BAVENO 10th HUTTON SYMPOSIUM · 2023 · Italy

ADAMELLO

Hutton Symposium on Granites and Related Rocks

Pre-conference field trip

6 – 9 September 2023

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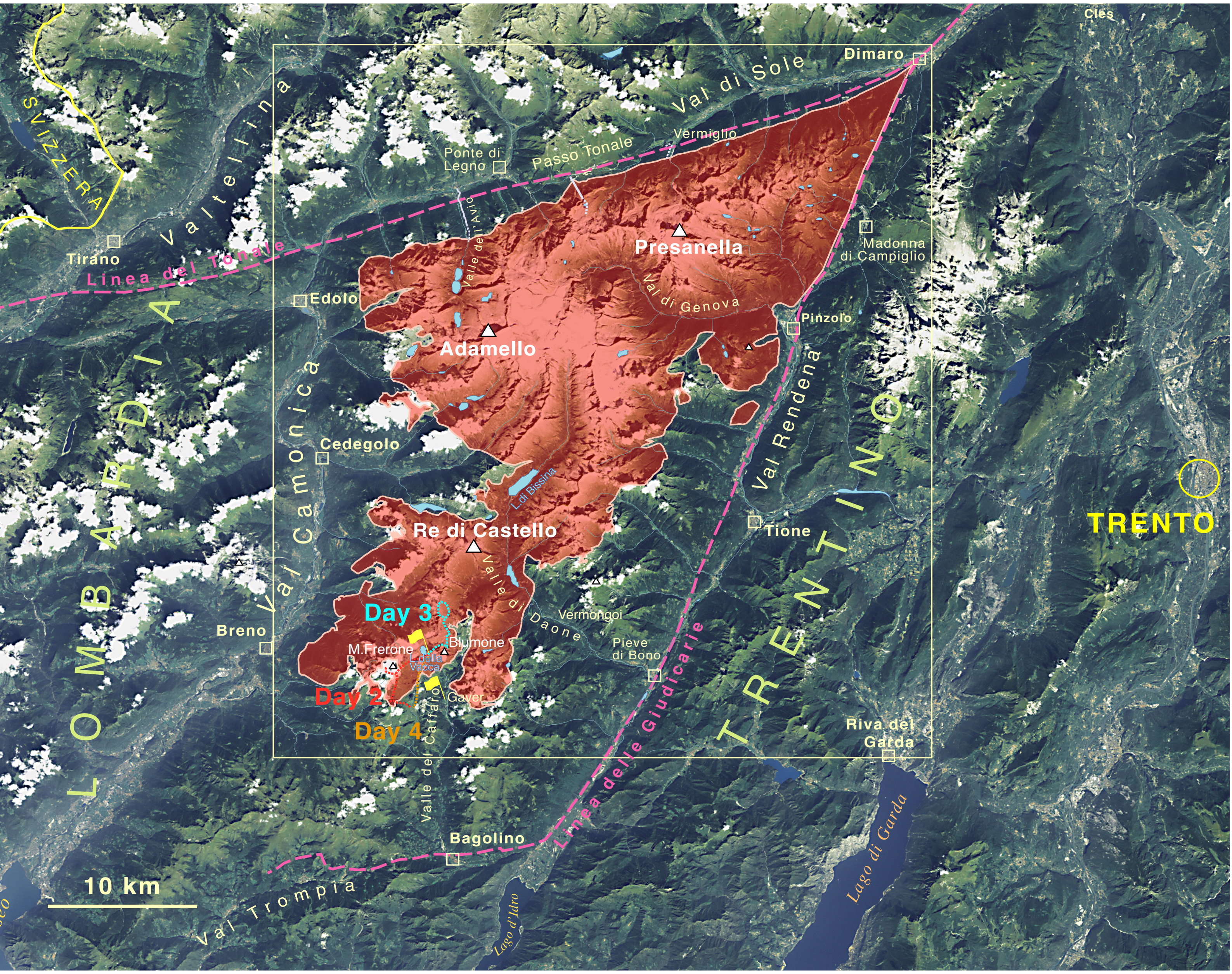
Cover photo:
Monte Adamello peak (3539 m) seen from West (Passo delle Granate).

X[th] Hutton Symposium 2023

ADAMELLO 2023



Field Guide Book - Peter Brack, Peter Ulmer

Xth Hutton Symposium 2023

PROGRAM

Topics of the excursion

The Cenozoic Adamello igneous complex –
an Alpine subduction related shallow crustal level plutonic complex.

