IZ070Re) plots inside the compositional field of amphibolite-facies rocks (Fig. 3) and displayssome compositional similarities with respect to the protolith composition IZ070c reconstructed in this study (Fig. 3). For instance, Al_2O_3, CaO, K_2O and H_2O are < 10 wt.% relative higher in IZ070Re sample, whereas SiO_2 is 6 wt.% relative lower. As a consequence, the topology of *P–T* pseudosection constructed using the protolith composition IZ070Re is very similar to that obtained in this study for the bulk composition IZ070c (Fig. S3). Also, a number of similarities in the first-order topology can be see in Fig. 2d and the original *P–T* pseudo section calculated by Redler et al. (2013) using THERMOCALC. In the latter case, ilmenite is predicted to be stable at peak conditions owing to the involvement of Fe^{3+}as chemical component (Fig. 9b in Redler et al., 2013).

Fig. 4 shows the calculated phase amounts for the model protolith compositions IZ070c and IZ070Re. Considering the uncertainties associated with phase equilibria modeling and the assumptions made to apply melt-reintegration approaches (Palin et al., 2016a; Bartoli, 2017; Koblinger and Pattison, 2017), it is clear that the phase amounts predicted along the prograde *P–T* path considerably match each other (Fig. 4). On the other hand, some discrepancies seem to exist when compositional isopleths are compared, in particular for X_{An}[Ca/(Ca+Na)]of plagioclase (Fig. 5). This makes sense, because the composition of feldspars is particularly sensitive to the melt composition.Despite these discrepancies overlap with the intrinsic uncertainties related to phase equilibria calculations (Powell and Holland, 2008; Angiboust et al., 2012; Palin et al., 2012; Koblinger and Pattison, 2017), the above results suggest that the feldspar compositional isopleths should not be considered toderive the *P–T* constraints once the melt-reintegration approach is applied.

4.2. Reintegrating composition of natural melts

Melt-reintegration approach has been routinely applied on a variety of melt-depleted rocks. In the majority of previous studies, the composition of melt to be reintegrated has been calculated by phase equilibria modeling, even though different ways of reintegrating calculated melt compositions have been proposed in the literature (reviewed by Bartoli, 2017). Recently, some authors have proposed to reintegrate natural melt compositions, rather than melt compositions calculated by thermodynamic modeling. For example, Anderson et al. (2013) investigated the high-grade metamorphism in the Anmatjira Range (Arunta region, central Australia). These authors calculated an average crustal melt composition using published S-type granite compositions derived from melting of aluminous rocks. This average leucogranite composition was then used to construct a T-M_{melt} section which was successfully applied to reconstruct the pre-melt loss bulk composition of the investigate rock (cf. Fig. 7 in Anderson et al., 2013). On the other hand, Wang and Guo (2017) reintegrated the average bulk composition of six leucosomes enclosed in residual HP granulites from the Yinshan Block (North China Craton).

Despite the composition of leucogranites and leucosomes has provided fundamental clues on the crustal melting mechanisms and geochemical differentiation of Earth's crust (e.g., Deniel et al., 1987; Stevens et al., 2007; Villaros et al., 2009; Zeng et al., 2005), they rarely reflect primary (i.e. unmodified) crustal melts. Rather the composition of these rocks may be variably affected by fractional crystallization process, accumulation of early-crystallized minerals, selective entrainment of residual and/or peritectic phases and wholesale entrainment of non-protolithlithologies (Chappell et al., 1987; Milord et al., 2001; Stevens et al., 2007; Sawyer, 2008, 2014; Clemens and Stevens, 2012; Brown et al., 2016; Carvalho et al., 2016, 2017).For these reasons, the composition of experimental glasses has beencommonly assumed as representative of melt composition at the source and used for geochemical considerations on anatectic terranes(e.g., Milord et al., 2001; Guernina and Sawyer, 2003; Carvalho et al., 2016). It is important to notice that the aforementioned studies adopted the same approach of this study (i.e., the used experimental melt compositions produced from starting material and at *P-T* conditions closest to the investigated rock).

