Production of hybrid granitic magma at the advancing front of basaltic underplating: Inferences from the Sesia Magmatic System (south-western Alps, Italy)

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ABSTRACT

The Permian Sesia Magmatic System of the southwestern Alps displays the plumbing system beneath a Permian caldera, including a deep crustal gabbroic complex, upper crustal granite plutons and a bimodal volcanic field dominated by rhyolitic tuff filling the caldera. Isotopic compositions of the deep crustal gabbro overlap those of coeval andesitic basalts, whereas granites define a distinct, more radiogenic cluster (Sri ≈ 0.708 and 0.710, re-spectively). AFC computations starting from the best mafic candidate for a starting melt show that Nd and Sr isotopic compositions and trace elements of andesitic basalts may be modeled by reactive bulk assimilation of ≈30% of partially depleted crust and ≈15%–30% gabbro fractionation. Trace elements of the deep crustal gabbro cumulates require a further ≈60% fractionation of the andesitic basalt and loss of ≈40% of silica-rich residual melt. The composition of the granite plutons is consistent with a mixture of relatively constant proportions of re-sidual melt delivered from the gabbro and anatectic melt. Chemical and field evidence leads to a conceptual model which links the production of the two granitic components to the evolution of the Mafic Complex. During the growth of the Mafic Complex, progressive incorporation of packages of crustal rocks resulted in a roughly steady state rate of assimilation. Anatectic granite originates in the hot zone of melting crust located above the advancing mafic intrusion. Upward segregation of anatectic melts facilitates the assimilation of the partially de-pleted restite by stoping. At each cycle of mafic intrusion and incorporation, residual and anatectic melts are pro-duced in roughly constant proportions, because the amount of anatectic melt produced at the roof is a function of volume and latent heat of crystallization of the underplated mafic melt which in turn produces proportional amounts of hybrid gabbro cumulates and residual melt. Such a process can explain the restricted range in isotopic compositions of most rhyolitic and granitic rocks of the Permo-Carboniferous province of Europe and elsewhere.

1. Introduction

A unique opportunity to directly study the processes that modulate chemical and isotopic compositions of silicic magmatic systems exists in the Sesia Valley of northwest Italy where an uplifted and tilted crustal section (Fountain, 1976; Handy et al., 1999; Rutter et al., 1999) is cut by the magmatic plumbing system beneath a Permian rhyolitic caldera which is exposed to depths of about 25 km, including deep crustal gabbros and upper crustal granites, and showing their relationships with country rocks (Quick et al., 2009). Herein referred to as the Sesia Magmatic System, following the informal nomenclature introduced by Sinigoi et al. (2010), these rocks are part of the larger Permo-Carboniferous igneous province of Western Europe (Wilson et al., 2004 and references therein), which, in the South-Alpine domain, includes the Atesina Volcanic District in the Dolomites (Barth et al., 1993; Marocchi et al., 2008; Rottura et al., 1998), the Lugano District (Schaltegger and Brack, 2007; Stille and Bulletti, 1987), plutonic and volcanic rocks in Sardinia and Corsica (Di Vincenzo et al., 1996) and the granites of the Serie dei Laghi of northwestern Italy (Pinarelli et al., 1988). In most European Permo-Carboniferous occurrences, the isotopic compositions of granitic and rhyolitic rocks are more homogeneous and less radiogenic than the encasing crust in the region (Liew and Hofmann, 1988), indicating a hybrid mantle–crustal heritage, and clustering of initial $^{87}Sr/^{86}Sr$ ratios (Sr_i) around 0.710 and εNd between −3 and −7 (Voshage et al., 1990 and references therein). This relative homogeneity is surprising considering the long times over which many silicic volcanic fields are active and the growing evidence that many plutons are assembled incrementally over millions of years (Coleman et al., 2004; Glazner et al., 2004; Miller et al., 2011). It follows that a common set of governing processes modulate the ratio of mantle and crustal components during the production of high-silica magmas (e.g.

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Bachmann et al., 2007). While significant insight into these processes has resulted from the application of physiochemical principles to well characterized volcanic and plutonic suites and several theoretical models have been proposed (e.g. MASH, Hildreth and Moorbath, 1988; DHCZ, Annen et al., 2006), the scales over which these processes operate have remained a matter of conjecture in the absence of an exhumed magmatic system exposing components crystallized at different crustal levels, from the surface to the deep crust.

In this paper, we integrate field relationships with major-element, trace-element, and Nd and Sr isotopic data to evaluate the processes that shaped the Sesia Magmatic System and governed the chemical and isotopic composition of its components, from mafic magma to granites and rhyolites. The inferred process explains how proportional amounts of anatectic- and mafic-derived granitic magmas may be produced.

2. Geological framework

Two lithostratigraphic belts (Fig. 1), the Ivrea–Verbano Zone and adjacent Serie dei Laghi (a.k.a. Strona–Ceneri Zone), have been the objects of intense research activity for more than 45 years following the discovery that a strong positive gravity anomaly indicative of dense mantle and lower crustal rocks is associated with the Ivrea–Verbano Zone (Berckhemer, 1968). Fountain (1976) first proposed on the basis of their geophysical properties that these two lithostratigraphic belts collectively comprise a section through the continental crust of northwest Italy that has been exposed tectonically along the Insubric Line. Consistent with exposure of progressively deeper crustal levels to the west, observations assembled over the last 35 years support Fountain's interpretation, among the most compelling of which are the increase in metamorphic grade and equilibration pressures (Demarchi et al., 1998; Ewing et al., 2013; Redler et al., 2012, 2013; Zingg, 1980, 1983) and the decrease in cooling ages (Siegesmund et al., 2008; Wolff et al., 2012) approaching the Insubric Line.

The Ivrea–Verbano Zone constitutes the lower part of the section. Within it, the so-called Kinzigite Formation, a pre-Permian volcano-sedimentary sequence metamorphosed in amphibolite to granulite facies (Zingg, 1980), is intruded by the 8-km-thick Mafic Complex, which is composed of mostly gabbroic rocks (Rivalenti et al., 1975). The Serie dei Laghi constitutes the upper part of the section and consists of lower-amphibolite-facies schists and gneisses (Boriani et al., 1977, 1988) intruded by granite plutons referred to as the "Graniti dei Laghi". Also, mafic and silicic rocks form small intrusions present near the contact of the Serie dei Laghi and the Kinzigite Formation. The south-eastern sector of the section is overlain by a bimodal suite of Permian volcanic rocks. Mesozoic rifting and Alpine tectonics tilted the section differentially so that foliation and layering are sub vertical in the Ivrea–Verbano Zone and the western-most volcanic rocks, but dip progressively less steeply to the east, eventually reaching dips of only 20° to 40° in the easternmost outcrops (Quick et al., 2009, online supplements).

The boundary between the Ivrea–Verbano Zone and the Serie dei Laghi has been historically described on regional maps of the area as the Cossato–Mergozzo–Brissago (CMB) Line based on the interpretations of Boriani and Sacchi (1973), who showed that this transition corresponds to a steeply dipping mylonite belt north of the area depicted in Fig. 1. In the absence of similar direct evidence, they projected the CMB Line to the south into the Sesia Valley based on the occurrence of small, intimately associated mafic and granitic intrusions, which they collectively termed "appinites" and interpreted to have formed as Permian

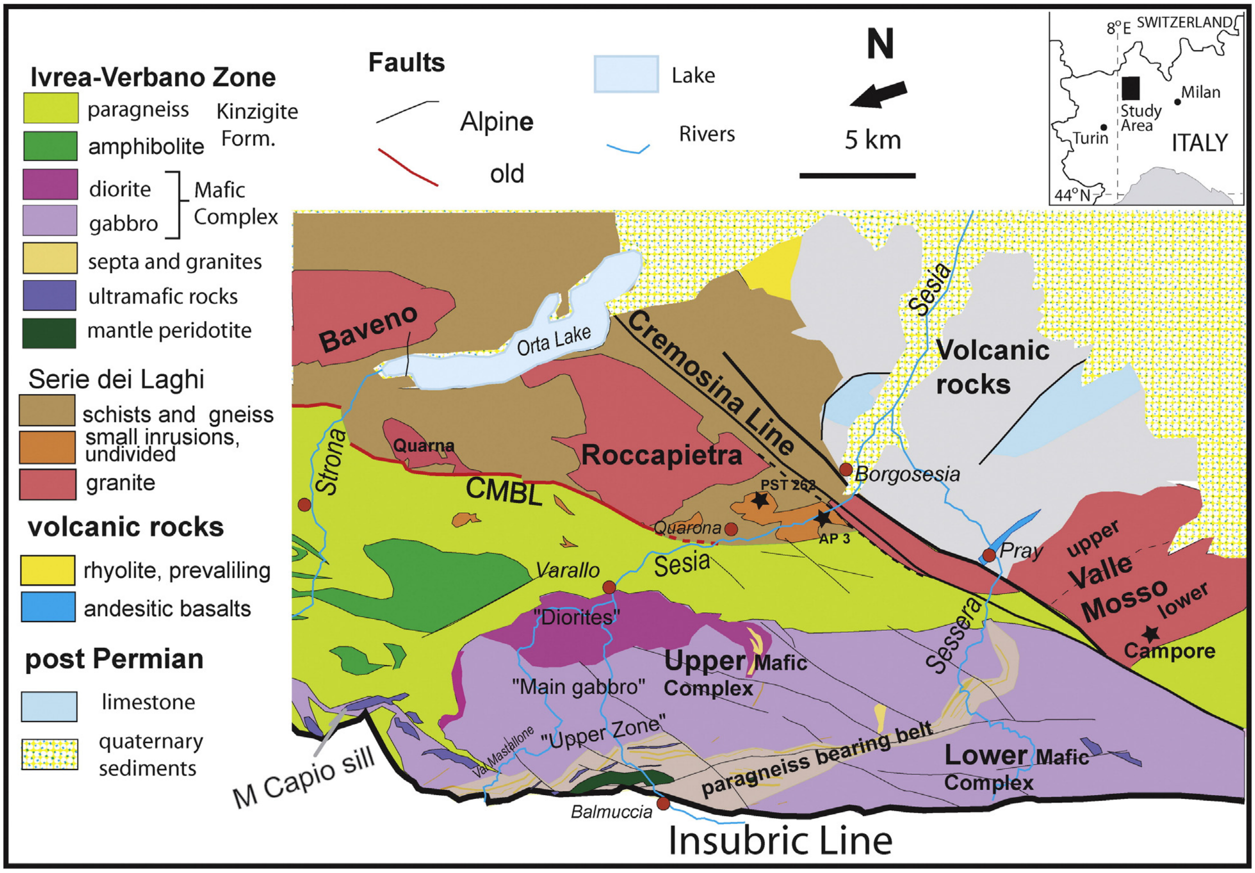

Fig. 1. Geological map of the central Ivrea–Verbano Zone and Serie dei Laghi, compiled from Schmid, 1967; Zingg, 1980; Boriani et al., 1988; Quick et al., 2003; and Rutter et al., 2007, rotated counter clockwise in order to approximate the original orientation of the crustal section before exhumation and tilting. Black stars indicate the location of critical samples, as the Campore dike and the anatectic granite AP3. The "Graniti dei Laghi" include also the Montorfano body, few kilometers North of the depicted area.

intrusions of silicic and mafic melts along a vertical suture between two unrelated terranes. Handy et al. (1999) has subsequently shown that the CMB Line in the north is best interpreted as an old listric fault that has been rotated into a subvertical orientation. Klötzli et al. (2014) showed that ages on different “appinite” bodies span 30 m.y., ranging from 311 to 280 Ma, a time lapse larger than the Sesia Magmatic System, and concluded that these small intrusions were emplaced episodically in the middle crust beneath the level at which larger granitic plutons eventually grew. Thus, the CMB Line appears to be a pre-Permian low-angle fault that was active during the assembly of the crustal section.

