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SCIENCE

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Structure and petrography of the Valle Mosso pluton, Sesia Magmatic System, Southern Alps

L. Tavazzani[a], S. Peres[b], S. Sinigoi[c], G. Demarchi[c] and G. Musumeci[b]

[a]Roy M. Huffington Department of Earth Sciences, Southern Methodist University, Dallas, TX, USA; [b]Dipartimento di Scienze della Terra, Università di Pisa, Pisa, Italy; [c]Dipartimento di Matematica e Geoscienze, Università di Trieste, Trieste, Italy

ABSTRACT
The Valle Mosso pluton (VMP) is a Permian granitic body intruded at intermediate to upper crustal levels in the rocks of the pre-Alpine basement of the Ivrea-Verbano Zone and Serie dei Laghi shortly after the end of Variscan orogeny. As a consequence of Triassic to Jurassic rifting and Alpine orogeny, the VMP and surrounding host rocks have been tilted more than 60° from their original Permian polarity. Thus at present day, the VMP offers the rare opportunity to study a roof-to-floor exposure of a granitic pluton, providing insights into pristine geometry of the magma chamber and its relations to the country rocks. This work presents a new drift and solid map of the VMP and its surrounding host rocks at 1:15.000 scale.

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Ivrea-Verbano Zone; Sesia Magmatic System; granitic facies; zoned pluton; roof-to-floor exposure

1. Introduction

The generation of granitic magma (e.g. Annen, Blundy, & Sparks, 2006; Brown, 2013; Chappell & White, 2001; Patiño Douce, 1999), its emplacement mechanisms in the upper crust (e.g. de Saint-Blanquat et al., 2011; Gudmundsson, 2011; Leuthold et al., 2012; Menand, 2011; Miller et al., 2011) and its link to caldera forming eruptions (e.g. Bachmann & Bergantz, 2008; Burgisser & Bergantz, 2011; Cashman & Giordano, 2014; de Silva & Gosnold, 2007; Eddy, Bowring, Miller, & Tepper, 2016; Frost, Frost, & Beard, 2016) are still unresolved and debated issues.

In this context, exposures of plutons thick vertical sections can disclose crucial information about their three-dimensional shape and reveal magmatic processes that develop during their assembly (Rosenberg, Berger, & Schmid, 1995). However, the vertical dimension of plutons is usually lacking due to limited relief or exposure. The rare occurrence of tilted sections of continental crust is a favorable opportunity to study the internal geometry and intact relationship of the pluton to its host rocks (Miller & Miller, 2002).

Here is presented a set of petrographic data and field observations collected on the Valle Mosso pluton (VMP), a Permian granitic intrusion outcropping in the Southern Alps that displays a marked roof to floor exposure. This dataset has led to the compilation of a 1:15,000 scale surface map of the intrusion and surrounding host rocks, which constitute a notable addition to present day knowledge of both the Ivrea-Verbano Zone regional geology and the overall development of layered granitic intrusions.

2. Geological background

A virtually complete crustal section of the pre-Mesozoic continental crust is exposed in the southalpine domain, Italy (Figure 1(a)). The crust was tilted and uplifted by Mesozoic and Alpine tectonics to reveal progressively deeper crustal levels approaching the Insubric Line (Beltrando, Stockli, Decarlis, & Manatschal, 2015; Berger, Mercolli, Kapferer, & Fügenschuh, 2012; Fountain, 1976; Handy, Franz, Heller, Janott, & Zurbriggen, 1999; Rutter, Khazanehdari, Brodie, Blundell, & Waltham, 1999; Siegesmund et al., 2008; Wolff, Dunkl, Kiesselbach, Wemmer, & Siegesmund, 2012; Zingg, 1980). The area includes two lithostratigraphic units (Figure 1(b)), the lower crustal Ivrea-Verbano Zone and the adjacent middle to upper crustal Serie dei Laghi (a.k.a. Strona-Ceneri Zone). The dip of metamorphic and igneous rocks increases progressively approaching the Insubric Line from 30° to 40° in Permo-Triassic sediments and volcanic rocks of the Serie dei Laghi to subvertical in metamorphic and plutonic rocks in the Ivrea-Verbano Zone (Handy et al., 1999).

The Ivrea-Verbano Zone constitutes the deepest part of the crustal section, wherein high-grade metamorphic volcano-sedimentary rocks (including metapelite, metapsammite, calcsilicate and amphibolite) collectively grouped as the Kinzigite Formation

CONTACT L. Tavazzani ltavazzani@smu.edu Southern Methodist University, Box 750240, Dallas, TX 75275-0240, USA

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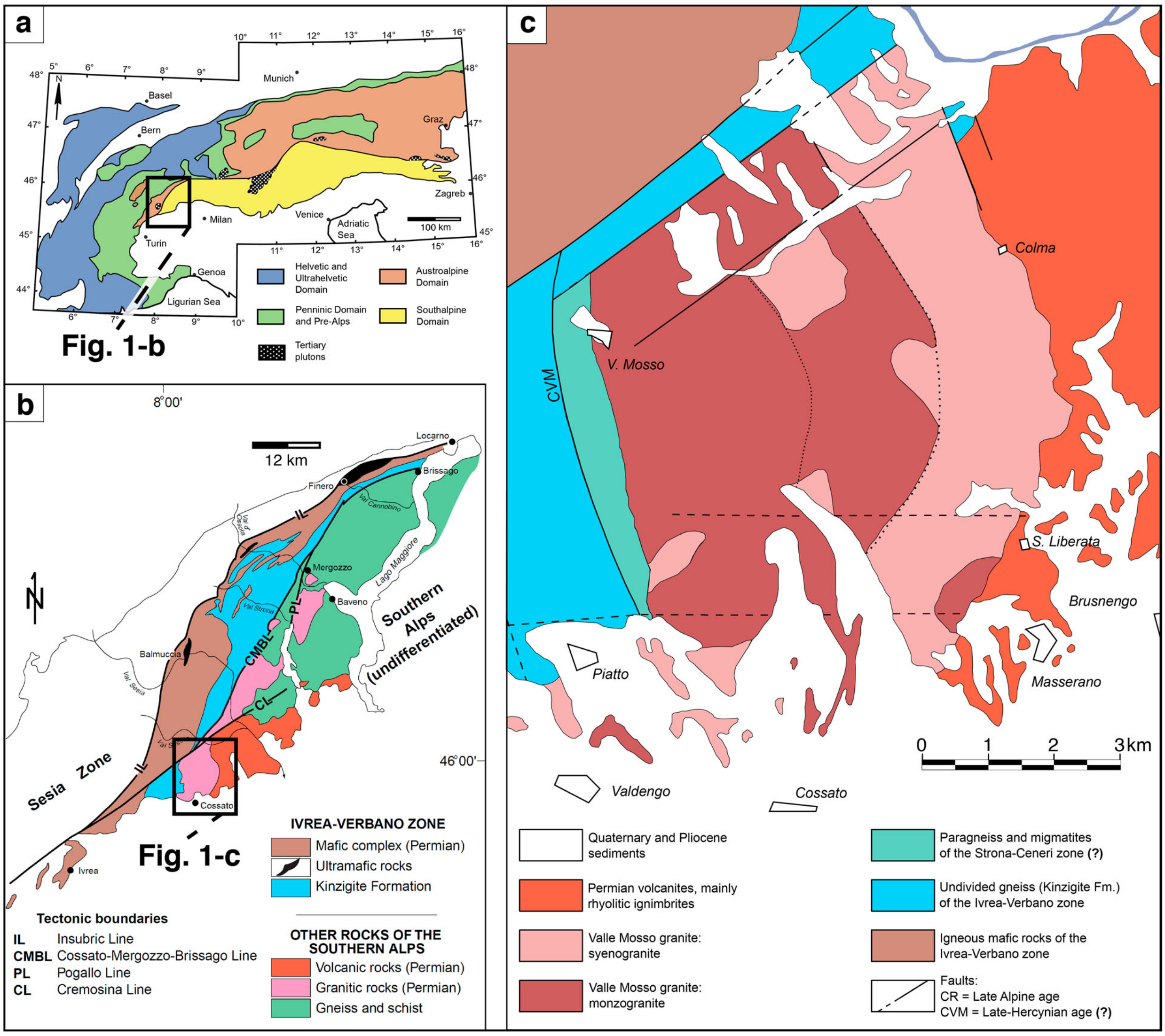