Recently, the appearance of the compositional database of nanogranitod inclusions has provided an additional useful geochemical tool (Bartoli et al., 2016a). For example, both the compositions of melt inclusions and experimental glasses have been considered to track the processes that control the leucosome compositions in metasedimentary granulites from the Limpopo Belt, South Africa (Taylor et al., 2014).

5. Future perspectives

5.1. Using the published compositional database

This study demonstrates that reintegrating the composition of nanogranitoid inclusions from the published geochemical databaseinto residual bulk rock compositions can be considered an additional useful method to reconstruct the prograde history of melt-depleted rocks by means of phase equilibria modeling. Adding back natural melt compositions may be a way to reduce the gap between natural systems and modelswhich represents, instead, simplified proxies of natural occurrences. In Fig. 6, the reintegrated compositions of melt inclusionsare compared with the melt compositions calculated from the thermodynamic modeling at the same conditions. Nanogranitoids generally show higher FeO, MgO and lower Al_2O_3 and Na_2O. CaO and K_2O are variable. It could be argue that such differencesare related to the use of nanogranitoid inclusions not coming from theinvestigated rock. However, a similar discrepancy–between calculated and measured melt compositions–has been already reported in other anatectic terranes (Bartoli et al., 2013c, 2016b) andin experimental runs (Grant, 2009), and seems to be related to the current melt model which needs some improvements (see White et al., 2011). Notably, the extent of the compositional discrepancyfound in this study recalls that previously observed between nanogranitoids and calculated melts coming from the same rock andformed at the same *P–T* conditions (Fig. 6).

Although the selected nanogranitoid compositions do not reflect the precise composition of melt produced in the investigated rock from Ivrea Zone, this study supports the inferences by Bartoli et al. (2016a) that using the melt inclusion compositions from the published data set for the conditions (*P*-*T*-bulk rock composition) closest to the investigated rock is a valid assumption which provide reliable results. This outcome is very important because melt inclusions are not present in all anatecticterranes worldwide. Notably, the published nanogranitoid database (Cesare et al., 2015; Bartoli et al., 2016a) is continuously being updated. For instance, Ferrero et al. (2018) recently recovered the composition of nanogranitoid inclusions from ultramafic granulites.

5.2. Some assumptions are unavoidably needed

Ivrea Zone has been intensively investigated during the past four decades and the *P–T* evolution of migmatites and granulites is pretty well constrained (see above). However, in other anatecticterranes the prograde *P–T* path may be rather uncertain and, in turn, deciding the number of melt-reintegration steps and the *P–T*conditions where melt should be added back can be not trivial. Some hints to recover the probable *P–T* evolution and, in turn, the possible melt-forming reactions may come from the tectonic model of the investigated areas and/or petrographic constraints. For example, felsic granulites from the Athabasca Granulite Terrane (Canada) show textural evidence suggesting minimum peak conditions of >14 kbar and >925 °C (Dumond et al., 2015). In agreement with the geology of the area, Dumond et al. (2015) inferred a *P–T* path corresponding to the prograde burial of sediments to a depth in excess of 50 km along which melt was reintegrated four times where the*P–T* path crossed the 1 mol.% melt isopleth.

On the other hand, Korhonen et al. (2013) constrained peak conditions for granulites from the Eastern Ghats Province (India) combining petrographic observations (i.e., identifying the peak phase assemblage) and phase equilibria calculations for the residual bulk rock composition. Then, these authors assumed a prograde *P–T* path of 150 °C/kbar for the melt reintegration procedure (Korhonen et al., 2013). Such a *P–T* evolution is considered typical of regions which experienced UHT conditions (Brown, 2006, 2007; Kelsey and Hand, 2014).

