BAVENO 10th HUTTON SYMPOSIUM · 2023 · Italy

The Ivrea Zone
A journey through the continental crust

Hutton Symposium on Granites and Related Rocks
Mid-conference field trip

13 September 2023

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Information

Abstract

This field trip will take you in one day from the crust-mantle transition of the Adriatic plate to the surface of a Permian volcanic system offering the opportunity to investigate trans-crustal magmatic systems and the complicated evolution of crustal migmatites. We will examine the different structural levels of this unique magmatic system from the bottom of the crust to the surface (or vice versa), looking at the world-famous continental mantle rocks in Balmuccia with several generations of pyroxenites, through lower crustal gabbros, mid-crustal migmatites, upper crustal granites and metasedimentary xenoliths including garnet xenocrysts, to associated ignimbrites and obsidian flows that are assembled in large Permian calderas. This will also lead us to discuss the complex nature of the continental crust in space and time and the role of the lower continental crust for bulk crust compositions.

We will investigate the genetic links between mantle and crust, the processes of melt generation and assimilation in the lower crust and the relations of pyroxenites in the mantle with the large mafic complex. We will discuss tempos and rates of magmatic accretion in transcrustal magmatic systems and possible transport rates of lower crustal xenocrysts that are now found in upper crustal granites. We will address the relationships between magmatic underplating and potential links to migmatite formation and (the lack of) links between granulite facies metamorphism and igneous underplating. Eventually, we will discuss the importance of the later Mesozoic and Alpine evolution for the emplacement of a near continuous section of the Permian continental crust in the context of major (micro-) plate re-organization.

The field trip will take place along the Sesia Valley between Balmuccia and Borgosesia, home of the Permian Sesia 'Supervolcano' and home of a large lower crustal intrusion into the metasedimentary basement of the Southern Alps. In addition to visiting fascinating outcrops of magmatic rocks and migmatites, you will have the opportunity to discover a region of beautiful landscapes, traditional small villages, a clear mountain stream, and experience the local production of Italian vine during a vine tasting event at the end of the field trip. Enjoy one of the most famous lower crustal section in the world.

Program Summary Wednesday 13.9.2023

- Leaving Hotel Dino at 8am. - There will be 4 buses, each bus has a different sequence of stops to avoid having too crowded outcrops. The program here describes the stops and the program of Bus 1. Note that in case of high water, Stop 3 may be skipped. The routes are chosen to minimize driving
- Bus 1: Outcrop stop sequence: Stop 1, 2, 3, 4, 5;

  Bus 2: Outcrop stop sequence: Stop 3, 2, 1, 4, 5

  Bus 3: Outcrop stop sequence: Stop 4, 1, 2, 3, 5

  Bus 4: Outcrop stop sequence: Stop 5, 4, 2, 1, 3

- Stop 1 – Balmuccia peridotite (arrival time ~9h30). Peridotite and pyroxenites of the Balmuccia peridotite along the gorge of the Sesia River. Interactions between peridotite and pyroxenites and the role of pseudotachylites. (leaving time ~11h00)
- Stop 2 – Layered gabbros and pyroxenites at Isola (3 min drive from Stop 1). Gabbronorites and pyroxenites of the mafic complex, emplacement mechanisms and syn-magmatic folding. Metasedimentary enclaves (charnokites) within the gabbro and the relations to assimilation and contamination processes. Lunch at the outcrops. (leaving time ~13h00)
- Stop 3 – Migmatites at Crevola (Varallo) (arrival time ~13h15). Garnet-sillimanite biotite gneisses, orthogneisses, and calc-silicates and their migmatite textures. Structures, metamorphism and migmatites. Discussion of Variscan versus Permian thermal effects and the role of melt production (leaving time 14h30)
- Stop 4 – Borgosesia, below the old bridge (arrival time 14h45) upper crustal intrusions and their field relations. Dioritic and metasedimentary enclaves (xenocrysts and country rocks). Pegmatites and aplites. Relationships with upper crustal country rocks and links with the mafic complex and lower crustal xenocrysts. (leaving time 16h15)

- Stop 5 – Permian volcanic rocks megabreccias (arrival time ~16h30). Outcrops provide an overview of Permian volcanic rocks related to megabreccias of a Caldera forming eruption (Sesia supervolcano). Andesites, Ignimbrites, rhyolite flows including (devitrified) obsidian, mid- and lower crustal xenoliths (leaving 17h30)
- Stop 6 – Vine tasting (20 minutes drive from Stop 5) (18h00-19h30) Cantina dei Colli Novaresi Via Cesare Battisti 56 28073 Fara Novarese (NO)

Practical information and logistics

The participants will leave Hotel Dino at 8am. Transport to the field trip locations and from site to site will be with 50-60-seater buses. Lunch packages are provided by the hotel and included in the total cost. At the end of the fieldtrip, there will be a winetasting at 18h. Participants will be dropped at Dino Hotel around 20h30

Safety

Usual field equipment (hammer, hand-lens, field book, camera,…). The trip will involve only short walks/hikes, outcrops are all along riverbeds – light field boots / running shoes are sufficient. Basic equipment must also include sun protection, warm clothes and waterproof jackets.

Hospital

Below are contact information for the nearest hospital during the field trip:

- Pietro and Paolo Hospital, Via Francesco Ilorini, 20, 13011 Borgosesia VC, Italy Phone nr. +39 016 342 61)

The Ivrea-Verbano zone: a section of Earth continental crust

Exposed crust–mantle sections are essential archives of the past and contemporary Earth's crust. At these locations, it is possible to conduct a thorough investigation of spatial and temporal relationships between lower crustal rocks and links with the upper mantle, which cannot be obtained by xenolith investigations alone. For example, lower crustal magmatic underplating linked to upper crustal magmatism and volcanism can only be studied in a few cross-sections worldwide, most of them are incomplete and none displays a complete Moho transition zone (Salisbury & Fountain 1990). They nevertheless provide important clues, albeit indirect, about the nature of the lowermost continental crust. For instance, they are useful in understanding the variation of chemical and physical properties with depth in the crust, including heat production (Galson 1983; Ashwal et al. 1987; Fountain et al. 1987; Hacker et al. 2015), seismic velocities (Fountain 1976; Kern & Schenk 1985; Chroston & Simmons 1989), and magnetic susceptibility (Wasilewski & Fountain 1982; Williams et al. 1985; Shive & Fountain 1988). These data, coupled with the geometry of rock units in exposed sections, form the basis of geophysical models and hypotheses concerning the chemical and physical identity of Earth's crust. For example, seismic models based on exposed cross-sections (Hale & Thompson 1982; Fountain 1986; Christensen & Mooney 1995; Behn & Kelemen 2006) indicate that large velocity variations associated with compositionally variable lithologic layers could be responsible for the pronounced seismic reflectivity in the lower crust (e.g., Bois et al. 1989).

Amongst the known non-Archean crustal cross-sections with continental (e.g., Sila Massif, Calabria, Italy; Prince Rupert, British Columbia, Canada; Doubtful Sound, Fiordland, New Zealand) and paleo-island arc signature (e.g., Kohistan, Pakistan; Talkeetna, Alaska, USA; Sierra de Famatina, Argentina), the Ivrea Verbano Zone (IVZ) in the Southern Alps (Piemonte, Italy; Fig. 1) represents the most complete, time-resolved crust–upper mantle archive in the world. The IVZ is host of a transcrustal magmatic system, known as the 'Sesia supervolcano' in the Sesia Valley (Quick et al. 2009). The IVZ is one of the best studied of all sections, yet many aspects of its evolution remain enigmatic and vigorously debated. Historically, the IVZ was the first terrain identified as an exposed cross-section of the continental crust (see special volume 48 issue 1 of Schweiz. Mineral. Petrogr. Mitt., 1968). With its pronounced positive Bouguer gravity anomaly (Fig. 2), the so-called Ivrea Geophysical Body (IGB) below the exposed IVZ served as a calibrating benchmark in search of other crustal sections in the world (e.g., Brooks 1970; Forman & Shaw 1973; Gibb & Thomas 1976).

The IVZ remains an extremely valuable guide to the processes that shape much of the continental crust. The contacts between granulite facies lower crustal rocks and upper mantle-type ultramafic bodies are, however, deformed, suggestive of partial removal of the section (Brodie & Rutter 1987; Fig. 1). Such contacts were therefore viewed as "tectonized Moho" (Fountain 1989; Quick et al. 1995). Nevertheless, mantle peridotite slivers embedded in lower crustal rocks and geophysical observations indicate the presence of the Moho transition zone at shallow depth (Figs. 2-3). Indeed, the large gravimetric, magnetic, and seismic anomaly of the IGB has sparked worldwide interest and indicates that dense, mantle-like rocks are located as shallow as ~3 km below the surface locally (e.g., Berckhemer 1968; Lanza 1982; Fig. 2). Given the extensive surface exposure of the crustal section, limited lower crustal removal, and the proximity of the geophysically identified Moho, the IVZ is currently the target of an ICDP drilling project (http://www.dive2ivrea.org/; https://www.icdp-online.org/projects/by-continent/europe/dive-italy/) for testing key hypotheses of formation, evolution, and modification of the continental crust through space and time (Pistone et al. 2017).

