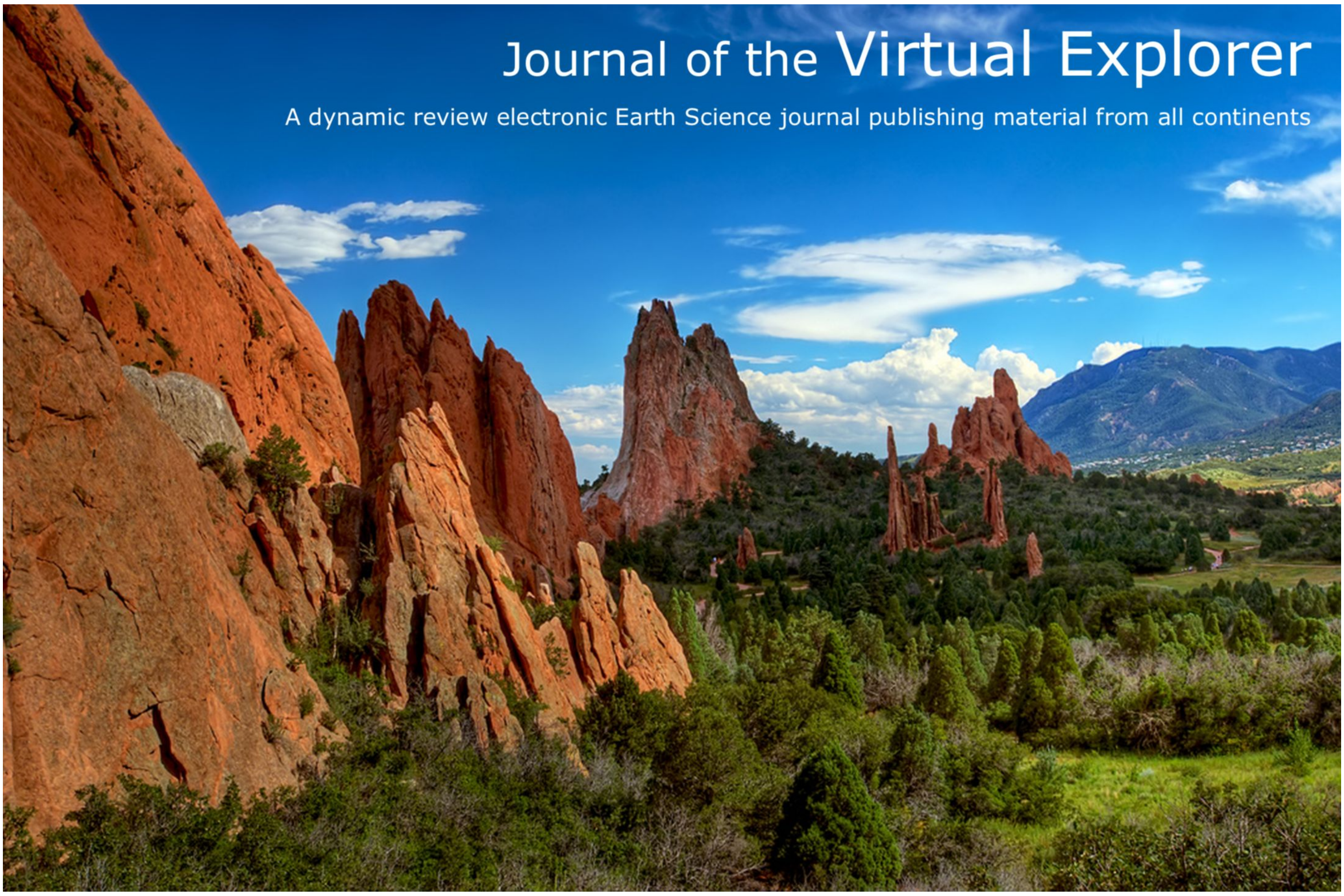

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The Sesia Magmatic System

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Abstract: The Ivrea-Verbano Zone (IVZ) and Serie dei Laghi (SdL) of northwest Italy, are two lithostratigraphic units that constitute the deep- and the middle- to upper-crustal components, respectively, of a tilted and exposed section through the pre-Alpine crust of northwest Italy. Both units were significantly affected by a Permian igneous event, leading to underplating of the Mafic Complex in the deep-crustal IVZ and intrusion of granitic bodies in the upper-crustal SdL, which is in turn capped by volcanic, predominantly rhyolitic rocks. SHRIMP U-Pb zircon ages of volcanic rocks (288 ± 2 to 282 ± 3 Ma), formation of granitic plutons in the SdL (289 ± 3 to 275 ± 5 Ma), and gabbro in the IVZ (289 ± 3 to 286 ± 6 Ma) indicate that the onset of bimodal volcanism and granitic plutonism was coincident with and probably triggered by intrusion of mantle-derived mafic melt in the deep crust, and that volcanic activity and presence of granitic melt at depth persisted after underplating had ceased. Collectively, all these coeval igneous rocks are grouped in the “Sesia Magmatic System”, whose activity culminated with the collapse of a caldera at least 13 Km across. In this paper we resume the most significant processes which affected the emplacement and igneous evolution of the IVZ Mafic Complex, briefly discussing its relationships with the upper-crustal igneous activity. Also, in the appendix we report a field guide for a two-days classic excursion across the entire sequence.

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Introduction

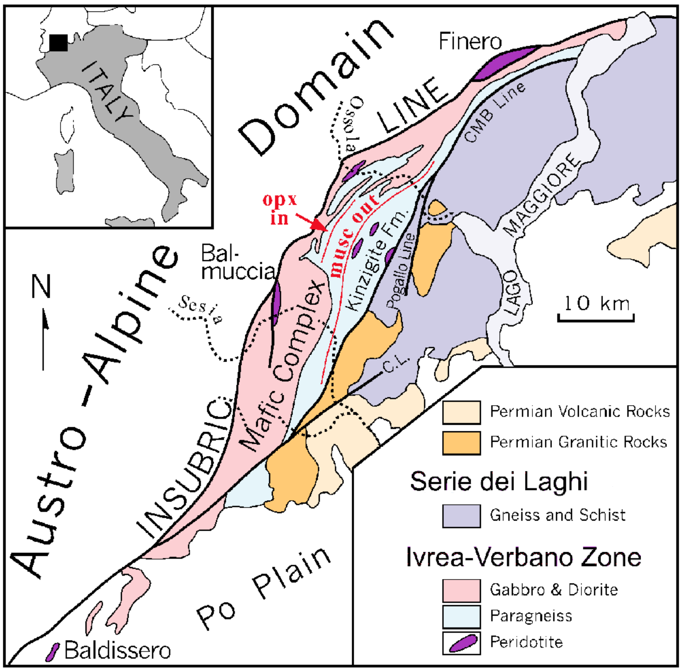
The famous deep crustal section of the Ivrea-Verbano Zone in northwest Italy has received enormous attention over the last three decades as one of the best examples of continental “magmatic underplating.” Within it, early Permian gabbroic rocks, reaching thicknesses >8 km in the southern Ivrea-Verbano Zone, intruded amphibolite- to granulite-faces paragneiss while they were present in the deep crust. The broader magmatic context of these voluminous intrusions remained unclear until Quick *et al.* (2009) demonstrated that a silicic volcanic complex, including extensive caldera deposits, was coeval with underlying silicic plutonic rocks of the Serie dei Laghi and gabbroic rocks of the Ivrea-Verbano Zone. In this paper, we review published data for this Permian igneous association, which we refer to as the Sesia magmatic system,.

Geologic Framework

The Sesia magmatic system is composed of coeval and genetically related intrusive and volcanic rocks within the Ivrea-Verbano Zone and Serie dei Laghi, two lithostratigraphic units in the Alps of northwestern Italy that have been historically studied as separate entities (Fig. 1). The Ivrea-Verbano Zone comprises plutonic and high-temperature, high-pressure rocks (Mehnert, 1975; Fountain, 1976) that are juxtaposed against the basement units of the Austro-Alpine Domain by the Insubric Line (Schmid *et al.*, 1987) and bounded to the southeast by amphibolite-facies metamorphic rocks and granites of the Serie dei Laghi (also known as Strona-Ceneri Zone, Boriani *et al.*, 1990b). North of the Sesia Valley, the boundary between the Ivrea-Verbano Zone and Serie dei Laghi corresponds to a high-temperature mylonite mapped as the Cossato-Mergozzo-Brissago Line (Boriani and Sacchi, 1973; Zingg, 1983; Handy, 1987; Boriani *et al.*, 1990), but within the Sesia Valley, a tectonic boundary is not evident (Quick *et al.*, 2003). Most investigators agree that the Ivrea-Verbano Zone together with the Serie dei Laghi are the deep- and the middle- to upper-crustal components, respectively, of a section through the pre-Alpine crust of northwest Italy (e.g. Fountain, 1976; Handy and Zingg, 1991; Henk *et al.*, 1997; Rutter *et al.*, 1999). A dissenting view has been offered by Boriani and Giobbi (2004), who interprete the Ivrea-Verbano Zone and Serie dei Laghi as distinct, unrelated terranes.

Gravity and seismic reflection data suggest that the Ivrea-Verbano Zone dips steeply to the southeast near the surface but flattens into a subhorizontal orientation at a depth of 20 to 30 km beneath the Po Plain (Nicolas *et al.*, 1990; also see Berckhemer, 1968). The emplacement of the Ivrea-Verbano rocks into the upper crust resulted from the combined effects of exumationdue to Mesozoic crustal thinning and subsequent lithospheric wedging related to Alpine collision (Schmid *et al.*, 1987; Nicolas *et al.*, 1990).

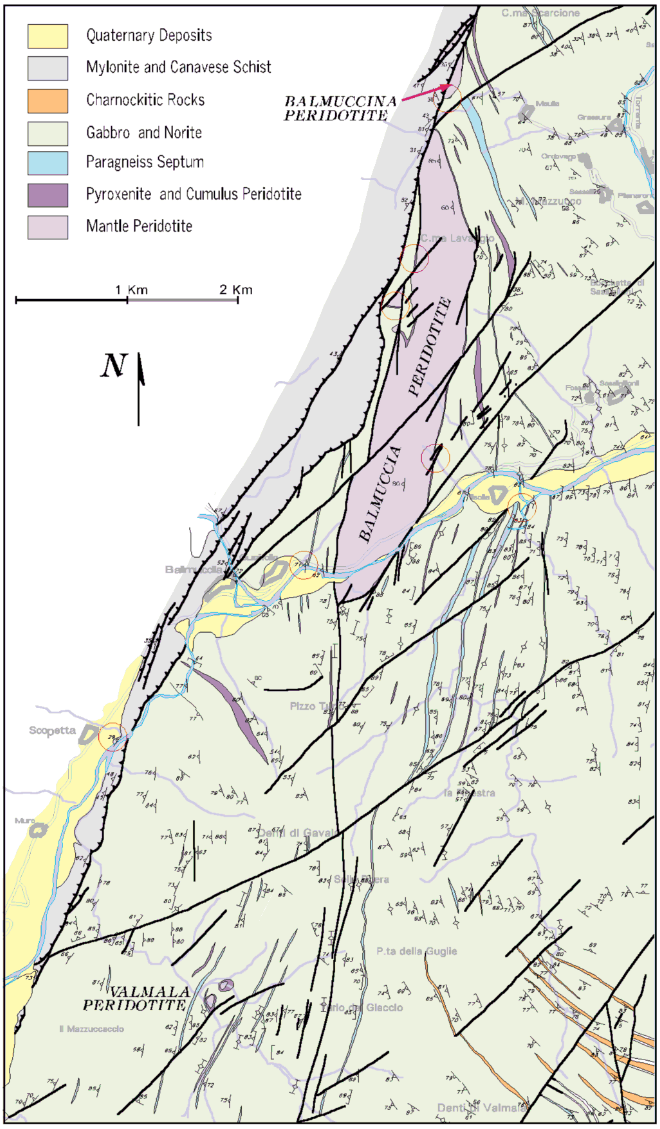
Figure 1. Geology of the southern Alps



Geology of the southern Alps in the vicinity of the Ivrea-Verbano Zone based on Zingg (1983). Ivrea-Verbano Zone contains pre-Permian peridotite, pre-Permian paragneiss of the Kinzigite Formation and Permian intrusive rocks of the Mafic Complex. Strona-Ceneri Zone contains pre-Permian gneiss and schist. Abbreviations are CMB Line, Cossato-Mergozzo-Brissago Line; C.L., Cremosina Line. Major mantle peridotites are identified by name. Muscovite-out (musc out) and orthopyroxene-in (opx in) isograds are shown in red.

Rocks of the Ivrea-Verbano Zone have been grouped historically in terms of two major units, the Kinzigite Formation and the Basic Formation (also referred to as the Mafic Formation). The Kinzigite Formation consists of amphibolite- to granulite-facies paragneiss that formed from protoliths dominated by pelitic sedimentary rocks and wackes, but also including limestone and mafic volcanic rocks (Zingg, 1983; Sills and Tarney, 1984; Wedepohl *et al.*, 1989). Amphibolite-facies assemblages dominate in the southeastern Ivrea-Verbano Zone and granulite-facies assemblages are volumetrically more significant in the northwest. The Basic Formation is subdivided into the voluminous Mafic Complex and lenses of mantle peridotite. The Mafic Complex (Rivalenti *et al.*, 1975, 1981, 1984) is a large composite body of mostly gabbroic plutonic rocks and subordinate amounts of dioritic, tonalitic, charnockitic and cumulus ultramafic rocks. These rocks are recrystallized to different degrees and are interleaved with and underlie the Kinzigite Formation in terms of pre-Alpine orientations.

Figure 2. Geology of the Balmuccia area



Geologic map of the Mafic Complex in the Balmuccia area (modified from Quick *et al.*, 1992).