Figure 1. (a) Simplified tectonic outline of the Alpine chain modified from Handy, Babist, Wagner, Rosenberg, and Konrad (2005). Inset shows the position of the Ivrea-Verbano Zone in the context of Southern Alps; (b) Generalized geological map of the Ivrea-Verbano Zone and environs after Snoke, Kalakay, Quick, and Sinigoi (1999), the map area of Figure 1(c) is outlined; (c) Geological sketch map of the VMP and its surroundings after Zezza et al. (1984a). Dotted lines represent limits between the mesozonal and epizonal plutonic rocks.

(Ewing, Rubatto, & Hermann, 2013; Kunz, Johnson, White, & Redler, 2014; Redler, Johnson, White, & Kunz, 2012; Redler, White, & Johnson, 2013; Rutter, Brodie, James, & Burlini, 2007; Schmid, 1967, 1978; Sills & Tarney, 1984; Zingg, 1980) record an increase in both metamorphic grade and equilibration pressure from southeast to northwest (Demarchi, Quick, Sinigoi, & Mayer, 1998; Henk, Franz, Teufel, & Oncken, 1997; Rutter et al., 2007; Zingg, 1980). In the southern and central area of the crustal section, rocks of the Kinzigite Formation are intruded by a gabbro-norite body about 8-km thick, which in literature is referred to as the Mafic Complex (Figure 1(b); Quick, Sinigoi, & Mayer, 1994; Quick, Sinigoi, Negrini, Demarchi, & Mayer, 1992; Quick et al. 2003; Rivalenti, Garuti, & Rossi, 1975; Rivalenti, Rossi, Siena, & Sinigoi, 1984; Sinigoi et al., 1991, 1994; Voshage et al., 1990). Incremental growth of the Mafic Complex occurred between 292 and 286 Ma (Klötzli et al., 2014; Peressini, Quick, Sinigoi, Hofmann, & Fanning, 2007; Sinigoi, Quick, Demarchi, & Klötzli, 2011).

East of the Ivrea-Verbano Zone, the Serie dei Laghi constitutes the middle to upper part of the crustal section and comprises Early Paleozoic metasedimentary schists and gneisses, locally banded amphibolites with eclogite-facies relicts and orthogneisses of Ordovician age (Boriani, Giobbi – Origoni, Borghi, & Caironi, 1990; Franz & Romer, 2007; Zurbriggen, Franz, & Handy, 1997; Zurbriggen, 2015). The Serie dei Laghi contains granitic plutons grouped as Graniti dei Laghi (Figure 1(b), which include the Valle Mosso (a.k.a.Valsessera-Biellese), Alzo-Roccapietra, Quarna, Mottarone-Baveno, and Montorfano bodies (Boriani et al., 1988) emplaced during Early Permian (spanning from 296 to 282 Ma; Klötzli et al., 2014; Köppel, 1974; Pinarelli, Del Moro, & Boriani, 1988; Quick et al., 2009; Schaltegger & Brack, 2007). The south-eastern sector of the Serie dei Laghi is overlain by volcanic rocks dominated by caldera fill deposit, including mainly rhyolitic tuff and ignimbrite and patches of megabreccia (Quick et al., 2009). Volcanic activity persisted from *circa* 290 to 282 Ma, and was coeval with the growth of the granitic plutons in the Serie dei Laghi and the Mafic Complex in the Ivrea-Verbano Zone (Quick et al., 2009). This association of coeval igneous rocks is referred to as the Sesia Magmatic System (Sinigoi, Quick, Demarchi, & Peressini, 2010), whose activity culminated with the collapse of a caldera at least 15 km across *ca.* 282 Ma ago (Quick et al., 2009*)*. This magmatic system belongs to the larger Late Carboniferous-Early Permian igneous province of Western Europe related to a large-scale rift system (Wilson et al., 2004 and references therein).

The boundary between Ivrea-Verbano Zone and Serie dei Laghi is historically considered tectonic, corresponding to the Cossato–Mergozzo–Brissago (CMB) Line (Figure 1(b); Boriani & Sacchi, 1973). However, whereas the CMB Line corresponds to a mylonitic belt in the North *(*Handy et al., 1999*)*, it was extrapolated based to the South based on the occurrence of small intrusive bodies (Appinites of Boriani, Colombo, Giobbi Origoni, & Peyronel Pagliani, 1974).

The VMP is part of a larger intrusion, which includes the Roccapietra body (Boriani & Sacchi, 1973; Zezza, Meloni, & Oddone, 1984a). The two granite bodies are separated by the Cremosina Line, a subvertical Alpine, northeast-striking, right-lateral strike-slip fault with an offset of about 12 km in its central section (Boriani & Sacchi, 1973; Figure 1(b)). Zezza (1964a, 1964b, 1969, 1973, 1977, 1984a, 1984b) recognized two granitic facies (‘a’ monzogranitic and ‘b’ syenogranitic facies), based on the textural, compositional and chromatic features of the granitic rocks (Figure 1(c)). To the West, the pluton exposes a subvertical primary contact between the monzogranitic facies and upper amphibolite facies gneisses of the Kinzigite Formation. To the East the syenogranitic facies, which shows myarolitic cavities (Section 4.1.6.), intrudes volcanic rocks and lower-amphibolite facies metamorphic rocks of the Serie dei Laghi. The latter contact dips ~60° to the East. The attitude of these primary contacts and the spatial distribution of granitic lithologies in the intrusion demonstrate that, whereas some granite bodies of the ‘Serie dei Laghi’ were tilted by only 20° (e.g. the Baveno body, Boriani et al., 1988), the Valle Mosso body was tilted by >60° during the exhumation of the crustal section, and exposes both the roof and floor contacts (Quick et al., 2009; Sinigoi, Quick, Demarchi, & Klötzli, 2016; Zezza, 1977).