3. Samples and methods

The already existing data set, published by various authors (Klötzli et al., 2014; Mazzucchelli et al., 1992a, 1992b; Pin and Sills, 1986; Pinarelli et al., 1988, 2002; Schnetger, 1994; Sinigoi et al., 1991, 1994, 1996, 2011; Voshage et al., 1990), was integrated with new samplings, including 33 crustal rocks, 53 gabbroic rocks from the Mafic Complex, 14 mafic rocks in the upper crust, 7 mafic volcanic rocks, 38 granite samples from the Valle Mosso body, 2 anatectic granites and 11 acidic volcanic rocks. After a petrographic screening, major and some trace elements, (Cr, Ni, Ba, Rb, Sr, Nb, La, Ce, Nd, Y and Zr) were determined by XRF at the Department of Mathematics and Geosciences of Trieste University. On selected samples, trace elements including REE were determined at ACME Laboratories (Canada) by inductively-coupled-plasma mass spectroscopy (ICP-MS). Replicate analyses of international standards and some samples obtained with the respective analytical methods are reported in online supplements Table OS1. Sr isotopic analyses on 18 samples were carried out at the Department of Mathematics and Geosciences of Trieste University with a VG 54E mass spectrometer and ‘Analyst’ software (Ludwig, 1994) for data acquisition and reduction. Samples were dissolved in Teflon vials using a mixture of HF–HNO3 and HCl purified reagents. Sr was collected after ion exchange chromatography; total blank for Sr was less than 20 pg. The $^{87}Sr/^{86}Sr$ ratio was corrected for fractionation to $^{87}Sr/^{86}Sr = 0.1194$. The measured ratios were corrected for instrumental bias to NBS 987 standard values of 0.71025 ± 0.00002 ($n = 12$). Nd isotope analyses were carried out at the GeoCosmoChronology laboratory, Department of Lithospheric Research, University of Vienna. A $^{143}Nd/^{144}Nd$ ratio of $0.5118444825 \pm 0.000003$ ($n = 4$) was determined for the La Jolla international standard during the period of investigation. Within-run mass fractionation for Nd isotope compositions (IC) was corrected for those relative to $^{143}Nd/^{144}Nd = 0.7219$. Uncertainties on the Nd and Sr isotope ratios are quoted as 2σ. The complete data set is reported in online Supplements OS2 to OS5, and the location of each sample (Lat/Long coordinates) is reported in OS 7.

4. Country rocks of the Sesia Magmatic System

Country rocks of the Sesia Magmatic System consist of metapsamite, metapelite, and metamorphosed ophiolitic rocks of the Serie dei Laghi (Boriani et al., 1988) and metapelite, metawacke, marble and calcsilicate, and metamafic intrusive and/or extrusive rocks (“amphibolite” in Fig. 1) of the Kinzigite Formation in the Ivrea–Verbano Zone (Quick et al., 2003; Schmid, 1967; Zingg, 1980). Although sparse relics of high-pressure metamorphism are preserved (Pinarelli and Boriani, 2007), the dominant paragenesis ranges from greenschist to amphibolite facies in the upper crustal Serie dei Laghi and from amphibolite to granulite facies in the deep crustal Kinzigite Formation.

Rocks of the Kinzigite Formation were investigated by Zingg (1980), Schmid (1967), Schnetger (1994), Bea and Montero (1999), Siegesmund et al. (2008), Ewing et al. (2013), Redler et al. (2012, 2013), Kunz et al. (2014), and Sinigoi et al. (2011). The granulite-facies rocks include lithologies identified repeatedly in the literature as “stronalite,” which are mainly exposed near the Insubric Line in the Strona Valley north of the Mafic Complex (Zingg, 1980), and thin sheet-like selvages within the Mafic Complex referred to as septa (Quick et al., 2003; Sinigoi et al., 1991). Field observations (Barboza et al., 1999), geochemistry (Sinigoi et al., 2011) and geochronology (Klötzli et al., 2014) indicate that a metamorphic gradient of this crustal sequence, including granulite-facies rocks at the deepest levels, predates the Sesia Magmatic System. At the roof of the Mafic Complex, the Kinzigite Formation consists of amphibolite-facies migmatitic rocks within 1 to 2 km of the contact (Snoke et al., 1999).

Within the Kinzigite Formation, the K_2O amount in paragneiss decreases progressively with increasing metamorphic grade from about 3% in amphibolite-facies to 2% in granulite (Schnetger, 1994) to values as low as 0.4% in septa contained in the Mafic Complex (Sinigoi et al., 2011). This variation is roughly indicative of biotite and K-feldspar modal decrease and is consistent with progressive removal of granitic components with increasing metamorphic grade.

Fig. 2 shows the normalized patterns of the Kinzigite Formation rocks (data in online supplements, Table OS2). Amphibolite facies paragneisses include the average kinzigite composition from Schnetger (1994) and the average composition of melanosome from the roof of the Mafic Complex. Granulite facies rocks include the average composition of stronalite from Schnetger (1994) and the average composition of paragneiss from septa occurring in the paragneiss bearing belt (PBB). The bulk composition of the septa (PBB bulk septa) is estimated as a mixture of 70% paragneiss and 30% charnockite, considering that charnockite was part of the septa and represents the final product of in situ melting of paragneiss (Sinigoi et al., 2011). Although individual samples display a wide range of compositions, the bulk average compositions reveal important systematic characteristics. The average composition of amphibolite-facies paragneiss from Schnetger (1994) matches well, except for Sr, the average composition of melanosome in the migmatite at the roof of the Mafic Complex, suggesting that, despite its lithologic diversity, the bulk composition of the amphibolite-facies Kinzigite Formation rocks may be treated as relatively uniform for geochemical modeling. Granulite-facies rocks (i.e. stronalites, Schnetger, 1994) collected north of the Mafic Complex in the Val Strona are enriched in HREEs, reflecting increased garnet abundance, and depleted in LILEs, consistent with removal of a granitic component. Paragneiss septa (PBB) included in the Mafic Complex overlap the stronalite from Schnetger (1994) as far as M-HREE but are slightly depleted in LREE and definitely more depleted in LILEs, except Ba, consistent with a more advanced depletion in granitic components (Sinigoi et al., 2011).

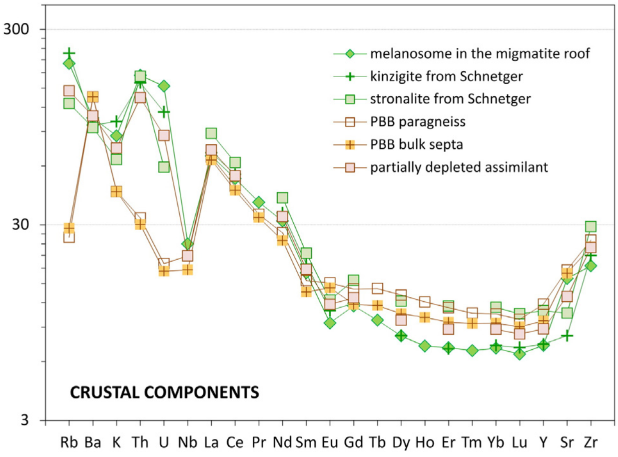

Fig. 2. Average compositions of the Kinzigite Formation crustal rocks normalized to the primitive mantle (Hofmann, 1988). The partially depleted assimilant (used in the following computations) is computed as a 50/50 mixture of amphibolite- and granulite-facies rocks (see text for explanation).

5. The Sesia Magmatic System

Quick et al. (2009) showed that the gabbroic rocks of the deep-crustal Mafic Complex, upper-crustal granite plutons and a bimodal volcanic field comprise a single, ~290- to ~282-Ma magmatic system, revealing the magmatic plumbing beneath a large rhyolitic caldera to a depth of >25 km, and displaying petrologic variations with depth consistent with geophysical models for the magmatic systems beneath active calderas. Now referred to as the Sesia Magmatic System (Sinigoi et al., 2010) these rocks range in composition from basalt and gabbro to rhyolite and granite and in age from 292 ± 4 to 282 ± 1 Ma (Quick et al., 2009), and include volcanic rocks of the Sesia Valley, the Roccapietra and Valle Mosso granite bodies, some small mid-crustal intrusions, minor anatectic granites, and the voluminous gabbroic Mafic Complex. Significantly, mafic and silicic components of the suite are exposed in both the deep and upper crustal parts of the section, as are their relationships with the country rocks.

The complete set of major-element, trace-element and isotopic compositions of the rocks of the Sesia Magmatic System, including data from this work and from literature, is reported in online supplements, Tables OS3, OS4 and OS5. In the following, we summarize the petrological and chemical features of each group of rocks. The suite displays a wide range in Sr and Nd isotopic compositions, from typical mantle values to a broad cluster defined by the country rocks (Fig. 3; data in online supplements Table OS5). However, within this compositional range, the rocks constituting the two largest plutons, i.e. gabbros of the upper Mafic Complex and granites of the "Graniti dei Laghi", define two distinct and relatively homogeneous clusters, with Sr_i ratios (computed at 280 Ma) around 0.708 and 0.710 respectively (Fig. 3).

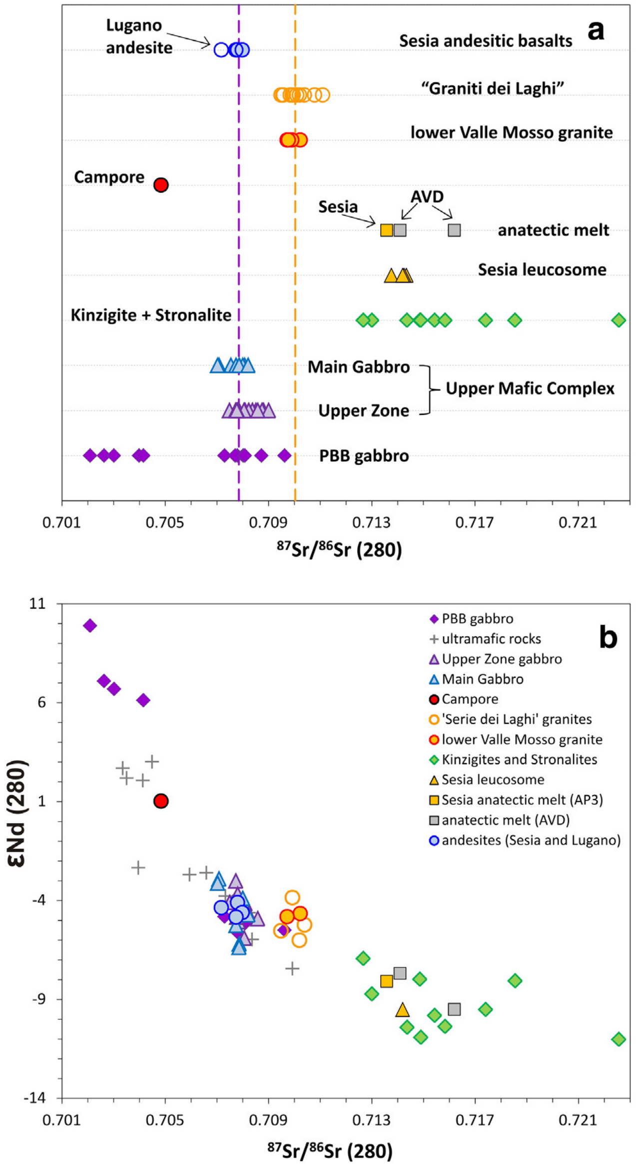

Fig. 3. a) Sr_i isotopic ratios computed at 280 Ma for rocks of the Sesia Magmatic System and metamorphic country rocks. Dashed violet line refers to the average value for Upper Mafic Complex, dashed orange line to the average value for "Serie dei Laghi" granites; b) plot of Sr_i vs. εNd.

5.1. Volcanic rocks

Volcanic rocks of the Sesia Valley form a bimodal volcanic field dominated by a densely welded, crystal- and lithic-rich rhyolitic tuff that fills the >13-km-diameter Sesia Valley caldera. Patches of megabreccia within the caldera fill include blocks of pre-caldera crystal-poor rhyolite, crystal-rich ignimbrite, andesite and andesitic basalts and schist of Serie dei Laghi. Volcanic activity lasted about 8 million years, from ~290 to ~282 Ma (Quick et al., 2009). Andesite and andesitic basalts dominate a 3 km-long exposure South-East of Pray (Fig. 1) and were erupted during the early phases of volcanic activity (288 ± 2 Ma; Quick et al., 2009), as observed in other sites of Permo-Carboniferous volcanism in the southern Alps (Marocchi et al., 2008; Schaltegger and Brack, 2007).