The most detailed investigations (Mulch *et al.*, 2002, Rutter *et al.*, 2007 Siegesmund *et al.*, 2008) agree that the motion on the CMB Line pre-dates the Permian intrusive event at which time the CMB line was invaded by small, bimodal mafic and granitic intrusions (termed “appinites” by Boriani *et al.* 1974). Therefore, we consider the CMB Line to be one of the several high-T shear zones involved in the pre-Permian mechanical assembly of the Ivrea-Verbano Zone-Serie dei Laghi crustal section. During this assembly, which is poorly contrained in age and may have involved multiple episodes, lenses of mantle peridotite were tectonically emplaced in the crust. In the Ivrea-Verbano Zone, these include the Alpe Morello mantle tectonite, which is bounded by the CMB and metamorphosed in amphibolite facies and the Alpe Piumero, Alpe Francesca, bodies, which occur deeper in the section, along the Rosarolo shear zone (Siegesmund *et al.*, 2008) and were deformed under higher-grade amphibolite facies conditions (Marchesi *et al.*, 1992). The largest of these bodies, the famous Balmuccia peridotite, shows a spinel foliation, consistent with flow at temperatures >1000°C (Boudier *et al.*, 1984), which becomes more intense approaching the borders of the body (porphyroblastic texture, Garuti and Friolo, 1979), suggesting granulite facies conditions during its crustal emplacement. An apparent increase from east to west of the metamorphic assemblages in these mantle lenses is consistent with emplacement at different depths in the crustal section.

The eastern contact of the Balmuccia peridotite (Fig. 2), has been repeatedly interpreted as an exhumed and preserved sub-continental, petrologic Moho (Shervais, 1979; Rivalenti *et al.*, 1981; Voshage *et al.*, 1990; Sinigoi *et al.*, 1983; Boudier *et al.*, 1984, Quick *et al.*, 1992). According to this interpretation, outcrops of the Mafic Complex west of the peridotite are tectonically repeated by a splay of the Insubric Line and the eastern boundary of the peridotite, which is sharp, magmatic and defined by cumulus pyroxenite in contact with mantle tectonite, represent the base of the Permian crustal section. If true, this interpretation would have significant implications for the Sesia magmatic system, as primitive mantle-melts should have reached this level of the section without crustal contamination. However, (Quick *et al.*, 1995) demonstrated that the Balmuccia body is, in fact, a lens of mantle tectonite, enveloped on all sides by a sheath of pyroxenite and gabbro containing belts of crustal paragneiss, termed septa. Similar relationships are present at the Valmala peridotite, about 3 km South of Balmuccia (Fig. 2). Collectively, these observations indicate that the Balmuccia peridotite was a lens that was tectonically incorporated into paragneisses of the Kinzigite Formation prior to the intrusion of the Mafic Complex, whenthe magmatic contacts and pyroxenite sheath were formed. Based on these observations, it must be concluded that the Permian subcontinental Moho of this crustal section was located at some undetermined distance beneath the current level of exposure.

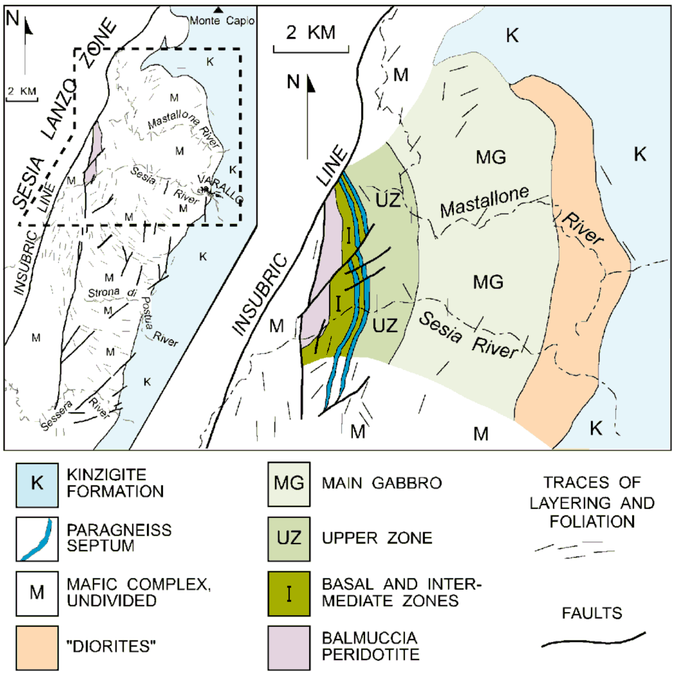
A clear case can be made that the southern Ivrea-Verbano Zone and the southern Serie dei Laghi were heavily impacted by the same early Permian magmatic event. SHRIMP U-Pb zircon ages for volcanic rocks south-east of the Cremosina line and for the spatially-related granite bodies of the Roccapietra- Valle Mosso pluton, which intrude the Serie dei Laghi, indicate that this volcanic/plutonic activity overlapped in time with crystallization and cooling of the Mafic Complex in the southern Ivrea-Verbano Zone (Quick *et al.*, 2009) and that peak magmatic activity was confined to approximately 10 m.y. from 288 to 278 Ma. Quick *et al.* (2009) also demonstrated that the volcanic field is largely occupied by caldera fill tuffs and megabreccia, concluding that volcanic and middle- to deep-crustal plutonic rocks collectively constitute an unprecedented exposure of the magmatic plumbing system to a depth of 25 km beneath a caldera with a minimum diameter of 13 kilometers. The association of these rocks in space and time points to a cause-and-effect link between intrusion of mantle-derived basalt in the deep crust and large-scale, silicic volcanism.

Historically, the Mafic Complex was considered as a single mafic body extending from Baldissero to the Finero area as reported in Figure 1. However, recent SHRIMP U-Pb zircon ages demonstrated that, while the central Mafic Complex crystallized at the Permo-Carboniferous boundary (Peressini *et al.*, 2007), gabbro constituting the Northern Mafic complex, in the Finero area, is Triassic and can no longer be regarded as part of the same igneous body (Mazzucchelli *et al.*, in progress).

The Mafic Complex

The Mafic Complex has been known since the pioneering work of Artini and Melzi (1900), who described these rocks as mafic granulites. Rivalenti *et al.*(1975) first recognized it as a huge igneous complex, despite the widespread recrystallization of most rocks. Using the eastern contact of the Balmuccia peridotite as reference for “the base of the intrusion,” a boundary condition we now know to be invalid, they divided the Mafic Complex along the Val Sesia profile in Basal Zone, Intermediate Zone, Upper Zone, Main Gabbro and Diorites, by analogy with the stratigraphy of well-known Layered Mafic Complexes like the Skaergaard. Although subsequent detailed field mapping (Quick *et al.*, 1995) demonstrated that the Balmuccia peridotite does not preserve the Moho and is not the base of the Mafic Complex, the polarity of the section remains the same, with the depth of the exposure increasing to the west, approaching the Insubric Line. Geobarometry indicates that the roof of the intrusion, which corresponds to its eastern contact with the Kinzigite Formation, equilibrated at a depth of 15 to 20 km and that equilibration pressures increase monotonically at a rate of 0.3 to 0.4 kb/km toward the Insubric Line where rocks equilibrated at depths of approximately 25 km (Fig. 4, Demarchi *et al.*, 1998).

Figure 3. The Mafic Complex in the Sesia Valley

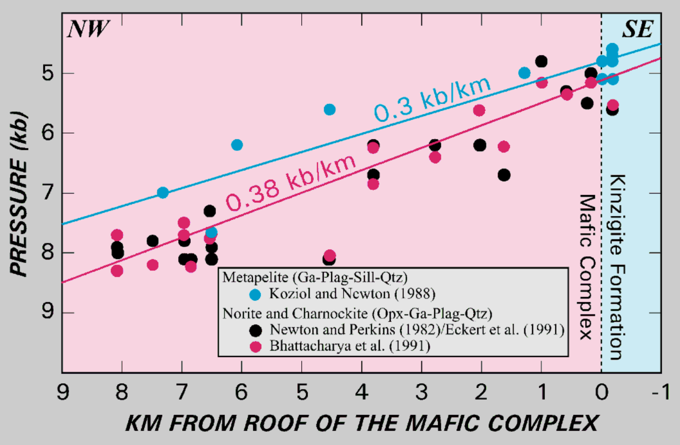


Geologic map of the Mafic Complex in the Sesia Valley area according to Rivalenti *et al.* (1975). In the inset, foliation patterns simplified from Quick *et al.* (2003).

The large scale internal structure of the Mafic Complex (Fig. 3) is dominated by an arcuate structure centered on the village of Varallo and defined by layering, foliation and mappable units (Quick *et al.*, 1994, 2003).

Granitic and dioritic bodies do not crosscut the gabbro. Instead, their concordance with foliation and banding is remarkable and crosscutting relationships are limited to faults, scarce dikes and late-stage melt segregations. Paragneiss septa derived from the Kinzigite Formation and granitic to dioritic bodies are traceable for kilometers around this arcuate structure without major breaks although they are increasingly attenuated with depth in the complex. In fact, disruption of the internal structure of the Mafic Complex is remarkably minor considering that the complex has been exhumed from a depth of >15 km and rotated 90°. Most faults displace mappable units and/or the roof of the Mafic Complex less than 100 m.

Figure 4. Equilibration pressure

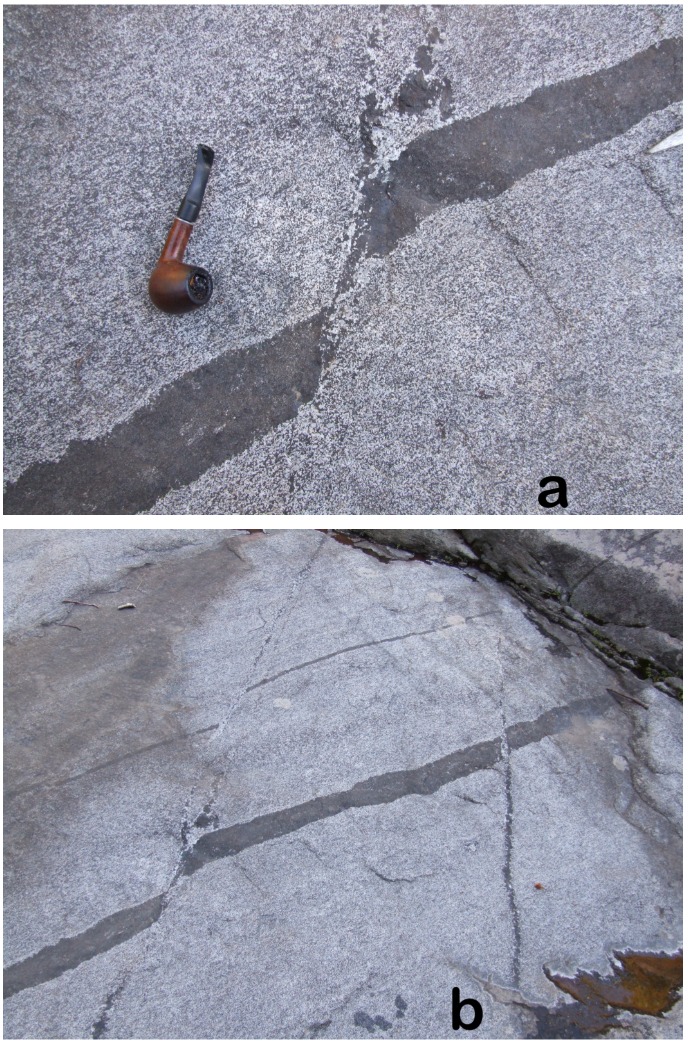


Equilibration pressure vs. distance from the Kinzigite Formation-Mafic Complex contact south of the Sesia River (modified from Demarchi *et al.*, 1998).

Isobars in the complex cut across the arcuate structure and parallel the contact with the Kinzigite Formation south of the Sesia River (Demarchi *et al.*, 1998). This indicates that the gross arcuate structure was established before equilibration pressures were locked in and is, therefore, a pre-Alpine feature. In terms of pre-Alpine orientations, the gross structure of the complex would have been a trough that was roofed and flanked on the north side by the Kinzigite Formation.

Synmagmatic deformation in the Mafic Complex was first described by Rivalenti *et al.* (1981), who interpreted intrafolial folds and high-temperature shears in terms of slumping of cumulates onto the floor on a large magma chamber. Quick *et al.* (1992a) observed that similar features are present in many places south of the Sesia Valley (Fig. 5) and suggested that these structures resulted from pervasive, large-scale deformation of crystal mush. Layer-parallel stretching is evidenced by boudinage and small stretching faults. Banding is locally deformed by tight to isoclinal folds with axial planes concordant with the regional foliation and fold axes parallel the stretching lineation. Locally, undeformed, poikilitic amphibole has grown across the foliation indicating that a small amount of interstitial melt was present when the foliation formed.