Specific topics of the field excursion:
- *incremental pluton emplacement and assembly*
- *differentiation and assimilation mechanisms from ultramafic cumulates to intermediate/acidic differentiates (plutonics and dike rocks)*
- *magma mixing and mingling of gabbroic and intermediate plutonics*
- *deformation, interaction with country rocks; Alpine thrust belt vs. Adamello intrusions*
- *forceful and "passive" emplacement of magma batches at upper crustal level*
- *origin and evolution of calc-alkaline magmas*
- *contact metamorphism, thermal constraints on mode of magma emplacement*

Excursion Leaders Peter Ulmer (ETH Zurich), Othmar Müntener (UNIL, Lausanne) and Peter Brack (ETH Zurich)

Program

Day 1
6 September

Travel by mini-van from ***Bergamo*** (Bellinzona, (Malpensa)) – Brescia – Bagolino – Val Caffaro. Introduction to the Adamello complex. When early enough overview over Southern Adamello.
Accommodation: **Blumon-Break,** I-25043 Breno-Gaver, phone +39 0365 904972

Days 2
7 September

Hike from Malga Cadino – Monte Mattoni – Passo Val Fredda – (Frerone W-flank) –Passo della Vacca. Folded Middle Triassic sediments with contact metamorphic overprint crosscut by intrusions. Contemporaneous gabbroic sheets and intermediate (tonalite) plutonic rocks of Val Fredda – Mattoni – Cadino area, deep versus shallow differentiation and assimilation, magma mixing/mingling, syn- and post-plutonic acidic and (primitive) mafic dykes.
Accommodation: **Rifugio Tita Secchi** (2367m) at Lago della Vacca. Phone +39 0365 902001

Day 3
8 September

Hike from Lago della Vacca – Passo Blumone – Listino Ring structure: Gabbro-diorite – tonalite suite of the Blumone complex (subvolcanic magma system) and the Lago della Vacca area; Listino Ring structure: syn-intrusive deformation, incremental emplacement and "cannibalism" of partially crystallized gabbroic cumulates by intermediate magmas.
Accommodation: **Rifugio Tita Secchi** (2367m) at Lago della Vacca. Phone +39 0365 902001

Day 4
9 September

Lago della Vacca area: complex pluton assembly, primitive post-plutonic dikes, ultra-high temperature contact metamorphism. **Hike** to Banca del Cadino.
Transfer by mini-van to Baveno, arrival late afternoon – early evening.

INTRODUCTION

The Adamello Batholith, situated in Southern Alps, some 50 km to the north-west of Lake Garda is split between the Lombardy and Trentino – Alto Adige regions. The massif has been the focus of geological research by Italian and Austrian geologists since the mid-nineteenth century. International interest in the Massif probably began with Wilhelm Salomon, whose substantive monographs "Die Adamello Gruppe" published in 1908-1910 (Salomon, 1908/1910) present the first geological synthesis of intrusive rocks and their origin. A vast body of work on the Adamello has since been published, both in Italian and international journals. Callegari and Brack (2002) provide a summary of previous work.

OBJECTIVES OF THE FIELD EXCURSION

Much of what happens in the magmatic systems beneath active volcanoes remains inaccessible. We can infer magmatic processes from petrological and geochemical studies or from monitoring earthquakes, gas emissions or ground deformation. However, it is only by studying the eroded roots of extinct volcanoes that we can gain real insight into the workings of subterranean magma systems. The aim of this field excursion is to examine in detail one such eroded magmatic terrane, the Adamello Batholith. We will concentrate primary field observations as a means to answering the following fundamental questions:

- Can we find evidence for sub-volcanic processes in plutonic rocks?
- Do plutonic rocks represent cumulates or melts?
- How are large-scale batholiths constructed?
- How is space made for magma emplacement in the shallow crust?
- How do chemically contrasted magmas interact?

OUTLINE OF THE GEOLOGY

The Adamello Batholith

The Adamello Batholith is exposed over an area of ~670 km^2 with up to 2 km of vertical relief, and is elongate in a NW-SE direction with a maximum length of 80 km (Fig. 1). It is the largest of the Tertiary Periadriatic plutons, emplacing during the final stages of the Alpine orogeny into the per-Alpine metamorphic basement and the non-metamorphic Permo-Triassic cover rocks of the Southern Alps. All of the periadriatic plutons (Bergell, Riesenferner, Sondrio, Biella-Traversella, Rensen, etc.) have a close spatial association with the Periadriatic lineaments, which may have played an important role in facilitating the ascent and emplacement of magmas and/or providing the tectonic framework to produce the space occupied by the plutonic rocks (Laubscher, 1985). The Adamello Batholith is bound to the north and east by the Tonale and Giudicarie Lines, respectively (Fig. 1). While there has been syn-emplacement deformation of the northern Adamello batholith along the dextral Tonale Line (Bianchi et al., 1970; Werling, 1992; Stipp et al., 2004), there is no clear evidence for Eocene to Oligocene movement along the sinistral Giudicarie Line (Brack, 1984; Castellarin and Sartori, 1983; Laubscher, 1990).