On the basis of the reached thermal peak (i.e., high or low suprasolidus temperatures), one can decide to perform one or more melt-reintegration steps, similarly to what done by Morrissey et al. (2016) to model multiple melt loss events (which consists in the inverse approach of melt-reintegration method). These authors assumed a *P–T* path and modeled three melt loss events: on the wet solidus and on the muscovite- and biotite-out curves.

5.3. Reconstruction of a plausible effective bulk composition

Residual bulk rock compositions can be inadequate to model the entire prograde history not only for the previous extraction of some batches of melt resulting in a residual bulk rock composition, but also for the occurrence of large, chemically zoned porphyroblasts which can cause chemical fractionation during their growth, changing the chemical composition of the reacting rock volume (Marmo et al., 2002; Evans, 2004). In such a case, different effective bulk compositions have to be considered to model different steps along the *P*–*T* path, modifying the bulk rock composition according to the predicted element incorporation in the fractionated mineral (Gaidies et al., 2006; Konrad-Schmolke et al., 2008; Groppo et al., 2009; Iaccarino et al., 2017). Occasionally, nanogranitoid inclusions show a systematic distribution in annuli around a melt inclusion-free garnet core(Fig. 7a; Carosi et al., 2015; Cesare et al., 2015). When this occurrenceis associated with low melting temperature (<750 °C) or short duration of HT metamorphism preventing a complete chemical re-equilibration of garnet prophyro blasts (i.e., a complete diffusive resetting; Caddick et al., 2010), the reconstruction of a plausible effective bulk composition for the melting event can take advantage of both the reintegration of melt inclusion composition and theremoval of elements fractionated in the subsolidus garnet core (Fig. 7a).

5.4. Modeling distinct anatectic events within a single rock

High-grade metamorphic terranes often show a polymetamorphic history related to one or more orogenic cycles (Korhonen et al., 2010; Ewing et al., 2015; Yakymchuk et al., 2015).Sometimes it is possible to find evidence of two distinct anatectic events within a single garnet crystal. For example, garnet from granulitic migmatites of the sequence of Jubrique (Betic Cordillera, S Spain) contains granitic melt inclusions associated to kyanite and rutile in the core, whereas granodioritic to tonalitic melt inclusions are associated to sillimanite and ilmenite at the rim of the host crystal (Fig. 7b; Barich et al., 2014; Acosta-Vigil et al., 2016). Clearly, this nanogranitoid occurrence will allow one to pursue an unique approach: the reintegration of the right melt composition for each anatectic event to be modeled.

6. Concluding remarks

Most granulitic terranes worldwide experienced loss of anatectic melt, resulting in residual bulk rock compositions. Although the investigated rock does not contain melt inclusions, reintegrating the composition of nanogranitoid inclusions from the published geochemical database, for the conditions (*P*-*T*-bulk rock composition) closest to the investigated rock, can be considered an additional useful method to reconstruct the prograde history of melt-depleted rocks by means of phase equilibria modeling.

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CAPTIONS:

Fig. 1: Schematic *P*–*T* diagram showing the formation of nanogranitoid inclusions in anatectic rocks. After onset of melting, the growing peritectic mineral traps droplets of melt produced by melting reaction. Along cooling path, melt inclusions partially to totally crystallizeinto a cryptocrystalline aggregate (nanogranitoid).

Fig. 2: Melt-reintegration approach for the residual migmatite IZ070 (Ivrea Zone). White dots indicate *P*–*T*conditions where melt was reintegrated. The chosen chemical

system is NCKFMASHT. Red line: solidus. Yellow line: muscovite-out curve. Light blue field: region where liquid H_2O is predicted. Labels referring to the bulk rock compositions used in the modeling are reported in parenthesis (see Table 1). *P–T*path reconstructed from Redler et al. (2013).

Fig. 3:Harker plots (wt.%) showing the final model protolith compositions (anhydrous compositions from Table 1) obtained (i) by reintegrating melt inclusion compositions and (ii) by Redler et al. (2013) applying the original melt-reintegration method proposed by White et al. (2004). Bulk rock compositions of granulite- and amphibolite-faciesmetapelites are from Redler et al. (2013).