Figure 5. Hypersolidus faults

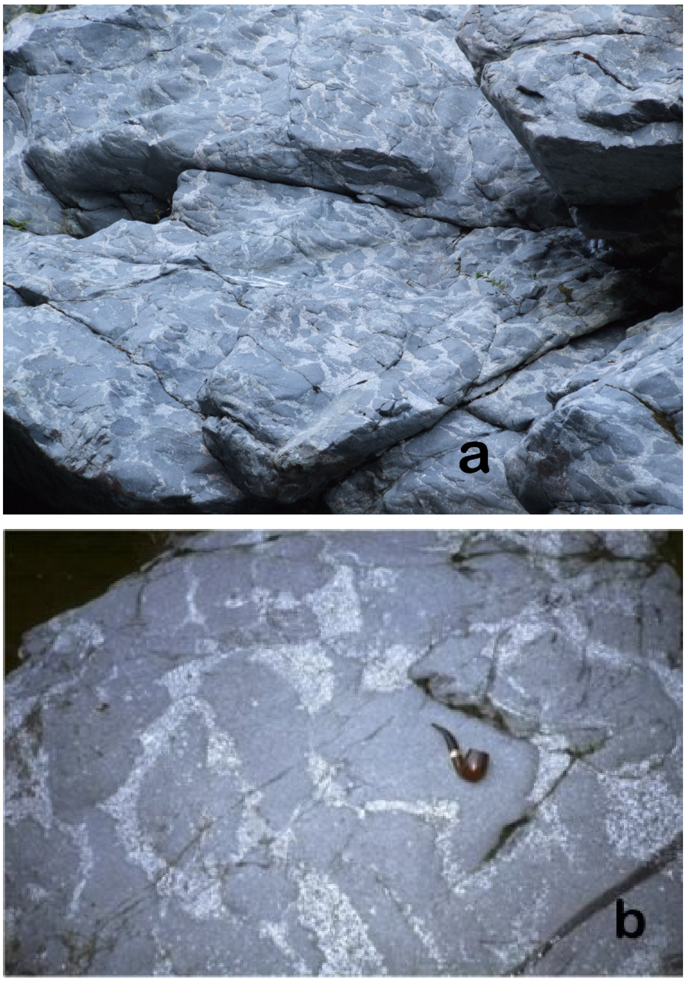


Hypersolidus extensional faults at deep levels in the Mafic Complex (Sessera Valley).

Many stretching faults are healed by thin, undeformed veins of leucogabbro, which crystallized from segregations of late-stage interstitial melts. Late-stage melts have segregated into undeformed patches that crosscut foliation and fill tension gashes and pressure shadows at the ends of boudins. Analogous relationships involving charnockitic anatectic melts occur in the paragneiss septa (Fig. 9).

A general increase in strain downward in the complex is suggested by the following observations: (1) mappable units are increasingly attenuated with depth. (2) magmatic textures and structures are commonly well preserved near the top of the complex (Fig. 6) but, excluding small melt segregations, are absent at deep levels. (3) granoblastic textures and synmagmatic deformation are more abundant in the lower third of the complex.

Figure 6. Magma mingling

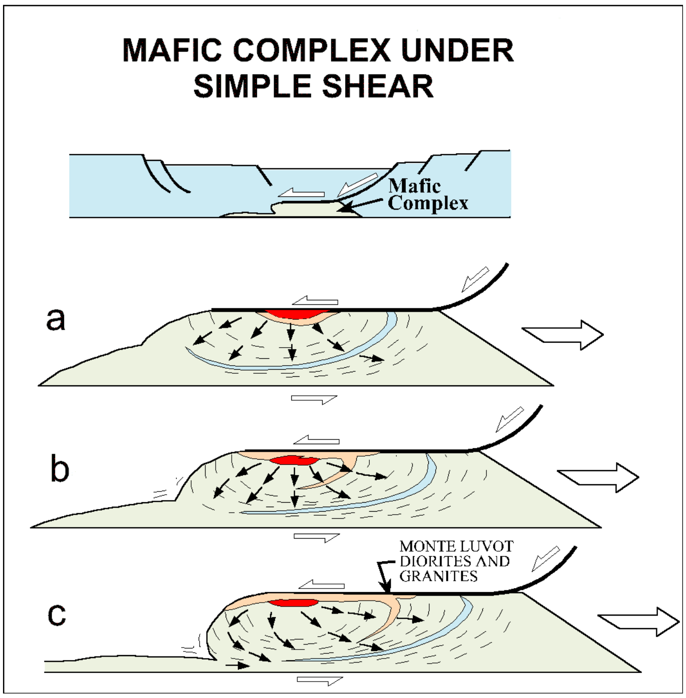


Magma mingling in the core of the arcuate structure, Val Mastallone.

The Gabbro-Glacier model

The gross structure and the distribution of hypersolidus deformations are best explained by the gabbro-glacier model (Quick and Denlinger, 1992, 1993; Quick *et al.*, 1992a, 1992b). Quick *et al.* (1992a, 1994) noted that well studied analogs for the arcuate structure and synmagmatic deformation of the Mafic Complex are found in ophiolitic gabbro (for review, see: Nicolas *et al.*, 1989, 1992; Quick and Denlinger, 1992, 1993). In addition, both the Mafic Complex and ophiolitic gabbro display similar strain gradients with increasing strain downward in the section. Numerical modeling (Quick and Denlinger, 1992, 1993; Phipps Morgan and Chen, 1993; Henstock *et al.*, 1993) demonstrates that these characteristics can be produced by large-scale necking of a thick section of partially molten cumulates beneath a small magma chamber as the crust moves away from a spreading center.

Figure 7. Evolution of the Mafic Complex



Schematic diagram summarizing the Permian evolution of the Mafic Complex in the context of a progressively extending crust under simple shear. Location of the Mafic Complex in the crust is followed by enlargements to show details of internal structure of the Mafic Complex. Red, magma chambers; green, cumulates, which contain variable amounts of interstitial melt; orange, dioritic and granitic rocks; blue, pre-underplating crustal rocks. Large, open arrows indicate direction of crustal movements. Small arrows in Mafic Complex indicate trajectories of cumulates and septa during ductile deformation. Foliation indicated by dashes.

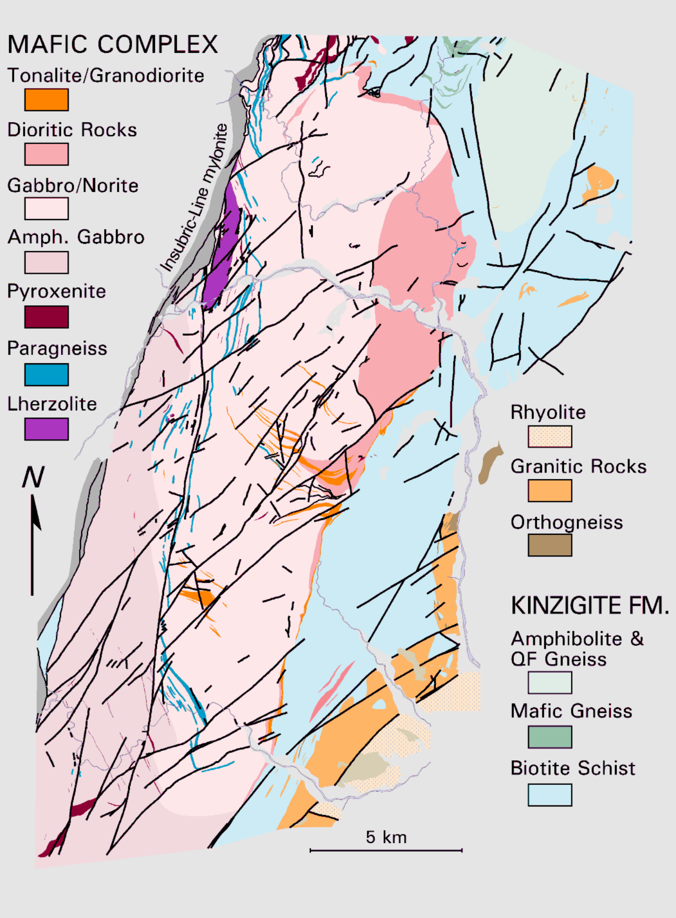
According to this model, a huge volume of gabbroic crystal mush is created from a relatively small and continuously-fed magma chamber, as crystallizing cumulates are continuously transposed outwards and downwards from the chamber. Consistently, the best preserved igneous textures, like swarms of mafic enclaves mingled in diorite (Fig. 6), are close to the roof in the vicinity of Varallo, at the core of the arcuate structure, while most feeders are annealed, as were largely transposed at low angle or parallel into the foliation.

Paragneiss septa

Numerous layers of granulitic paragneisses, termed septa, comprising metapelites, wackes and minor calc-silicates are found within the Mafic Complex . These layers are characterized by an extreme aspect ratio and some may be followed along strike for kilometers although they are only a few meters thick. Compared to the amphibolite-facies roof rocks, they are richer in garnet and extremely depleted in micas. Feldspars are generally antiperthitic and sillimanite forms discrete crystals, as opposite to fibrolite at the roof of the complex. Measured density of these rocks range from 2.9 to 3.4 gr/cm^3, while roof rocks are within 2.7 to 2.9. The increase in density of the septa correlates with decreasing SiO_2 and Rb abundance and increasing Al_2O_3 and FeO abundance, consistent with decrease of micas and increase of garnet in the restite as a result of larger extraction of anatectic granitic melt from the septa than from the roof rocks. Both measured densities of gabbro and computed densities the parental gabbroic melt at 5 Kb are close to 3gr/cm^3, i.e. intermediate between the septa and roof rocks (Sinigoi *et al.*, 1995).

The following mechanism has been proposed by Sinigoi *et al.*, (1995) to explain the density, field and geochemical data. A basaltic sill ponded in the lower crust at its level of neutral buoyancy (Ryan, 1993). Upward migration of anatectic melt from the roof rocks left behind an increasingly dense restite until the density of the restite exceeded that of the underlying mafic magma. Local weakening due to the coalescence of the upward migrating anatectic melts may have facilitated detachment of the roof rocks. These denser roof rocks were incorporated into the complex as new additions of mafic melt ponded over them. A septum was formed and the new roof began to melt as a new cycle of intrusion, melting and density change began. After having been incorporated in the growing Mafic Complex, the melting septa were transposed together within the crystallizing gabbro glacier, so attaining their extreme aspect ratio and parallel fabric.

Figure 8. Geologic map of the Mafic Complex



Geologic map of the Mafic Complex in the southern Ivrea-Verbano Zone simplified from Quick *et al.* (2003).

Figure 8 shows the appearance that most septa are grouped near the transition between the lower Mafic Complex, dominated by mafic, granoblastic amphibole gabbro and the upper Mafic Complex, comprising gabbro, norite and diorite. Based on this distribution of the septa, Sinigoi *et al.* (1996) introduced the term “paragneiss bearing belt,” with the aim of defining a region where septa are more abundant. In fact, septa flair upward into higher levels of the Mafic Complex and their apparent concentration at deeper levels is a consequence of flow within the gabbro glacier. Thus, the paragneiss bearing belt should not be interpreted as a well defined layer with any temporal or stratigraphic significance. Furthermore, it should be noted that rare septa, too small to depict in Figure 8, are present in both the upper and lower Mafic Complex. In several cases, septa diverging upwards in the Mafic Complex connect with foliated granitoid bodies, suggesting segregation of anatectic melts from melting paragneiss septa during the growth of the gabbro glacier.

Figure 9. Paragneiss septum

Fault in paragneiss septum healed by charnockite. Fault curves into foliation plane to left of photo.

In the paragneiss bearing belt, septa are interleaved with mafic gabbros, a suite of rocks ranging from norite to charnockite and ultramafic cumulates. Among the latter, cumulus peridotites layers are up to 100 m thick East of the Balmuccia peridotite, in the area between Sesia and Mastallone Valleys (Intermediate Zone of the previous stratigraphic subdivision of Rivalenti *et al.* (1984) (Fig. 3) but become attenuated to few meters to the South. In the Sesia area, cumulus peridotite shows up to 2cm-thick reaction rims of pyroxene +spinel at the contact with gabbro (Figs. 11a,b,c). These rims developed under high-T subsolidus conditions, possibly still in presence of interstitial melt, as witnessed by synmagmatic deformation structure in proximal gabbros, (Fig. 11d) and were previously interpreted as cooling growths over slump structures (Rivalenti *et al.*1981). The cumulus peridotites in the Sesia area and associated gabbros are interleaved with paragneiss septa and most-likely crystallized in sills rather than in a huge magma chamber. Moreover, they show North-dipping lineations consistent with lineations of the gabbro (Figs. 11a,c). Collectively, these observations lead to the conclusion that these structures are better interpreted as sheath folds developed at very high temperature during stretching at the deep levels of the glacier. The reaction ol+plag = px+spinel is very sensitive to P and less sensitive to T (Presnall, 1976). The fact that these features developed beneath the core of the mafic body suggests they formed during the increase in pressure that affected these cumulates in axial position during stretching as they were transposed downward within the deforming gabbro glacier and buried beneath several kilometers of gabbro.

Figure 10. Paragneiss septa at deep levels

Paragneiss septa at deep levels in the lower Mafic Complex.

Figure 11. Sheath folds

Sheath folds with reaction rims between peridotite and gabbro, developed during stretching at high-T, increasing P.