Normalized patterns of rhyolitic rocks are shown in Fig. 4a (data in online supplements Table OS3). Despite the variable alteration of the rocks, their trace-element patterns are similar. Within the available sampling there is no clear distinction between the crystal-rich rhyolite of the caldera fill and the older blocks of crystal-poor or crystal-rich

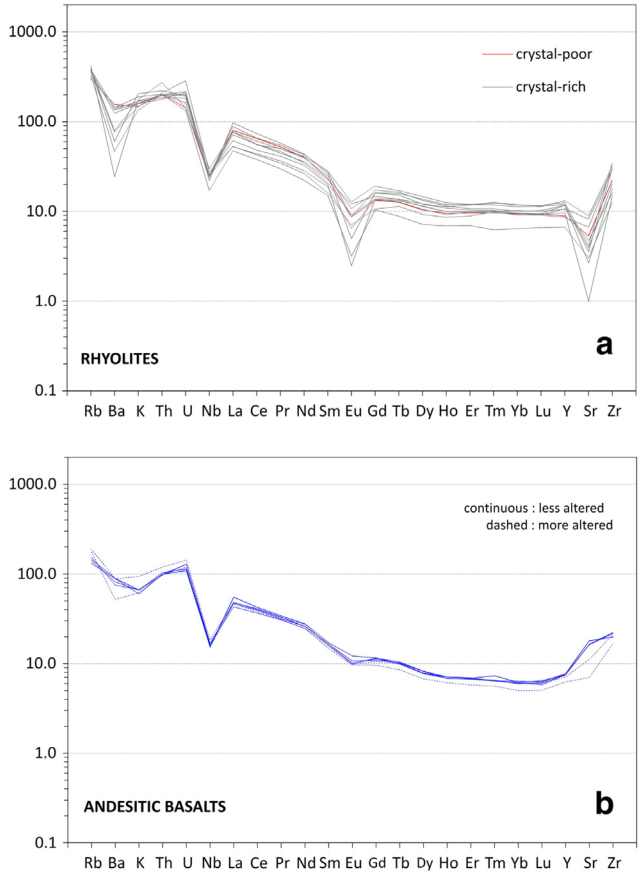

Fig. 4. Normalized patterns of a) rhyolitic rocks and b) andesitic basalts normalized to the primitive mantle (Hofmann, 1988). The patterns of the most altered andesitic basalts do not deviate much from those of the less altered samples.

rhyolite. All rhyolitic rocks are characterized by LREE enrichment, flat HREE patterns, and moderately negative Ba, Eu, and Sr anomalies. Nd and Sr isotopic compositions of rhyolite where not measured in this study because of the strong alteration, although Hunziker (1974) reports a $^{87}Sr/^{86}Sr$ intercept of 0.710 ± 0.001 for these rocks at ≈270 Ma.

Andesite and andesitic basalts display remarkably similar normalized patterns despite variable alteration and MgO content, which ranges from 4.5% to 8.2% (data in online supplements Table OS4). LREE and LILE are enriched, and the patterns are characterized by clear negative Nb anomalies and virtually no Eu anomaly (Fig. 4b). Sr and Nd isotope ratios measured on the two most fresh samples of these rocks ($Sr_i =$ 0.7078 and 0.7080; $\varepsilon Nd_{280} = -4.1$ and -4.6) are similar to andesites reported by Stille and Bulletti (1987) ($Sr_i = 0.7077$ and 0.7072; $\varepsilon Nd = -4.4$ and -4.8; Fig. 3) in the proximity of Lugano, in the Valganna area (about 50 km to the East), where Schaltegger and Brack (2007) report concordant zircon ages ranging from 298 to 288 Ma for the oldest ignimbrite, and an age of 281.3 ± 0.5 Ma for a granophyre indicating that the Lugano volcanic field is coeval to the Sesia Magmatic System.

5.2. The Valle Mosso granite

Granitic rocks in the Sesia Valley area have been historically described in terms of two bodies, the Roccapietra and the Valle Mosso, which are actually fragments of a single large pluton that were displaced in Alpine time by about 12 km of right-lateral motion on the Cremosina Line (Bortolami, 1965; Fig. 1). These bodies belong to the "Graniti dei Laghi" suite (Boriani et al., 1988), which also include the Montorfano, Baveno and Quarna bodies (Fig. 1). Field relations of the Valle Mosso body and its internal chemical zonation are consistent with exposure of an essentially vertical section through a differentiated pluton that has been uplifted and rotated approximately by 60°–90° (Quick et al., 2009; Zezza, 1977; Zezza et al., 1984). The roof of the Valle Mosso body intrudes the Sesia volcanic rocks and dips approximately 60° to the east. The intrusive nature of the contact is demonstrated by inclusions of volcanic rock in the granite, and development of a hornfels contact metamorphic aureole cut by dikes of porphyritic granite and hydrothermal veins of quartz (Balconi, 1963). The floor of the pluton is exposed at its western contact where the granite intrudes subvertical migmatitic orthogneiss and paragneiss (Balconi, 1963). A lower (to the west) and an upper (to the east) facies are distinguished within the pluton (Zezza, 1977; Zezza et al., 1984). The upper Valle Mosso granite is a relatively homogeneous Ca-poor leucogranite, which near the contact with the volcanic rocks becomes reddish and contains myarolitic cavities and patches of granophyre. The lower Valle Mosso granite is more heterogeneous, with patches of coarse-grained, medium-grained and locally porphyritic Ca-rich monzogranite, which near its basal contact with the country rocks is faintly foliated. This subdivision is confirmed by our sampling (Fig. 5a, data in online supplements, Table OS3). The lower Valle Mosso granite locally contains mafic enclaves, and is intruded by sparse mafic dikes. SHRIMP U–Pb zircon ages from three samples of the lower Valle Mosso granite yield 282.5 ± 3.5, 290.7 ± 4.3 and 296.4 ± 4.2 Ma, respectively (Klötzli et al., 2014). The age range is well outside the analytical error, confirming that the pluton grew by incremental intrusions over a time interval corresponding, within errors, to the volcanic activity of the Sesia Magmatic System. Younger zircon ages of 275 ± 4 and 278 ± 5 Ma reported for the upper Valle Mosso granite by Quick et al. (2009) are likely affected by lead loss.

Normalized patterns of the lower Valle Mosso granite are characterized by variable enrichments in LREE, which are most pronounced in samples with modal allanite, and moderate Eu, Sr and Ba anomalies. In contrast, the upper Valle Mosso granite shows flatter and more uniform REE patterns, and large Eu, Ba and Sr anomalies (Fig. 5b; data in online supplements Table OS3). Two samples of the lower Valle Mosso granite yield εNd values of −4.7 and −4.8, and four samples yield Sr_i ratios ranging from 0.7097 to 0.7102 (data in online supplements, Table OS5). These values are within the range reported for the Montorfano and Baveno plutons by Pinarelli et al. (1988, 2002) and are consistent with formation of the Valle Mosso granite as a hybrid of mantle and crustal components (Fig. 3). The petrographic and chemical differences between upper and lower Valle Mosso granite lead to the interpretation of the upper granite as a cupola of leucogranite segregated from underlying granitic crystal mush after the caldera collapse. The average composition of the whole Valle Mosso granite before the segregation of the upper granite cupola was calculated as 70% lower and 30% upper granite, based on the proportions of the two outcrop areas in the map. Noteworthy, the so estimated average composition of the Valle Mosso granite fits well the average composition of the rhyolite (Fig. 6b).

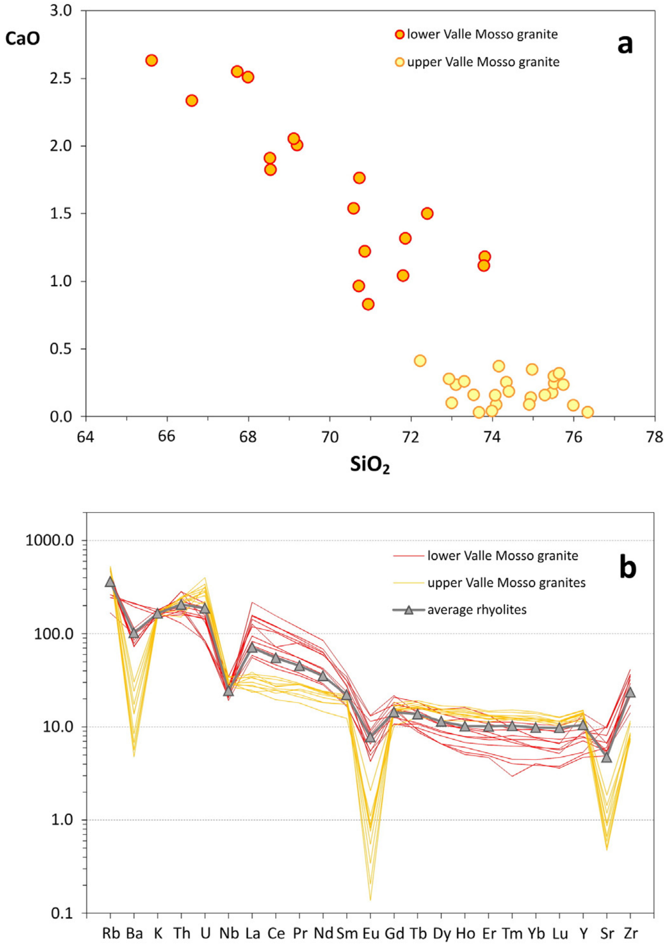

Fig. 5. Samples from the Valle Mosso granite. a) CaO vs. SiO2. b) Patterns normalized to the primitive mantle (Hofmann, 1988). The average rhyolite composition is shown for comparison.

5.3. Small igneous bodies in middle crust

Small stocks and dikes of igneous rocks showing a wide range of compositions and ages intrude the Kinzigite Formation and the lower Valle Mosso granite. They include anatectic products and a variety of mafic rocks.

5.3.1. Anatectic products

Rocks interpreted as anatectic products include leucosomes in the migmatite at the roof of the Mafic Complex and small stocks and dikes of two-mica, fine grained granite at higher crustal levels. One of these two-mica fine-grained granites intrudes the lower Valle Mosso granite (sample LS 63). Another two-mica granite, intruded in the Kinzigite

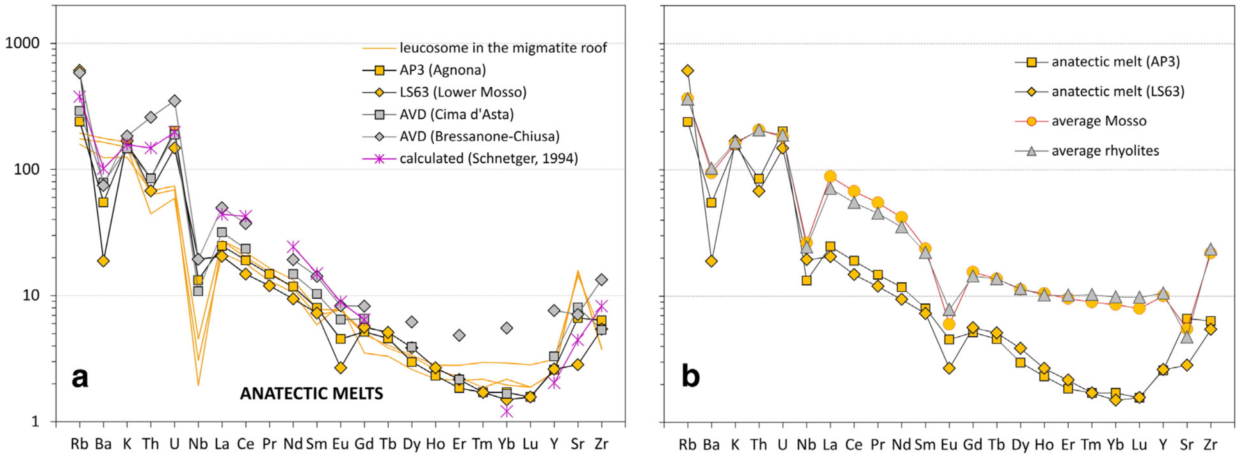

Fig. 6. a) Patterns of anatectic melts normalized to the primitive mantle (Hofmann, 1988), including leucosomes at the roof of the Mafic Complex, samples AP3 and LS63 (Sesia Magmatic System), anatectic granites from the Atesina Volcanic District (AVD, Rottura et al., 1998) and anatectic melt calculated by Schnetger (1994). b) Patterns of the anatectic granites compared with the average compositions of rhyolites and Valle Mosso granite.

(sample AP3, Fig. 1), is dated at 280 ± 1 Ma (Klötzli et al., 2014), and therefore crystallized during the last stages of the Sesia Magmatic System. The chemical and petrographical fingerprint of these rocks is consistent with melts originated from dehydration melting of the Kinzigite Formation. Fig. 6a shows the normalized patterns of anatectic products of the Sesia Magmatic System together with two anatectic granites from the coeval Atesina Volcanic District in the central Alps (AVD, Rottura et al., 1998), and the theoretical anatectic melt computed by Schnetger (1994) (column 7 in Table 5 from Schnetger, 1994). Anatectic melts have Sr_i values between 0.7136 and 0.7162 and εNd between −7.7 and −9.5 (including AVD data; Fig. 3a, data in online supplement Table OS5). They show a large range of Rb and Sr absolute contents, as expected considering the compositional variability of the source rocks and the variable degrees of partial melting involved in the formation of these bodies. All anatectic rocks display a strong depletion in HREE and limited Eu anomalies. Fig. 6b illustrates striking differences in the trace-element patterns of these rocks with those of rhyolites and the Valle Mosso granite. Overall, anatectic melts are lower in all REEs and Th and display opposing behaviors of Sr compared to the average compositions of the rhyolite and Valle Mosso granite.