Coeval volcanic rocks are scarce in the southern Alps, although detritus occurs in sedimentary rocks of Eocene-Oligocene age throughout the Alps and the Biella-Traversella plutonic body is intimately associated with the Canavese volcanics (Callegari et al., 2004). Rare outcrops of clastic sediments of Late Eocene age preserved in a few places east of the Giudicarie Line and contain debris of andesitic rocks possibly derived from volcanoes in the Adamello area and which could be equivalent in age with the intrusions of the Re di Castello Pluton. The Periadriatic intrusions, therefore, provide the most comprehensive insight into the magmatic consequences of Tethyan subduction and closure.

The Adamello Batholith is a composite intrusion comprising at least twelve petrographically distinct plutonic units sub-divided by Bianchi et al. (1970) into four groups or superunits: the Adamello unit in the center and west; the Presanella unit in the northeast; the Avio unit in the northwest, and the Re di Castello unit in the south (Fig. 2). The volumetrically most abundant rock types in the batholith are tonalites and granodiorites with lesser quartzdiorites. A small number of basic and ultrabasic intrusions are satellitic to the major plutons, notably around the western and southern margins of the batholith. Mafic synplutonic dikes, inclusions and schlieren occur throughout the intermediate to felsic rocks. A series of late basic dikes, predominantly aphyric or hornblende-phyric spessartites of picrobasaltic to andesitic compositions occur in the southern Adamello (Kaghami et al., 1991; Ulmer et al., 1985, Hürlimann et al., 2016).