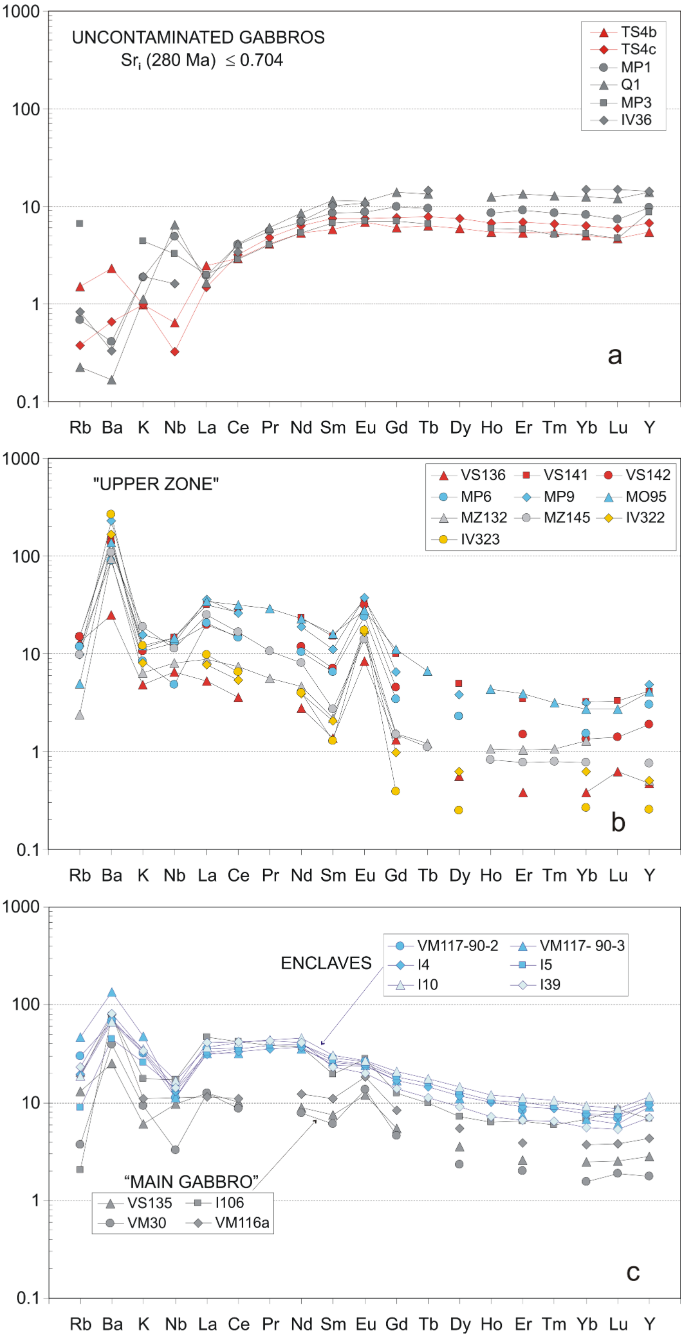
Geochemistry of the Mafic Complex

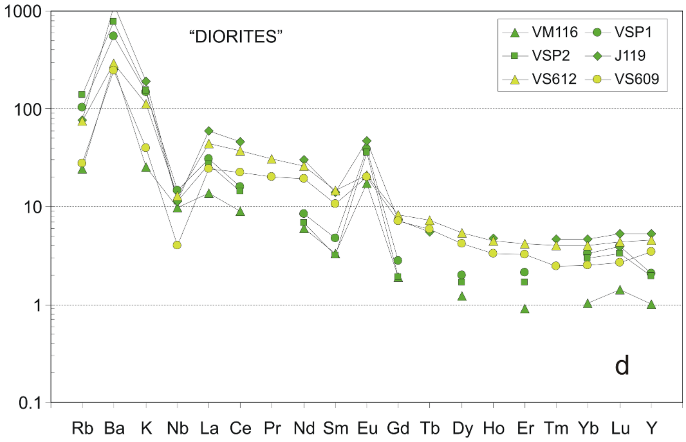
Most of the numerous papers discussing the geochemistry of the Mafic Complex are based on samples collected along the Sesia and Mastallone Valleys, which crosscut the upper Mafic Complex and paragneiss bearing belt. Rivalenti *et al.* (1975, 1981, 1984) demonstrated that whole-rock and mineral major-element data indicate open-system crystallization of the Mafic Complex. Across the basal, intermediate and upper zones, Mg/Mg+Fe decreases with height in the section from 0.78 to 0.35 although numerous stratigraphic oscillations occur that are similar in scale to those in ophiolitic gabbros. Mg/Mg+Fe ratios in the main gabbro are more restricted (0.58 to 0.35), suggesting that crystallization occurred under approximately steady-state conditions.

Voshage *et al.* (1990) first showed that igneous rocks within the paragneiss-bearing belt (their basal and intermediate zones) have initial Nd° and Sr° isotopic ratios that display considerable variation, as opposite to a relatively more homogeneous isotopic composition of the upper Mafic Complex (their Main gabbro and “Diorites”). Within the paragneiss-bearing belt, Voshage *et al.* (1990) report a few gabbros with isotopic compositions compatible with uncontaminated, mantle-derived melts (Sr° 0.702 to 0.704, εNd 6.2 to 7.2), which show MORB-like, depleted REE patterns. Sinigoi *et al.* (1996) report an additional sample with these MORB-like characteristics within the paragneiss-bearing belt and close to the mantle peridotite.

Although some of these uncontaminated samples could be interpreted as older mafic granulites unrelated to the Mafic Complex, one sample, TS4 (Mayer *et al.*, 2000) is an undeformed gabbroic dike that intrudes the Balmuccia peridotite border zone from outside, cross-cutting the intense spinel foliation and boudinaged Cr-diopside and Al-augite dykes and bands. The TS4 dike clearly post-dates the emplacement of the mantle tectonite in the deep crust and appears to have preserved its primary composition, with Sr°=0.7021 (Voshage *et al.*, 1988) and depleted REE patterns (Fig. 12) as a consequence of intruding peridotite rather that isotopically evolved paragneiss. Dike TS4 provided an internal Sm-Nd isochron of 274 Ma (Mayer *et al.*, 2000) consistent with slow cooling after emplacement of the entire Mafic Complex at about 288±4 Ma (Peressini *et al.* 2007). Thus its intrusion is bracketed within the emplacement of the mantle tectonite and the cooling of the Mafic Complex, an age difficult to be unrelated to the main Permian event. These considerations support the interpretation of Voshage *et al.*, (1990) that the first mantle melts intruded into the IVZ deep crust quenched too rapidly for their compositions to be influenced significantly by crustal contaminationSubsequently, after repeated intrusions heated the country rocks above their solidi, intruding mantle melts were contaminated by isotopically evolved crust.

Figure 12. REE patterns

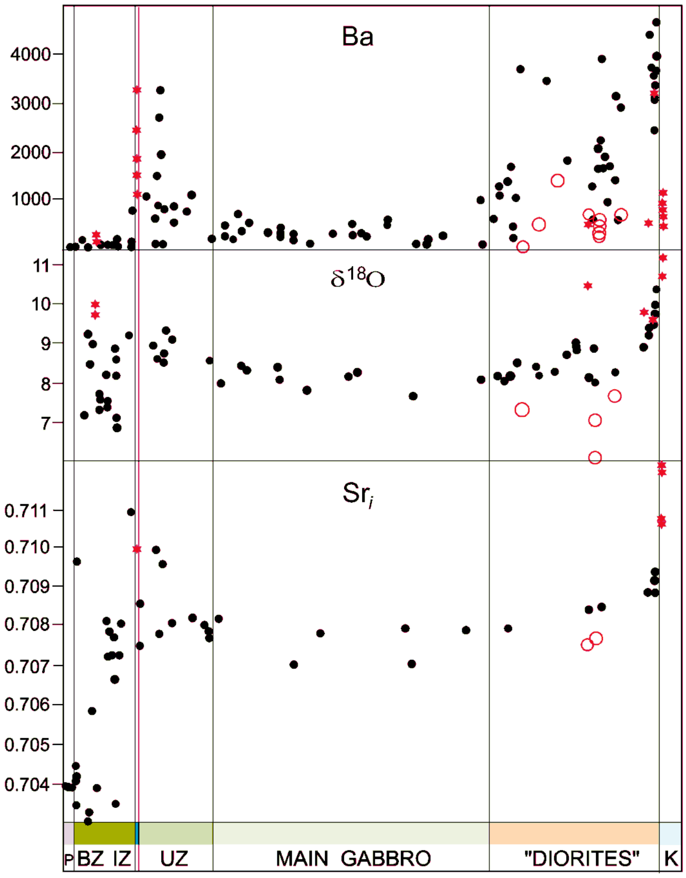




REE patterns of samples collected along Val Sesia. 12 a: uncontaminated gabbros in the Paragneiss bearing belt (Basal Zone of Rivalenti *et al.*,1984). 12 b to d: gabbroic cumulates at the bottom of upper Mafic Complex, Main gabbro and "Diorites."

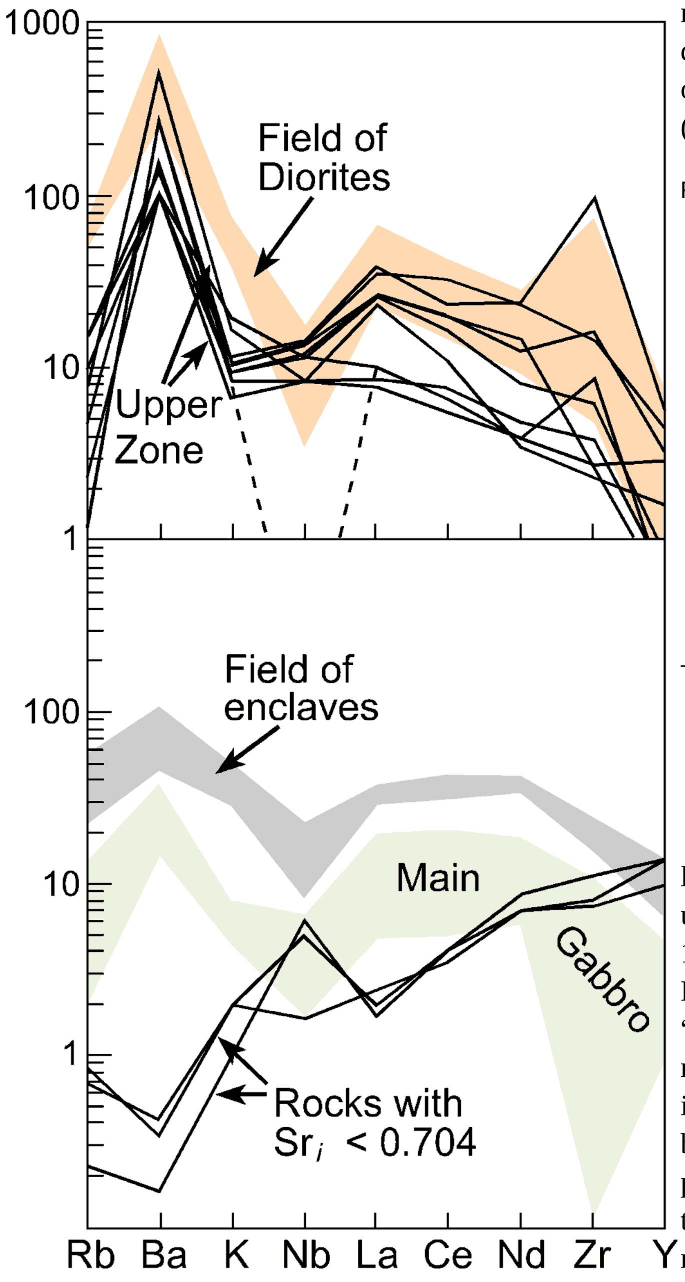
Excluding the few uncontaminated gabbros discussed above, the isotopic and trace-element compositions of most igneous rocks of the Mafic Complex indicate high degrees of crustal contamination. Voshage *et al.* (1990) showed that the εNd of the upper Mafic Complex (their Upper Zone, Main Gabbro and "Diorites" according to the stratigraphy of Rivalenti *et al.*, 1984) was relatively uniform and concluded that these rocks had crystallized from a magma chamber that had achieved a thermal balance between magma input, anatexis, assimilation and crystallization. Sinigoi *et al.* (1994) extended the analysis to include Sr and O isotopic compositions and trace element abundances. Most of the Mafic Complex is characterized by $Sr_i > 0.706$, $\delta^{18}O > 7.5$ enrichment in LREE and an enrichment in Ba relative to K and Rb (Figs. 13 and 14). The absence of this characteristics in rocks with $Sr_i < 0.704$ indicates that they are an effect of crustal contamination and that the contaminant was enriched in Ba relative to K and Rb. Mazzucchelli *et al.* (1992) found positive Eu anomalies in plagioclase, clinopyroxene and garnet at deep levels of the upper Mafic Complex (their upper zone), which they interpreted to indicate that the melt that crystallized these phases had acquired a positive Eu by crustal contamination. Ba and Eu anomalies are in general positively correlated, indicating contamination by a biotite- and feldspar-enriched source that was previously depleted in Rb and K by dehydration melting and separation of anatectic melt. Positive Ba and Eu anomalies are also characteristics of the charnokites present as dikes or bands in the paragneiss bearing belt, which are interpreted as anatectic melts delivered from the septa. Similar Eu-enriched charnockites are described in other parts of the Ivrea-Verbano Zone (Schnetger, 1988) and in other granulite terranes (e.g., Pride and Muecke, 1982; Barbey *et al.*, 1990; Harris *et al.*,1986). Sinigoi *et al.* (1995) concluded that the septa must have been stripped in K and Rb by fractional melting before being peeled off from the KF and incorporated into the Mafic Complex, according to the process driven by evolving density contrast previously described.

Figure 13. Ba, δO and Sr° vs. stratigraphy



Ba contents (ppm) and isotopic composition of O and Sr_i ($^{87}Sr/^{86}Sr$ calculated at 270 Ma) plotted against the stratigraphy of the Mafic Complex in the Sesia Valley. Subdivisions of the Mafic Complex are the same as in Figure 12. Solid circles, gabbro, norite and diorite; solid red stars, charnockite or leucosomes; open red circles, mafic enclaves in dioritic rocks. (From Sinigoi *et al.*, 1994).

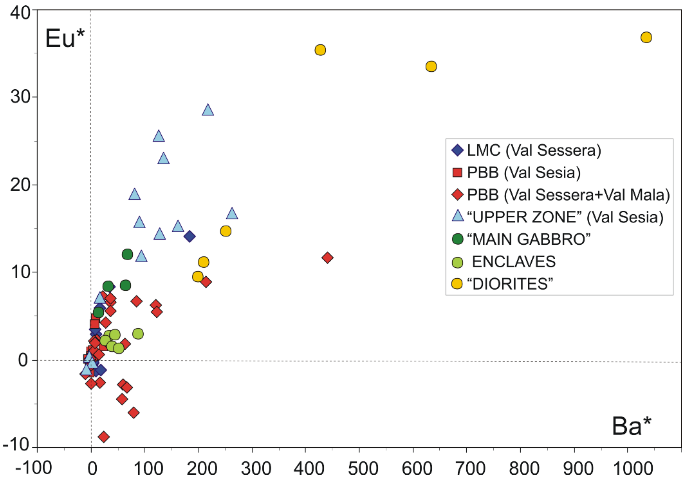
Figure 14. Normalized incompatible elements



Abundances of incompatible elements in mafic and intermediate rocks of the Mafic Complex normalized to primitive mantle abundances (Hofmann, 1988).