Fig. 4: Calculated mineral and melt abundance along prograde paths of Figs. 1a and S3.

Fig. 5: Contours for X_{Mg} (Mg/(Mg+Fe)) value of biotite, for X_{An} (Ca/(Ca+Na)) of plagioclase and for almandine component of garnet, for pseudosections in Figures 1a and S3. Continuous and dotted lines as in Fig. 4.

Fig. 6:Bivariant diagrams (wt.%) comparinganhydrous compositions of reintegrated nanogranitoid inclusions (squares; Table 1) and melts calculated at the same conditions (ellipses). Grey arrows indicate increasing *P–T* conditions. Black lines connect calculated composition (white star) with the corresponding melt inclusion composition (black star) from Ronda diatexites (data from Bartoli et al., 2016b). See text for details.

Fig. 7: Sketch of two different modes of occurrence of nanogranitoid inclusions in anatectic rocks. (a) Garnet from Himalaya in which hundreds of melt inclusions (black dots) show a systematic distribution in an annulus around a nanogranitoid-free core (see Carosi et al., 2015; Cesare et al., 2015; Rolfo et al., 2015). (b) Garnet from Ronda area (Betic Cordillera, Spain) containing two different types of nanogranitoid inclusions. Inclusions corresponding to a H_2O-poor leucogranitic melt (black dots) coexist with rutile and kyanite at the garnet core, whereas H_2O-rich granodioritic to tonalitic melt inclusions (blue dots) are present towards garnet rim along with sillimanite and ilmenite (see Barich et al., 2014; Acosta-Vigil et al., 2016).

Table 1: Bulk rock and melt compositions (wt.%) used in the phase equilibria modeling.

Appendix A. Supplementary data

Fig. S1: Schematic map of Val Strona di Omegna (redrawn from Redler et al., 2012, 2013). The locality of the residual granulite IZ070 used for the calculations is given.

Fig. S2: Bivariant diagrams (wt%) comparing bulk rock compositions of migmatites and granulites containing melt inclusions used in this study (data from Bartoli, 2017; Bartoli et al., 2016a; Barich et al., 2014) and granulite IZ070 from Val Strona di Omegna.

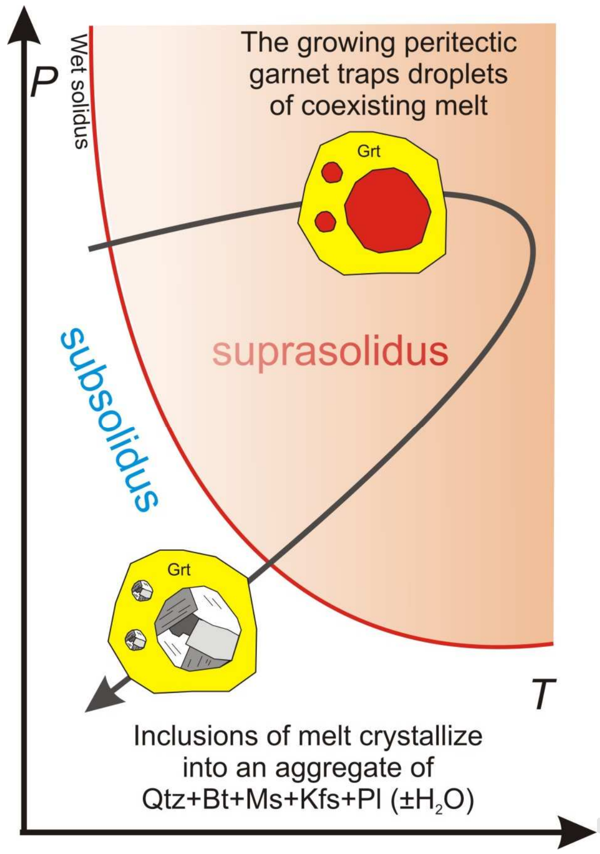
Fig. S3: Phase equilibria modeling considering the bulk composition IZ070Re obtained by Redler et al. (2013). The chosen chemical system is NCKFMASHT. Red line: solidus. Yellow line: muscovite-out curve. Light blue field: region where liquid H_2O is predicted.