Overview of the field area

The Southern Alps cover an area of more than 400 km, from the Piemonte (Ivrea) in the West to Carnia (Friuli) in the East and are separated by the Insubric line, a mid-Tertiary transpressive fault zone (Fig. 1), along which the central Alps have been uplifted by some 15-20 km. The Southern Alps are a S-vergent fold and thrust belt in which Variscan crystalline basement rocks and Upper Palaeozoic to Miocene sediments are involved. In contrast to the Central Alps, the Southern Alps display very limited Alpine metamorphic overprint.

It was recognised more than half a century ago that geophysical data indicated dense rocks relatively close to the surface in the internal arc of the Alps (Niggli 1946; Coron 1963). The IVZ is faulted against the South-Austroalpine domain along the Oligocene-Miocene Insubric Line (Schmid et al. 1987; Nicolas et al. 1990; Schmid 1993; Berger et al. 2012; Fig. 1). To the east, it is juxtaposed against middle to upper crustal rocks by two major faults identified as the Permian Cossato-Mergozzo-Brissago Line (CMB; Snoke et al. 1999) and the late Permian (Boriani & Sacchi 1973; Boriani et al. 1990; Garde et al. 2015) or Jurassic (Zingg 1983; Handy 1987) Pogallo Line. The IVZ records a polyphase tectono-metamorphic history that allows investigating the entire range of processes controlling the generation and evolution of the continental crust, ranging from continental accretion and amalgamation from Ordovician to Carboniferous (Handy et al. 1999), orogenic collapse with synchronous magmatic underplating during late Carboniferous to Permian (Rutter et al. 1993; Sinigoi et al. 1994), to continental rifting, thinning and exhumation during late Triassic to Jurassic (Handy & Zingg 1991; Beltrando et al. 2015; Ewing et al. 2015; Fig. 1). The increase in the metamorphic grade towards NW (e.g., Zingg 1980), the steep foliations sub-parallel to the Insubric Line (Quick et al. 1992), and the available thermobarometric estimates (e.g., Henk et al. 1997; Demarchi et al. 1998; Redler et al. 2012) demonstrate that the IVZ represents a tilted, largely preserved cross-section of the LCC. Peak metamorphic conditions for the rocks in the vicinity of the Insubric Line vary in the range 8-11 kbar and 750-900°C. The IVZ was tilted by Jurassic rift-related exhumation and Alpine compressional tectonics (Henk et al. 1997; Demarchi et al. 1998; Rutter et al. 2007), combined, perhaps, with some Permian tilting (Boriani & Giobbi 2004).

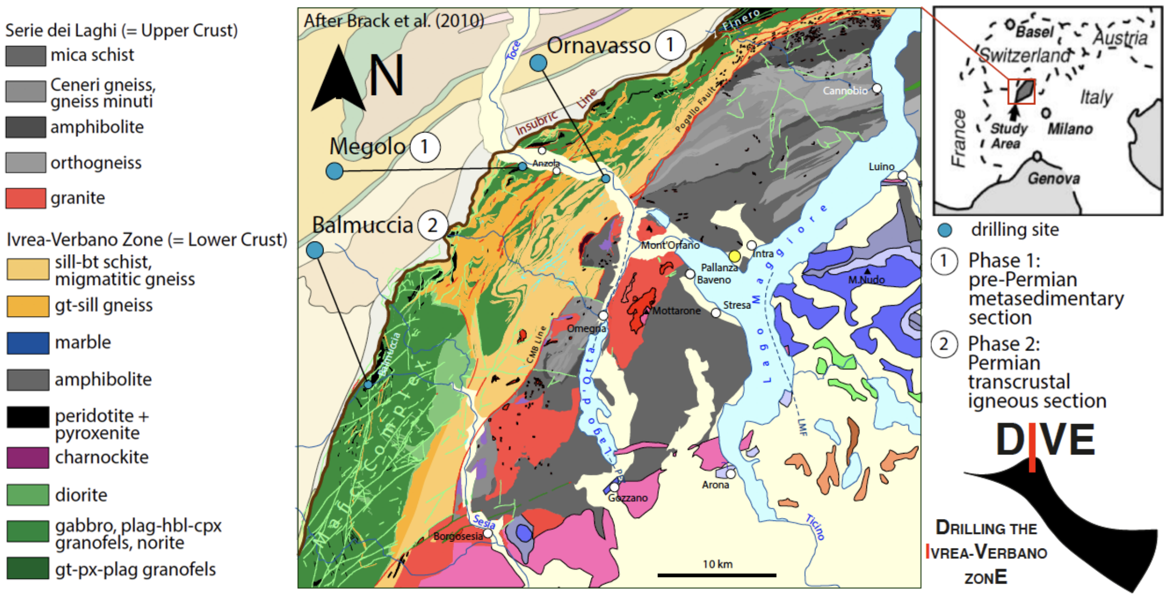

Figure 1. Present-day geology of the IVZ (after Brack et al. 2010, and references therein) with location and corresponding depth of the proposed drilling sites of Megolo, and Ornavasso (Val d'Ossola) of Phase 1, and Balmuccia (Val Sesia) of Phase 2.

The Ivrea Geophysical Body

The IGB is a piece of Adria lower crust and lithospheric mantle at shallow depth causing the largest positive gravity anomaly in the Alps (e.g., Kissling 1984; Fig. 2A), and its surface expression, the IVZ, is a type locality for the study of lower crustal processes. The IGB extends from Locarno in southern Switzerland to the vicinity of the Ligurian Sea and follows the arcuate shape of the mountain belt near the topographic transition. It dips steeply near the surface, usually towards the Adria plate, and flattens to sub-horizontal at a depth of ~30 km beneath the Po plain (Nicolas et al. 1990), as indicated by the presence of a distinct magnetization (Lanza 1982), high density and high seismic velocity of the Bird's Head shape of the anomaly (Berckhemer 1968; Fig. 2) at or near the surface, locally as shallow as ~3 km (e.g., Giese 1968; Fig. 2B). If projected to the surface, these locations, where the Adria Moho seismically "vanishes", roughly follow the Insubric Line within ~15 km distance. This suggests that the exposed parts of the IGB were perhaps tectonically detached from the Adria plate and back-thrusted towards the southeast as a consequence of the Adria–Europe collision. 3D seismic tomography using local earthquakes produced a compressional wave velocity model in which the Ivrea body roots to depths ranging from 15 to 45 km, with the continental Moho as shallow as 12-15 km (Diehl et al. 2009; Fig. 2B) along a significant length of the Western Alps as observed in the ECORS-CROP and NFP-20-

West geological-geophysical transects (e.g., Schmid et al. 2004) and in the CIFALPS passive seismic experiment (Zhao et al. 2015; Solarino et al. 2018). The spatial resolution of the seismic tomographic grid is an order of magnitude larger than the scale of geological units and depths of interest in the IVZ (Fig. 2B) and, thus, cannot be taken for a precise depth estimate. Recent gravity studies show the IGB as close as 0-2 km depth below sea level (Scarponi et al. 2020). A recent seismic campaign around the Balmuccia peridotite (Fig. 3) show that dense rocks with v_p of >7.0 km/s are expected between 1-2km beneath the present surface (Ryberg et al. 2023).

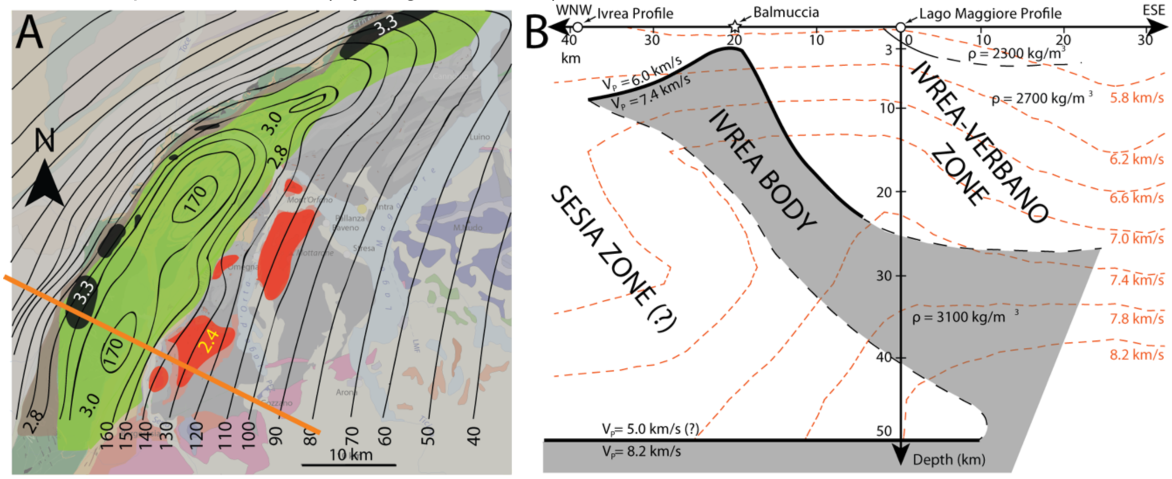

Figure 2. (A) Background geological map from Fig. 1, with an overlay of bulk density [g/cm3] distribution of granites (red), gabbros (light green), ultramafic (black) and Insubric Line rocks (brown), as well as the modelled gravity effect of the IGB (black contours, values in mgal) in the IVZ (redrawn after Kissling, 1984). Location of profile in B is shown as orange line (B) Cross-section across the Bird's Head of the IGB, displaying seismic-refraction-derived wave velocities and density anomalies from Berckhemer (1969)'s model in black, and iso-P-wave-velocities in orange interpolated from Diehl et al. (2009)'s local earthquake tomography, originally resolved at 25x25(horizontal)x15 (vertical) km spatially.