5.3.2. Small mafic intrusive bodies

Minor mafic intrusions ranging in age from 311 to 286 Ma (Klötzli et al., 2014) occur near the boundary between the Ivrea–Verbano Zone and the Serie dei Laghi. Bodies older than 300 Ma or of unknown age are not considered in this work because they are or may be older than the igneous activity the Sesia Magmatic System. Mafic rocks also form dikes and swarms of enclaves in the lower Valle Mosso granite (data in online supplements Table OS4). These dikes, as well as the mafic body represented by sample PST 262 (Fig. 1), which intruded the Kinzigite at 286.6 ± 4.6 Ma (Klötzli et al., 2014), crystallized during the main igneous event, and therefore are considered part of the Sesia Magmatic System. The patterns of three samples from the body PST 262 are similar to those of samples collected in the cores of mafic dikes in the lower Valle Mosso granite (Fig. 7a). The rims of dikes and the enclaves intruded in the Valle Mosso granite are enriched in LREE and LILE relative to their cores suggesting mixing or diffusive exchange with the host granite. We conclude that the best representatives of mafic melts that intruded at upper crustal levels are samples collected from the core of larger dikes such as that cropping out in proximity of Campore (Fig. 1). Significantly, the core of the Campore dike also has the lowest Sr_i (0.70484) and highest εNd (1.03) value identified in this study (online supplements, Table OS5), and is less enriched in LILE and LREE than the andesitic basalts (Fig. 4b) and therefore is considered the most primitive mafic melt in the available sampling of the Sesia Magmatic System.

5.4. The Mafic Complex

The deepest rocks of the Sesia Magmatic System are dominated by gabbroic rocks of the >8-km-thick and >30-km-long Mafic Complex

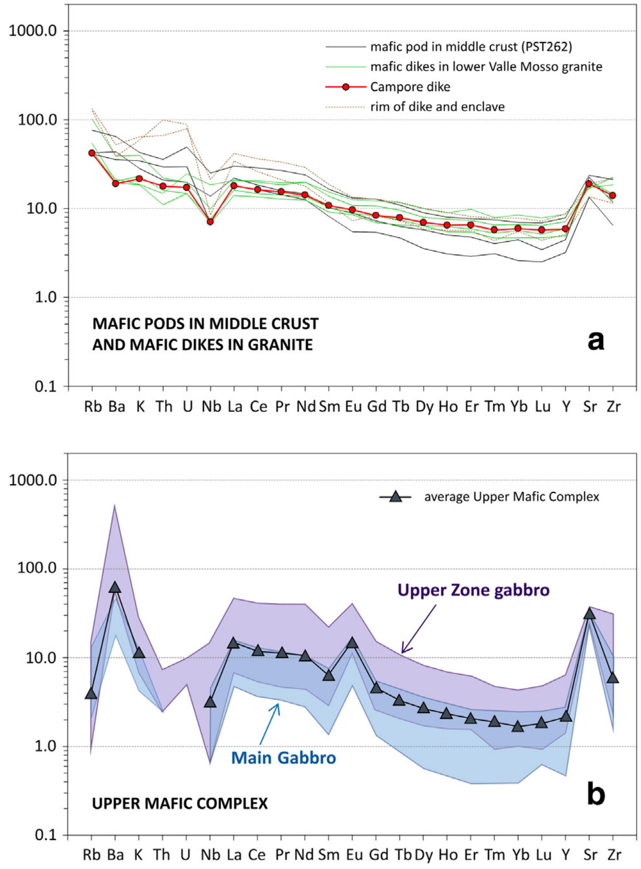

Fig. 7. Patterns of mafic intrusive rocks of the Sesia Magmatic System normalized to the primitive mantle (Hofmann, 1988). a) Samples from the mafic pod PST 262 intruded in the middle crust, mafic dikes intruded in the Valle Mosso granite (highlighting Campore dike), the rim of a dike and a mafic enclave. b) Upper Mafic Complex, showing the fields of Main Gabbro (light blue) and Upper Zone (light purple), and the average composition computed as 70% Main Gabbro and 30% Upper Zone.

(Quick et al., 1992, 1994; Rivalenti et al., 1975; Sinigoi et al., 1991, 2011), which intruded the deep crust at depths between 25 and 17 km (Barboza and Bergantz, 2000; Barboza et al., 1999; Demarchi et al., 1998). Rotation of the Mafic Complex by approximately 90° from its original orientation is indicated by a subvertical foliation and a progressive increase in equilibration pressures from east to west (Demarchi et al., 1998). The current map view effectively presents a cross section through the complex with its roof corresponding to its eastern contact with the Kinzigite Formation. Along this contact, a zone of migmatite up to >1 km thick is developed in the amphibolite-facies country rocks (Barboza and Bergantz, 2000; Snoke et al., 1999).

Various schemes have been proposed for subdividing the rocks within the Mafic Complex based on their mineralogy and chemistry. Whereas early subdivisions (Rivalenti et al., 1975, 1981) were only applicable in the Sesia and Mastallone valleys in the northern part of the Mafic Complex, Sinigoi et al. (1996) showed that the entire body can be described in terms of three zones: a) the Lower Mafic Complex consisting primarily of amphibole gabbro contaminated by granulite-facies crustal components, b) the "paragneiss bearing belt", wherein noritic rocks interlayered with paragneiss septa are characterized by extreme, meter-scale variations in crustal contamination which increases with proximity to crustal septa (Sinigoi et al., 2011), and c) the voluminous Upper Mafic Complex characterized by relatively uniform crustal contamination. In the Sesia and Mastallone Valleys, the Upper Mafic Complex was subdivided in terms of an "Upper Zone," a "Main Gabbro," and "Diorites" by Rivalenti et al. (1975). Paragneiss septa are increasingly depleted in granitic components with depth in the Mafic Complex (Sinigoi et al., 2011). The Mafic Complex is characterized by an arcuate internal structure defined by well mapped layering, foliation and lithologies (Quick et al., 2003). This structure is best explained by the "gabbro glacier" model (Quick and Denlinger, 1992, 1993; Quick et al., 1992, 1994), by which large mafic plutons are generated within extensional environments by downward and outward flow of crystal mush beneath a small magma chamber perched at the roof of the growing gabbro body.

Since the pioneering work of Rivalenti et al. (1975), numerous studies have produced geochemical data on the Mafic Complex (Sinigoi et al., 1991, 1994, 1996, 2011; Voshage et al., 1990 and references therein). This paper focuses on the upper Mafic Complex because it is demonstrably coeval with the granites and volcanic rocks of the Sesia Magmatic System (Peressini et al., 2007; Quick et al., 2009), whereas the age of the Lower Mafic Complex is less well constrained (Peressini et al., 2007; Sinigoi et al., 2011), and the rocks of the paragneiss belt are volumetrically minor components of the body.

All gabbros of the Upper Mafic Complex have compositions indicative of significant crustal contamination. Sr_i ranges from 0.7070 to 0.7090, and εNd ranges from −3.1 to −6.4 (Fig. 3, data in online supplements Table OS5). Voshage et al. (1990) demonstrated that the Nd and Sr isotopic composition of the Mafic Complex in the Sesia Valley could be explained by crystallization from a hybrid magma formed by an AFC-bulk mixing process involving assimilation of roughly uniform proportions of crustal material by a mantle-derived, MORB-like melt with isotopic composition equivalent to the uncontaminated gabbro samples in the complex and a crust with the average composition of the Kinzigite Formation. Voshage et al. (1990) concluded that the Mafic Complex may represent the lower-crustal 'roots' of upper-crustal Hercynian granitoid intrusions based on the similar Nd isotopic composition of the Mafic Complex and Hercynian granites in the region.

Rocks of the Upper Mafic Complex are enriched in LREE and show prominent positive anomalies in Sr, Eu and Ba (Fig. 7b, data in online supplements Table OS4). Positive Eu, Sr and Ba anomalies may be artefacts of both cumulus of plagioclase and assimilation of a depleted crustal contaminant produced by fractional melting of paragneiss in which Ba and Eu were retained in residual feldspar and biotite of the restite whereas Rb and K were removed by fugitive anatectic melts during earlier stages of melting (Sinigoi et al., 1994, 1995). However, the Eu, Sr and Ba anomalies are so extreme in many samples of the Upper Mafic Complex (Mazzucchelli et al., 1992a) that they cannot be explained by assimilation alone, and require a cumulus effect. The cumulus character of most rocks of the Upper Mafic Complex is also consistent with their low absolute contents in REE compared to coeval mafic rocks in the middle/upper crust (Fig. 7).

6. Mass transfer in the Sesia Magmatic System

Fig. 8 presents a schematic model for the mass transfer during the evolution of the Sesia Magmatic System based on observations collected over the last three decades. The internal structure of the Mafic Complex indicates that its formation was dominated by crystallization from a magma chamber perched at its interface with the Kinzigite Formation (Quick et al., 1992, 1994). This magma chamber was replenished by a parental mafic melt (pathway A), which assimilated crustal material from the overlying Kinzigite Formation (pathway B), and crystallized gabbroic cumulates that flowed downward and outward beneath it (pathway C) via the "gabbro glacier" model (Quick and Denlinger, 1992, 1993; Quick et al., 1992). The remarkably uniform isotopic composition of the Upper Mafic Complex suggests that a rough equilibrium was attained between assimilation of crust, fractional crystallization and magma recharge (Sinigoi et al., 1994; Voshage et al., 1990). Positive Eu, Sr and Ba anomalies that characterize the Upper Mafic Complex are antithetic to the negative Eu, Sr, and Ba anomalies that characterize the Valle Mosso granite (Figs. 6b and 7b), suggesting a link between the mafic and silicic magmatic systems involving fractionation of feldspar-rich gabbro and migration of late-stage, silicic melt from the deep crust to feed the growing granite pluton higher in the section (pathway D). However, Sr isotopic compositions of the Valle Mosso granite are intermediate between those of the Mafic Complex and those of the anatectic granites and crustal rocks (Fig. 3), requiring that the granitic

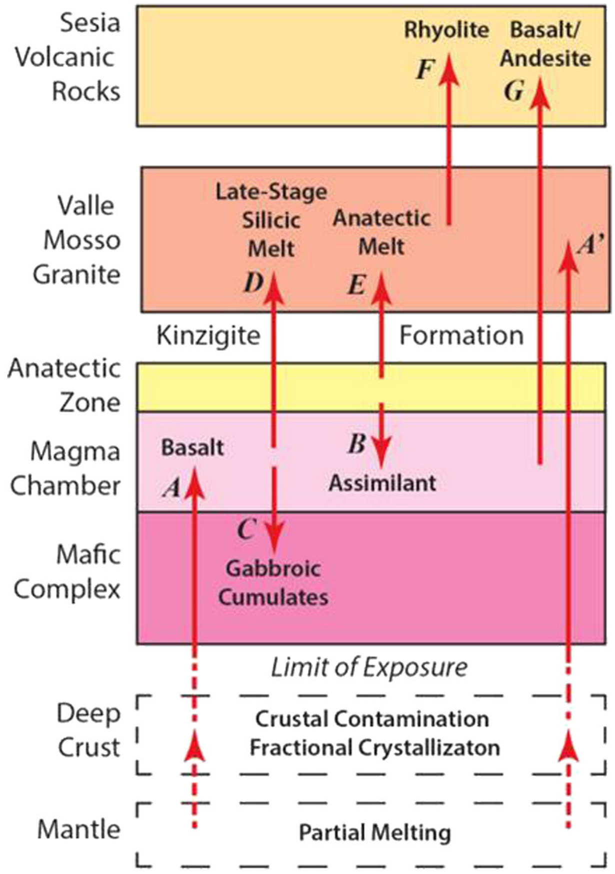

Fig. 8. Schematic model for mass transfer in the Sesia Magmatic System.

pluton also received a direct contribution of anatectic melts (pathway E). The bimodal volcanic field at the top of the section is dominated by rhyolite erupted from the Valle Mosso granitic reservoir (pathway F, Quick et al., 2009) but also includes minor andesitic flows with isotopic compositions corresponding to the Upper Mafic Complex (Fig. 3), which indicate that melts from the Upper Mafic Complex magma chamber (pathway G) also reached eventually the surface. The relatively low Sr_i and high εNd Campore dike cutting the lower Valle Mosso granite demonstrates that small volumes of almost uncontaminated mafic melt also reached higher crustal levels (pathway A′).

We have evaluated the roles of assimilation, fractional crystallization and hybridization in each of the mass-transfer pathways in Fig. 8 by searching for solutions that best model both the trace-element data and Nd and Sr isotopic data. Average compositions used in these computations are summarized in online supplement Table OS6. Trace elements and isotopic compositions were determined by AFC (assimilation and fractional crystallization) equations of DePaolo (1981). The contaminant/magma ratios are obtained using the equation $\rho = (r * (F - 1)) / (r - 1)$ (Aitcheson and Forrest, 1994),where r is the ratio of assimilation and fractional crystallization rates, F is the fraction of remaining liquid, as defined by DePaolo (1981), and ρ is the ratio of assimilated crustal mass and original magma mass in non recharge situation. The percentage of assimilated crust is calculated as $\rho / (1 + \rho) * 100$ (Aitcheson and Forrest, 1994).

7. Components used for the conceptual model

The Sesia Magmatic System exposes a variety of igneous and crustal lithologies, among which we chose the compositions which better represent the components used to reconstruct the igneous evolution.