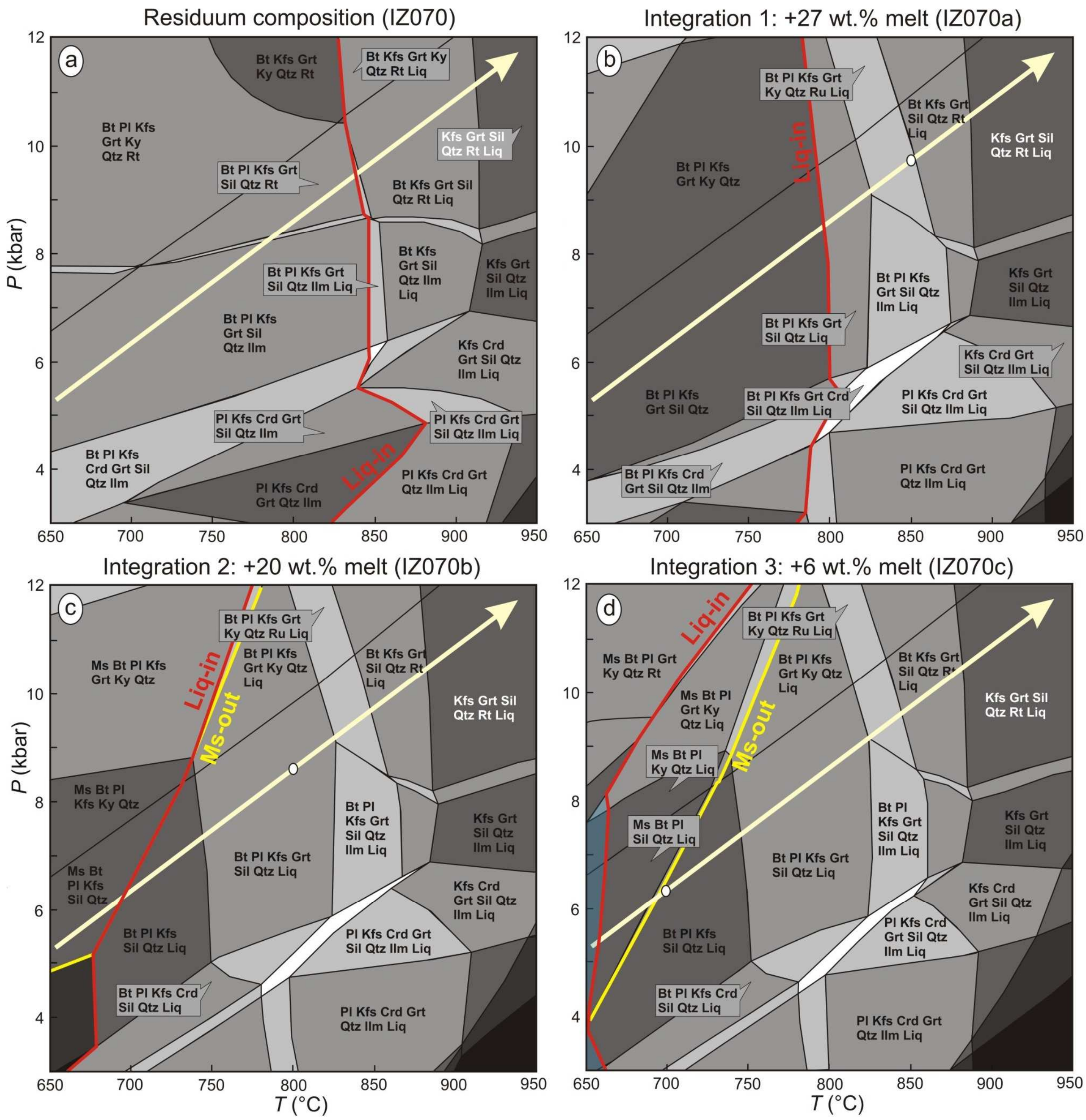
Table 1. Bulk rock and compositions (wt.%) used in the modeling.