3. Mapping method and representation

Geological mapping has been performed at 1:10,000 scale using topographic maps produced by the Regione Piemonte and downloadable in both vector and raster format from the ‘GeoPortale Piemonte’ website (http://www.geoportale.piemonte.it/cms/).

The bedrock exposure in the mapped area is poor due to a thick widespread colluvial cover and good outcrops are limited to streambeds and rare road cuts. The inferred lithostratigraphic configuration has been represented on a ‘drift and solid’ map, in which surfacing rocks are separated by rocks blanketed in drift cover (Delleani, Iole Spalla, Castelli, & Gosso, 2013; Kupfer, 1966; Rau & Tongiorgi, 1972a, 1972b; Spalla, De Maria, Gosso, Miletto, & Pognante, 1983, 2002). Thus, geological units are represented on the map with outcrop dependent color intensity, softer colors are indicative of drift-covered (and thus interpreted) bedrock while full-colors indicate outcropping bedrock (Main Map).

Both textural and compositional criteria have been used together for the characterization of the different granitic petrofacies (Farina, Dini, Innocenti, Rocchi, & Westerman, 2010). Size, shape and modal abundance of the main rock-forming minerals, nature of the ferromagnesian minerals, color index and enclave abundance paired with later thin-section petrography and whole-rock geochemistry helped to clarify and refine the field-based criteria.

4. Rock units

4.1. Granitic rocks of the VMP

A suite of Permian (296–282 Ma; Klötzli et al., 2014) intrusive rocks emplaced between polymetamorphic rocks of the Kinzigite Formation and volcanic rocks of the Sesia caldera (Sbisà, 2009) constitutes the VMP. It is a composite intrusion of granodioritic to syenogranitic rocks comprising subordinate volumes of dioritic, gabbroic and aplitic rocks, which has been further subdivided into different intrusive facies. The main features of the granitic facies identified during the mapping are presented in Table 1 and Figures 2 and 3.

4.1.1. Granodioritic monzogranite – Lower Valle Mosso facies (vgrL)

This facies constitutes the westernmost sector of the pluton and shows a wide compositional variability ranging from diorite to monzogranite. Coarse-grained monzogranite, locally foliated (Figure 2(a); Section 5.1), constitutes the bulk of the unit but several pods of granodioritic composition, rich in mafic material (syn-plutonic dioritic to gabbroic sheets and dikes associated to mafic enclaves swarms; Figure 2(c)) are

Table 1. Main petrographic features of the VMP intrusive facies.

Granitic facies	Lower Valle Mosso facies	Fila facies	Vaudano facies	Monte Bastia facies	Montaldo facies	Upper Valle Mosso facies
Lithology	Granodioritic monzogranite	Two-mica micro-leucogranite	Inequigranular to porphyric monzogranite	Granitic porphyry	Equigranular white monzogranite	Equigranular pink leucosyenogranite
Color Index	10–15	< 5	5–10	15–30	5	< 5
Rock-forming minerals	Qtz, Pl, Kfs, Bt, ± Am	Qtz, Pl, Kfs, Mu, Bt	Qtz, Pl, Kfs, Bt, ± Mu	Qtz, Pl, Kfs, Bt, ± Am	Qtz, Kfs, Pl, Bt, ± Mu	Qtz, Kfs, Pl, Bt, Mu
Accessory minerals	Zr, Ap, Ep (ortite), Ttn	And, Zr, Ap	Zr, Ap, Ep (ortite)	Zr, Ap, Ep (ortite), Ttn	Mu, Ep, Zr, Ap	Zr, Ap, Ep, Tur
Texture	Inequigranular seriate. Locally oriented due to magmatic flux	Equigranular	Inequigranular strongly to slightly porphyritic	Inequigranular, strongly porphyritic	Equigranular seriate, uniform texture	Equigranular, granophyric domains locally abundant
Grain size	Coarse grained	Fine grained	Coarse-grained K-feldspar in a fine-grained matrix	Coarse-grained K-feldspar, plagioclase and quartz in a quasi-aphanitic matrix	Medium to coarse grained	Medium to coarse grained
Alkali feldspar	Microcline	Microcline and Pertitic Orthoclase	Pertitic Orthoclase	Pertitic Orthoclase	Pertitic Orthoclase	Pertitic Orthoclase
Size of alkali feldspar	0.5–2.0 cm	< 0.3 cm	0.5–4.0 cm	0.3–3.0 cm	0.5–1.5 cm	0.2–1.5 cm
Plagioclase morphology	Euhedral, sometimes as oikocrysts.	Small and euhedral	Euhedral, sometimes as oikocrysts.	Usually corroded and resorbed as xenocrysts	Euhedral	Small and euhedral
Enclave type and abundance	Variable vol% Common mafic to intermediate enclaves. Country-rock xenoliths present	Rare mafic and intermediate enclaves	Variable vol% Common mafic and intermediate enclaves	Variable vol% (up to 30–40% vol%) Mafic enclaves are locally common	Rare mafic enclaves	Extremely rare intermediate enclaves

Note: Abbreviations: Qtz: quartz; Pl: plagioclase; Kfs: K-feldspar (Mc: microcline; Or: orthoclase); Bt: biotite; Mu: muscovite; Am: amphibole; Tur: tourmaline; And: andalusite; Ep: epidote; Chl: chlorite; Ttn: titanite; Zr: zircon; Ap: apatite. Mineral abbreviations from Siivola and Schmidt (2007).

common. In the dominant monzogranite, texture is inequigranular for homogeneously distributed K-feldspar crystals of microcline 1–2 cm in size (Figure 3(a)). Plagioclase is euhedral and frequently shows oscillatory zoning. Quartz is anhedral with interstitial nature. Biotite forms clots and stripes that are stretched concordantly to the main anisotropy (Figure 2(a)). An U-Pb zircon age of 282.1 ± 3.4 Ma (Klötzli et al., 2014) has been obtained for a foliated monzogranite sample of this facies.

4.1.2. Two-mica leucogranite – Fila facies (vgrF)

Fila facies crops out in the western part of the pluton as metric to decametric, NNW-striking leucocratic bodies (Figure 2(b)). The rock texture is allotriomorphic with widespread granophyric intergrowths between quartz and K-feldspar (Figure 3(b)). Its mineral constituents are K-feldspar, quartz, plagioclase, muscovite and biotite. The K-feldspar is usually perthitic orthoclase while plagioclase is small and usually lacks any optical zoning pattern. Biotite and muscovite can vary in proportion between the individual bodies. Moreover, andalusite has been observed in a few samples.