In our sample set, the Campore dike has a composition within the boundaries of a possible mantle melt ($Sr_i = 0.70484$; εNd = 1.03). Only few gabbroic and ultramafic cumulates reported by Voshage et al. (1990) have less radiogenic compositions. In the data set by Voshage et al. (1990), εNd ranges from 9 to 6 in uncontaminated gabbros whereas pyroxenite cumulates show a broad range of isotopic compositions, from a cluster of four samples with εNd ≈ 2.5 to very radiogenic compositions of two samples collected in proximity to a thick paragneiss septum and mineralized for Ni sulfides (Fig. 3b). According to Voshage et al. (1990), the uncontaminated gabbros crystallized from the first mafic pulses which quenched in a still cool crust, so preserving the composition of the primary mantle melt. However, all these cumulus rocks were collected in the paragneiss bearing belt, and may be older than the Sesia Magmatic System (Klötzli et al., 2014). We conclude that the Campore dike may either maintain an isotopic signature close to the mantle magma which fed the upper Mafic Complex, or may be slightly contaminated, if the interpretation by Voshage et al. (1990) is correct. In the latter case, an estimate based on Nd and Sr isotopic mixing requires that the Campore dike contains 3% to 12% of crustal component, computed assuming that the primary mantle melt had the isotopic compositions of the less radiogenic pyroxenites or gabbros respectively, the absolute contents of Nd and Sr of an E-MORB (Sun and McDonough, 1989), and the assimilant described in the next paragraph. Concluding, in the following computations we use the Campore dike as starting mafic melt because, notwithstanding that it may contain minor amounts of crustal component, it is a real and available rock of the Sesia Magmatic System.

The assimilant composition was modeled as a 50–50 mixture of fertile and depleted kinzigite, using the average of kinzigite from Schnetger (1994) and melanosomes outcropping above the Mafic Complex for the fertile component, and the average stronalite from Schnetger (1994) and bulk septa from the paragneiss-bearing belt (Sinigoi et al., 2011) for the depleted component (Fig. 2; data in online supplements, Table OS2). This partially depleted assimilant was chosen because the composition of the Upper Mafic Complex cannot be modeled via assimilation of fertile (amphibolite facies) crust but requires a crustal component intermediate between fertile kinzigite and depleted stronalite (Sinigoi et al., 2011).

The average composition of the gabbroic cumulates of the upper Mafic Complex was calculated using samples collected along the Sesia Valley and computed as a mixture of 70% average composition of the "Main Gabbro" and 30% average composition of the "Upper Zone" based on the areal distribution of those rocks in the Sesia Valley (data in online supplements, Table OS4). The "Diorites" were disregarded in this estimate because they are plagioclase cumulates variably enriched in late-stage residual fluids/melts percolating in a crystal mush body, far from a simple cumulus component (Solano et al., 2014).

The average composition of the Valle Mosso granite is estimated as 70% of the average composition of the lower Valle Mosso Granite and 30% of the upper Valle Mosso Granite based on the areal extent of those units; this composition is assumed to approximate the bulk composition of the pluton before the segregation of the upper Valle Mosso granite (data in online supplements, Table OS3).

8. From the Campore dike to andesitic basalts

Fig. 9 shows the trace-element abundances of an AFC model melt computed to match the composition of andesitic basalts starting from the Campore dike and using the partially depleted assimilant and cumulus phases approximating the modal mineralogy of the most mafic gabbros of the Upper Mafic Complex (35% plagioclase; 25% clinopyroxene; 20% amphibole; 10% orthopyroxene; 10% garnet). At $r = 0.75$ and $F = 0.86$, the model melt reproduces the normalized pattern of the andesitic basalt at $Sr_i = 0.7078$ and εNd = −4.38, which are both very close to the average values of andesitic basalt (0.70789; −4.35) and gabbros of the Upper Mafic Complex (0.70785; −4.55; used Kd and modeling in online supplements, Table OS6). Similar results for both isotopic ratios and REE patterns may be obtained covarying r values higher than 0.75 with F values higher than 0.85. However, at r values <0.7, the F values needed to fit the isotopic data yield increasingly higher REE patterns and a single solution for both REE abundances and Nd and Sr isotopic ratios cannot be achieved. The amount of crustal contaminant contained in the average andesitic basalt of the Sesia Magmatic System, computed according to Aitcheson and Forrest (1994), remains between 29% and 31% for any result matching both isotope ratios and REE computed with $r > 0.7$ and $F > 0.85$. Using as assimilant the kinzigite from Schnetger (1994), i.e. the most fertile crustal component, the Sr_i results too low (0.7068) in the melt computed to match both εNd and REE patterns of andesitic basalt.

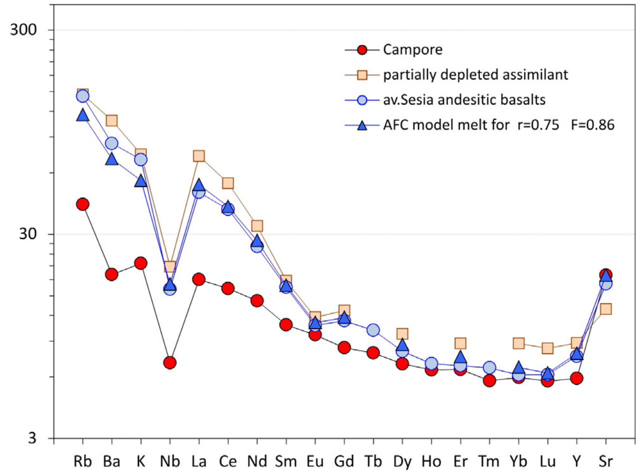

Fig. 9. Comparison of the average composition of andesitic basalts with the AFC model melt computed starting from the Campore dike after assimilation of partially depleted crustal component and minor fractionation. Values are normalized to the primitive mantle (Hofmann, 1988).

Mass balance computations on major-elements support the results obtained by simple AFC. Starting from a hybrid composition obtained after addition of 33% of assimilant to Campore, which is required to fit by bulk mixing the isotope ratios of andesitic basalts, we used as fractionated material the average of the six MgO-richest gabbro samples and one anorthosite of the upper Mafic Complex (online supplements, Table OS4). Using XL-FRAC (Stormer and Nicholls, 1978), the best approximation to the average andesitic basalt is obtained by fractionation of 25% of gabbro and 4% anorthosite, yielding a $\sum \text{res}^2 = 2.4$ (online supplements, Table OS6). The same computation by bulk mixing and 30% gabbro fractionation fits perfectly the trace elements as well (modeling data and figure in OS6, sheet "trace elements modeling"). Notwithstanding the relatively high $\sum \text{res}^2$, which is expected because the few chosen gabbro samples are poorly representative of the real cumulates, we conclude that the major element modeling is also consistent with the results of the trace element modeling, involving assimilation of ~30% of partially depleted crust accompanied by fractionation to obtain the andesitic basalts.

To test considerations on energy constraints, we ran the calculations with the energy-constrained AFC routine (EC-RAXFC, Bohrson and Spera, 2007). Liquidus temperatures, specific heat of mafic magma and assimilant and heat of crystallization and fusion were obtained by rhyolite-MELTS code (Gualda et al., 2012). Simulations were run assuming both linear and non-linear melting functions within the range of values suggested by Bohrson and Spera (2007), and a single pulse (i.e. no recharge) into a paragneiss already close to the solidus (850 °C, Vielzeuf and Holloway, 1988). Input parameters and results obtained with different assumptions are reported in online supplements Table OS6. In these simulations, the most questionable parameters are the bulk D values for Nd and Sr in the assimilant (Da). Therefore, different runs were performed using alternatively the bulk Da values given by Bohrson and Spera (2007) for "standard" upper crust (Nd = 0.25; Sr = 1.5), those estimated from our data set, which shows that Nd is compatible in our crustal rocks, possibly retained in accessory mineral phases (Da Nd = 2.6; Sr = 2.15, computed as the ratio between our average crust and anatectic melts) and intermediate values. As expected, the ratio of anatectic mass/initial magma mass (Ma*) increases progressively at increasing compatibility of Sr and Nd. The best match between Sr and Nd isotopes (Sr = 0.70767 vs. 0.70789; εNd = −4.67 vs. −4.35) is obtained for intermediate Da values at the equilibrium temperature of ~1100 °C. In these conditions, the Ma* value, conceptually equivalent to the ρ value of Aitcheson and Forrest (1994), is higher than that computed by simple AFC (0.57 vs. 0.42, which corresponds, in the sense of Aitcheson and Forrest (1994), to an effective crustal contamination of 36 vs. 30% respectively). The mass of cumulate calculated with the assumption of non-linear melting functions is ~40%, suggesting that the amount of cumulates needed to supply the heat required to melt the assimilant is higher than that computed from simple AFC. Therefore, choosing intermediate ("ad hoc") Da values and the thermal parameters reported in OS6, the result obtained by EC-RAXFC is close to the result obtained by simple AFC as far as Nd and Sr systematic are concerned. However, an important difference between classical and energy-constrained AFC is that in the latter the assimilant is a computed anatectic melt instead of bulk paragneiss. In our natural case, when using as assimilant the anatectic granite instead of the partially depleted crust it is impossible to obtain a single solution which satisfies not only isotopes but also major elements. The model melt computed by the addition to Campore of 36% of our real anatectic melt and fractionation of 40% mafic cumulate (as required by the EC-RAXFC simulation) would be much more silica-rich than andesitic basalt (~68% vs. ~57%). Also, a simple mixing requires an addition of 63% anatectic melt to Campore to get the isotopic composition of andesitic basalts, resulting in ~65% SiO2 (see figure in sheet "trace elements modeling", online supplements OS 6). Moreover, field evidences at the roof of the Mafic Complex show that the first fraction of anatectic melt escaped upward, driven by buoyancy forces, without interacting with the underneath magma (Snoke et al., 1999). We thus conclude that the composition of andesitic basalts favors a process of reactive bulk assimilation (Beard et al., 2005) of a partially depleted paragneiss rather than mixing with granitic melt, which is generally formulated in the most popular thermal models.

9. Relationship between the Mafic Complex and the Valle Mosso granite

Antithetic Ba, Eu, and Sr anomalies in the Valle Mosso granite and the Mafic Complex (Figs. 5 and 7b) strongly suggest that the two are genetically linked. However, the Valle Mosso granite could not have simply crystallized from a residual silica-rich melt separated from the Mafic Complex because its Sr_i isotopic compositions are intermediate between those of Mafic Complex and the Kinzigite Formation, indicating that the bulk composition of the granite requires an addition of crustal component to the residual melt delivered from the Mafic Complex (Fig. 3).

Trace elements of the residual melt released from the Mafic Complex may be calculated either by fractionation of gabbro from andesitic basalt or by subtracting from the bulk Valle Mosso granite the anatectic component (computed as the average of anatectic granite samples AP3 and LS63, Fig. 6b, assuming that the isotopic composition of the anatectic melt corresponds to the average of available anatectic products, OS5). Fig. 10a compares the normalized patterns obtained with both methods (modeling in online supplements, Table OS6). A subtraction of 40% of anatectic melt from the bulk Valle Mosso granite provides a melt with Sri = 0.7078 and εNd = −4.6, compatible with a residual melt delivered from andesitic basalt after gabbro fractionation (see figure in sheet "trace elements modeling", online supplements OS 6). Using alternatively the isotopic composition of only the least radiogenic anatectic sample AP3, the amount of subtracted anatectic melt results in 45%. The normalized pattern of the melt computed in this way matches the composition of a residual melt computed by gabbro fractionation from andesitic basalts at F values of 0.30–0.40 (Fig. 10a). A more advanced fractionation, at $F < 0.3$, produces an excessive enrichment in REE. Moreover, cumulus gabbros calculated by 60% fractional crystallization from andesitic basalts ($F = 0.40$), provide extended REE patterns consistent with the average composition of gabbros of the Upper Mafic Complex (Fig. 10b; modeling in online supplements, Table OS6).