	Bulk rock composition					Melt inclusion composition**		
Label	IZ070*	IZ070a	IZ070b	IZ070c	IZ070Re*			
Temp.						≈700 °C	≈800 °C	≈850 °C
No. analyses						240	53	79
SiO_2	58.74	61.90	64.09	64.62	61.20	72.80	74.55	73.58
TiO_2	1.39	1.11	0.92	0.88	1.04	0.08	0.05	0.08
Al_2O_3	22.13	20.35	18.93	18.56	20.27	12.51	13.30	13.78
FeO	10.58	8.67	7.49	7.12	8.10	1.21	1.47	1.59
MgO	3.49	2.78	2.31	2.23	2.64	0.14	0.14	0.15
CaO	0.30	0.41	0.36	0.34	0.38	0.26	0.35	0.82
Na_2O	0.34	0.88	1.18	1.26	0.97	2.83	2.79	2.90
K_2O	2.58	3.16	3.62	3.65	3.94	4.88	5.12	5.29
H_2O	0.45	0.74	1.09	1.34	1.45	5.29	2.23	1.81
Tot.	100.00	100.00	100.00	100.00	99.99	100.00	100.00	100.00

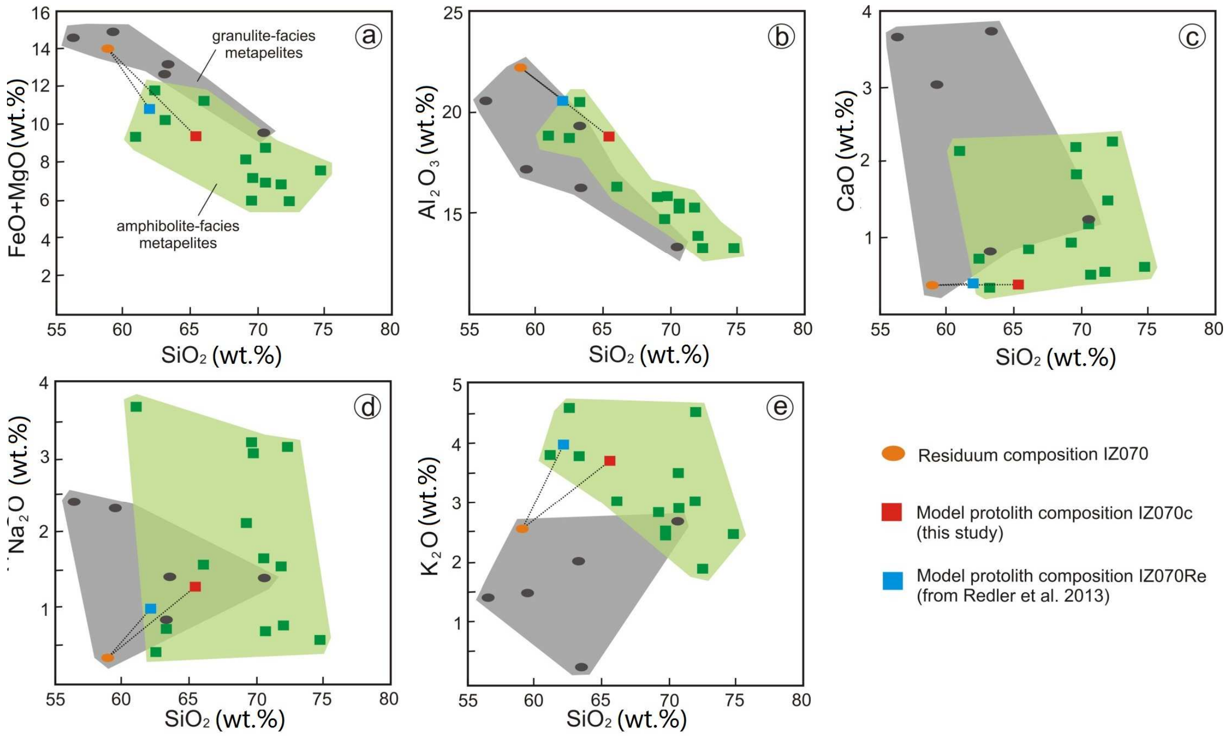
* From Redler et al. (2013)