4.1.3. Porphyritic monzogranite – Vaudano facies (vgrP)

The Vaudano facies, set in the central sector of the VMP, is a porphyritic monzogranite with K-feldspar phenocrysts (1–4 cm length of c-axis) set in a medium- to fine-grained holocrystalline matrix. The typical K-feldspar that constitutes both the cm-sized phenocrysts and the matrix intergrowth is perthitic orthoclase, which is usually poikilitic and infrequently presents weak microclinitization (Figure 3(c)). Growth of plagioclase mantle on orthoclase crystals to form rapakivi texture (Sederholm, 1891) and, of an alkali-feldspar rim around plagioclase (antirapakivi texture), is a local feature of these porphyritic rocks. Quartz is anhedral and interstitial in the matrix; however, rounded mm-sized quartz crystals are locally abundant. The biotite is the mafic phase of this facies, and only minor muscovite content is locally reported. An U-Pb zircon age of 290.3 ± 4.2 Ma is reported for this facies (Klötzli et al., 2014).

4.1.4. Granite porphyry – Monte Bastia facies (vgrM)

The Monte Bastia facies, characterized by a fine-grained to aphanitic matrix and a phenocrysts content ranging between 5% and 45%, constitutes a singular hectometric NNW-elongated body inside the Vaudano facies (Figure 2(d)). The phenocrysts are rounded K-feldspar, plagioclase, biotite and quartz crystals set in a sub-mm matrix. Most phenocrysts are anhedral and appear to be highly corroded; K-feldspars have plagioclase rims producing usually rapakivi texture (Figure 3(d)). Mafic enclaves are common: they span from cm-sized rounded blobs with sharp or interdigitated contacts with their host rock, to mm-sized biotite aggregates.

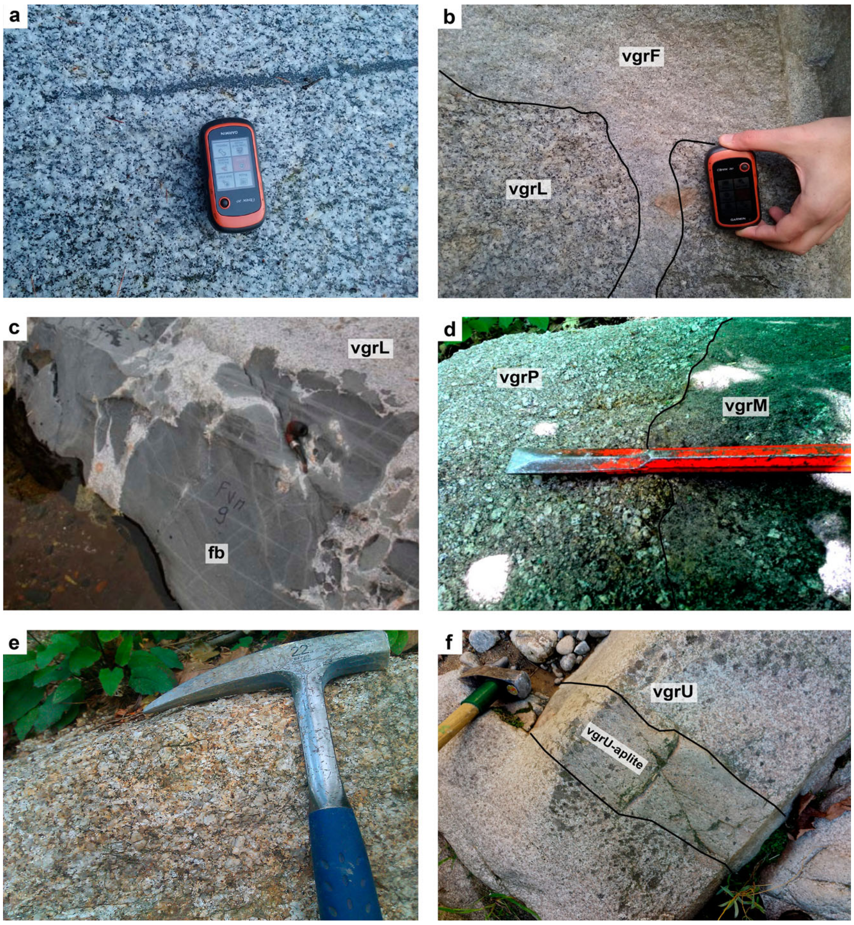

Figure 2. Outcrop-scale view on granitic facies of the VMP. (a) Biotite-rich layer (schlieren) parallel to the magmatic foliation in the Lower Valle Mosso facies (vgrL); (b) Lower Valle Mosso facies (vgrL) cross cut by diklet of Fila facies fine-grained leucogranite (vgrF) that forms a m-sized sill; (c) Permian doleritic dike (fb) intrusion into the foliated Lower Valle Mosso facies (vgrL), showing soft contact and the production of a thin layer of hybrid dioritic melt at the dike-granite interface; (d) Porphyritc granite of the Vaudano facies (vgrP) in soft contact with the granitic porphyry of Monte Bastia facies (vgrM) (e) Partly weathered equigranular monzogranite of the Montaldo facies (vgrE); (f) Sharp aplitic dike (vgrU-aplite) cross cut the Upper Valle Mosso facies (vgrU). GPS device, sizzle, hammerhead and sledgehammer head are respectively 10, 20, 15 and 20 cm in length.

4.1.5. White equigranular monzogranite – Montaldo facies (vgrE)

This monzogranitic facies is peculiar for its homogeneity over a large area of the mapped zone retaining the same textural and compositional features throughout a 7 km long and 1.5 km wide body. This facies consists of coarse-grained monzogranite (Figure 2(e)) with hypidiomorphic texture (Figure 3(e)). Biotite is the only mafic mineral and constitutes no more than 5% in modal abundance. A system of aplitic dikes striking mostly along E–W direction crosscuts the whole intrusive unit (see Section 4.1.7). An U-Pb zircon age of 296.4 ± 4.2 Ma (Klötzli et al., 2014) has been obtained for this facies.

4.1.6. Pink equigranular syenogranite – Upper Valle Mosso facies (vgrU)

The easternmost facies of the intrusion consists of coarse equigranular syenogranite marked by strong pink coloring of K-feldspars (due to kaolinitization; Figures 2(f) and 3(f)). It shows hypidiomorphic texture with euhedral and usually perthitic orthoclase crystals surrounded by anhedral quartz and rare plagioclase grains (Figure 3(f)). Biotite is usually deeply chloritized and locally replaced by secondary muscovite. Approaching the contact with the volcanic rocks, granophyre bodies become volumetrically relevant, showing fine grain size and incipient micrographic texture. Pegmatitic veins and pockets, miarolitic cavities and up to m-sized quartz dikes are common features of Upper Valle Mosso facies outcrops, together with ubiquitous aplitic dikes (Figure 2(f)) and locally abundant schlieren. Two different samples from this facies give U-Pb zircon ages of 275 ± 4 and 278 ± 5 Ma respectively (Quick et al., 2009).