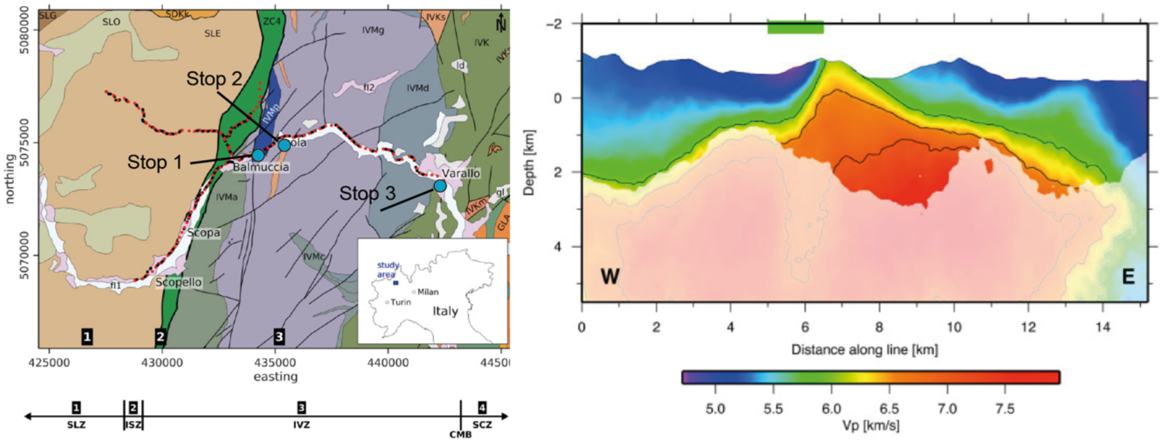

Figure 3. Left: Geological map of the Balmuccia area (Val Sesia, after Piana et al. 2017, Quick et al. 2003) - Right: Vertical cross section of P-wave velocity roughly along the W-E seismic line (left panel). The cross section shows an asymmetric high velocity body, outcropping at Balmuccia. The 6.0, 6.5 and 7.0 km/s isolines are shown, weakly colored area indicates areas with large (<0.5km/s) uncertainty areas. Stop numbers refer to the sites visited during the field trip. Figures from Ryberg et al. (2023).

Geological background

The Serie dei Laghi and the IVZ (Fig. 1) have been interpreted as a near-continuous section through the continental crust (Boriani et al., 1990; Schaltegger and Brack, 2007; Brack et al., 2010). To the northwest, the IVZ is juxtaposed against the Central and Western Alps by the Insubric Line. On geological maps, the IVZ can therefore be viewed as a near-vertical cross section through the pre-Alpine deep crust, tilted by ~90° along a N-NE-striking axis (Fig. 1). The rocks of the IVZ can be divided into a pre-Permian sequence and Permian magmatic additions. The pre-Permian basement of the IVZ records a protracted, polyphase tectonic history of supracrustal rocks including small bodies of mantle peridotite, perhaps assembled in an accretionary wedge (e.g. Schmid et al. 1990, Quick et al. 1995, Wyatt et al.

2022). After crustal amalgamation and accretion in the Carboniferous, regional metamorphism reached granulite- and amphibolite-facies in the mid to lower crust and greenschist facies in the upper crust (e.g. Zingg et al. 1990, Schuster and Stüwe, 2008). The regional metamorphic grade and equilibration pressures in the middle and lower crust increase from amphibolite (~0.4 GPa) to granulite grade (~0.9 GPa) near the Insubric Line (Zingg, 1983; Henk et al., 1997; Demarchi et al., 1998) with barometric gradients of ~0.3 to 0.35 kbar/km over most the exposed area (Fig. 4, Petri et al. 2019). The Pre-Permian upper crust ("Serie dei Laghi") consists of greenschist to lower amphibolite facies gneisses and schists intruded by Caledonian granites (Boriani et al. 1988; Tavazzani et al. 2017).

During the Permian the IVZ and Serie dei Laghi were affected by transcrustal magmatism, with underplating in the lower crust, siliceous intrusions in the upper crust, and corresponding volcanics at the surface (e.g. Sinigoi et al. 2005). The three main granite bodies, known as Baveno, Roccapietra and Valle Mosso, are displaced by the Pogallo and Cremosina faults (Fig. 1).

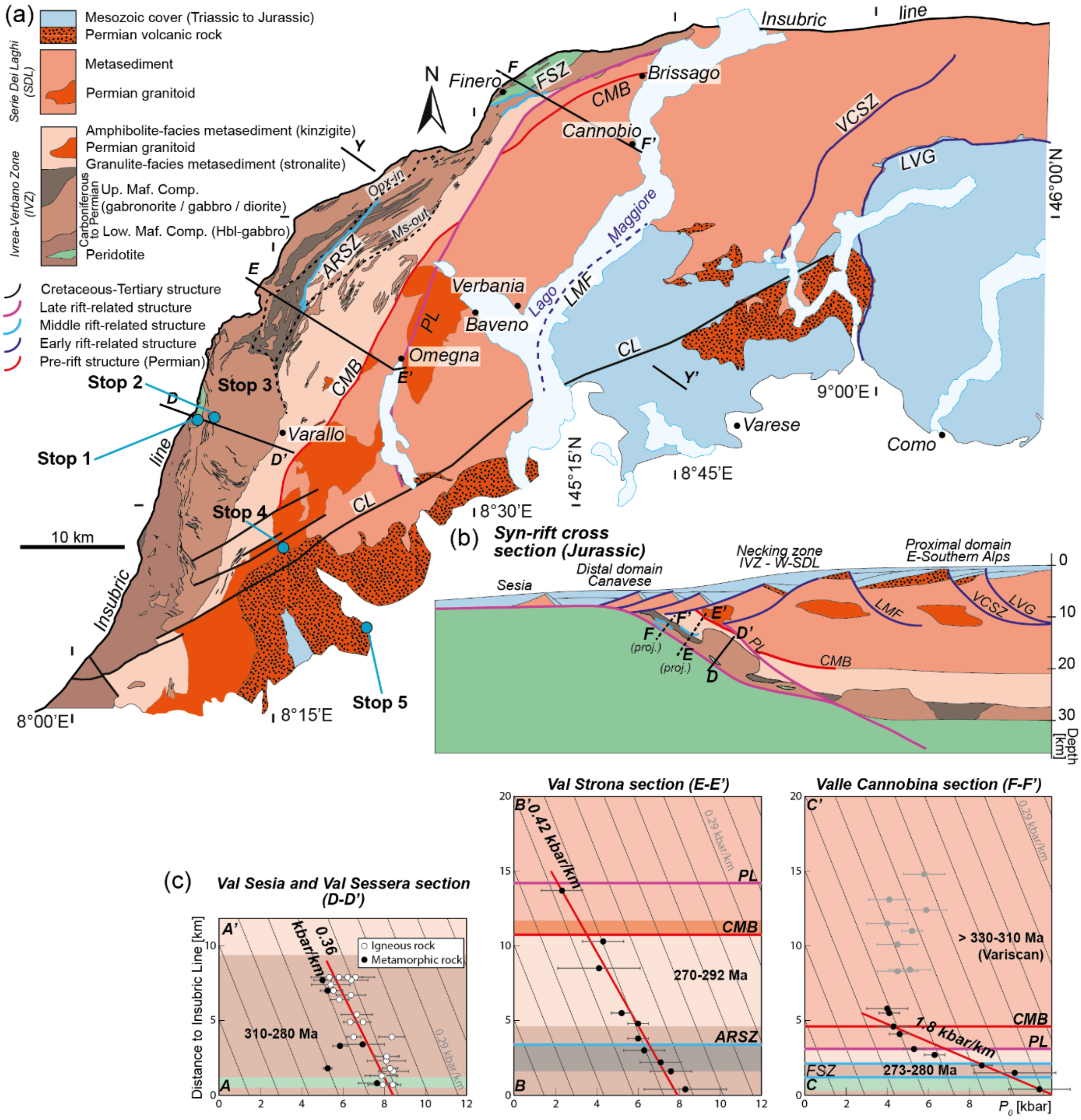

Figure 4. (A) Simplified geological map of the Southern Alps. (B) Reconstructed post-rift section modified from Beltrando et al. 2015. (c) P0-depth diagrams for the the Val Sessera – Val Sesia section (D-D'), the Val Strona section (E-E') and the Valle Cannobina section (F-F'), with P0 denoting the distance to the Insubric line as the Ivrea zone is tilted almost to 90°. ARSZ: Anzola-Rosarolo shear zone; CL: Cremossina Line; CMP Cossato-Mergozzo-Brissago Line; FSZ: Finero Shear zone; LMF Lago Maggiore fault; LVG: Lugano Val Frande fault; PL: Pogallo line; VCSZ: Val Cola shear zone. Figure from Petri et al. (2019).