These computations are obviously influenced by the absolute amounts of Sr and Nd, by the selected Kd values and by possible isotopic disequilibrium between anatectic melts and source-rock, and therefore are presented only as an approximation. For instance, the experimental study of Knesel and Davidson (1999) shows that incipient melting of a granite may produce a melt richer in radiogenic Sr than the source rock because of significant contribution of biotite-derived Sr, and that this disequilibrium may be mitigated at more advanced degree of melting. Conversely, we observe that our anatectic samples have Sr_i values within the range of the country rocks, suggesting a rough equilibration attained at eutectic melting of a quartz-feldspatic assemblage rather than incipient melting dominated by mica breakdown. Also, the Sr absolute content of the two anatectic samples of the Sesia Magmatic System is very different (52 vs. 121 ppm), making their average questionable and compromising the reliability of computations based on Sr isotopes. The Nd absolute content in anatectic melts is much lower than both the bulk Valle Mosso granite (Fig. 6b) and the residual melt, and this returns a poor sensibility of the Nd systematic to the addition of anatectic melt to the residual melt (see figure in sheet "trace elements modeling", online supplements OS 6). Also, the Eu amounts computed for gabbro cumulates are low (Fig. 10b) and those for the residual melt computed by fractionation are high (Fig. 10a) compared to the observed values. Both cases fit much better by selecting a Kd of Eu for plagioclase around 2, which is more appropriate for dacite (Schnetzler and Philpotts, 1970), instead of the value of 1.2 for andesite used in our computations. Acknowledging the large uncertainties, the results obtained either subtracting the anatectic component from the bulk granite or by gabbro

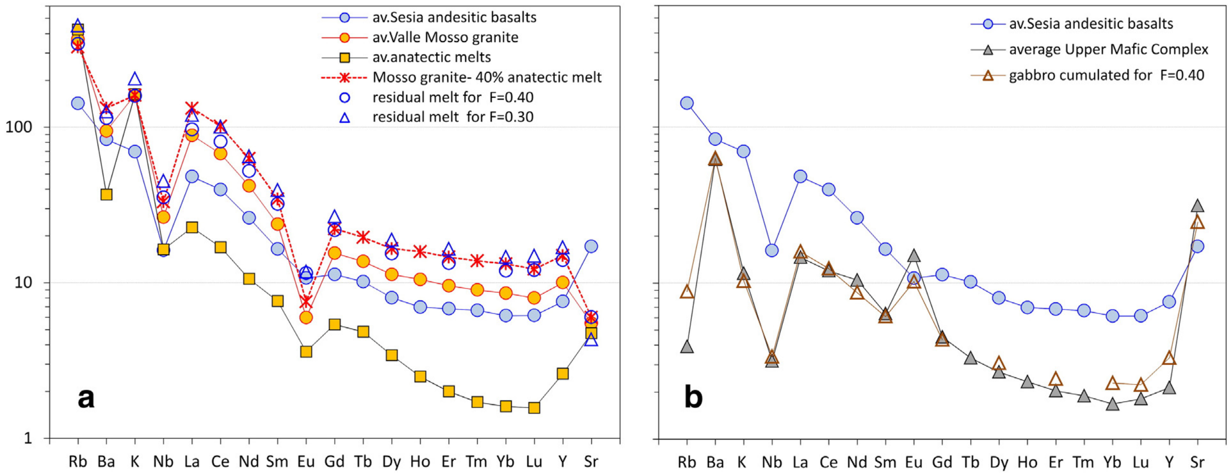

Fig. 10. a) Comparison of the composition of a melt calculated by subtracting 40% of anatectic melt from the bulk Valle Mosso granite (providing Sri = 0.7078 and εNd = −4.6) and the residual melts obtained after 60% and 70% of gabbro fractionation from basaltic andesite. b) Comparison of the computed composition of gabbro cumulated from the andesitic basalt at *F* = 0.40 and the average Upper Mafic Complex. Values are normalized to primitive mantle (Hofmann, 1988).

fractionation from andesitic basalts are surprisingly similar. In conclusion, a residual melt originated by fractionation of about 60%–70% of gabbro from the andesitic basalt appears to be a reasonable candidate for the component delivered from the Mafic Complex. This residual melt represents approximately 55% to 60% of the Valle Mosso granite.

10. Discussion

Andesitic basalts erupted at the early phases of volcanic activity demonstrate the existence of mafic melts with Sr and Nd isotopic compositions corresponding to those of gabbro accumulated in the upper Mafic Complex. Both require assimilation of about 30% of partially depleted crust as the mafic magma evolved in composition from the starting melt (Campore) to the average andesitic basalts. 30% is a minimal estimate of contamination, because the Campore dike may already contain a minor amount of crustal component. This relatively high degree of assimilation requires favorable environmental conditions, i.e. fertile and already hot country rocks (e.g. Thompson et al., 2002). Both these conditions were attained during the growth of the upper Mafic Complex. Whereas the lower Mafic Complex intruded deep and depleted crustal levels in granulite facies before the main event, later on (after ca. 295 Ma) mafic magma invaded progressively more fertile crust in amphibolite facies giving rise to the upper Mafic Complex (Sinigoi et al., 2011). At the same time the main activity of the Sesia Magmatic System began, with the incremental growth of granite plutons and volcanic activity. The intrusion of the lower Mafic Complex and sporadic injections of mafic magma at higher crustal levels (Klötzli et al., 2014) may have caused a pre-heating of the crustal section, especially in the crustal levels immediately above the lower Mafic Complex. Once the country rocks at the contact with mafic melt are close to the solidus, the sensible heat needed to reach the melting point is strongly reduced, increasing the thermal budget available for assimilation. In the Sesia Valley, it is evident that the country rocks at the roof of the Mafic Complex were partially molten in a layer about 1 km thick (Snoke et al., 1999). In a migmatite level, paleosomes are fragments of crustal rocks wherein crystals may be separated by interstitial melt, an assemblage which may be easily disaggregated and assimilated favoring reactive bulk assimilation (Beard et al., 2005). This requires a reduced amount of heat compared to thermal models which assume that the assimilant is an anatectic melt (e.g. Bohrson and Spera, 2007). The common finding of inherited zircons in gabbro of the Mafic Complex (Peressini et al., 2007) is consistent with the reactive bulk assimilation (Beard et al., 2005). Bulk assimilation is also consistent with our AFC calculations, which provide a single solution for both Nd and Sr isotopes and trace elements assuming as assimilant the partially depleted kinzigite but not granite.

After the first AFC step to obtain the hybrid andesitic basalt, 60% to 70% fractional crystallization is required to match the composition of the gabbro cumulated in the upper Mafic Complex (Fig. 10b), leaving behind a residual melt with the appropriate composition to be added to anatectic granite to obtain the bulk composition of the Valle Mosso pluton (Fig. 10a).The composition of the Valle Mosso granite requires contributions of approximately 40% to 45% anatectic melt and approximately 55% to 60% of residual melt delivered from the upper Mafic Complex. These proportions are affected by large uncertainty (see Section 9) and provide only a rough estimate.

It has been shown that the Sr isotopic composition of the Valle Mosso granite shows a restricted range around $Sr_i = 0.710$ (Fig. 3) which matches closely the majority of other Permian granite plutons in Europe (Liew and Hofmann, 1988). This relative homogeneity requires a common process which modulates the production of proportional amounts of anatectic and residual granite (delivered from mafic cumulates) which may have acted not only in the case of the Sesia Magmatic System but also elsewhere. Field evidences and zircon ages (Klötzli et al., 2014) indicate that the Valle Mosso pluton grew incrementally, precluding the possibility that the relative homogeneity was achieved by convection in a large magma chamber.

On the basis of the presented computations and of already published concepts and field observations we propose a conceptual model which explains the relatively homogeneous composition of the Valle Mosso granite, and may have acted in many other Permian granite plutons and elsewhere.

The internal structure of the Mafic Complex indicates that it grew incrementally by downward and outward flow of cumulates from a small, episodically replenished magma chamber perched at its roof according to the “gabbro glacier” model (Quick et al., 1992, 1994). Measured densities of gabbros are intermediate between less dense amphibolite-facies paragneiss at the roof and denser granulite septa included in the Mafic Complex, leading to infer a sort of density controlled stoping, where crustal levels may be incorporated only after they become denser than the mafic magma (otherwise they float). This density increase of roof rocks results from upward segregation of buoyant anatectic melt from the migmatite level above the mafic intrusion, which left behind an increasingly denser, partially depleted residue (Sinigoi et al., 1995).

Consistent with upward migration of anatectic melt, leucosome abundance in the Kinzigite Formation increases from about 20% near the contact with the Mafic Complex to a peak value of about 50% about 1 km from the contact (Snoke et al., 1999), a point beyond which migration of small volumes of melt was possibly impeded by the steep thermal gradient above the Mafic Complex.

These observations collectively point toward an open system within a narrow (<1 km.) partially molten zone at the interface of a growing mass of gabbro cumulates and the overlying crust. Thermal equilibrium in such a system requires a rough balance between advective heat transfer of magma and conductive heat transfer, and will be strongly modulated by the latent heat of fusion of the mafic intrusion and the overlying crust. Starting from the average andesitic basalt with 1.5% H_2O at 6 kb, we calculate with rhyolite-MELTS code (Gualda et al., 2012) that 60% to 65% crystallization is achieved at 900° to 850° with a residual dacitic to rhyodacitic magma. Acknowledging that the use of MELTS is not recommended for systems containing amphibole, we observe that this temperature range corresponds to a plateau of 10% to 60% of melt production in metapelite (Vielzeuf and Holloway, 1988). Temperatures within this range are recorded by the metamorphic assemblage of granulite-facies rocks at the deepest levels in the proximal crustal sequence exposed in Val Strona di Omegna (north of the Mafic Complex) by Redler et al. (2013). Also, temperatures up to 900° are estimated by Ti in zircon and Zr in rutile in granulites of the same section by Ewing et al. (2013), who also report temperatures up to 1000 °C in the paragneiss septa incorporated at deeper levels in the Mafic Complex in Val Mastallone.

Fig. 11 illustrates the inferred evolution of the igneous system. In a deep, fertile and pre-heated crust, a mafic intrusion beneath amphibolite-facies rocks induces partial melting of a roof layer which splits in buoyant anatectic melts and a denser restite (Fig. 11a). When the restite layer is depleted enough to exceed the density of the mafic melt, it is incorporated and assimilated in the growing mafic body. Reactive bulk assimilation is enhanced by the fragmented nature of the partially molten restite (Beard et al., 2005), giving rise to a hybrid crystal mush containing a mixture of pheno- and xenocrysts. If the incorporated mass exceeds the amount which may be assimilated (~30%), it may partially survive as a septum. The hybrid mafic magma cannot cool beneath the temperature of the melting roof, which is buffered at the dehydration melting of biotite (Vielzeuf and Holloway, 1988), around 850°–900°. In this condition, the hybrid magma cannot crystallize more than ~60%/65% (according to rhyolite-MELTS). The accumulation of gabbro produces a residual melt, which migrates upward, joining the anatectic melt delivered from the roof rocks (Fig. 11b). The two silicic melts coexist in the migmatite at super-solidus temperatures, and may eventually mix because they are similar in temperature and major-element composition. If they percolate atop the migmatite level and crystallize before mixing, they may easily re-melt and mix at the next cycle of intrusion/incorporation, when a new mafic pulse intrudes the neutral buoyancy level above the new restite. What is important is that the amounts of the two granitic components are produced in roughly constant proportions, because the amount of anatectic melt produced at the roof is a function of volume and latent heat of crystallization of the intruded mafic melt which in turn produces proportional amounts of crystallized gabbro and residual melt. In conclusion, the roughly constant proportions of the two granitic components contained in the magma which feed the main granite plutons are a consequence of the thermally buffered conditions of the migmatite level located above the advancing front of underplating. This conceptual model may operate only if the necessary conditions are attained, as in the case of the Sesia Magmatic System. The crustal section must be thick, fertile and possibly pre-heated to address conditions favorable for assimilation (see Thompson et al., 2002). Tectonic regime and crustal rheology must allow ponding of mafic melts in the deep crust.