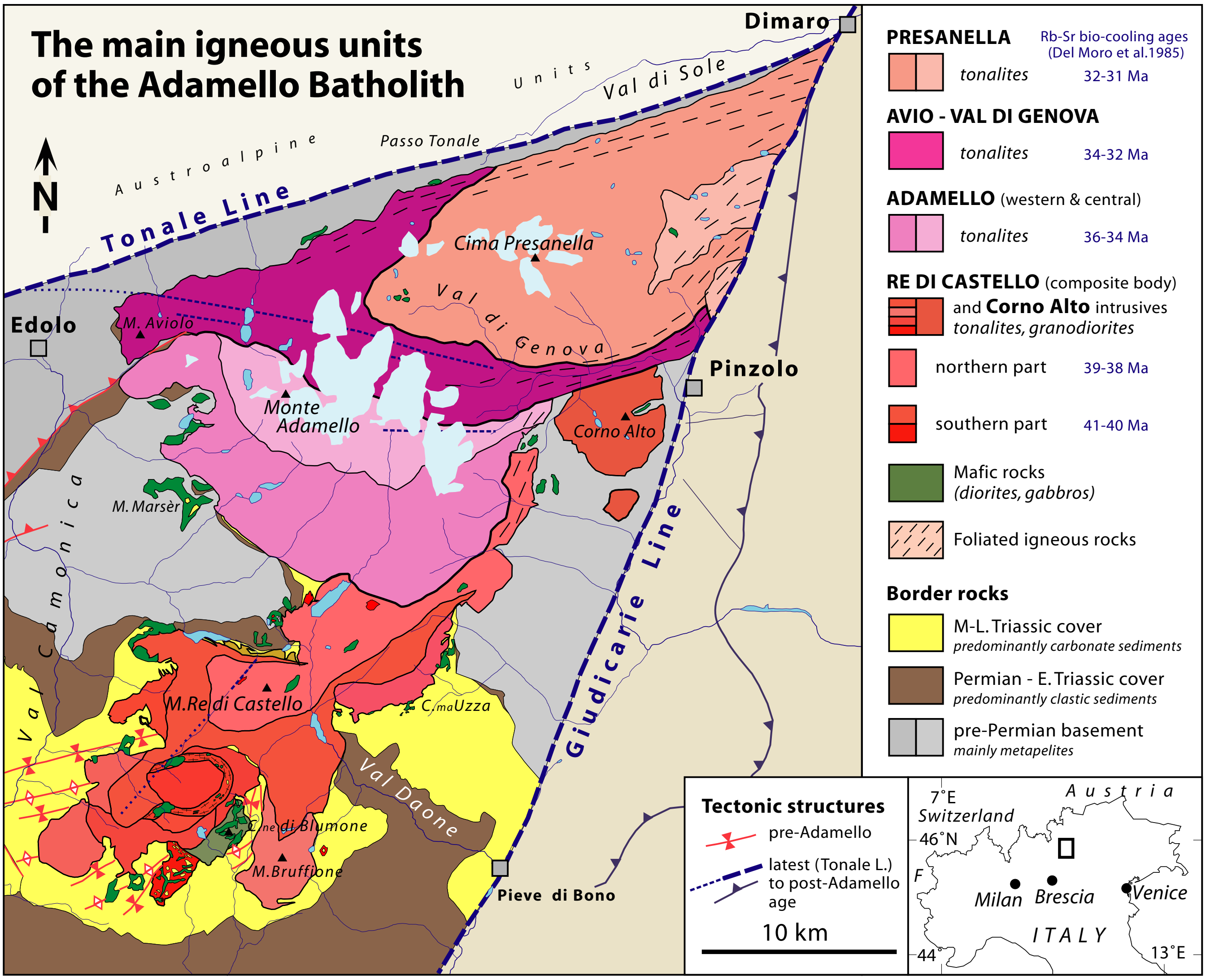


Fig. 1 - Overview map of the Adamello Batholith and its surroundings. Some of the named main igneous units (plutons) are composite bodies (e.g., Re di Castello). Pre-Adamello tectonic structures (red) and late to post-Adamello structures (blue) are indicated.

With a few exceptions, the Adamello plutons show a sequential emplacement from the oldest in the south (~42 Ma) to the youngest in the north (~32 Ma) (Del Moro et al., 1985, Ji et al., 2019; Schaltegger et al., 2019). Geochemical (Dupuy et al., 1982; Macera et al., 1985) and isotopic (Cortecci et al., 1979; Del Moro et al., 1985, Pimenta Silva et al., 2023b) studies of the batholith reflect the sequential nature of emplacement (Fig. 2 and 3).

There is a progressive increase in $^{87}Sr/^{86}Sr$ ($=Sr_i$) and $^{18}O/^{16}O$ ratios from south to north, coupled with increasing concentrations of incompatible elements such as U, Cs and K. Sr_i values vary from very low (0.7036) in the south and increase to 0.7121 in the north.

The mafic rocks associated with the granitoids range in composition from cumulate olivine-pyroxene wherlites to hornblendites to hornblende gabbros and diorites (Blundy and Sparks, 1992; Ulmer et al., 1985). Sr_i values of mafic rocks have partly mantle-like isotopic compositions (Sr_i: 0.7036-.7038, $d^{18}O$: +5.9-6.0), which overlap with those of the less radiogenic granitoids. There is a demonstrable geochemical link between the mafic and felsic rocks of the batholith (Bigazzi et al., 1986; Thompson et al., 2002) and taken as a whole the basic and felsic rocks define a typical calc-alkaline fractionation trend. This feature together with the sequential nature of the isotopic data has leas several workers to propose an assimilation fractional crystallization (AFC) model for the derivation of the Adamello batholith (Bigazzi et al., 1986; Macera et al., 1985; Taylor, 1980; Kagami et al., 1991; Thompson et al., 2002; Pimenta Silva et al., 2023b), whereby mantle-derived magmas fractionate and assimilate progressively larger amounts of lower to middle crustal material, such that the latest plutons are the most evolved and most radiogenic. Conversely, Cortecci et al. (1979) favor derivation of the batholith from partial fusion of isotopically variable middle crustal rocks. The progressive influence of radiogenic crustal sources with time is consistent with the deep crustal hot-zone model of Annen et al. (2006), in which hydrous mafic sills in the lower crust produce evolved residual melts by a combination of crystallization and crustal melting with the proportion of the latter increasing with time.