4.1.7. Valle Mosso dikes system (fq – fb)

Based on their field and petrographic features the observed dikes fall into three groups:

- Aplitic dikes: Ubiquitous throughout the intrusion, they vary from several centimeters to meter in

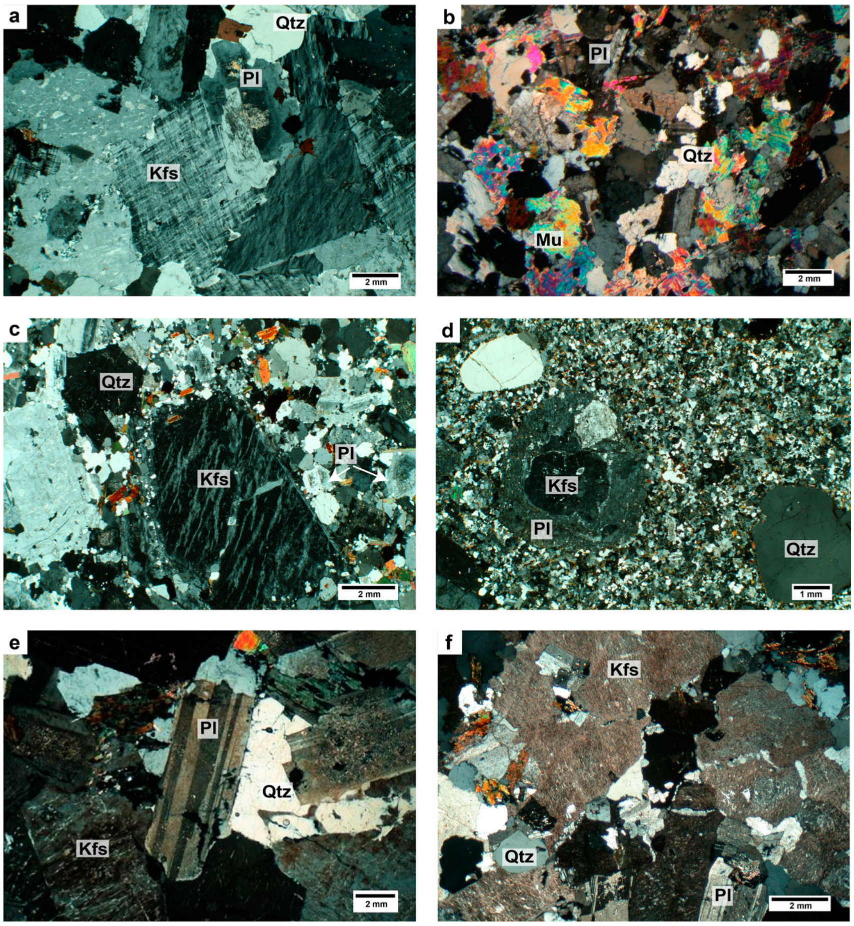

Figure 3. Crossed polars thin-section microphotographs exemplifying textural features of the Valle Mosso granitic facies. (a) Zoned plagioclase, euhedral microcline and interstitial quartz form an hypidiomorphic texture in the unfoliated portion of the Lower Valle Mosso facies (vgrL); (b) High muscovite content and allotriomorphic texture are the main features of leucogranitic rocks from the Fila facies (vgrF); (c) Vaudano facies (vgrP) cm-sized perthitic orthoclase crystals set in a sub-mm sized holocrystalline matrix: (d) Monte Bastia facies (vgrM) typically shows cm-sized anhedral k-feldspar (usually surrounded by prominent plagioclase rim) and rounded quartz phenocrysts set in a very fine-grained matrix; (e) Interlocking texture of cm-sized euhedral orthoclase and plagioclase crystals together with interstitial quartz, in the Montaldo facies (vgrE); (f) Interlocking texture paired with kaolinitization of orthoclase component characterize syenogranites of Upper Valle Mosso facies (vgrU).

width (Figure 2(f)) striking mainly along E–W direction.

- Mafic dikes (*fb*): The Lower Valle Mosso facies is intruded by sparse metric to decametric wide mafic dikes, which are best exposed in the streambed of the Strona River near the town of Valle Mosso. These dikes develop a variety of textures at the interface with the granitic host rock, from sharp contacts characterized by chilled margins and no evidence of mingling between the two melt batches, to soft contacts associated with generation of hybrid melts and swarms of mafic enclaves (Figure 2(c)). Mafic dikes are mainly basaltic in composition with ophitic texture and a mineral assemblage given by Pl + Cpx (mainly Ti-rich augite) + Opx + Am (in uralitic aggregates around pyroxenes) ± Ol ± Ilm (mineral abbreviations after Siivola & Schmid, 2007). They usually present chilled margins.
- Hydrothermal quartz dikes (*fq*): in the Upper Valle Mosso facies numerous quartz dikes have been mapped. They range from cm- to m-sized and are reported to crosscut the intrusion's roof (Zezza, Callegari, & Oddone, 1984b). The most representative quartz dike has hectometric length, apparent width of *ca.* 5 m and subvertical attitude, it is mostly made up of whitish quartz, abundant epidote and chlorite.

4.2. Volcanic rocks of the Sesia caldera (r)

Volcanic rocks are dominantly crystal-rich rhyolites, with quartz, K-feldspar and plagioclase phenocrysts, in which the glassy matrix has undergone diffused hydrothermal alteration and pervasive devitrification. Inside the volcanic unit, Sbisà (2009) has identified several megabreccia domains, in which metric to decametric blocks of pre-caldera lavas and intrusive rocks are welded in a rhyiolitic matrix. In proximity of the roof of the VMP (*ca.* 600 m wide zone; Sbisà, 2009), rhyiolitic rocks underwent contact metamorphism. In the contact aureole area the volcanic rocks becomes more resilient to alteration, progressively changing color and becoming glassy blue and massive. At the microscopic scale, it is possible to observe a homogeneous re-crystallization of the ignimbrite groundmass.

4.3. The Mafic Complex (mcg)

Intrusive rocks of the Ivrea-Verbano Zone Mafic Complex are exposed in the NW corner of the map; they consist mostly of gabbroic and noritic rocks with subordinate ultramafic, intermediate, and silicic plutonic rocks. In the mapped area the dominant lithologies are gabbro and norite. The main textural anisotropies are given by a weak foliation defined by pyroxene and amphibole preferred orientation together with centimeter-scale to meter-scale banding defined by abrupt changes in color index. In addition to the main gabbroic rock volume, cumulus ultramafic rocks crop out in a variety of settings and comprise dunite, harzburgite, and websterite. However, subtle lithological variations and ultramafic cumulus bodies are not represented on the map, for a detailed account of Mafic Complex geology the reader is addressed to Quick et al. (2003).