11. Conclusions

In the Sesia Magmatic System a large volume of granitic melt was incrementally stored in the upper crust or erupted during the growth of the Mafic Complex (Quick et al., 2009). The isotopic composition of this granitic melt is intermediate between that of the Mafic Complex

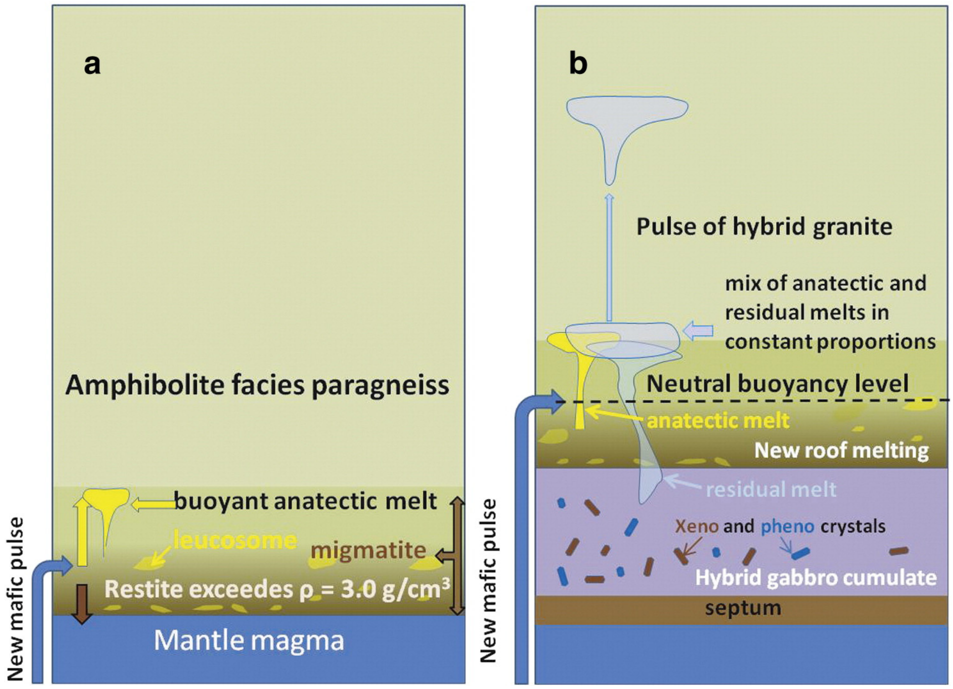

Fig. 11. Schematic illustration of the proposed model. a) Heat delivered from basaltic magma induces melting at the roof, which splits in buoyant anatectic melt and an increasingly denser restite. When the density of the restite exceeds the density of the mafic melt, a new mafic pulse may pond above, incorporating the previous crustal level. b) The incorporated restite underwent reactive bulk assimilation; xenoliths and xeno-crystals are partially or totally dissolved. Eventually, a septum may survive. The new roof starts melting, and the underneath hybrid magma cannot cool beneath the temperature of the melting roof, which is buffered at the biotite breakdown. Crystallization of hybrid gabbro delivers residual melt which percolates across the migmatite mixing with anatectic melt. The mixture of anatectic and residual melts in constant proportions feeds incrementally the upper crustal granite pluton. The next mafic pulse intrudes at the new neutral buoyancy level and so on.

and the average crust, requiring a contribution from both mafic-derived and anatectic components in subequal amounts.

Our computations show that the chemistry of the Mafic Complex and andesitic basalts requires about 30% assimilation, in contrast with recent works which question the efficiency of crustal assimilation by basaltic melts (e.g. Karakas and Dufek, 2015) and thus call for fractionation as the primary means for producing silicic magmas (e.g. Jagoutz, 2010; Lee and Bachmann, 2014; Rioux et al., 2010; Walker et al., 2015). Whereas we do not contest that the latter may be the case in several geologic settings, we stress that the efficiency of assimilation is strictly dependent on the thermal evolution and the compositional and tectonic conditions of the intruded crust. Thus assimilation may be enhanced in a deep, fertile and hot crust (Thompson et al., 2002). These conditions were attained during the evolution of the Sesia Magmatic System, where the crustal section was thickened by the Variscan orogeny and likely pre-heated by the emplacement of the huge lower Mafic Complex and by sporadic mafic pulses at higher crustal levels (Klötzli et al., 2014; Sinigoi et al., 2011). The transtensional tectonic of Permian Europe (Wilson et al., 2004) is consistent with extension having been moderate enough to avoid efficient diking, which would promote a different scenario, with minimal assimilation, as observed in continental flood basalts and predicted by thermal models for extending crust (Karakas and Dufek, 2015). The proposed model may be effective if and when crustal rocks above underplated basalt exceed their solidus in a hot layer whose thickness depends on the established geotherm, a condition which may trigger the process of density-driven stoping. The fragmented nature of the incorporated restite enhances its dissolution according to the reactive bulk assimilation model (Beard et al., 2005), consistent with the common occurrence of inherited zircons at various levels in the Mafic Complex (Peressini et al., 2007), and requiring a heat budget which is significantly lower than that inferred by thermal models which assume that the country rocks are assimilated as melts (Beard et al., 2005; Grove et al., 1988). The growth of the Mafic Complex occurred by repeated intrusion of fresh basalt at the neutral buoyancy level, which in turn migrates upward step by step as the intrusive front advanced progressively in the crust. The source of the anatectic component is largely digested in the Mafic Complex, hiding in its 30% of assimilated crust. This explains the absence in the Sesia Magmatic System of significant volumes of migmatite representing the source of the anatectic component of the granite, which has been invoked as evidence of a negligible thermal effect of the Mafic Complex on the crust (Barboza et al., 1999). Finally, the inferred process results in the remarkably uniform level of contamination through a thickness of more than 8 km of gabbroic cumulates, which indicates that repeated intrusion of mafic melt and bulk assimilation achieved and sustained a state of relative equilibrium.

We conclude that the origin of large silicic complexes may be modulated by processes operating in the melting zone at the roof of the advancing deep-crustal mafic intrusion. At this interface the temperature is buffered at the biotite breakdown, a condition at which anatectic and residual granitic melts are produced in subequal proportion, resulting ultimately in the production of upper-crustal granites with relatively constant contributions of anatectic and mafic-derived components. The attainment of similar conditions during the Permian magmatism of Europe may explain the clustering of Permian silicic rocks in a restricted compositional range (Liew and Hofmann, 1988), and may have an analog in the present day volcanic areas of southwestern United States.

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References

Aitcheson, S.J., Forrest, A.H., 1994. Quantification of crustal contamination in Open Magmatic Systems. Journal of Petrology 35, 461–488.

Annen, C., Blundy, J.D., Sparks, R.S.J., 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology 47, 505–539.

Bachmann, O., Miller, C.F., de Silva, S., 2007. The volcanic–plutonic connection as a stage for understanding crustal magmatism. Journal of Volcanology and Geothermal Research 167, 1–23.

Balconi, M., 1963. Il contatto tra graniti e porfidi dalla Val Sessera al Biellese. Rendiconti della Società Mineralogica Italiana 19, 17–23.

Barboza, S.A., Bergantz, G.W., 2000. Metamorphism and anatexis in the Mafic Complex contact aureole, Ivrea Zone, Northern Italy. Journal of Petrology 41, 1307–1327.

Barboza, S.A., Bergantz, G.W., Brown, M., 1999. Regional granulite facies metamorphism in the Ivrea zone: is the Mafic Complex the smoking gun or a red herring? Geology 27, 447–450.

Barth, S., Oberli, F., Meier, M., Blattner, P., Bargossi, G.M., Di Battistini, G., 1993. The evolution of a calc-alkaline basic to silicic magma system: geochemical and Rb–Sr, Sm–Nd, and $^{18}O/^{16}O$ isotopic evidence from the Late Hercynian Atesina–Cima d'Asta volcano-plutonic complex, northern Italy. Geochimica et Cosmochimica Acta 57, 4285–4300.

Bea, F., Montero, P., 1999. Behavior of accessory phases and redistribution of Zr, REE, Y, Th, and U during metamorphism and partial melting of metapelites in the lower crust: an example from the Kinzigite Formation of Ivrea–Verbano, NW Italy. Geochimica et Cosmochimica Acta 63, 1133–1153.

Beard, J.S., Ragland, P.C., Crawford, M.L., 2005. Reactive bulk assimilation: A model for crust–mantle mixing in silicic magmas. Geology 33, 681–684.

Berckhemer, H., 1968. Topographie des "Ivrea-Koerpers" abgeleitet aus seismischen und gravimetrischen daten. Schweizerische Mineralogische und Petrographische Mitteilungen 48, 235–246.

Bohrson, W., Spera, F., 2001. Energy-constrained open-system magmatic processes II: Application of Energy-Constrained Assimilation-Fractional Crystallization (ECAFC) Model to magmatic systems. Journal of Petrology 42, 1019–1041.

Bohrson, W., Spera, F., 2007. Energy-constrained recharge, assimilation, and fractional crystallization (EC-RAXFC): a visual basic computer code for calculating trace element and isotope variations or open-system magmatic systems. Geochemistry, Geophysics, Geosystems 8 (11).

Boriani, A., Sacchi, R., 1973. Geology of the junction between the Ivrea–Verbano and Strona–Ceneri Zones (Southern Alps). Memorie degli Istituti di Geologia e Mineralogia dell'Universita di Padova 28, 1–36.

Boriani, A., Bigioggero, B., Giobbi Mancini, E., 1977. Metamorphism, tectonic evolution and tentative stratigraphy of the "Serie dei Laghi". Geological map of the Verbania area (northern Italy). Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova 32, 1–25.

Boriani, A., Burlini, L., Caironi, V., Giobbi Origoni, E., Sassi, A., Sesana, E., 1988. Geological and petrological studies on the Hercynian plutonism of Serie dei Laghi—geological map of its occurrence between Valsesia and Lago Maggiore (N-Italy). Rendiconti della Società Italiana di Mineralogia e Petrologia 43, 367–384.

Bortolami, G., 1965. Rapporti cronologico-genetici tra graniti e vulcanite permiane. Atti della Società Italiana di Scienze Naturali e Museo Civico di Storia Naturale di Milano 104, 155–173.

Claeson, D.T., Meurer, W.P., 2004. Fractional crystallization of hydrous basaltic "arc-type" magmas and the formation of amphibole-bearing gabbroic cumulates. Contributions to Mineralogy and Petrology 147, 288–304.

Coleman, D.S., Gray, W., Glazner, A.F., 2004. Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology 32, 433–436.

Demarchi, G., Quick, J.E., Sinigoi, S., Mayer, A., 1998. Pressure gradient and original orientation of a lower-crustal intrusion in the Ivrea–Verbano Zone, Northern Italy. The Journal of Geology 106, 609–622.

DePaolo, D.J., 1981. Trace-element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth and Planetary Science Letters 53, 189–202.

Di Vincenzo, G., Andriessen, P.A.M., Ghezzo, P., 1996. Evidence of two different components in a Hercynian peraluminous cordierite-bearing granite: the San Basilio Intrusion (Central Sardinia, Italy). Journal of Petrology 37, 1175–1206.

Ewing, T.A., Hermann, J., Rubatto, D., 2013. The robustness of the Zr-in-rutile and Ti-in zircon thermometers during high-temperature metamorphism (Ivrea–Verbano Zone, northern Italy). Contributions to Mineralogy and Petrology 4, 757–779.

Fountain, D.M., 1976. Ivrea–Verbano and Strona–Ceneri zones, northern Italy—cross section of continental crust—new evidence from seismic velocities of rock samples. Tectonophysics 33, 145–165.

Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., Taylor, R.Z., 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? GSA Today 14, 4–11.

Green, T., Blundy, J., Adam, J., Yaxley, G., 2000. SIMS determination of trace element partition coefficients between garnet, clinopyroxene and hydrous basaltic liquids at 2–7.5 GPa and 1080–1200 °C. Lithos 53, 165–187.

Grove, T.L., Kinzler, R.J., Baker, M.B., Donnelly-Nolan, J.M., Lesher, C.E., 1988. Assimilation of granite by basaltic magma at Burnt Lava flow, Medicine Lake volcano, northern California: decoupling of heat and mass transfer. Contributions to Mineralogy and Petrology 99, 320–343.

Gualda, G.A.R., Ghiorso, M.S., Lemons, R.V., Carley, T.L., 2012. Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems. Journal of Petrology 53, 875–890.

Handy, M.R., Franz, L., Heller, F., Janott, B., Zurbriggen, R., 1999. Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland). Tectonics 18, 1154–1177.

Hildreth, W., Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of Central Chile. Contributions to Mineralogy and Petrology 98, 455–489.

Hofmann, A.W., 1988. Chemical differentiation of the Earth: the relationship between mantle, continental crust and oceanic crust. Earth and Planetary Science Letters 90, 297–314.

Hunziker, J.C., 1974. Rb–Sr and K–Ar age determination and the alpine tectonic history of the Western Alps. Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova 31, 3–54.

Jagoutz, O., 2010. Construction of the granitoid crust of an island arc. Part II: a quantitative petrogenetic model. Contributions to Mineralogy and Petrology 160, 359–381.

Karakas, O., Dufek, J., 2015. Melt evolution and residence in extending crust: thermal modeling of the crust and crustal magmas. Earth and Planetary Science Letters 425, 131–144.

Klötzli, U., Sinigoi, S., Quick, J.E., Demarchi, G., Tassinari, C.C.G., Sato, K., Günes, Z., 2014. Duration of igneous activity in the Sesia Magmatic System and implications for high-temperature metamorphism in the Ivrea–Verbano deep crust. Lithos 206-207, 19–33.

Knesel, K.M., Davidson, J.P., 1999. Sr isotope systematics during melt generation by intrusion of basalt into continental crust. Contributions to Mineralogy and Petrology 136, 285–295.

Kunz, B.E., Johnson, T.E., White, R.W., Redler, C., 2014. Partial melting of metabasic rocks in Val Strona di Omegna, Ivrea Zone, northern Italy. Lithos 190-191, 1–12.

Lee, C.-T.A., Bachmann, O., 2014. How important is the role of crystal fractionation in making intermediate magmas? Insights from Zr and P systematic. Earth and Planetary Science Letters 393, 266–274.

Liew, T.C., Hofmann, A.W., 1988. Precambrian crustal components, plutonic associations, plate environment of the Hercynian Fold Belt of central Europe: indications from a Nd and Sr isotopic study. Contributions to Mineralogy and Petrology 98, 129–138.