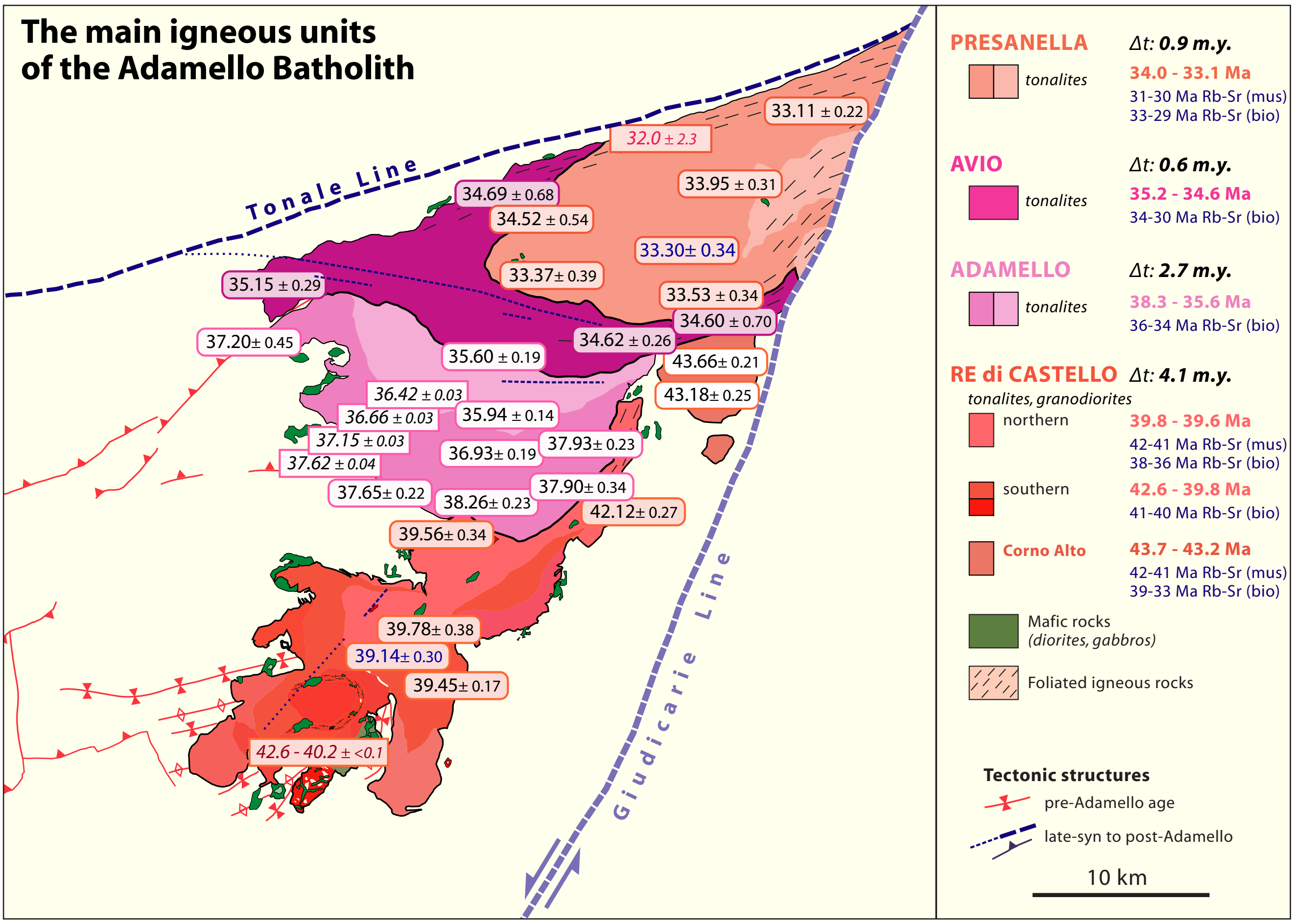


Fig. 2 - Petrographic subdivisions and U-Pb-zircon age data of the Adamello Batholith after Schaltegger et al. (2019)