The upper crust is overlain by a bimodal association of volcanic rocks, dominated by rhyolitic tuffs and lava flows, and minor andesite. The occurrence and distribution of megabreccia units indicates the presence of large caldera forming eruptions (Quick et al. 2009). The entire transcrustal magmatism is tightly constrained to 282±2 Ma (Karakas et al. 2019). Two major tectonic lineaments (Cossato–Mergozzo–Brissago and Pogallo) divide the lower and upper crust of the present-day IVZ section in its SE and NW sector, respectively (Handy, 1987; Bertotti et al., 1993). The IVZ, however, is affected locally by minor post-Permian crustal attenuation (Handy et al. 1990, Petri et al., 2019).

The Ivrea-Verbano zone

The Ivrea-Verbano zone (Fig. 4) is dominated in its lower metamorphic grade (south-eastern) part by a thick unit of variably migmatized metasedimentary schists (garnet, biotite, plagioclase, quartz, sillimanite ± muscovite), known locally as *kinzigite*, that forms a strikingly continuous and uniform tract about 3 or 4 km wide along the entire length of the outcrop of the Ivrea zone. As metamorphic grade increases north-westward (Fig. 4), the metasedimentary rock texture changes due to progressive replacement of muscovite and biotite by sillimanite, K-feldspar, and garnet (Schmid and Wood, 1976; Zingg, 1980, Bea and Montero 1999, Williams et al. 2022), from schistose to a massively banded migmatitic gneiss, known locally as *stronalite*. In the middle of the kinzigites a more heterogeneous group of metasediments is exposed, comprising marbles, quartzites and quarzo-feldspatic gneisses (Fig. 1). These supracrustal rocks are probably stratigraphically younger than the enveloping kinzigites and may represent shallow water deposits. This comprises the quartzofeldspatic gneisses at the top, followed by a quartzite layer, marbles, metapelites and marls. Below is a thick quartzofeldspatic and metapelitic layer followed by interlayered 1-10m thick bands of amphibolite that have been interpreted as coeval mafic lavas or intrusives interlayered within an early (Palaeozoic) accretionary complex represented by the kinzigite formation (Sills and Tarney, 1984, Wyatt et al. 2022), alternatively these could simply be marls. Finally, there is a thick (up to 1 km) sequence of amphibolites, beginning with banded, then spotted and then massive amphibolites.

The lithologic succession is preserved from erosion in a large, isoclinal antiformal syncline structure (the Candoglia-Strona Syncline) that is probably coeval with the earliest large scale folding of the area. The amphibolites are commonly concordant with the lithologic banding in the host metasediments, but occasionally show cross-cutting relationships. These have distinctive REE patterns compared to the older amphibolites interlayered with the kinzigites, but they cannot readily be distinguished in the field (Sills and Tarney, 1984). The geology of the southern end of the Ivrea-Verbano zone is dominated by an intrusive, layered mafic complex, up to 10km thick and extending along strike for some 40 km (Figure 4). The mafic complex (Rivalenti et al., 1980; Zingg, 1983, Quick et al. 2003) is dated radiometrically (Pin, 1986, Quick et al., 2003, Peressini et al. 2007) at about 280-295 Ma (Permian) with a main peak at 284±2Ma (Karakas et al. 2019). The rocks of the Mafic complex on the western side have been held at high temperatures in the subsolidus regime sufficiently long for granular, metamorphic textures to develop, whereas the originally shallower, eastern side of the complex (diorites) still displays igneous textures. The mafic complex and the complex of thinner intrusive sheets extending further northeast represent an excellent example of lower crustal mafic underplating incorporating lower crustal metasedimentary rocks (septa, Sinigoi et al. 2004). Different emplacement mechanisms have been discussed by Barboza and Bergantz 1990, Quick et al. 1992, 1995, and Sinigoi et al. 1994).

The Serie dei Laghi

The Ivrea-Verbano zone is in contact along its south-eastern margin with the Serie dei Laghi (Boriani et al., 1990a; 1990b) (Fig. 4). The CMB line, which forms the main contact, is a poorly exposed tract that sometimes displays ‘annealed‘ mylonitic textures, but is often ‘decorated‘ by gabbro-dioritic and other intrusive rocks of Permian age (Fig. 1). The CMB line is itself transected at a small angle by a younger mylonitic fault zone, the Pogallo fault (Handy, 1987), that has been interpreted as a low-angle extensional fault of Jurassic age (Hodges and Fountain, 1984; Schmid et al., 1987). However, it continues the same movement picture as the higher temperature stretching events recorded in the mylonitic rocks of the Ivrea-Verbano zone. The rocks of the Serie dei Laghi were probably displaced into contact with the underlying Ivrea-Verbano zone rocks along a low-angle CMB shear zone early in the post-Hercynian stretching event which culminated in the emplacement of the mafic complex. The rocks of the CMB line themselves do not appear to be affected by any of the major folding events that affected the adjacent Ivrea-Verbano zone.

The Serie dei Laghi comprises a series of metasedimentary schists and gneisses (Boriani et al., 1990a; 1990b) with occasional amphibolite sheets with rare ultramafic rocks, that are cut by orthogneisses of Ordovician age. The rocks are folded at least twice on a range of scales (Zurbriggen et al., 1997; 1998). All fold structures and their associated schistosities are cut by the Pogallo fault zone, as well as apparently undeformed gabbrodioritic rocks of Permian age cutting the CMB line. Thus, Permian deformation and magmatism postdates all folding events.

The Serie dei Laghi additionally hosts a number of undeformed granitic intrusions of Permian (275-286 Ma) age (Boriani et al., 1995, Schaltegger and Brack 2007, Karakas et al. 2019), ranging in diameter from 1 km to more than 10 km. The dominant schistosity of the metasediments of the Serie dei Laghi dips gently (25°) towards the south-east in the region east of the main granitic bodies (Fig. 4), which themselves show evidence of only little post-Permian tilting. Immediately to the west of the granites and also to the north-east away from the granites the host rock schistosity is mostly subvertical, where it remains across the outcrop of the Ivrea-Verbano zone.

Geochronology and geological evolution

The Serie dei Laghi (SdL) and the Ivrea-Verbano Zone (IVZ) record a cross-section through the Permian lower to upper crust. The magmatic rocks, dioritic to gabbroic intrusions into a granulite-facies basement of the IVZ at the base of the continental crust, and mid to upper crustal granitoid plutons within, and ignimbrites and rhyolitic lava flows on top of the SCZ form a Permian transcrustal magmatic system (Schaltegger and Brack 2007, Karakas et al. 2019). The magmatism is explained by large-scale, intracontinental lateral shearing between the lower and upper Permian (Schaltegger and Brack 2007).

Strona-Ceneri Zone (SCZ, syn. Serie dei Laghi)

The basement of the SCZ is characterized by a suite of granitoid magmatic rocks of Ordovician age, intruding into a pre-Ordovician metamorphic basement. The magmatic rocks show a wide range from S-type granites to amphibole-bearing I-type tonalites, whose U-Pb zircon ages range between 450 and 500 Ma. The S-types are interpreted as products of partial dehydration melting of metasedimentary gneisses, and carry inherited Pb components of Neo- to Paleoproterozoic age. The I-type granodiorites and tonalites are rather considered fractionates from mantle melts. The zircon ages are predominantly interpreted as magmatic crystallization ages (see Boriani & Villa 1997 for an alternative view). An overview of the Ordovician history is given in Zurbriggen et al. (1997, 1998).

Granulite-facies metamorphism of the Ivrea-Verbano Zone

The age of granulite-facies metamorphism is a long-term debate. Since the temperatures of the metamorphic overprint probably exceeded 800-900°C, the isotopic mineral systems at least partly yield cooling ages. Siliciclastic metasediments in the IVZ contain prismatic, < 2Ga detrital zircon grains interpreted to be derived from calc-alkaline igneous rocks (Vavra et al. 1996; Vavra and Schaltegger 1999, Ewing et al. 2013; Guergouz et al. 2018; Wyatt et al. 2022). The youngest of these cores range from ~389 Ma to ~352 Ma (Kunz et al. 2018, Vavra et al. 1996, Vavra and Schaltegger 1999), indicating that sediment deposition was active to about 350 Ma at the latest and may be continued until the 'onset of regional metamorphism at ~316±3 Ma (Ewing et al. 2013). In contrast to some earlier studies, this clearly indicates that high temperature regional metamorphism predates the emplacement of the mafic complex (292-275 Ma, Peressini et al. 2007, 286-282 Ma, Karakas et al. 2019), see Figure 5. However, some mafic sills might be as old as 314±5 Ma, indicating that granulite facies metamorphism and some mafic magmatic activity might be coeval (Klötzli et al. 2014).