4.4. Metamorphic units

The VMP is located in the southernmost sector of the Ivrea crustal section, on the boundary between the medium to high-grade metamorphic rocks of the Kinzigite Formation (Rutter et al., 2007; Sills & Tarney, 1984; Zingg, 1983) and the medium to low-grade metamorphic rocks of the Strona-Ceneri Zone (Boriani et al., 1990; Franz & Romer, 2007; Zurbriggen et al., 1997, 2015). The main mineralogical and textural features of the country rock lithotypes are presented in Table 2; all mineral abbreviations used in this paragraph are after Siivola and Schmid (2007).

4.4.1. Kinzigite formation (pgn)a

Metamorphic rocks on the northern and western ends of the VMP range from medium to upper amphibolite facies paragneiss with intercalated amphibolite lenses, to small, foliated intrusive bodies (granodioritic to tonalitic in composition) and undeformed leucosomes. North of the Cremosina Line is an upper amphibolite facies paragneiss that consists of medium- to coarse-grained Qtz + Bt + Pl + perthitic Kfs + Crd + And + Sil ± Al-spinel. In the western sector of the map, Kinzigite Formation is represented by a quartzo-feldspathic paragneiss, consisting of fine- to medium-grained Qtz – Pl – Kfs with lesser amount of Bt ± Mu ± Grt ± And ± Crd ± Sil ± Al-spinel (Figure 4(a) and (b)). In proximity of the contact with the VMP, the paragneiss show stromatic metatexite migmatite structure in which granitic to tonalitic leucosome is interlayered with residuum pelitic and quartzo-feldspathic paragneiss (Figure 5(a)). Both in migmatitic and non-migmatitic paragneiss, amphibolites typically form fine-grained melanocratic boudins, which range in size from decimeters to meters and consist of fine- to medium-grained Am ± Kfs ± Fe-Ti Ox ± Ttn (Figure 4(c)).

4.4.2. Strona-Ceneri Zone (ogn)

At the northeastern termination of the VMP crops out a 100 m wide sliver of quartzo-feldspathic gneisses with interlayered fine-grained amphibolite lenses. This N–S striking sliver consists of fine-grained paragneiss and alternating leucocratic and melanocratic bands of orthogneiss; mineralogy of melanocratic bands is given by Bt + Qtz + Pl + Kfs ± W-mica (Figure 4(c)), while leucocratic bands are mostly made up of Wmca + Qtz + Pl + Kfs ± Bt. These metamorphic

Table 2. Main mineralogical and textural features of the metamorphic lithotypes in the VMP area.

Lithological unit	Rock-type	Modal composition	Metamorphic/structural texture
Strona-Ceneri Zone	Orthogneiss	Qtz 40%, Kfs 30%, Pl 10%, Bt 15–20%, Chl < 3%	Medium grained gneissic rock; texture is granoblastic, coarse Bt marks a spaced foliation; fine-grained Bt defines a secondary micro localized fabric (Figure 4(d)).
	Paragneiss (metapelite)	Qtz 30%, Kfs 20%, Pl 20%, Bt 10–20%, Wmca 10%, Grt 3–5%, Chl < 5%	Fine-grained mylonitic texture with Qtz SGR recrystallization; mm-sized cataclastic domains marked by Kfs and Qtz BLG.
	Amphibolite	Qtz 10%, Pl 30%, Am 30%, Bt / Chl 20%, Ilm 10%	Light green colored fine-grained rocks with continuous foliation evidenced by Bt/Chl, Am and Pl SPO.
Kinzigite Formation			
West of VMP	Paragneiss (metarkose)	Qtz 40%, Kfs (Or, Mc) 40%, Pl 10%, Bt 1%, Chl < 5%, Mu < 5%, Grt < 5%	Fine-grained rock with a continuous foliation defined by Chl and Oxides; the texture ranges from inequigranular ameboidal to granoblastic.
	Paragneiss (metapelite)	Qtz 40%, Pl 15%, Kfs (Mc) 10%, Bt 25%, Mu 5%, ± Grt 2%, ± Crd 2–5%, ± Sil (Fibrolite) 2%, ± And 1% ± Al-Spl < 1%	Fine-grained medium grade paragneiss with gneissic inequigranular texture marked by spaced foliation of Bt (Figure 4 (a,b)).
	Amphibolite	Qtz 5%, Pl 30–40%, Am 40–50%, Bt 1–2%, Ilm 10%	Light green colored fine- to medium-grained rock with continuous foliation evidenced by Ilm, Am and Pl SPO (Figure 4(c)).
North of VMP	Paragneiss (metapelite)	Qtz 30%, Kfs 30%, Pl 5–10%, Bt 20%, And 5%, Crd 5%, Sil < 5%, Al-Spl < 1%	Coarse-grained rock composed by an association of Qtz, Kfs, Pl, Bt, And, Spl, Crd, Sil that shows a granoblastic texture.

Note: Abbreviations: Cpx: clinopyroxene; And: andalusite; Ilm: ilmenite; Wmca: white-mica; Chl: chlorite; Spl: spinel; Crd: cordierite; Grt: garnet; Mu: muscovite; Bt: biotite; Kfs: K-feldspar (Mc: microcline; Or: orthoclase); Pl: plagioclase; Qtz: quartz; Am: amphibole; SPO: shape preferred orientation; BLG: bulging; and SGR: sub-grain recrystallization. Mineral abbreviations from Siivola and Schmidt (2007).

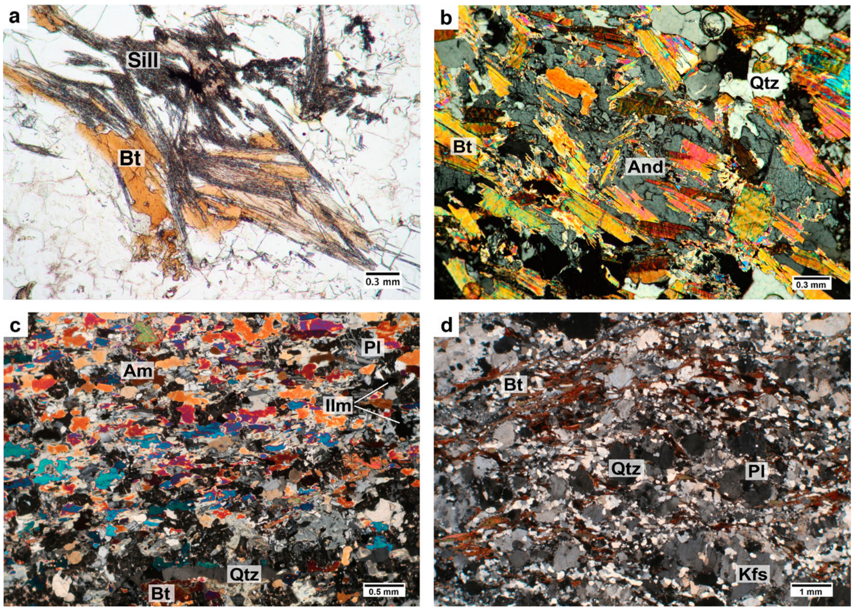

Figure 4. Microphotographs of selected metamorphic lithologies from VMP host rocks. (a) Fibrolitic sillimanite aggregates are observed in the paragneiss residuum of stromatic metatexite migmatite find in proximity to the contact with the VMP; (b) Andalusite and granoblastic quartz are features of the Kinzigite formation paragneiss highlighted in this enlargement. (c) Medium-grained amphibolite in which a continuous foliation is defined by Am and Qtz-Pl domains; (d) Medium-grained orthogneiss form the Strona-Ceneri Zone dominated by a Kfs-Pl-Qtz mineralogy in which biotite marks a weakly developed foliation.

rocks acquire a reddish coloring in proximity of the contact with the intruding Upper Valle Mosso facies granite.