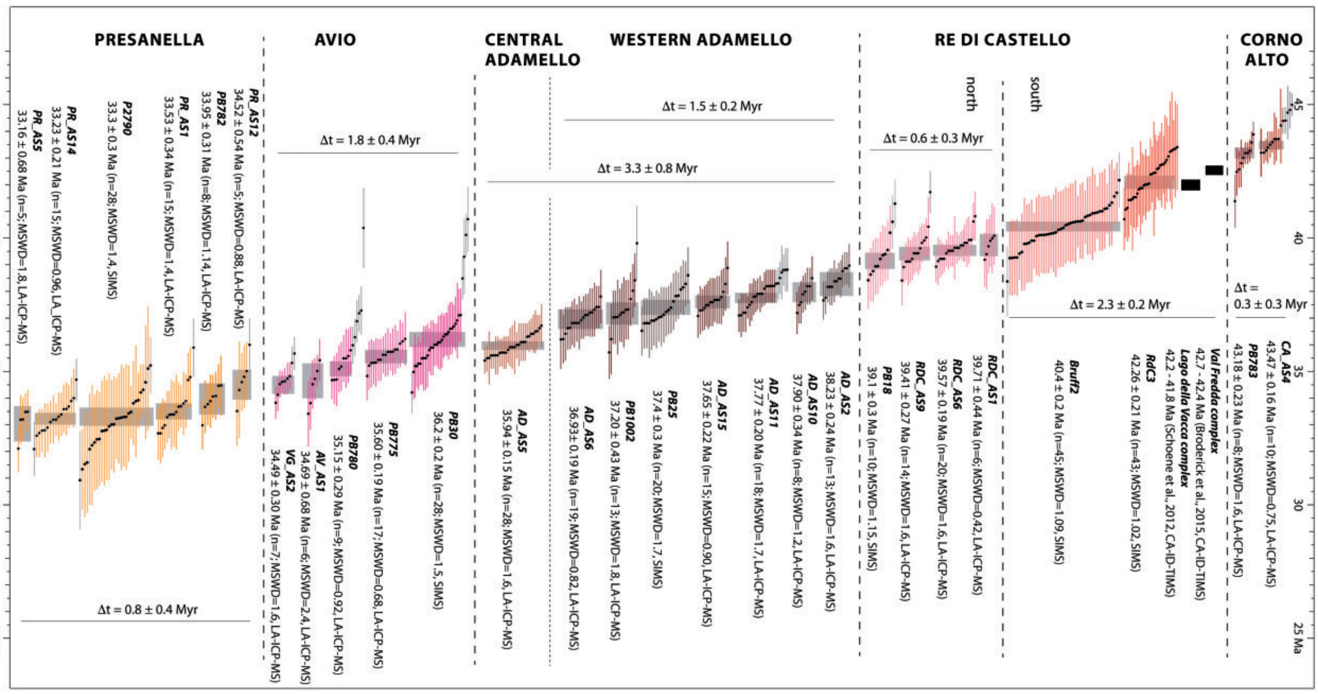


Fig. 3a - Compilation of 206Pb/238U age determinations of zircon from all super-units of the Adamello Intrusive Suite by laser-ablation sector-field single-collector ICP-MS and secondary ion mass spectrometry techniques. The mean ages of the Val Fredda complex and the Lago della Vacca complex (both part of the Re di Castello S unit) are from Broderick et al. (2015) and Schoene et al. (2012), respectively. From Schaltegger et al. (2019).