The regional thermal peak of the IVZ occurred either during or after the amalgamation of the Ivrea crustal section, but there is little consensus about the heat source. It seems clear though, that heat release from the mafic complex can only explain the post-peak thermal overprint around a fairly narrow contact aureole with cordierite, hercynite and andalusite, that overprints regional amphibolite to granulite facies metamorphism (e.g. Zingg et al. 1990, Barboza and Bergantz 2000). UHT metamorphism reaching up to 1000°C has only be recorded by Zr in rutile thermometry in metasedimentary septa within the mafic complex (Ewing et al. 2013).

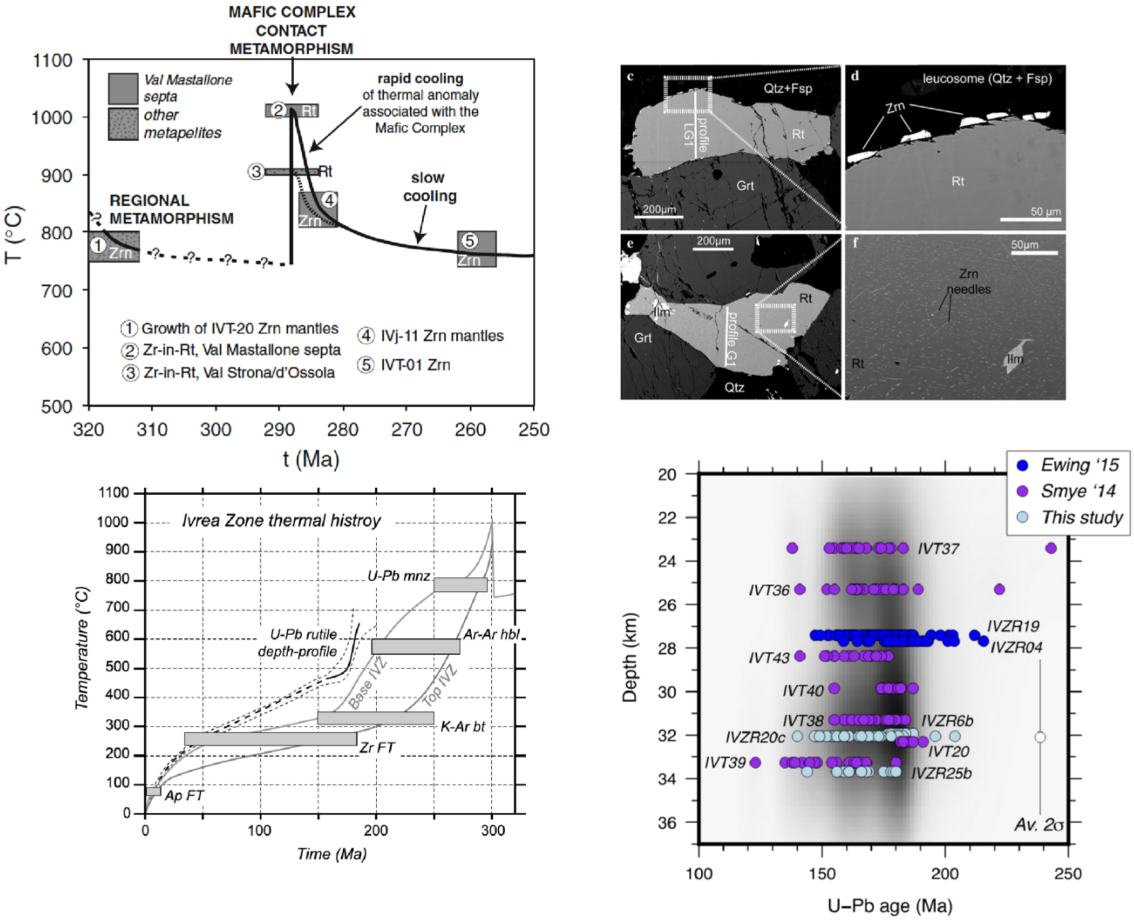

Figure 5. Top Left panel: Simplified temperature-time plot (T-t) for the base of the IVZ crustal section. UHT metamorphism is only recorded by Zr-in-rutile from metasediments within the mafic complex (Ewing et al. 2013). Top Right panel: aspects of rutile from metapelites from the Ivrea zone (Ewing et al. 2013). Bottom right panel: U-Pb dating of rutile provide ages between 220 Ma and ~140 Ma with most ages clustering between ~180 and 150 Ma, indicating that the IVZ cooled and was exhumed mostly in the Jurassic (Smye et al. 2019). Bottom left panel: various geochronometers and the temperature evolution of the Ivrea Zone since 300 Ma. K-Ar on biotite and U-Pb ages on rutile record mostly Jurassic ages, while Zr-fission track record ages from the Jurassic to the Eocene. Most of the Ivrea zone cooled below 300°C during the Jurassic (from Smye and Stockli 2014).

Triassic – Jurassic exhumation history

The post-Permian history of the IVZ was characterized by conductive cooling and interspersed short lived episodes of magmatic and hydrothermal activity. Alkali magmatism during the initiation of continental breakup caused partial disturbance of the U-Pb systems, and new growth of both zircon and monazite. This rift related igneous activity lead to the formation of alkaline nepheline syenites to metasomatic dykes (with zircon crystals up to 7 cm) (Stähle et al. 1990, Schaltegger et al. 2015) and the emplacement of carbonatite dykes (Galli et al. 2019). Zircon ages from nepheline syenite, carbonatite and some chromitites in peridotites range from ~220 – 180 Ma and are commonly assigned to initial rifting (Fig. 4b). Similar U-Pb zircon ages of the Finero gabbros in the NE IVZ provide similar Triassic ages of 232±3 Ma, with rims of 219±3 and 205±3 Ma (Zanetti et al. 2013), however, the importance of the Triassic magmatism has been questioned since diorite dikes with zircons of up to 297 Ma cut the Finero gabbros. This record of spatially restricted magmatism may be related to the release of substantial amount of fluids and hydrothermal recrystallization of zircon and monazite, yielding ages ranging from 260-200 Ma (Vavra and Schaltegger, 1999, Ewing et al. 2013). Despite textural equilibration during the Permian high temperature metamorphism, rutile U-Pb dates span a range from ~220 to ~150 Ma, (Ewing et al. 2015, Smye et al. 2019) indicating resetting of U-Pb ages of rutile during Tethyan rifting (Fig. 5). A schematic reconstruction of the passive margin in the Jurassic with the exhumation of the IVZ is given in Figure 4b.

The Val Sesia crustal section

The Balmuccia Massif

The largest peridotite bodies in the Ivrea zone are from south to north, the Baldissero, Finero and Balmuccia massifs (Fig. 1). The Baldissero and Balmuccia massifs are the least depleted (most fertile, lherzolitic, e.g. Hartmann and Wedepohl 1993) and least metasomatized peridotites, whereas the Finero peridotite is highly depleted (harzburgitic) and pervasively metasomatized by K-rich (crustal?) fluids, or, alternatively, by subduction-related silicate melt metasomatism (Zanetti et al. 1999).

The Balmuccia massif in the Sesia and Mastallone valley has the form of an elongated, NNE-trending lens, ~5 km long with a maximum width of ~0.8 km. The peridotite is locally sheared to the west by the Insubric fault system and is in tectonic contact with mylonitized members of the Mafic Complex or with metasediments of the Kinzigite Formation. Intrusive contacts are locally preserved at the western contact and common at the Eastern contact (e.g. Rivalenti et al. 1980). The dominant rock-type is a spinel-facies lherzolite. Harzburgitic or dunitic compositions are rare and mostly occur at the contact of pyroxenites dykes or in layers along with spinel streaks. Amphibole is present in trace amounts, phlogopite is basically absent, except in a few places along the eastern contact. The central part is dominated by secondary proto-granular textures, but foliated textures are also common. Locally, the foliated texture fades into porphyroclastic textures with olivine and orthopyroxene porphyroclasts contained in a fine-grained matrix of the same minerals.

Pyroxenite dykes form approximately 5% of the Balmuccia outcrops. The dykes can be distinguished into the Cr-diopside and Al-augite suites. Rare hornblendite dikes are found (for details, see Shervais and Mukasa 1991, Mukasa and Shervais 1999).

The Cr-diopside pyroxenites represent at least 3 pulses of melt injection into the peridotite distinguished on cross-cutting relationships. They are websterites varying in thickness from less than 1 cm to about 1m, composed of clinopyroxene, orthopyroxene, Cr-spinel and minor olivine. In the field they are recognized by the intense green color of the Cr-diopside clinopyroxenes. Some of them are folded and boudinaged. The foliation of the peridotite crosscuts these pyroxenites at a low angle. The peridotite – pyroxenite contacts are generally sharp and the immediately adjacent peridotite is cpx-depleted without reaction rims between the two lithologies.

The Al-augite pyroxenites, up to 150 cm thick, are easily distinguished in the field by their gray color and the high abundance of spinel that may reach 20%. They consist of Cr-poor clinopyroxene, orthopyroxene, hercynitic spinel, and sometimes plagioclase and/or amphibole. Several dyke generations, all younger than the Cr-diopside suite can be distinguished by crosscutting relationships. The dyke contacts are always sharp and marked by thin reaction rims of pyroxenites. Locally they replace Cr-diopside dikes. As a result of melt infiltration, the adjacent peridotite is enriched in clinopyroxene and sometimes amphibole.