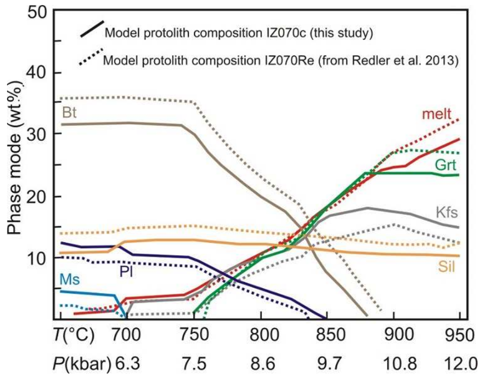
** From Cesare et al. (2015), Bartoli et al. (2016)


The growing peritectic
garnet traps droplets
of coexisting melt
P
Wet solidus
Grt
suprasolidus
subsolidus
Grt
T
Inclusions of melt crystallize
into an aggregate of
Qtz+Bt+Ms+Kfs+Pl (±H2O)

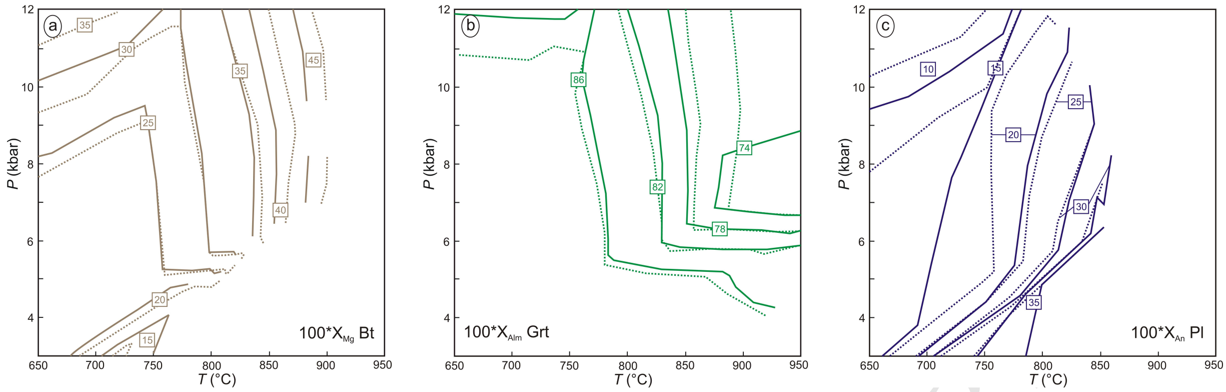


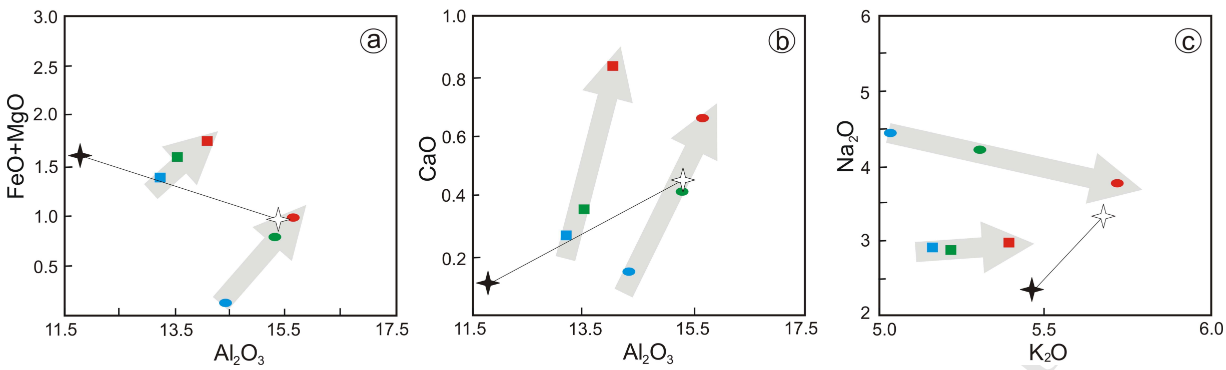
Residuum composition (IZ070)
Integration 1: +27 wt.% melt (IZ070a)
Integration 2: +20 wt.% melt (IZ070b)
Integration 3: +6 wt.% melt (IZ070c)
P (kbar)
T (°C)
Liq-in
Ms-out


granulite-facies metapelites
amphibolite-facies metapelites
FeO+MgO (wt.%)
Al2O3 (wt.%)
CaO (wt.%)
Na2O (wt.%)
K2O (wt.%)
SiO2 (wt.%)
a
b
c
d
e
Residuum composition IZ070
Model protolith composition IZ070c (this study)
Model protolith composition IZ070Re (from Redler et al. 2013)

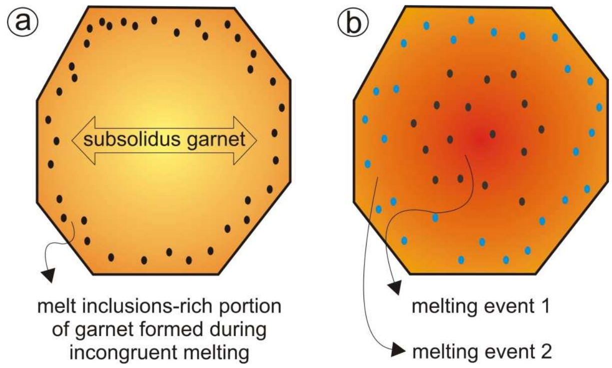


Model protolith composition IZ070c (this study)
Model protolith composition IZ070Re (from Redler et al. 2013)