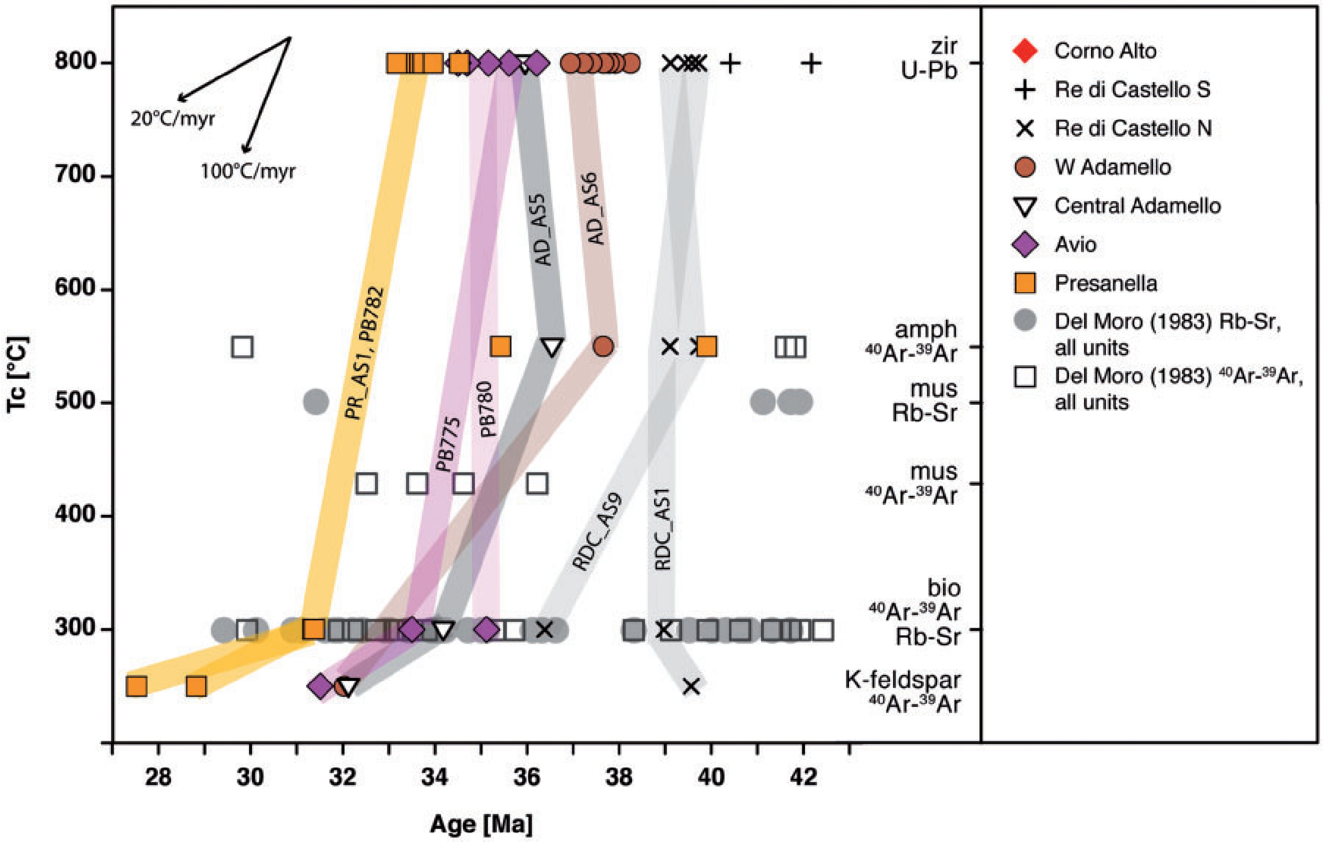


Fig. 3b - ^{40}Ar–^{39}Ar age determinations on amphibole, biotite and K-feldspar from different super-units of the Adamello Intrusive Suite. Single sample trends are marked with individual sample names. A general zircon crystallization temperature of 800°C has been adopted for simplicity; closure temperatures for amphibole, muscovite and biotite are generally accepted estimates. Rb–Sr and biotite ^{40}Ar–^{39}Ar dates of Del Moro et al. (1985a,1985b) for amphibole, muscovite and biotite are shown for comparison. From Schaltegger et al. (2019).

Intrusive rocks of the Re di Castello Pluton (RdC)

The intrusions of the southern Re di Castello Pluton (RdC-S) have been studied in considerably greater detail than elsewhere in the Adamello and will be the subject of this excursion. They consist mainly of fine-grained tonalites to granodiorities (Bianchi et al. 1970; Callegari & Dal Piaz 1973; Ulmer et al. 1985; Brack 1985, 1984; John & Blundy, 1993). Individual intrusions are, in some cases, homogenous and abut sharply against one another, elsewhere, however, contacts between individual magmatic pulses can only be discerned through subtle differences in texture, mineralogy and chemistry. The overall variation in ages of the different plutonic units of RdC-S suggests a short period magmatism of only ~3 Ma or less (Fig. 4). Along the intrusion borders, limbs of sediments up to several kilometers long are found separating different magmatic bodies. Gabbros and diorites occur as associated intrusions especially along the margins of the RdC-S, but are present also as small inclusions in the acidic rocks. Structures of syn-intrusive (forceful) deformation are observed in several magmatic bodies of the southern RdC-S.

On the basis of clear cross-cutting field relationships a succession of at least six main phases of emplacement of larger magma batches has been established in the RdC-S. U-Th age data (Fig. 4) [zircon, titanite, thorite] (Hansmann 1986; Hansmann & Oberli 1991; Schaltegger et al. 2009; Schoene et al. 2012; Broderick et al. 2015) fully overlap and indicate a narrow time span of < 3 Ma for the emplacement and rapid cooling of the southern RdC intrusive rocks. Only two main periods of intrusion (43-41 Ma and 40-38 Ma) for central to northern RdC, Fig. 3) can be resolved on the basis of the data with highest resolution power (U/Pb data on thorites and zircons).

Small, strongly differentiated trondhjemite and granite bodies, aplites and pegmatites as well as different generations of swarms of lamprophyric dykes were emplaced throughout the entire period of intrusion. A swarm of NE-SW to E-W striking, steeply dipping lamprophyric dykes cuts all magmatic members of the RdC and can be traced west over several tens of km into the folded and thrusted Permian and Triassic sediments of the Eastern Bergamasc Alps. Interestingly the orientations of different swarms of basic dykes reflect a profound modification of the pattern of crustal stresses during the period of magmatism. In contrast to the characteristic fine-grained textures of the tonalities to granodiorites of the RdC, the magmatic rocks of the younger northerly adjacent Adamello Pluton are generally coarser-grained and form larger and apparently quite homogenous units.

This excursion will focus on four major plutonic units of the southern Re di Castello Pluton. These are: the intermingled basic and silicic rocks of the Val Fredda Complex (VFC); the layered and disrupted basic/ultrabasic Blumone Complex; the highly heterogeneous and variably deformed Lago della Vacca Complex (LVC), and its relationship to the Blumone Complex; and the enigmatic „Listino Ring Structure", a deformed and heterogeneous sub-circular dyke-like feature in the north of the area (Fig. 1). Each evolved as a chemically or texturally discrete group of rocks, and was emplaced at relatively shallow level in the crust by a variety of intrusive mechanisms.