Locally the Balmuccia peridotites are cut by mm-thick pseudotachylites (Obata and Karato, 1995, Ueda et al. 2008, Souquière and Fabbri 2009) with displacements of up to 3m. Different generations of pseudotachylites have been identified, subvertical and subhorizontal ones. While the first generation is thought to form at elevated pressures and temperatures, the 2nd generation is thought to be formed at less than 10km and are likely related to the more recent Alpine history (Souqière and Fabbri 2009). Both types are related to (ultra-) mylonitization and cataclasis and are interpreted as fossil earthquakes.

The Mafic Complex

The Mafic Complex (MC) intrudes the Kinzigite Formation and primary contacts are preserved locally. It reaches its maximum thickness of ~10km in the southern part of the IVZ, in the Sesia Valley (Fig. 1). Primary igneous features (layering, intrusive contacts, magma mingling, synmagmatic tectonics) are generally preserved. All igneous rocks of the Mafic Complex underwent slow isobaric cooling which induced re-equilibration of the primary igneous phases, resulting in the common occurrence of granoblastic and coronitic textures and unmixing in coexisting low- and high-Ca pyroxenes. Reequilibration pressures have been estimated to vary between 0.8 and 0.5 GPa from bottom to roof in the region south of Val Sesia and slightly higher (0.8-0.9 GPa) in the lower units of Val Sesia (Rivalenti et al., 1981).

Detailed mapping of the Southern Ivrea-Verbano zone (Quick et al., 1994; Snoke et al., 1999) support previous conclusions (Rivalenti et al., 1975; Rivalenti et al., 1981) that the mafic complex represents a voluminous magmatic system with synmagmatic deformation and assimilation of metasedimentary rocks. Val Sesia roughly corresponds with the major axis of the magmatic system and, therefore, Val Sesia exhibits the most complete overview of various lithological units. The Val Sesia section consists, from bottom to top, of a layered series of cumulus rocks, a virtually homogenous gabbro (main gabbro, MG), and an upper dioritic zone (diorite units) in contact with the metasedimentary sequence. The original work of Rivalenti et al. (1981) was strongly influenced by studies of the Skaeergaard intrusion and used a similar terminology. They distinguished the layered series into a basal (BZ), an intermediate (IZ) and an upper (UZ) zone (Rivalenti et al. 1981). The basal and intermediate zones consist of alternating ultramafic and mafic (gabbro) layers, which crystallized under a pressure gradient documented by the coexistence of clinopyroxene and spinel in BZ and olivine and plagioclase in the IZ. The upper zone has only rare ultramafic layers and the lithology is dominantly gabbro (norite) and norite, containing garnet megacrysts in the regions close to metasedimentary septas. These horizons (septa) and lenses of the Kinzigite Formation are very common in the layered series (Quick et al. 2003) and a major metasedimentary horizon occurs at the top of the IZ. The septas have granulite-facies mineral assemblages (quartz, plagioclase, garnet, mesoperthite (K-feldspar), ± silimanite, ± corundum, ± rutile, ±graphite) and are geochemically highly depleted. Associated to these rocks are charnokite lenses and layers (quartz, mesoperthite, ± opx, ± garnet) interpreted as crystallized anatectic melts.

The main gabbro (MG) consists of a hornblende-bearing norite and gabbro-norite. On more recent maps hornblende gabbro and gabbronorite are distinguished (Quick et al .2003). Biotite bearing diorite dominates the uppermost unit, xenoliths of the Kinzigite Formation are abundant in the roof region of the complex and also occur close to the thick metasedimentary septum separating IZ and UZ. Magma mingling is evidenced by the presence of swarms of gabbroic enclaves in the diorite – main gabbro contact zone. Evidence of synmagmatic deformation occur all over the Val Sesia and result in spectacular structures in IZ, where slumping induces mixing between ultramafic cumulates and gabbros.

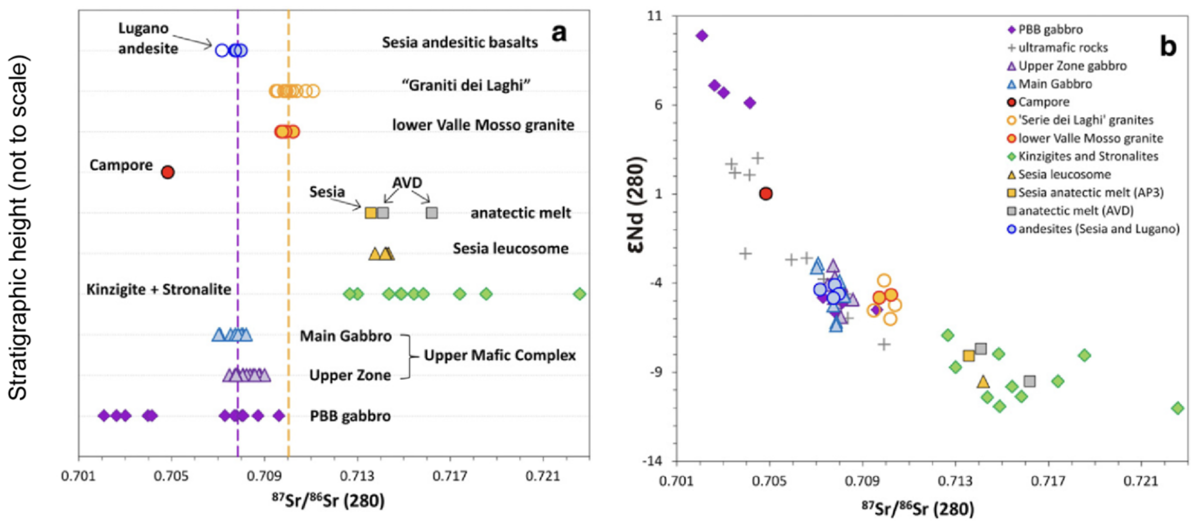

Figure 6. Sr and Nd isotopic composition from the bottom of the Sesia magmatic systems to the volcanic rocks. Only a few isotopically primitive rocks are found in the lowermost part of the gabbros, while most of the Sesia magmatic systems displays (crustal) contamination signatures (from Sinigoi et al. 2016).

Bulk rock and mineral compositions

Whole-rock and mineral chemical compositions indicate that: (1) the first gabbroic layers and most of the first pyroxenites layers of the basal zone have MORB-like trace element patterns and Sr and Nd isotope compositions compatible with their derivation from a depleted mantle source (Voshage et al. 1990, Sinigoi et al. 2016); (2) with increasing stratigraphic height in the basal zone the gabbroic and pyroxenitic layers display variably enriched trace element patterns and isotope signatures; (3) in the intermediate and upper zone, all rocks exhibit variable, and sometimes extreme, incompatible element enrichment and high $\delta^{18}O$, $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ characteristics (Sinigoi et al. 1994; Sinigoi et al. 2016; Voshage et al.1990) accompanied by marked Eu, Sr, and Ba enrichments in bulk rocks and minerals, (4) the large main gabbros unit, in contrast, is characterized by modest geochemical variability with isotopes that remain enriched and constant; (6) the upper main gabbro unit, again, is characterized by dramatically enriched rocks similar to the UZ forming the transition to the 'diorites' that display pervasively enriched characteristics. These features have been explained by assimilation processes (e.g. Voshage et al. 1990, Sinigoi et al. 1994). The 'diorites' record the incompatible element enrichment of the last residual liquids derived from the crystallization of the main gabbro unit mixed with increasing amounts of anatectic melts derived from the roof and the septa. Endmembers are inferred to be a mantle-derived basaltic liquid and a crustal anatectic melt derived from the metasediments of the Kinzigite Formation induced by the heat released from the intrusion and crystallization of the basaltic melts in the lower crust (Fig. 6).

In the field, the anatectic melts are represented by charnokitic lenses and layers occurring close to the metasedimentary horizons within the mafic complex and in the roof of the complex, where the metasediments have been migmatized over a distance of several hundred meters (e.g. Snoke et al., 1999).

Permian mafic magmatism of the Ivrea-Verbano Zone

The most complete geochronological study of the mafic intrusives of the IVZ is the one of Peressini et al. (2007), complementing datasets of Quick et al. (2003), Pin (1986), Ewing et al. (2013) and Klötzli et al. (2014). The mafic complex shows the following age relationships: The Upper Mafic Complex (Val Mastallone, Val Sesia around Varallo), consisting predominantly of diorites, quartz-diorites and gabbros, yielded consistent U-Pb ages with a mean age value of 288 ± 4 Ma (5 samples), corroborated by more recent TIMS data with a mean age of 286-282 Ma (Karakas et al. 2019). Both the Lower Mafic Complex as well as the Main Gabbro containing paragneiss septa yield largely scattering age values between 320 and 260 Ma. In both, kinzigitic paragneiss septa and gabbros, there is evidence for the presence of Carboniferous zircon, clustering around a mean value of 310 Ma. The indication of a Carboniferous magmatic event 20-30 m.y. prior to the intrusion and final crystallization of the Mafic Complex age information is in agreement with the findings of Vavra et al. (1996, 1999) and Klötzli et al. (2014), who also detected pre-300 Ma magmatic zircon in some of their samples. This older magmatism may mark the initiation of the mafic underplating of the Ivrea lower crust, but more likely is completely unrelated.