Following incorporation of the septa by the Mafic Complex, advanced anatexis of residual biotite and especially K-feldspar, enriched in Ba and Eu, would provide the observed compositions. Ba and Eu are both compatible in K-feldspar, while only Eu is compatible only in plagioclase. In the Mafic Complex, the Ba an Eu anomalies are in general correlated positively, consistent with advanced melting of residual K-feldspar in the crustal source. A decoupling from this behavior may be caused by fractionation of plagioclase, with the result of increase Ba but decrease Eu up to cause a minor negative Eu anomaly, as observed in some norite from the paragneiss bearing belt (Fig. 15).

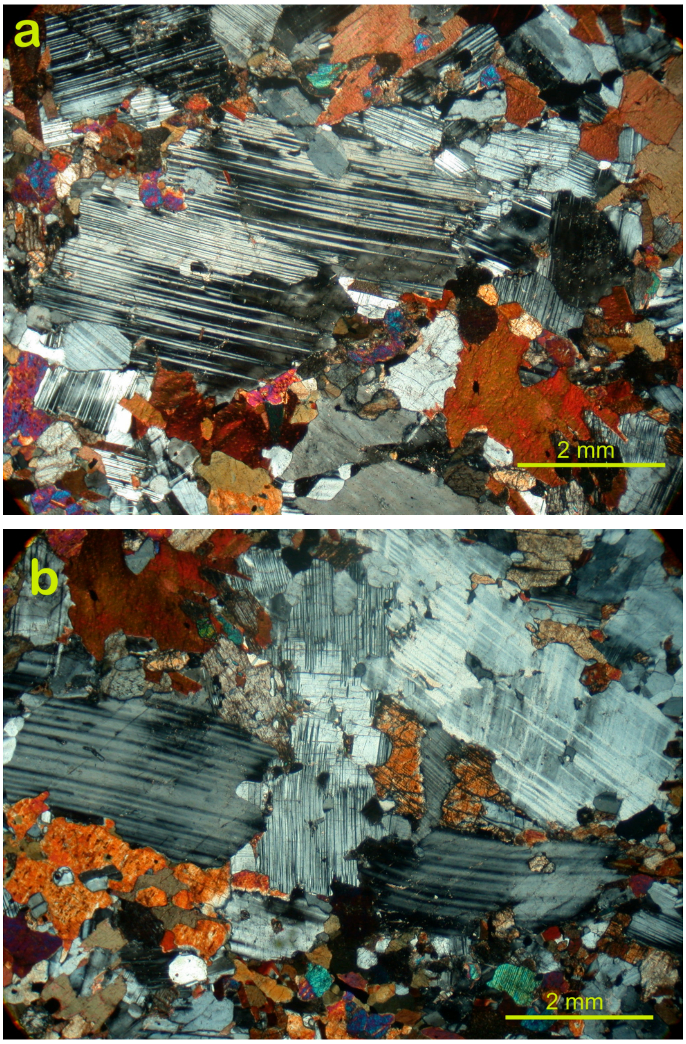
Figure 15. Ba* vs. Eu*



Ba* vs Eu*, computed as Ba* = Ba-(K+Rb)/2 and Eu*= Eu-(Sm+Gd)/2 normalized values.

The highest Ba and Eu anomalies are found in cumulates above the paragneiss bearing belt, at the base of the upper Mafic Complex (Upper Zone of Rivalenti *et al.*, 1984), an in the "Diorites," while they are minor in the Main gabbro and in the mafic enclaves intruded in the "Diorites" (Figs. 13 and 15). This suggests that the "Diorites" are not differentiated melts (they should be lower in Eu, after fractionation of plagioclase-rich cumulates) but rather cumulates, as suggested also by the petrography (Fig. 16). If so, the "magma chamber" at the core of the arcuate structure was actually a cumulitic crystal mush within which swarms of mafic enclaves intruded as amoeboidal bodies.

Figure 16. “Diorites”



Although recrystallized, the texture of “Diorites” suggests they are cumulates of predominant plagioclase.

Age of the Sesia Magmatic System

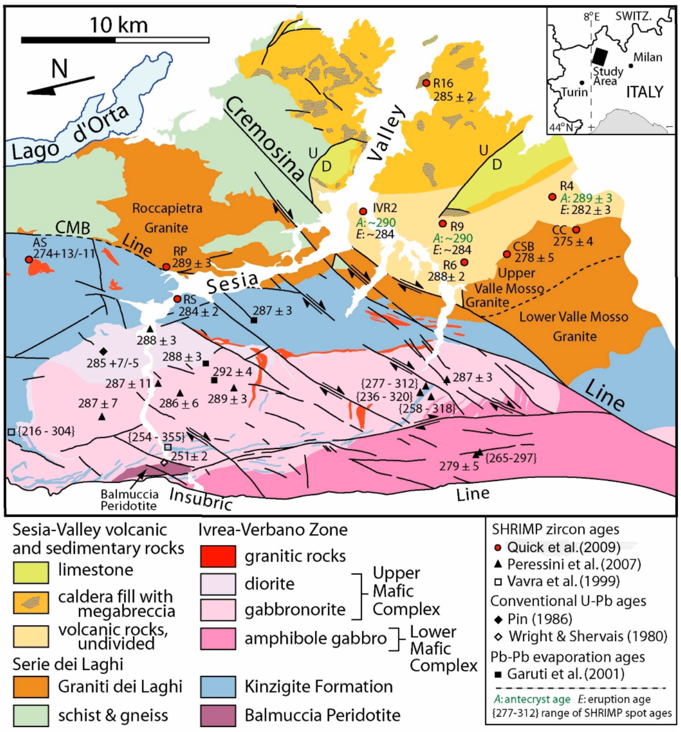
The geochronologic framework of the Mafic Complex is reviewed in detail by Peressini *et al.* (2007). More than 30 years of geochronologic investigations of the Mafic Complex resulte in published ages ranging from 600 Ma (Hunziker, 1974; Hunziker & Zingg, 1980, Pin & Sills, 1986, Voshage *et al.*, 1987; Gebauer *et al.*, 1992) to 30 Ma (Gebauer *et al.*, 1992). However, ages older than 400 Ma were generated by Rb-Sr and Sm-Nd whole-rock methods and can be interpreted as mixing lines with no age significance (Voshage *et al.*, 1990). Ages in the range of 30 Ma date Alpine events that clearly postdate the igneous crystallization age of the Mafic Complex (Mayer *et al.*, 2000).

Peressini *et al.* (2007) provided age determinations based on SHRIMP U-Pb analyses on zircons from 11 samples of the Mafic Complex. Five samples from the upper Mafic Complex range in age from 289±3 to 286±6 Ma, in agreement with a conventional U-Pb zircon age measured by Pin (1986) and three Pb-Pb evaporation ages measured by Garuti, *et al.* (2001) and providing the best age constraint on the injection of mantle-derived melt into the deep crust to form the Upper Mafic Complex. Individual SHRIMP spot ages at deeper levels of the Mafic Complex range from >310 to <250 Ma, reflecting inheritance and continuous recrystallization of zircons during a prolonged period of intrusion, slow cooling and deformation in the deep crust punctuated by repeated intrusive events.

Quick *et al.*, (2009) determined SHRIMP U-Pb ages on zircons from granites intruded in both the IVZ and Serie dei Laghi above the Mafic Complex and from volcanic rocks exposed in Val Sesia across the Cremosina line. As described by Quick *et al.* (2009), the exposed volcanic field is dominated by caldera fill tuffs and megabreccia, the distribution of which indicate a caldera ≥13 km across. SHRIMP ages are reported on the geologic map of the Sesia magmatic system in Figure 17. The oldest single-age for the volcanic rocks is of 288±2 Ma, determined on zircons from andesitic basalt sample, R6. This age matches very well, within errors, that of a granodiorite collected at deep levels in the Roccapietra granite and that of the upper Mafic Complex determined by Peressini *et al.*, (2007). Zircons from samples of the predominant rhyolitic tuffs provided bi-modal ages, with a cluster of zircons at about 289±3 Ma which were interpreted as “antecrysts” produced in early phases of related magmatism (e.g. Charlier *et al.*, 2004; Bryan *et al.*, 2008) and younger zircon ages spreading towards 282 Ma. The youngest ages of 278±5 or 275±4 were measured for the upper Valle Mosso aplitic granite, which constitutes the highest part of the Valle Mosso body and intrudes the volcanic rocks. An intermediate age of 282 Ma is reported by Schaltegger and Brack (2007) on the Montorfano Granite, 12 km north of Figure 17. A palinspastic restoration of the Alpine effects, considering the displacement of Alpine faults and the differential tilting, places the caldera and the Roccapietra-Valle Mosso pluton above the Mafic Complex (Fig. 18)

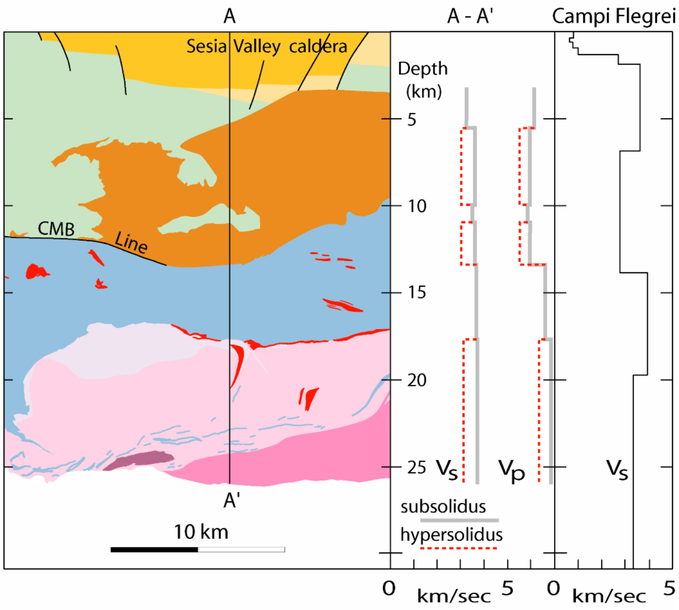
These data indicate that, in the Sesia Valley, bimodal volcanism and incremental growth of granitic plutons occurred within about 5 to 10 million years, during a time interval similar to early Permian volcanic activity elsewhere in the Alps (Schaltegger and Brack, 2007; Marocchi *et al.*, 2008) and well within the time frame for volcanic activity in silicic large igneous provinces (e.g. Bryan *et al.*, 2008) and the growth of zoned granitic plutons (Coleman *et al.*, 2004). The coincidence of ages in the upper Mafic Comples indicates that onset of bimodal volcanism and granitic plutonism was most likely triggered by intrusion of mantle-derived mafic melt in the deep crust.

Figure 17. Geologic map of the Sesia magmatic system



Geologic map of the Sesia Magmatic system, modified from Quick *et al.*, (2009). The map is oriented with north to the lower left to approximate the original setting of the plumbing system of the caldera before the Alpine tilting. Numbers refer to SHRIMP zircon ages.

Figure 18. Palinspastic restoration of the Sesia magmatic system



Palinspastic reconstruction of Early Permian Sesia Magmatic system, from Quick *et al.*, (2009).

Conclusions

The Sesia magmatic system constitutes and unprecedented exposure of a plumbing system of a caldera and, more in general, of a Silicic Large Igneous Province (SLIP), exposed with good continuity from the surface to a depth of about 25 km (Quick *et al.*, 2009). In this framework, the Mafic Complex records processes that affected the deep crust beneath the caldera. The onset of volcanic activity correlates strictly with the climax of the growth of the upper Mafic Complex, when the crust was pervasively heated. Igneous activity may have continued for as much 10 million years. In the middle to upper crust, this activity was dominated by silicic melts produced by anatexis in the deep crust, but included a minor amount of mantle component. During the life of volcanic activity, the Mafic Complex was a huge, hot crystal mush body of slowly sinking cumulates, within which the magma chamber was limited to small bodies at the core of the arcuate structure, where injections of fresh, although still contaminated, mafic melt were mingled with dioritic cumulates. All available evidence indicates that large, predominantly molten magma chambers were not involved and that the magmatic plumbing system beneath the active volcanic field was composed of crystal mush bodies consistent with inferences from geophysical data (Guidarelli *et al.*, 2006).

In Appendix A we propose a sequence of stops for a 2-days field excursion in the Sesia magmatic system.

In Appendix B we provide a JPEG copy of the Ivrea-Verbano geologic map from Quick *et al.*, (2009)

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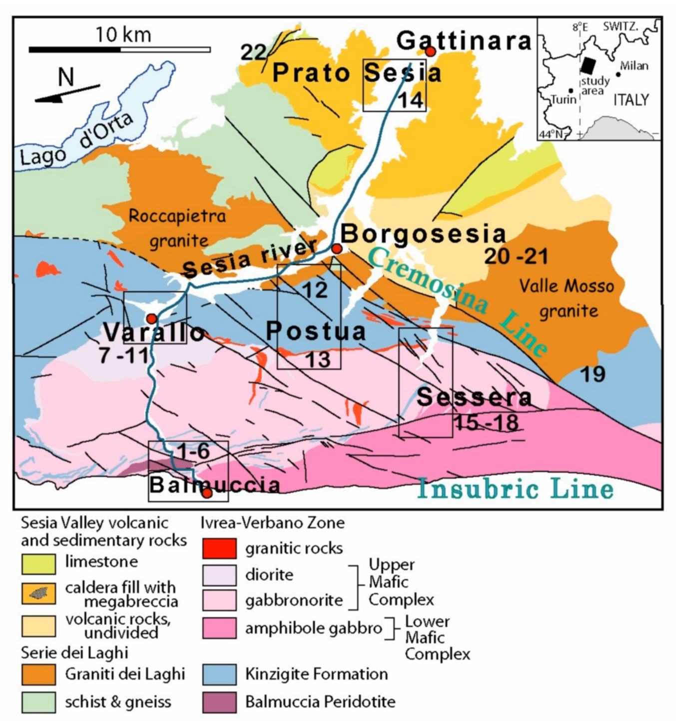
A. Two-day fieldtrip in the Sesia magmatic system

The two-day fieldtrip will lead people across the Sesia magmatic system, starting from the deepest exposure of the crustal section and rising progressively up-section to the volcanic rocks at the surface. Stops are grouped in localities indicated by rectangles in Figure A1.