Phase mode (wt%)
50
40
30
20
10
Bt
melt
Grt
Kfs
Sil
Ms
Pl
T(°C) 700 750 800 850 900 950
P(kbar) 6.3 7.5 8.6 9.7 10.8 12.0


a
100*X$_{Mg}$ Bt
b
100*X$_{Alm}$ Grt
c
100*X$_{An}$ Pl
P (kbar)
T (°C)
12
10
8
6
4
650
700
750
800
850
900
950
35
30
25
20
15
35
40
45
86
82
78
74
10
15
20
25
30
35



a
FeO+MgO
3.0
2.5
2.0
1.5
1.0
0.5
11.5
13.5
15.5
17.5
Al2O3
b
CaO
1.0
0.8
0.6
0.4
0.2
11.5
13.5
15.5
17.5
Al2O3
c
Na2O
6
5
4
3
2
5.0
5.5
6.0
K2O


a
subsolidus garnet
melt inclusions-rich portion of garnet formed during incongruent melting
b
melting event 1
melting event 2

- Nanogranitoid inclusions have the potential to provide the primary composition of crustal melts at the source

- A novel use of the nanogranitoid compositional database is presented here

- Reintegrating melt inclusion compositions from the published database into residual rock compositions can be a further useful method to reconstruct a plausible prograde history of melt-depleted rocks