Ludwig, K.R., 1994. Analyst: a computer program for control of a thermal-ionization single-collector mass spectrometer. US Geological Survey Open File Report, pp. 92–543.

Marocchi, M., Morelli, C., Mair, V., Klötzli, U., Bargossi, G.M., 2008. Evolution of large silicic magma systems: new U–Pb zircon data on the NW Permian Athesian Volcanic Group (Southern Alps, Italy). The Journal of Geology 116, 480–498.

Mazzucchelli, M., Rivalenti, G., Vannucci, R., Bottazzi, P., Ottolini, L., Hofmann, A.W., Parenti, M., 1992a. Primary positive Eu anomaly in clinopyroxenes of low-crust gabbroic rocks. Geochimica et Cosmochimica Acta 56, 2363–2370.

Mazzucchelli, M., Rivalenti, G., Vannucci, R., Bottazzi, P., Ottolini, L., Hofmann, A.W., Sinigoi, S., Demarchi, G., 1992b. Trace element distribution between clinopyroxene and garnet in gabbroic rocks of the deep crust: an ion microprobe study. Geochimica et Cosmochimica Acta 56, 2371–2385.

Miller, C.F., Furbish, D.J., Walker, B.A., Clairborne, L.L., Cotheas, G.C., Bleick, H.A., Miller, J.S., 2011. Growth of plutons by incremental emplacement of sheets in crystal-rich host: evidence from Miocene intrusions of the Colorado River region, Nevada, USA. Tectonophysics 500, 65–77.

Namur, O., Charlier, B., Toplis, M.J., Higgins, M.D., Hounsell, V., Liégeois, J.P., Vander Auwera, J., 2011. Differentiation of tholeiitic basalt to A-type granite in the Sept Iles layered intrusion, Canada. Journal of Petrology 52, 487–539.

Peressini, G., Quick, J.E., Sinigoi, S., Hofmann, A.W., Fanning, M., 2007. Duration of a large mafic intrusion and heat transfer in the lower crust: a SHRIMP U/Pb zircon study in the Ivrea–Verbano Zone (Western Alps, Italy). Journal of Petrology 48, 1185–1218.

Pin, C., Sills, J.D., 1986. Petrogenesis of layered gabbros and ultramafic rocks from Val Sesia, the Ivrea Zone, NW Italy: trace element and isotope geochemistry. Geological Society, London, Special Publications 24, 231–249.

Pinarelli, L., Boriani, A., 2007. Tracing metamorphism, magmatism and tectonics in the southern Alps (Italy): constraints from Rb–Sr and Pb–Pb geochronology, and isotope geochemistry. Periodico di Mineralogia 76, 5–24.

Pinarelli, L., Del Moro, A., Boriani, A., 1988. Rb–Sr geochronology of lower Permian plutonism in Massiccio dei Laghi, Southern Alps (NW Italy). Rendiconti della Società Italiana di Mineralogia e Petrologia 43, 411–428.

Pinarelli, L., Del Moro, A., Boriani, A., Caironi, V., 2002. Sr, Nd isotope evidence for an enriched mantle component in the origins of the Hercynian gabbro-granite series of the “Serie dei Laghi”(Southern Alps, NW Italy). European Journal of Mineralogy 14, 403–415.

Quick, J.E., Denlinger, R.P., 1992. The possible role of ductile deformation in the formation of layered gabbros in ophiolites. Ofioliti 17, 249–253.

Quick, J.E., Denlinger, R.P., 1993. Ductile deformation and the origin of layered gabbro in ophiolites. Journal of Geophysical Research 98, 14015–14027.

Quick, J.E., Sinigoi, S., Negrini, L., Demarchi, G., Mayer, A., 1992. Synmagmatic deformation in the underplated igneous complex of the Ivrea–Verbano Zone. Geology 20, 613–616.

Quick, J.E., Sinigoi, S., Mayer, A., 1994. Emplacement dynamics of a large mafic intrusion in the lower crust, Ivrea–Verbano Zone, Northern Italy. Journal of Geophysical Research 99, 21559–21573.

Quick, J.E., Sinigoi, S., Snoke, A.W., Kalakay, T.J., Mayer, A., Peressini, G., 2003. Geologic map of the southern Ivrea–Verbano Zone northwestern Italy. U.S. Geological Survey, Geologic Investigations Series Map I-2776, scale 1:25,000.

Quick, J.E., Sinigoi, S., Peressini, G., Demarchi, G., Wooden, J.L., Sbisa, A., 2009. Magmatic plumbing of a large Permian caldera exposed to a depth of 25 km. Geology 37, 603–606.

Redler, C., Johnson, T.E., White, R.W., Kunz, B.E., 2012. Phase equilibrium constraints on a deep crustal metamorphic field gradient: metapelitic rocks from the Ivrea Zone (NW Italy). Journal of Metamorphic Geology 30, 235–254.

Redler, C., White, R.W., Johnson, T.E., 2013. Migmatites in the Ivrea Zone (NW Italy): constraints on partial melting and melt loss in metasedimentary rocks from Val Strona di Omegna. Lithos 175–176, 40–53.

Rioux, M., J., Mattinson, Hacker, B., Kelemen, P., Blusztajn, J., Hanghøj, K., Gehrels, G., 2010. Intermediate to felsic middle crust in the accreted Talkeetna arc, the Alaska Peninsula and Kodiak Island, Alaska: an analogue for low-velocity middle crust in modern arcs. Tectonics 29, 1–17 (TC3001).

Rivalenti, G., Garuti, G., Rossi, A., 1975. The origin of the Ivrea–Verbano Basic Formation (Western Italian Alps)—whole rock geochemistry. Bollettino della Societa Geologica Italiana 94, 1149–1186.

Rivalenti, G., Garuti, G., Rossi, A., Siena, F., Sinigoi, S., 1981. Existence of different peridotite types and of a layered igneous complex in the Ivrea Zone of the Western Alps. Journal of Petrology 22, 127–153.

Rollinson, H., 1993. Using geochemical data: evaluation, presentation, interpretation. Longman Group UK, Harlow.

Rottura, A., Bargossi, G.M., Caggianelli, A., Del Moro, A., Visonà, D., Tranne, C.A., 1998. Origin and significance of the Permian high-K calc-alkaline magmatism in the central-eastern Southern Alps, Italy. Lithos 45, 329–348.

Rutter, E.H., Khazanehdari, J., Brodie, K.H., Blundell, D.J., Waltham, D.A., 1999. Synthetic seismic reflection profile through the Ivrea Zone–Serie dei Laghi continental crustal section, northwestern Italy. Geology 27, 79–82.

Rutter, E., Brodie, K., James, T., Burlini, L., 2007. Large-scale folding in the upper part of the Ivrea–Verbano zone, NW Italy. Journal of Structural Geology 29, 1–17.

Schaltegger, U., Brack, P., 2007. Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. International Journal of Earth Sciences 96, 1131–1151.

Schmid, R., 1967. Zur petrographie und strukur der zone Ivrea–Verbano zwischen Valle d'Ossola und Valle Grande. Schweizerische Mineralogische und Petrographische Mitteilungen 47, 935–1117.

Schnetger, B., 1994. Partial melting during the evolution of the amphibolite- to granulite-facies gneisses of the Ivrea Zone, northern Italy. Chemical Geology 113, 71–101.

Schnetzler, C.C., Philpotts, J.A., 1970. Partition coefficients of rare-earth elements between igneous matrix material and rock-forming mineral phenocrysts. II. Geochimica et Cosmochimica Acta 34, 331–340.

Siegesmund, S., Layer, P., Dunkl, I., Vollbrecht, A., Steenken, A., Wemmer, K., Ahrendt, H., 2008. Exhumation and deformation history of the lower crustal section of the Valstrona di Omegna in the Ivrea Zone, Southern Alps. Geological Society, London, Special Publications 298, 45–68.

Sinigoi, S., Antonini, P., Demarchi, G., Longinelli, A., Mazzucchelli, M., Negrini, L., Rivalenti, G., 1991. Interactions of mantle and crustal magmas in the southern part of the Ivrea Zone (Italy). Contributions to Mineralogy and Petrology 108, 385–395.

Sinigoi, S., Quick, J.E., Clemens-Knott, D., Mayer, A., Demarchi, G., Mazzucchelli, M., Negrini, L., Rivalenti, G., 1994. Chemical evolution of a large mafic intrusion in the lower crust, Ivrea–Verbano Zone, northern Italy. Journal of Geophysical Research 99, 21575–21590.

Sinigoi, S., Quick, J.E., Mayer, A., Demarchi, G., 1995. Density-controlled assimilation of underplated crust, Ivrea–Verbano Zone, Italy. Earth and Planetary Science Letters 129, 183–191.

Sinigoi, S., Quick, J.E., Mayer, A., Budahn, J.R., 1996. Influence of stretching and density contrasts on the chemical evolution of continental magmas: an example from the Ivrea–Verbano Zone. Contributions to Mineralogy and Petrology 123, 238–250.

Sinigoi, S., Quick, J.E., Demarchi, G., Peressini, G., 2010. The Sesia Magmatic System. In: Beltrando, M., Peccerillo, A., Mattei, M., Conticelli, S., Doglioni, C. (Eds.), Journal of the Virtual Explorer 36, pp. 1–33.

Sinigoi, S., Quick, J.E., Demarchi, G., Klotzli, U., 2011. The role of crustal fertility in the generation of large silicic magmatic systems triggered by intrusion of mantle magma in the deep crust. Contributions to Mineralogy and Petrology 162, 691–707.

Snoke, A.W., Kalakay, T.J., Quick, J.E., Sinigoi, S., 1999. Development of a deep-crustal shear zone in response to syntectonic intrusion of mafic magma into the lower crust, Ivrea–Verbano Zone, Italy. Earth and Planetary Science Letters 166, 31–45.

Solano, J.M.S., Jackson, M.D., Sparks, R.S.J., Blundy, J., 2014. Evolution of major and trace element composition during melt migration through crystalline mush: implications for chemical differentiation in the crust. American Journal of Science 314, 895–939.

Stille, P., Bulletti, M., 1987. Nd–Sr isotopic characteristics of the Lugano volcanic rocks and constraints on the continental crust formation in the South Alpine domain (N-Italy-Switzerland). Contributions to Mineralogy and Petrology 96, 140–150.

Stormer, J.C., Nicholls, J., 1978. XLFRAC: a program for the interactive testing of magmatic differentiation model. Computers and Geosciences 4, 143–159.

Sun, S.-s., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications 42, 313–345.

Thompson, A.B., Matile, L., Ulmer, P., 2002. Some thermal constraints on crustal assimilation during fractionation of hydrous mantle-derived magmas with examples from central alpine batholiths. Journal of Petrology 43, 403–422.

Vielzeuf, D., Holloway, J.R., 1988. Experimental determination of the fluid-absent melting relations in the pelitic system. Contributions to Mineralogy and Petrology 98, 257–276.

Voshage, H., Hofmann, A.W., Mazzucchelli, M., Rivalenti, G., Sinigoi, S., Raczek, I., Demarchi, G., 1990. Isotopic evidence from the Ivrea Zone for a hybrid lower crust formed by magmatic underplating. Nature 347, 731–736.

Walker Jr., B.A., Bergantz, G.W., Otamendi, J.E., Ducea, M.N., Cristofolini, E.A., 2015. A MASH Zone revealed: the Mafic Complex of the Sierra Valle Fertil. Journal of Petrology 56, 1863–1896.

Wilson, M., Neumann, E.R., Davies, G.R., Timmerman, M.J., Heeremans, M., Larsen, B.T., 2004. Permo-Carboniferous magmatism and rifting in Europe: introduction. Geological Society, London, Special Publications 223, 1–10.

Wolff, R., Dunkl, I., Kiesselbach, G., Wemmer, K., Siegesmund, S., 2012. Thermochronological constraints on the multiphase exhumation history of the Ivrea–Verbano Zone of the Southern Alps. Tectonophysics 579, 104–117.

Zezza, U., 1977. Studio petrografico del massiccio granitico del biellese. Atti della Società Italiana di Scienze Naturali e del Museo Civico di Storia Naturale di Milano 118, 65–102.

Zezza, U., Meloni, S., Oddone, M., 1984. Rare-earth and large-ion-lithophile element fractionation in late-Hercynian granite massif of the Biellese area (southern Alps, Italy). Rendiconti della Società Italiana di Mineralogia e Petrologia 39, 509–521.

Zingg, A., 1980. Regional metamorphism in the Ivrea Zone (Southern Alps, N-Italy); field and microscopic investigations. Schweizerische Mineralogische und Petrographische Mitteilungen 60, 153–179.

Zingg, A., 1983. The Ivrea and Strona–Ceneri zones (Southern Alps, Ticino and N-Italy)—a review. Schweizerische Mineralogische und Petrographishe Mitteilungen 63, 361–392.