Figure A1. Map of the Sesia magmatic system



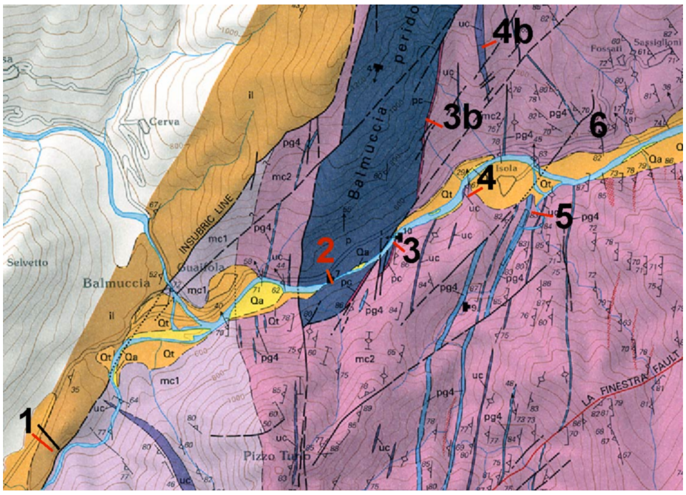
Geologic sketch map of the Sesia magmatic system, rotated about 100° anticlockwise to approximate the original setting before alpine tilting, modified from Quick *et al.* 2007. The Insubric Line, located at the bottom of the Figure, bounds the deepest exposure of the crustal section. Rectangles indicate multiple-stop localities as described in subsequent figures.

First day

The excursion begins with a traverse across the Mafic Complex in the Sesia River, starting at the Insubric line, followed by stops in the Balmuccia area and ending in the upper Mafic Complex in the vicinity of Varallo up to the roof contact with the Kinzigite Formation. The excursion continues, cross-cutting the Kinzigite Formation to see otho- and paragneisses in anatectic facies, and mingling of mafic and acidic magmas at the base of the large granitic pluton of Roccapietra. After crossing the Cremosina Line, the excursion ends in the area of Prato Sesia to see the best outcrops of megabreccia filling the caldera.

Stops in the Balmuccia area.

Figure A2. The Balmuccia area

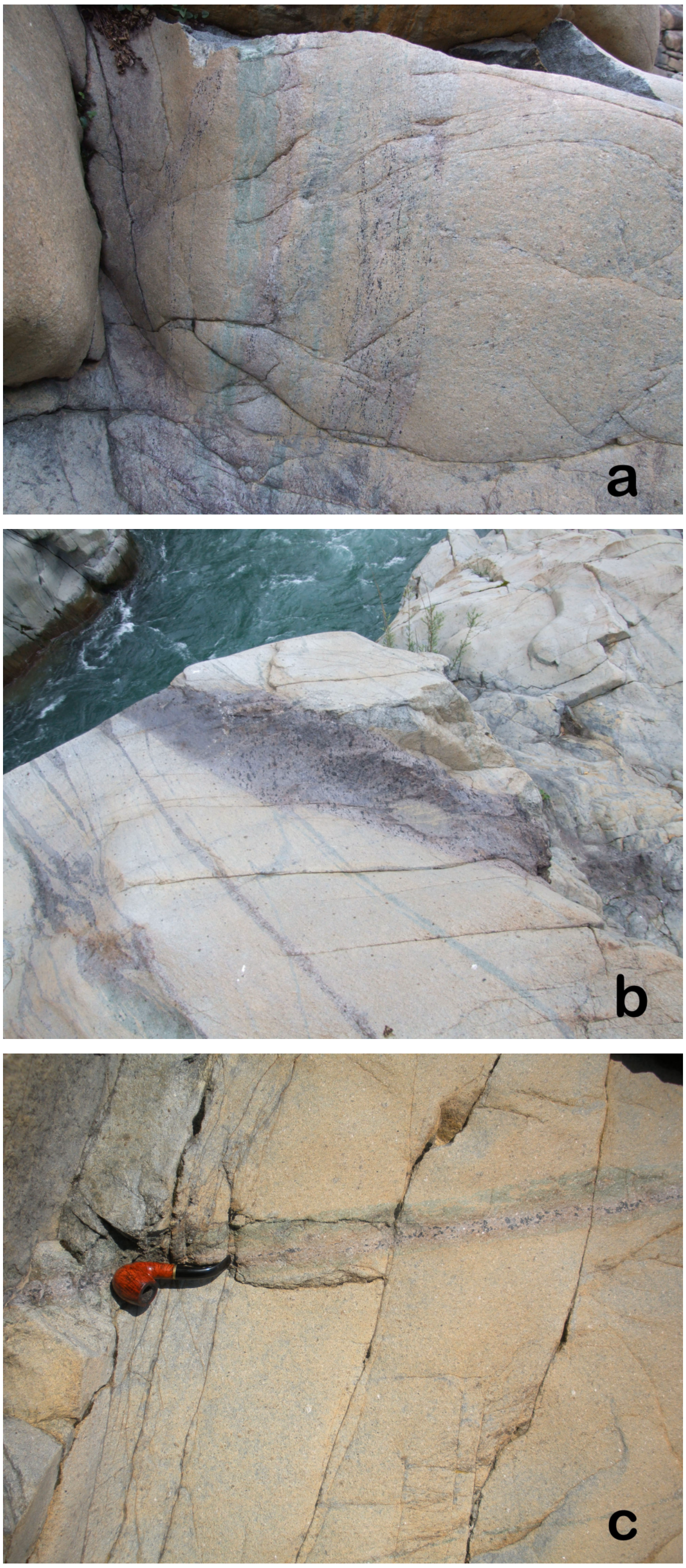


The Balmuccia area cut out and modified from Quick *et al.*, (2003), reported in Appendix B.

Stop 1) Mylonite of the Insubric Line. Leave the car at the locality “Dinelli” (N 45 48 25; E 8 7 26) and follow a short path to reach an old bridge over the Sesia river where the mylonites of the Insubric Line are well exposed (N 45 48 21.3; E 8 7 32.8). The geomorphology, in this segment of the Valley, is strongly controlled by the Insubric fault.

Stop 2) Balmuccia peridotite (N45 49 12.6 E8 09 11.5). Once thought to be the mantle basement above which the Mafic Complex was underplated at the crust-mantle boundary, this lens of mantle rocks was interfingered within the Kinzigite Formation before the Permian mafic intrusion. Even though it does not present a true petrologic Moho and is not directly involved in the igneous evolution of the Sesia magmatic system, it is worth a look because it is one of the best preserved mantle peridotites in the world. The peridotite suffered a number of partial melting events which are recorded by networks of Cr-diopside and Al-augite dikes and bands (Fig. A3)

Figure A3. Advanced spinel foliation



3a, b, c: Cr-diopside and Al-augite bands and dikes in the Balmuccia peridotite (Stop 2).; 3d, advanced spinel foliation and boudinage of Cr-diopside dykes in the border zone of the Balmuccia peridotite (Stop 3b).

Stop 3) Balmuccia Peridotite-Mafic Complex contact. Park the car at Isola (N45 49 35; E8 10 13), walk through the village towards the west and follow a path along the right bank of the Sesia river for about 15 minutes and then descend to the river, after the first outcrops of peridotite. (N45 49 24; E8 09 38) Along the river, exposure of the primary contact between mantle peridotite and a cumulus sequence of pyroxenite, pegmatoidal clinopyroxenite and finally gabbro. These rocks crystallized within the paragneiss bearing belt, at the boundary between the mantle lens and paragneisses of the Kinzigite Formation. Another exposure of the contact between strongly foliated mantle tectonite and of the cumulus sequence might be seen climbing the facing slope above the left-bank of the Sesia to a waterfall (Fig. A4, Stop 3b). We do not recommend this climb!! The climb may be dangerous!

Figure A4. Paragneiss septum, Isola

4a, b At stop 5, outcrop of paragneiss septum close to the Ni-mine.

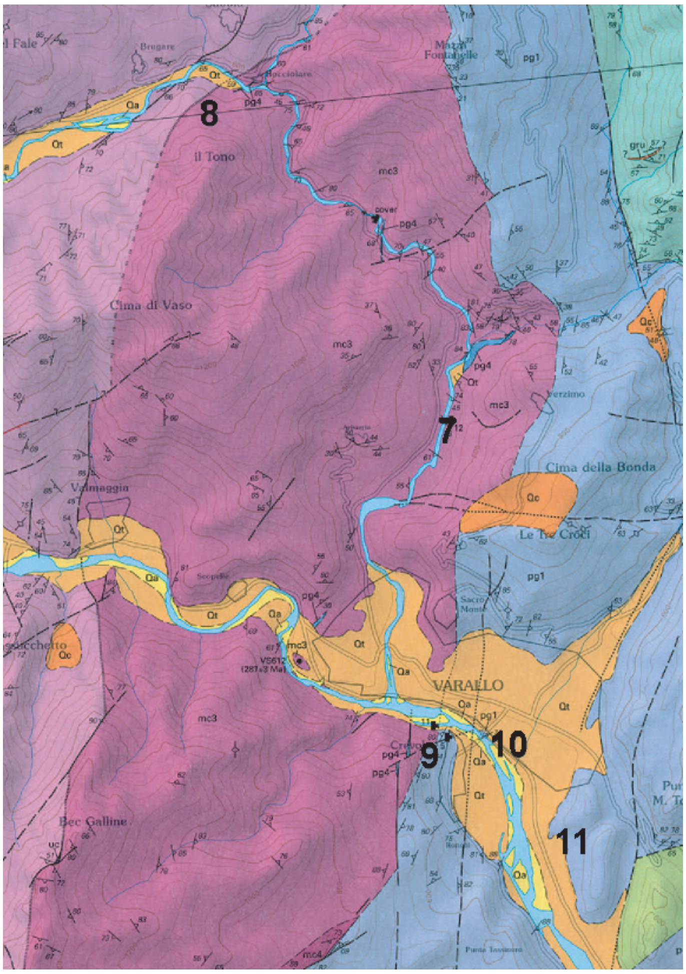
Stop 4) Deformation of ultramafic cumulates (N45 49 31; E8 09 55). Coming back toward Isola, we stop on a large outcrop on the river, where gabbros show advanced stretching foliation, isoclinal folds and boudinage of ultramafic cumulates, which are common at this depth in the Mafic Complex. These high-T deformations are better exposed uphill on the opposite slope of the valley (Stop 4b), but this would require about 1 hour of hiking on a trail overgrown with thornbush and then a scramble on a steep slope to reach the locality where pictures reported in Figure 11 of the main text were shot.

Stop 5) Paragneiss septum (N45 49 24; E8 10 18). Follow a trail from Isola to the south toward the “croso della Gavala.” Within a few minutes, you will reach a bridge crossing the stream above a paragneiss septum. The rock is a metapelitic granulite with strongly parallel fabric and contains abundant garnet, quartz, plagioclase ± graphite, sillimanite and very rare biotite (Fig. A4b). The septum is in primary contact with foliated norite. At a distance of about 20 metes, it is possible to observe the entrance of an abandoned nickel mine, from which Fe/Ni sulphides in cumulus pyroxenite were mined up to WWII.

Stop 6) Gabbroic cumulates (approximatively N45 49 44.4 E8 10 33.6). Following the road to Sassiglioni, we can observe banded and foliated gabbroic cumulates at the deepest level of the upper Mafic Complex.

Stops in the Varallo area

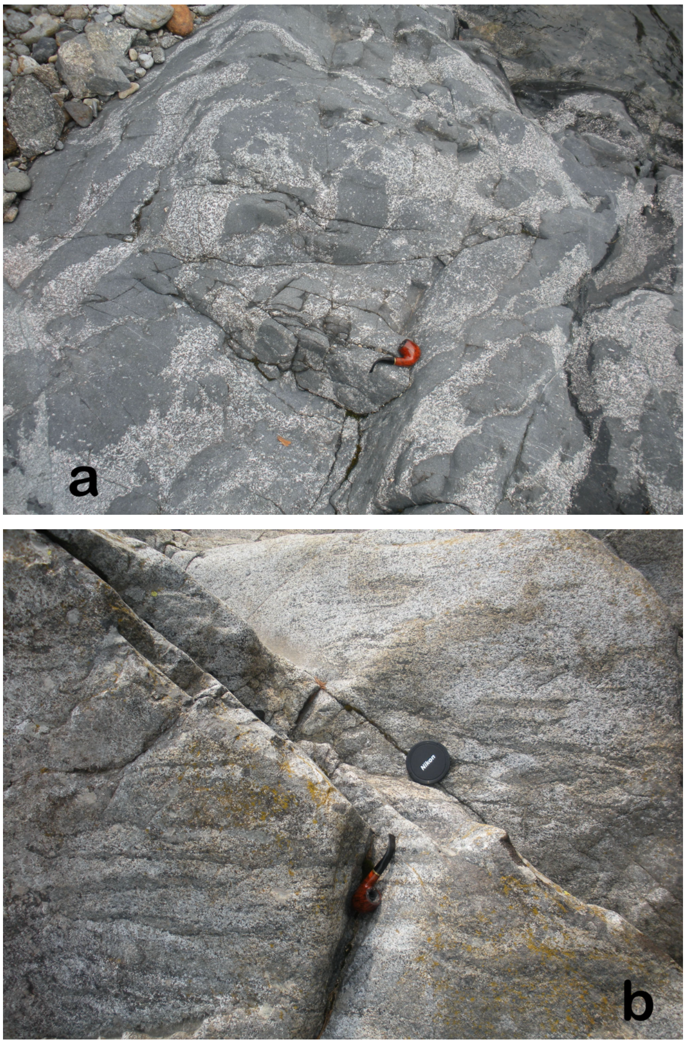
Figure A5. The Varallo area



The Varallo area, cut out and modified from Quick *et al.*, (2003), reported in Appendix B.