The upper crustal granitoids are mostly granodiorites, monzogranites and granites, including the famous Baveno and Mont´Orfano granites used as building stones. The different plutonic rocks show a continuous evolution in geochemistry from an estimated depth of 6km to the surface with the uppermost plutonic rocks resembling ignimbrites and rhyolite flows (Fig. 7, Tavazzani et al. 2020).

Volcanic rocks in the Sesia Valley are mostly rhyolite to rhyodacite, with minor basalt, andesite, and dacite. These rocks comprise lava flows, massive porphyry, ignimbrites, and fragment-rich tuff intermixed with a spectacular megabreccia containing large inclusions of schist and volcanic rock in a matrix of welded tuff. Distribution of megabreccia, its intimate involvement in the volcanic stratigraphy (Govi, 1977), and the pyroclastic nature of its matrix makes formation of the megabreccia by faulting an unlikely process (Quick et al. 2009). Similar megabreccias have been shown to be diagnostic of caldera-forming eruptions, forming as the subsiding caldera fills with volcanic ash mixed with landslide debris derived from the caldera walls (Lipman, 1997). East of the Sesia Valley, the contact between volcanic rocks and basement two-mica schist appears to be a relic of such a caldera wall based on an increase in schist inclusions towards the contact.

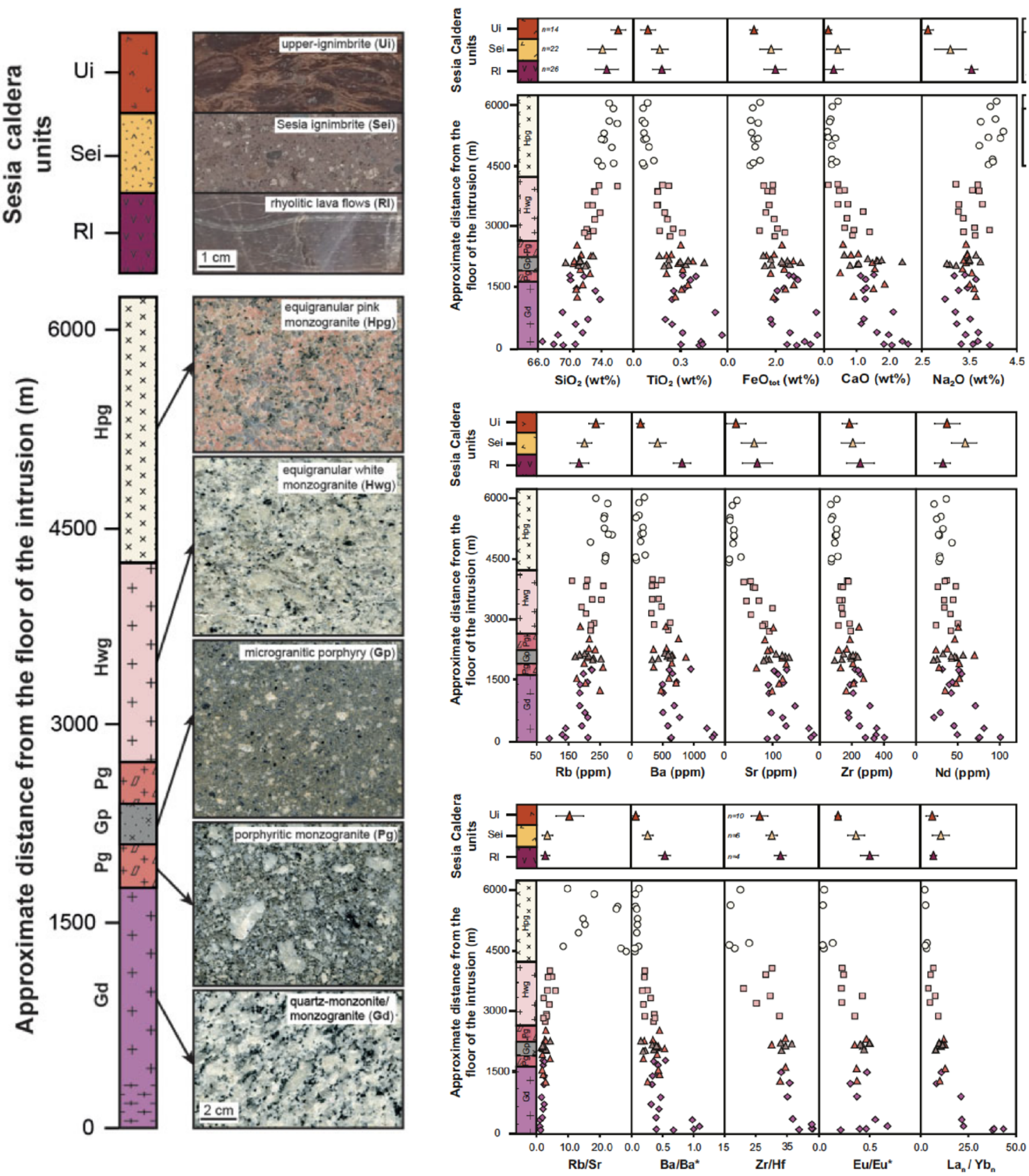

Figure 7. Variability of upper crustal granitic rocks in terms of textures and geochemistry. The plutonic stratigraphy covers approximately 6km (from Tavazzani et al. 2020).

Sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon ages for volcanic rocks range from 288±2Ma, 285±2 Ma and 282±3Ma (Quick et al. 2009) in agreement with U-Pb data on volcanic rocks from the southern Alps (Schaltegger and Brack 2007). Recent high precision CA-TIMS U-Pb dates for caldera fill ignimbrite resulted in precise ages of 283.37±0.14 Ma and 284.61±0.09 Ma (Karakas et al. 2019). Residence times of igneous garnets from the Borgosesia monzogranite were determined from diffusion of major and trace elements, indicating about 12’000y between initial emplacement at 820°C and cooling to 770°C (Devoir et al. 2021). The P-rich cores and other trace elements point to a granulite facies origin of the xenocrystic core and indicate 15 – 20 km transport of garnet xenocrysts to the upper crust.

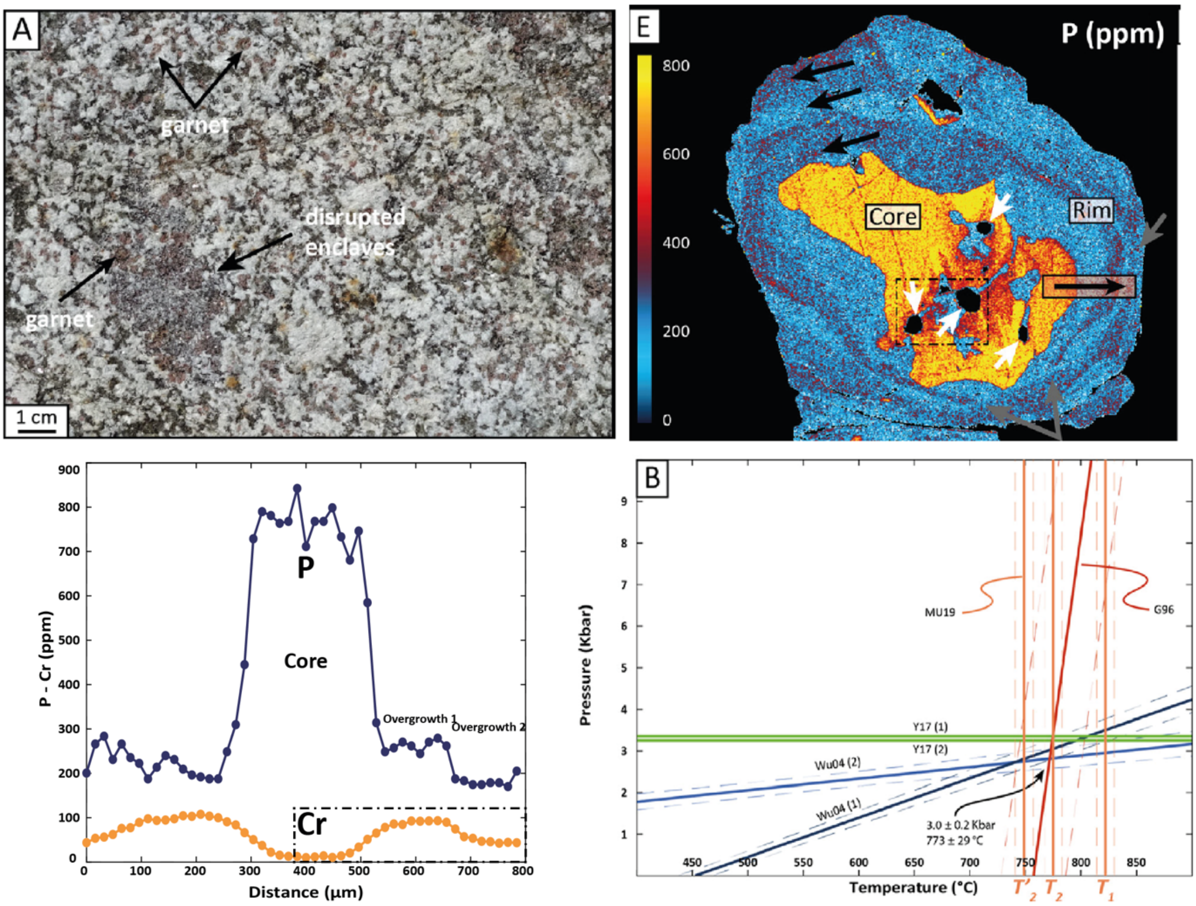

Figure 8. Disrupted metasedimentary enclaves and isolated garnets in the Borgosesis monzogranite. Some garnets show P-rich cores and oscillatory P magmatic overgrowth. P show sharp profiles while Cr is diffused. Thermobarometry indicates between 770 and 820°C and pressures around 3.2 kbars, in agreement with other felsic rocks from the Val Mosso pluton. Diffusion of the two overgrowth were modeled by multispecies diffusion in garnet and result in ~12ky (from Devoir et al. 2021).