4.5. Surficial covers (Qtu, Qt, Qa)

Moderately consolidated deposits of conglomerate, sandstone, and shale with minor carbonate, whenever encountered, have been mapped as undivided Tertiary to Quaternary sedimentary deposits (*QTu*). Poorly consolidated to unconsolidated materials ranging in grain size from boulders to clay and deposited up to 30–40 m above the currently active flood plains have been represented in map as terrace deposits (*Qt*). Finally, active flood plains deposits, boulders, cobbles, gravel, sand, and silt that constitute riverbanks and small islets along the main rivers have been mapped as alluvium (*Qa*).

5. Structural data

5.1. Magmatic structures

In the proximity of pluton's floor, granodioritic monzogranite of the Lower Valle Mosso facies (vgrL) displays magmatic foliation (Sm) and lineation (Lm), which are defined by shape preferred orientation (SPO) of igneous minerals (K-feldspar, plagioclase, minor amphibole and biotite) and preferred orientation of dioritic enclaves and xenoliths (Figures 2(a) and 5(b)). The magmatic nature of this foliation is also testified at the microscopic scale by absence of solid-state deformation in the igneous minerals, euhedral grains, straight grain boundaries and interstitial anhedral quartz grains (pre-RCMP, Paterson, Vernon, & Tobisch, 1989; Tribe & D'Lemos, 1996).

5.2. Relationship between intrusive facies

Gradational contacts mark the boundaries between the four main Valle Mosso intrusive facies (Lower Valle Mosso, Vaudano, Montaldo and Upper Valle Mosso). These progressive transitions usually take place in a 10–100 m interval in which textural features of a facies gradually fade into that of the nearby facies. On the other hand, the two lesser facies, Fila and Monte Bastia, show diverse contact morphology to the main granitic body. In fact, the Fila facies is represented by decametric to hectometric bodies of fine-grained granite, which sharply crosscut the Lower Valle Mosso and Vaudano facies, dislocating crystals (Figure 2(b)) and locally mafic enclaves. Instead the contact between the Monte Bastia and Vaudano facies is usually soft and lobate (Figure 2(d)), also characterized by a gradual transition over a distance of 10–20 cm.

5.3. Floor and roof contacts

The floor of the pluton is represented by weakly foliated granodioritic monzogranite of the Lower Valle Mosso facies showing a steeply dipping (70–75° NE) primary contact with migmatitic paragneiss of the Kinzigite Formation (Figure 5(b)). The magmatic foliation developed by the in the monzogranite (Section 5.1) ranges from concordant to slightly discordant to the

Figure 5. (a) Kinzigite formation paragneiss showing stromatic metatexite migmatite structure in proximity of the VMP floor contact. View of an horizontal outcrop surface approximately perpendicular to the steep foliation, which shows two discordant dikes of leucogranite on the center that exhibits petrographic continuity (with similar microstructure, mineralogy, and mode) with leucosome in foliationparallel stromata; (b) Floor of the VMP, migmatitic foliation in Kinzigite Formation paragneiss (pgn) is parallel to the weakly developed magmatic foliation in Lower Valle Mosso facies (vgrL); (c) Metric-sized Kinzigite septum (pgn) close to the floor of the pluton; (d) Presence of garnet in the Lower Valle Mosso granite, 10 cm away from the contact with a Kinzigite septum; (e–f) Aplitic dike that cut across the main schistosity of orthogneiss (ogn) from the Strona-Ceneri Zone; (g) Pink syenogranite of the Upper Valle Mosso facies (vgrU) intrudes rhyolites of the Sesia Caldera at the roof of the pluton.

migmatitic foliation in metamorphic host rocks (Figure 6(a,b)). In the first 20–30 m from the floor contact, several slices of metamorphic rocks (up to 2–3 m wide and several meters long) have been incorporated into the foliated monzogranite and retain parallelism to the granite foliation (Figure 5(c)). In the proximity of metamorphic slices, there is a peculiar growth of garnet inside the foliated granodiorite of the Lower Valle Mosso facies (Figure 5(d)). At the pluton's roof, pink syenogranite of the Upper Valle Mosso facies intrudes both volcanic rocks of the Sesia caldera and a sliver of metamorphic rocks of the Strona-Ceneri Zone. In the streambed of the Ponzone river aplitic dikes, which vary in size from cm- to meter-wide, crosscut the pluton – host rock boundary intruding both gneiss and amphibolite of the Strona-Ceneri Zone discordant to their main foliation pattern (Figure 5(e,f)). Primary contacts where granitic rocks intrude rhyolites are well exposed at least in three outcrops in the NE area of the map, near San Bononio village, along the Ostola riverbanks (Figure 5(g)) and on the flanks of Monte Localà. The contact is always sharp, steeply dipping (up to 70°), and sub concordant to the eutaxitic and flow foliation preserved in the ignimbrites and rare lava flows of the Sesia caldera (Figure 6(c)). The interface is locally characterized by the development of intrusive breccia, in which rhyolitic fragments are set in a granophyric granite matrix that extends up to several meters from the main granites-volcanites interface.

5.4. Ductile structures

Except from volcanic rocks intruded by the VMP at its easternmost termination, which are Permian in age (Quick et al., 2009), all the other intrusion's host rock