Stop 7) “Diorites” of the upper Mafic Complex(N45 49 28; E8 14 52). From Varallo, take the road to Val Mastallone until locality Aniceti where you may park beside the road. Exposed in the stream is a swarm of mafic enclaves in the “Diorites”. The enclaves are fine-grained, porphyritic gabbro with plagioclase phenocrysts. (Fig. A6a)

Figure A6. Enclaves, Aniceti



6a, swarm of faintly elongated enclaves at stop7.; 6b, more intense stretching of enclaves at deepest levels, in proximity to the transition between “diorites” and Main Gabbro, stop 8, (N45 51 11.6 E8 14 12.8)

Stop 8) Stretched mafic enclaves (N45 51 11 E8 14 17). In the stream at locality Bocciolaro, an example of mingled diorite and mafic enclaves crops out at the transition between Main gabbro and “Diorites”. More advanced stretching of mingled rocks (Fig. A6b) is visible about 100 meters upstream, at (N45 51 11.6 E8 14 12.8).

Stop 9) Mafic Complex – Kinzigite Formation contact (N45 48 38 E8 15 25). Take the bridge from Varallo to Crevola, and within 100 meters of crossing the bridge, you may enter a drive way on the right for a parking lot for tennis courts on the south bank of the Sesia River. Along the river there is one of the best exposures of the contact between Mafic Complex and the Kinzigite Formation. Amphibolite-facies migmatite, (Fig. A7) with chaotic deformation, is in primary contact with garnet-bearing diorite (following upstream about 200 meters).

Figure A7. Migmatite and Boudinage

7a Migmatite at Crevola, stop 9.; 7b,. Boudinage in metapelitic gneiss interlayered with calc-silicate bands, stop 10.

Stop 10) Boudinage in the Kinzigite Formation (N45 48 39; E8 15 35). Recross the bridge toward Varallo and park the car at the north side of the river. Under the bridge, rocks of the Kinzigite Formation contain boudinaged metapelites within ductile calc-silicates (Fig. A7b). Small granite bodies are boudinaged within calc-silicate (Fig. A8a) and crosscut the foliation, consistent with segregation of granitic melts during deformation.

Figure A8. Leucosome and boudinaged granite

8a, granitic leucosome cross-cutting calcsiliscate. 8b, Boudinaged granite in calc-silicate band.

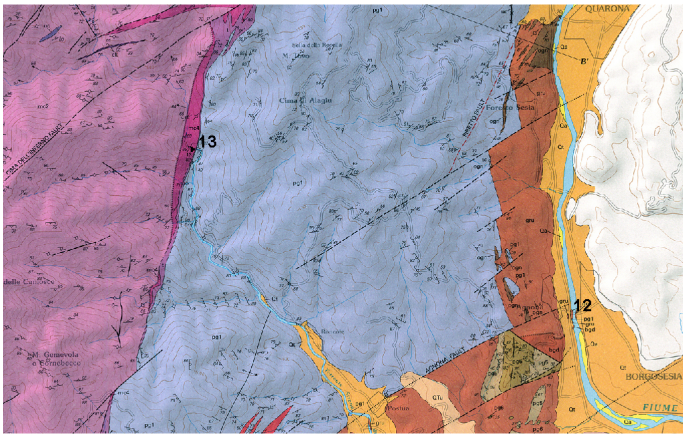
Stop 11) Granite dike cutting the Kinzigite Formation (N45 47 46; E8 16 19). Along the road from Varallo to Borgosesia, the Kinzigite Formation is cross-cut by a dike of fine-grained granite (Fig. A9) that is similar, both petrologically and chemically, to microgranite mingled with granodiorite in the Roccapietra pluton.

Figure A9. Dike

Granite dike in the Kinzigite Formation at stop 11.

The Agnona - Postua area

Figure A10. Agnona - Postua area



Stops in the Agnona - Postua area. (Cut out and modified from Quick *et al.*, (2003), reported in Appendix B.)

Figure A11. Granitoid with inclusions, Postua

Xenoliths-bearing granitoid at the contact between Mafic Complex and Kinzigite Formation, Val Strona di Postua, stop 13.

Stop 12) Deep levels of the Roccapietra Pluton (N45 43 24; E8 15 44). Following the road from Varallo to Borgosesia on the right bank of the Sesia, park the car immediately after having passed beneath an old bridge connecting Agnona and Borgosesia towns. This stop is within the deepest levels of the Roccapietra pluton, where mingled dioritic and granitic rocks, with locally abundant inclusions of the country rock, are exposed in a good outcrop on the river.

Stop 13) Roof of the Mafic Complex in Val Strona di Postua. This stop necessitates a deviation and a hike that collectively requires about half a day, and should be considered as a separate excursion, as it is hard to be included in the same, single day. After having reached the village of Postua (N45 42 47; E8 13 50) continue for about

5 km along a dirt road on the left bank of the stream. Formal permission is needed to use this road and can be obtained at the office of the municipality office in Postua (open only in the morning of working days!). Park the car in locality “ponte rosso” (N45 44 04; E8 12 03). Continue following a path upstream on the right bank for about 20 minutes, reaching the stream at the contact between Kinzigite Formation and the Mafic Complex (N45 44 35; E8 12 03) The contact is characterized by unfoliated granitoids, which contain a number of inclusions from the roof rocks (Fig. A11). Continuing up the river, inclusion-bearing granitoids grade into faintly foliated gabbros. A foliation defined by flattened, locally abundant large poikilitic amphibole is discordant to layering in the rocks indicating a sense of shear consistent with flow of the “gabbro glacier” beneath the melting roof rocks of the Kinzigite Formation.

The Prato Sesia area

Stop 14) Caldera Megabreccia. This area is located within the caldera fill, and exposes one of the better outcrops of megabreccia. From Borgosesia, follow the the Sesia River downstream, taking the left bank south of Serravalle. 3 kilometers after the bridge over the Sesia (immediately after “La Pipa”, at N45 39 31; E8 21 32) turn to the right following the indication “Spazzacamini”. After crossing the railway, continue along the dirt road, turn to the left at the crossing and continue for about 2 km. Park the car close to the bridge over a drainage canal (N45 39 10; E8 21 23). From here walk west to the bed of the Sesia (N45 39 09; E8 21 10) arriving within a few minutes to outcrops of megabreccia (Fig. 12). Outcrops on the river are reachable only when water levels are low in the river. If the stream conditions do not allow reaching the outcrop, an alternative may be a stop on the opposite side of the river, following the road on the right bank. South of Vintebbio, after “Regione Cave”, park the car at N45 39 07, E8 21 06, and descend to the river, where megablocks included in welded tuff are exposed,.

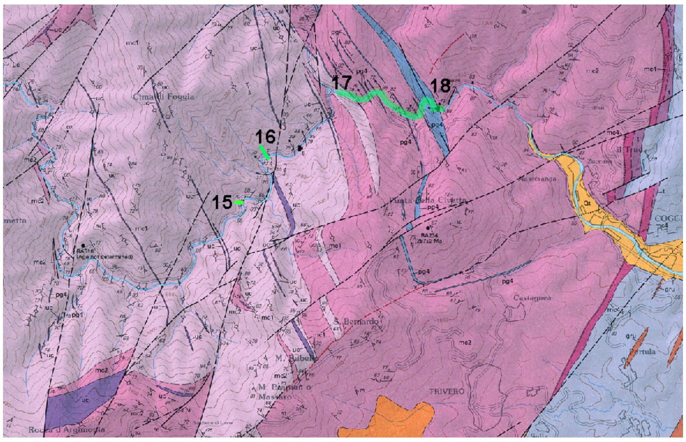
Figure A12. Megabreccia

At stop 14, megabreccia contains blocks of red, glassy rhyolite, beside other lithologies, wrapped in welded tuff of the caldera fill.

Second day, in the morning – the Val Sessera area

The second day of the field trip provides another transect across the Sesia magmatic system, starting from outcrops of the lower Mafic complex and paragneiss bearing belt in the Sessera Valley (Fig. A12). Subsequent stops are at the Valle Mosso granitic pluton and the contact between the Valle Mosso granite and volcanic rocks.

Figure A13. Val Sessera area



Stops in the lower Mafic Complex and paragneiss bearing belt along the Val Sessera. Cut out and modified from Quick *et al.*, (2003), reported in Appendix B.

Stop 15) Synmagmatic deformation in gabbros. From Trivero, follow the asphalt road to Castagnea and then continue along a dirt road for about 7 km into the Sessera Valley. Park the car about 300 m before the only house in proximity to stop 15 (N 45 41 22; E8 7 30, locality “La Frera”), and descend to the stream to look at small synmagmatic normal faults cross-cutting recrystallized and foliated amphibole gabbro of the lower Mafic Complex (Fig. A13a), and other high-temperature deformation structures.

Figure A14. Lower Mafic Complex, Sessera Valley

14a, at stop 15 Hypersolidus normal faults in amphibole gabbro. 14 b, at stop 16, hypersolidus normal fault cross-cutting a pyroxenite.

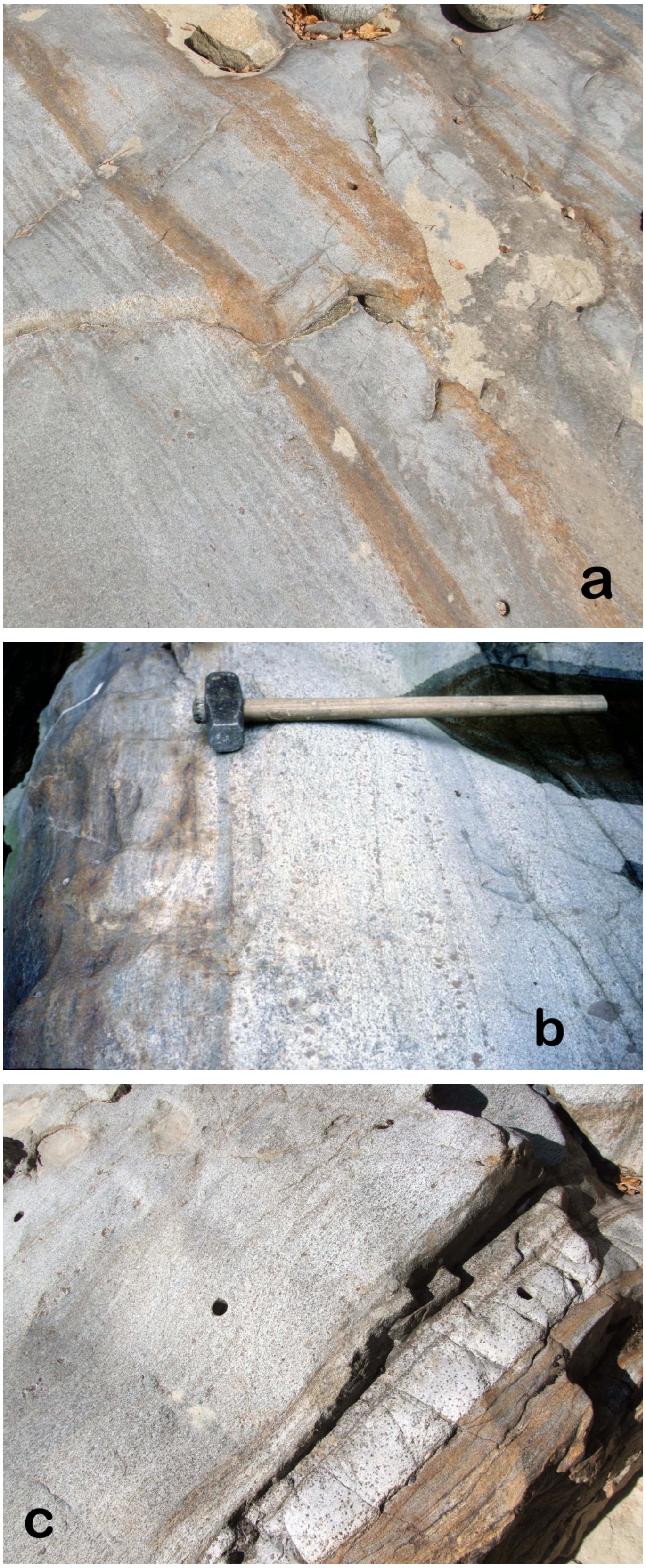
Stop 16) Synmagatic deformation in gabbros. (N45 41 38; E8 7 41) Some more features similar to stop 15 (Fig. 13b)

Stop 17 to 18) Traverse across a large paragneiss septum. This is a hike of about 1.3 km along the riverbed, which is feasible only if the water in the stream is low. Descend to the stream in proximity to the Piancone power station, underneath the confluence of the Sessera and Confienzo streams, and continue downstream. After the first outcrops of amphibole gabbro, noritic rocks become more abundant approaching the first paragneiss septum of the paragneiss bearing belt (N45 42 01; E 8 8 20). From here downward, the stream cross-cuts the paragneiss bearing belt, where norites, quartz-norites and charnockites are abundant and interlayered with restitic paragneiss septa and minor amphibole gabbros (Figs. A14 and A15).