These new data collectively suggest that there is a close relationship between magma underplating, magma transport, granite crystallization and silicic volcanism, similar to active caldera-forming silicic volcanism today. The close temporal relationships between magmatic rocks at all crustal levels supports the Caldera hypothesis and led to an increasing popularisation of the Val Sesia 'supervolcano'.

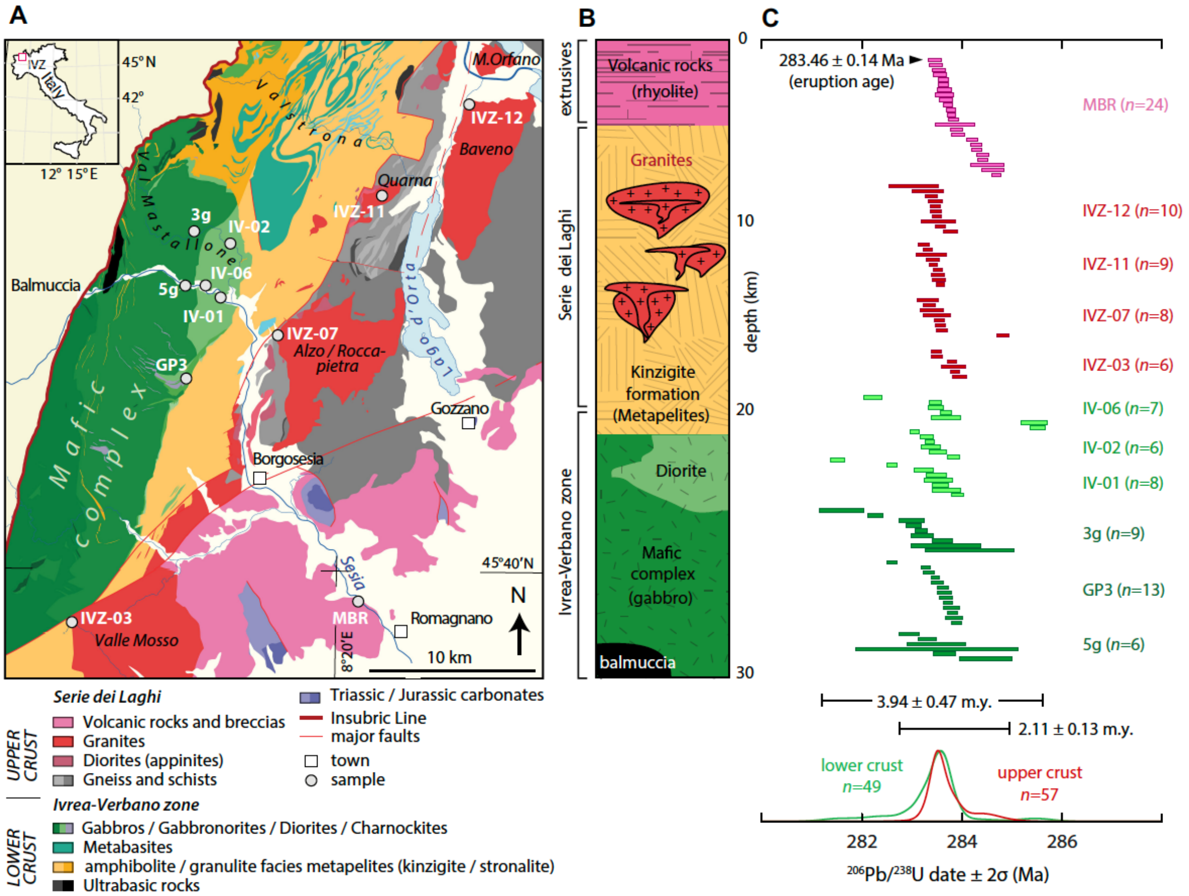

Figure 9. Crustal scale architecture and geochronology of the Sesia magmatic system. The single CA-TIMS U-Pb dates on zircon in felsic plutonic and volcanic rocks are tightly constrained to 284±2 Ma, with a larger spread in the mafic complex. From Karakas et al. (2019)

Hutton Ivrea field trip: scientific questions and themes

- Linking geophysical data to the geological evolution of the continental crust
- Heat balance between regional high-temperature metamorphism, partial melting, and contact metamorphism in a complete crustal section
- Links between pyroxenite dikes in the mantle and the emplacement of mafic magmas in the lower crust
- The role of accessory phases in tracking the metamorphic evolution during subduction and collisions
- Melt transport rates in a transcrustal magmatic system from the lower to the upper crust and links to large silicic eruptions
- The role of igneous additions to the chemical evolution of the continental crust
- Fingerprinting the geological evolution of lower crust from the base of the crust to exhumation in during Tethyan rifting

Itinerary

Mid-conference Ivrea field trip 13.9.2023

Stop 1 – Balmuccia peridotite

Coordinates bus parking: Lat. 45°49'223" N; Long. 08°09'208'' E

Coordinates outcrop: Lat. 45°49'183" N; Long. 08°09'164'' E

Location: Balmuccia, gorge SE of village

Topic/Geological context: Ultramafic rocks of the Balmuccia peridotite and related pyroxenites, pseudotachylite. Residual peridotites related or unrelated to the mafic complex ?

Polished outcrops of peridotite and pyroxenite along the Sesia river, field relations between peridotite deformation and generations of pyroxenites, Pseudotachylites in ultramafic rocks and relations to the Insubric Line

Stop 2 – Layered gabbros, pyroxenite and metasedimentary enclaves (known as septa)

Coordinates bus stop: Lat. 45°49'655" N; Long. 08°10'322" E

Coordinates gabbronorite: Lat. 45°49'538" N; Long. 08°09'917'' E

Coordinates charnokite septum: Lat. 45°49'400" N; Long. 08°10'263'' E

Location: Isola in Val Sesia

Topic/Geological context: Layered gabbroic rocks and pyroxenites; Metasedimentary enclaves in layered gabbros

Layered gabbro

Charnokite septa

Stop 3 – Migmatite outcrop on top of mafic complex

Coordinates bus stop (Tennis Club): Lat. 45°48'621" N; Long. 08°15'435'' E

Coordinates migmatite outcrop: Lat. 45°48'680" N; Long. 08°15'384'' E

Location: Polished migmatites at Crevola (Varallo) along Sesia River

Topic/Geological context: Migmatites and relationships to regional and contact metamorphism

Kinzigite, orthogneisses, calcsilicate and their mutual rheology, mobilization of felsic melts by syndeformation melting

Stop 4 – Upper crustal granitoids and metasedimentary enclaves

Coordinates bus stop Borgosesia: Lat. 45°43'372" N; Long. 08°15'738'' E

Coordinates granite outcrop: Lat. 45°43'418" N; Long. 08°15'757'' E

Location: Granitoids and enclaves at Borgosesia along Sesia River

Topic/Geological context: Transcrustal magmatism, granitoids, enclaves and time-scales

Diorites, (monzo-) granites, upper crustal and lower crustal metasedimentary enclaves, garnet xeno (pheno) crysts in granite and petrological significance, pegmatites and aplites

Stop 5 – Permian volcanics, Calderas and the Sesia – 'Supervolcano'

Coordinates bus stop Vintebbio: Lat. 45°39'120" N; Long. 08°21'090'' E

Coordinates Megabreccia outcrop: Lat. 45°39'101" N; Long. 08°21'163'' E

Location: Volcanic rocks (ignimbrites, obsidian flow, megabreccias) and crustal xenoliths at Vintebbio along Sesia River

Topic/Geological context: Volcanic rocks of a transcrustal magmatic system, eruptive dynamics and crustal enclaves

Ignimbrites and obsidian lava flows, brecciated together with andesite and crustal xenoliths, transcrustal magmatism and timescales.

Stop 6 – Wine tasting in Fara Novarese

Coordinates bus stop: Lat. 45°33'000" N; Long. 08°27'033'' E

Location: Cantina dei Colli Novaresi, Via Cesare Battisti 56 28073 Fara Novarese (NO)

Topic/Geological context: Wine and food tasting at the interface of silicieous volcanic rocks and Triassic dolomites (enjoy the difference…).

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