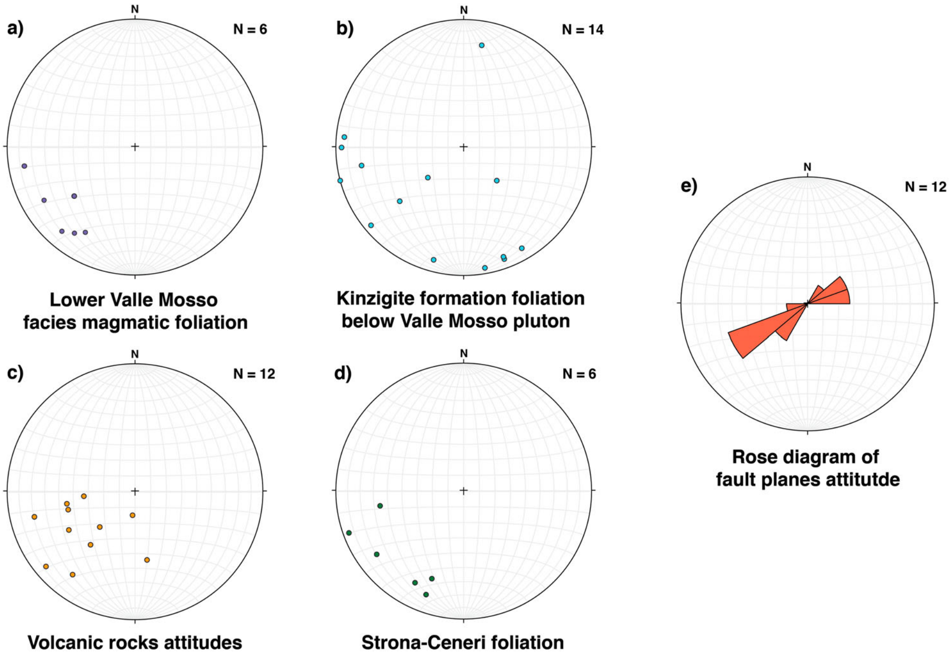

Figure 6. Equal area lower hemisphere projection of structural data (poles of foliation) from igneous and metamorphic rocks of the map area. (a) Lower Valle Mosso magmatic foliation close to the contact with Kinzigite Formation host rock; (b) Foliation in Kinzigite Formation paragneiss to the West of the VMP. The main N–S trend in the foliation turns to an E–W trend in the Valle San Nicolao area; (c) Attitude of volcanic rocks strata of the Sesia caldera; (d) Foliations measured on the Strona-Ceneri slice between the intrusion roof and the volcanic rocks; (e) Rose diagrams showing the attitude of the major brittle structures in the map area (NNE-SSW trending).

lithologies are metamorphic sequences that underwent complex polyphase metamorphism and deformation histories prior to the VMP emplacement. Kinzigite formation has been affected by polyphase deformation yielding complex fold patterns at mesoscopic scale. A steeply E–NE dipping foliation is the dominant structure in these rocks and can be followed for more than 5 km along the Kinzigite – granite boundary (Figure 6(b)). Metamorphic rocks of the Strona-Ceneri Zone present compositional banding and a gneissose structure that dips steeply (60–70°) to the NE and is constant both along and across strike throughout the whole metamorphic sliver (Figure 6(d)).

5.5. Brittle structures

In the mapped area the Cremosina Line represents the tectonic structure of Alpine age that affected the southern Alpine Ivrea-Verbano basement from the Oligocene onward. This structure is a regional-scale, northeast-striking, steeply dipping fault (Figure 6(e)), which constitutes the northern boundary of the VMP. Regional compilations show it joining the Insubric Line to the southwest and having an apparent dextral slip of about 12 km (Boriani & Sacchi, 1973). There are at least three outcrops in the map area where a thick level (20–30 m across strike) of damaged and fluid circulated granitic and metamorphic rocks suggests the existence of a regionally significant brittle structure. Rocks sampled along this level present cataclastic fabric, wherein deformed and fragmented feldspars and quartz grains are set in a very fine-grained comminuted matrix. Minor brittle structures have orientation, displacement, and style of deformation to be considered riedel shears (Sylvester, 1988) related to motion along the Cremosina Line.

6. Conclusions

A detailed field survey, including geological mapping and petrographic-geochemical investigations allowed the compilation of a new 1:15,000 scale geological map of the VMP and its surroundings, which gives new insights about the granitic Permian magmatism in the Ivrea-Verbano Zone and its relations to the other units of the Ivrea crustal section.

Specifically, from the lithological point of view:

- The VMP is more compositionally and texturally heterogeneous than previously described, new facies have been recognized other than the type ‘a’ monzogranite and type ‘b’ syenogranite described in Zezza, 1977. Notably a well-defined porphyritic unit, a granitic porphyry body and several Mu-rich leucogranitic sills/dikes have been identified for the first time;
- Sheet-like intrusions of increasing degree of differentiation define the VMP geometry. They range from granodioritic composition at the floor to Si-rich syenogranite at the roof contact;

- The Monte Bastia facies step aside for its peculiar textural characteristics. Abundance of mafic enclaves, resorption and regrowth textures on corroded phenocrysts and an extremely fine-grained groundmass are inconsistent with an undisturbed cooling history at middle crustal depth. The observed features suggest that an episode of rejuvenation at the expense of a melt-rich crystal-mush has possibly affected portion of the Vaudano facies. Reheating and rejuvenation of a cooling granitic magma chambers by Wiebe, Manon, Hawkins, and McDonough (2004) and Wiebe, Wark, and Hawkins (2007) to produce the same textural features in the Vinalhaven pluton.

From the structural point of view:

- The VMP is intruded between two different metamorphic units, Kinzigite Formation paragneiss at the floor and quartzo-feldspathic gneiss of the Strona-Ceneri Zone at the roof. The mapped slice of Strona-Ceneri rocks at the roof of the pluton, which is uncomformably covered by Permian volcanic deposits and intruded by the Upper Valle Mosso facies, could be interpreted either as a roof pendant or as a fragment of intact pre-Permian crust.
- Previous geological literature on the area (Boriani & Sacchi, 1973; Zezza, 1977) postulated the existence of a pre-Permian NNW-striking ductile shear zone in the proximity of the floor of the VMP. Named as CVM (Cossato-Valle Mosso) line after Boriani and Sacchi (1973), it was interpreted as the southern continuation of the CMB line (see Section 2), which is generally considered as the boundary between the Ivrea-Verbano and Strona Ceneri units. However, no convincing field evidence for the existence of such a tectonic discontinuity has been identified and field relations are consistent with primary contact between floor portion of VMP and rocks of the Kinzigite formation. Therefore, the earlier advocated CVM line has not been reported on this new compilation on the VMP geology.

This new geological map of VMP represents an enlightening example of an intrusive body emplaced into middle crustal metamorphic rocks at the floor and cogenetic volcanic rocks at the top. Such a unique floor to roof exposure makes it a perfect natural laboratory for testing physical and geochemical models of magma emplacement and differentiation in the continental crust.

Software

Topographic maps in vector format were acquired from Carta Tecnica Regionale of the Regione Piemonte (http://www.geoportale.piemonte.it/cms/). Outcrop locations and sampling sites coordinates were acquired using a portable GPS receiver (Garmin®, eTrex 20). Lithologies and structural data collected as the results of the 1:10,000 scale survey were respectively drawn and stored using Qgis v.v. 2.12.3 Lyon. The generated curves and polylines were then added to the hill-shaded DEM, which was generated from the interpolation of elevation data (points and level curves) available in vector format from the *Carta Tecnica Regionale della Regione Piemonte*. The final output was then imported into Adobe Illustrator CC 2017® in SVG format to assemble the final geological map at a scale of 1:15,000. Polar projections of structures were plotted using Stereonet 9.5 (Cardozo & Allmendinger, 2013) and completed in Adobe Illustrator CC 2017®.

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