Figure A15. Bands of norite and amphibole gabbro; Restitic paragneiss

15a, Bands and norite and amphibole gabbro with a brittle crack filled by gabbro. 15b, band of restitic paragneiss, made of predominant garnet and plagioclase, with minor sillimanite and antiperthite, eventually corundum.

Figure A16. Thin septa, quartz-norite and charnockite



16a and b: restitic paragneiss septa in contact with garnet-bearing norite. Figure A16 c, d and e: foliated bands of quartz-norite and charnockite, abundant within the Paragneiss bearing belt, especially in proximity to paragneiss septa.

At the end of the traverse is the thickest paragneiss septum, which is about 100 m across (N 45 41 59; E 8 9 03). Before arriving at this septum, smaller septa of paragneiss are included in norite and cut by small normal faults filled by fine-grained gabbro (Fig. A16). In the septum, charnockite is present either as bands or discordant dikes (Fig. A17) within a garnet-rich metasediment in which thin corundum bands may easily be found. Biotite is present, although rare. At the eastern contact of the septum, garnet-bearing norites are present. Immediately above, bands of charnockite mingled with norite are transposed into the foliation. The composition of these granitoids is very similar to that of leucosomes observed at the roof of the Mafic Complex (Fig. A7a), suggesting that the last septum incorporated in the Mafic Complex was as fertile as the roof Kinzigite (Sinigoi *et al.*, in prep)

Figure A17. Shreds in norite

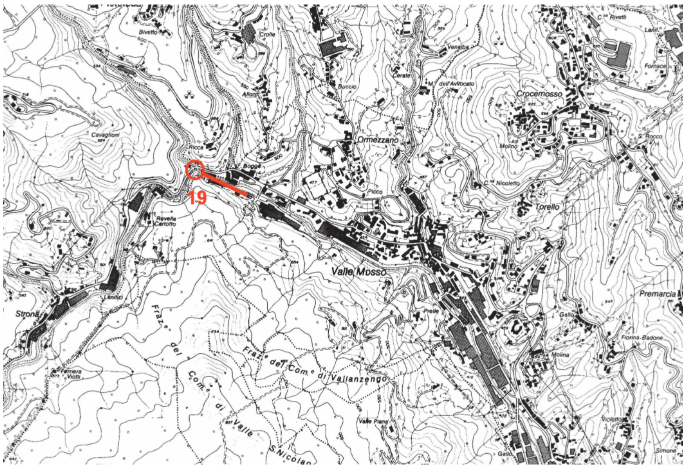
Shreds of paragneiss encased in norite and cut by synmagmatic faults beneath the thickest septum.

Figure A18. Charnockitic dike

Discordant dike of charnockitic granitoid cross-cutting banding and foliation of the thickest septum (at the end of traverse from stop 17 to stop 18).

Second day, in the afternoon. From the Valle Mosso granite to the volcanic rocks of the Sesia.

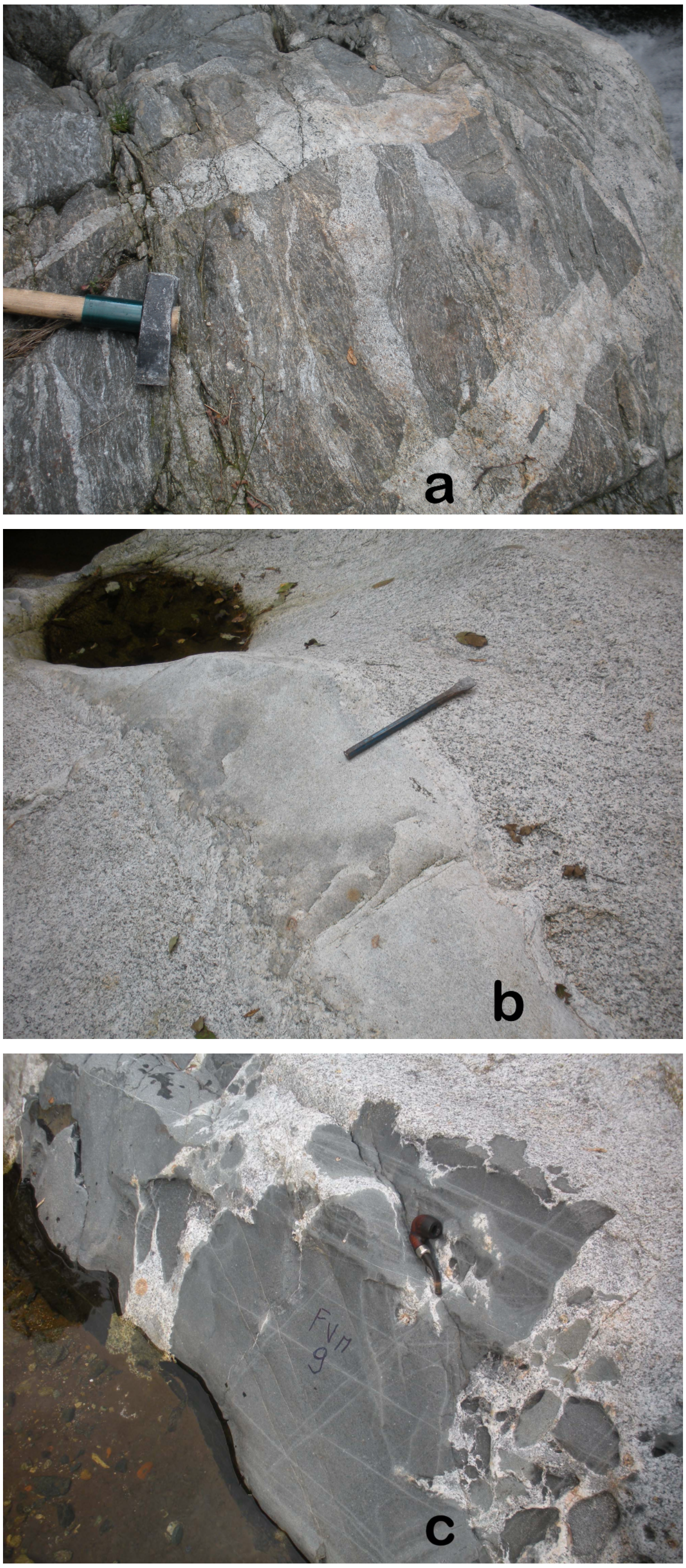
Figure A19. Valle Mosso area



Location of stop 19, in proximity to Valle Mosso town. Topography from CTR, Regione Piemonte. Detailed geologic map in progress and not yet available).

Stop 19) At the western end of Valle Mosso village, park the car close to a small church (N45 38 17, E8 07 43) and descend to the stream beneath the bridge on the main road. Walking downstream, ortho- and paragneiss in migmatite facies (Fig. A18a) are in primary contact with the base of the granitic pluton, where faintly foliated granodiorite is cross cut by aplitic and mafic dikes (Figs. A18 b and c). The outcrop is continuous for more than 200 m.

Figure A20. Orthogneiss, aplite and mafic dyke



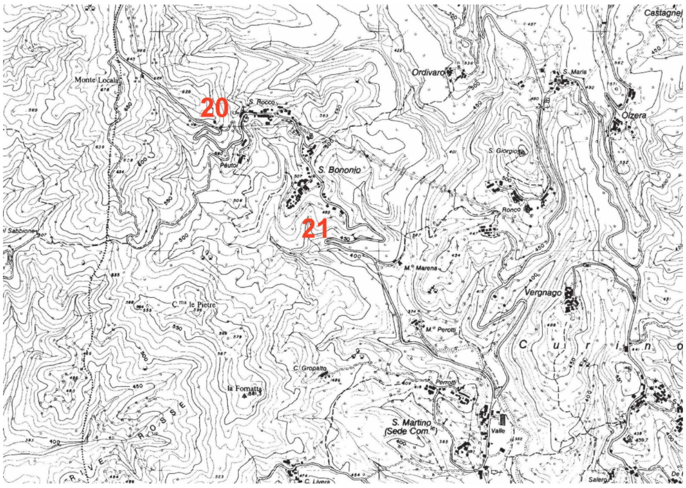
At the base of the Valle Mosso granitic pluton (Stop 19): a) orthogneiss migmatite, b) aplite dyke in granodiorite, c) mafic dyke intruded and dismembered in granodiorite.

After stop 19, the excursion will traverse the Valle Mosso pluton to reach its roof, where it is intruding volcanic rocks. The granite is monotonous, and the distinction between lower and upper Valle Mosso, defined solely on the basis of chemistry, is hardly detectable in the field. Follow the road to Ponzone (en route an easy brief stop may be made in a small quarry inside the town, at N45 39 08.9 E8 10 59.2, to see an aplitic dike cross-cutting the granite) and than turn to the right in direction of Baltigati and continue towards San Bononio.

Stop 20) (N45 38 30; E8 13 13) The upper Valle Mosso granite becomes granophyric approaching the contact with volcanic rocks.

Stop 21) After San Bononio, stop the car at the hairpin turn (N45 38 13; E8 13 36) and follow the path to the West towards an abandoned quarry (less than 100 meters). Immediately after a small valley, volcanic rocks, here represented by an aphyric dacite, are clearly intruded by granite with granophyric patches. From here to the East we reenter the caldera fill.

Figure A21. San Bononio area



Stops 20 and 21 in the San Bononio area. Topography from CTR Regione Piemonte.

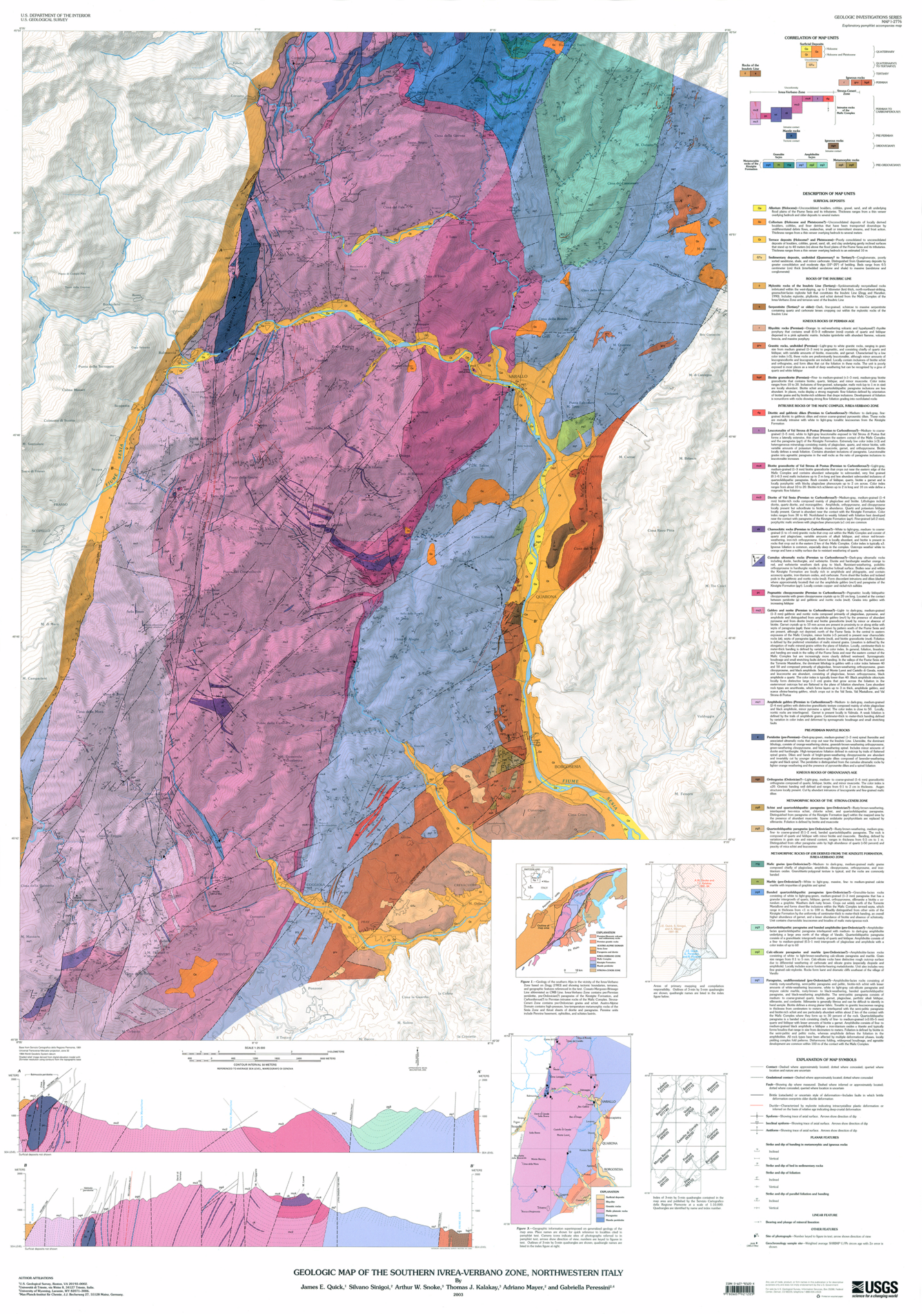
Supplementary stop 22) If the time does allow, an additional stop may be considered to see the caldera wall, which is exposed at the northern margin of the caldera. Drive to the north-west of Borgomanero, reaching the entrance of a dirt road between Piovino and Gargallo at N 45 43 34, E 8 25 22, and follow the road for about 3 km. Park the car at a crossing (N45 43 32; E 8 23 45) and climb up hill on a wide path. Caldera fill tuffs contain stretched shreds of pumice and, immediately above, a big boulder of schist. Welded tuff reappears above the schist boulder, before reaching the basement schists at N 45 43 41, E 8 23 37.

Figure A22. Location of the caldera wall

Access to the caldera wall exposure. The location of the caldera wall and of the schist block is only approximative, since mapping is in progress.

B. Ivrea-Verbano geologic map from Quick *et al.*, (2009).

Figure B1. Ivrea-Verbano geologic map



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