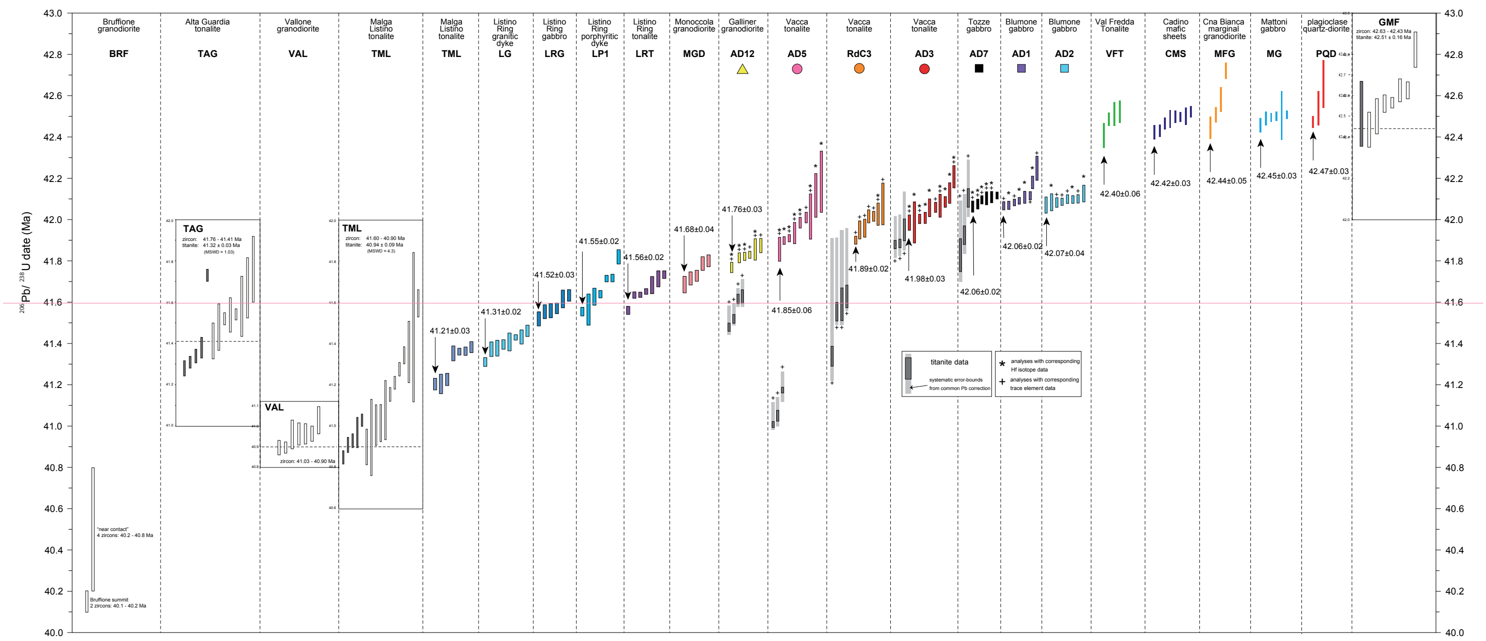


Fig. 4 - Compilation of 206Pb/238U age determinations of zircon from the southern part of the Re di Castello unit.
Age data from Schaltegger et al. (2009), Schoene et al. (2012), Broderick et al. (2015 and unpublished) and Verbene (unpubl.).

COUNTRY ROCK STRATIGRAPHY

At the present level of exposure the Re di Castello intrusives cross-cut the pre-Permian crystalline basement and Permian to Upper Triassic lithologies (Fig. 1 and 5) which bear a distinct contact aureole, between a few hundred meters and 2 km wide. Permian volcanics and lacustrine sediments (Collio Fm.) and redbeds (Verrucano Lombardo) of varying thickness (several hundred meters) and distribution are found along the northern margins of the Re di Castello Pluton, whereas the southern margins consist of Triassic carbonates and subordinate clastics.

A laterally persistent succession of Lower Triassic, shallow marine mixed clastics and carbonates (Servino Formation, 100-150 m thick) is overlain by a thin interval of locally evaporite-bearing peritidal carbonates (Bovegno Carnieules). In areas affected by pre-intrusive deformation this layer served as an important detachment horizon. Middle Triassic strata show a rather complex pattern of shallow to deep marine lithologies alternating with occasional thick platform carbonates. The original thickness of this package varies between 500 and 1500 m. Remarkable are the thinly bedded to nodular limestone/marl intercalations of the Angolo Limestone which show intense internal deformation in the folded zones. To the southeast (area of Monte Corona) several distinct algal banks (Dosso dei Morti Limestone) are found at this level. A continuous, originally 120m thick succession of pelagic sediments and thin volcanic tuffs (Prezzo Limestone, Buchenstein Beds) is an excellent marker across the entire area. Upper Ladinian shallow water carbonates form huge platforms to the west (Concarena) and east (sediment rim south of Monte Bruffione). Between the platforms, the carbonates are replaced by a thin interval of pelagic sediments (Pratotondo Limestone). The heterogeneous Middle Triassic succession is covered by 100-500m of fine-grained clastics (Lozio Shales) and shallow-water carbonates with thin clastic intercalations (Breno, Gorno, San Giovanni Bianco formations). Upper Triassic platform carbonates (Dolomia Principale) and associated dark lagoonal sediments are the youngest lithologies cut by the Adamello intrusives. Further afield these units are up to 1500 m thick but only their lowermost portions are still preserved in direct contact with the intrusive rocks.

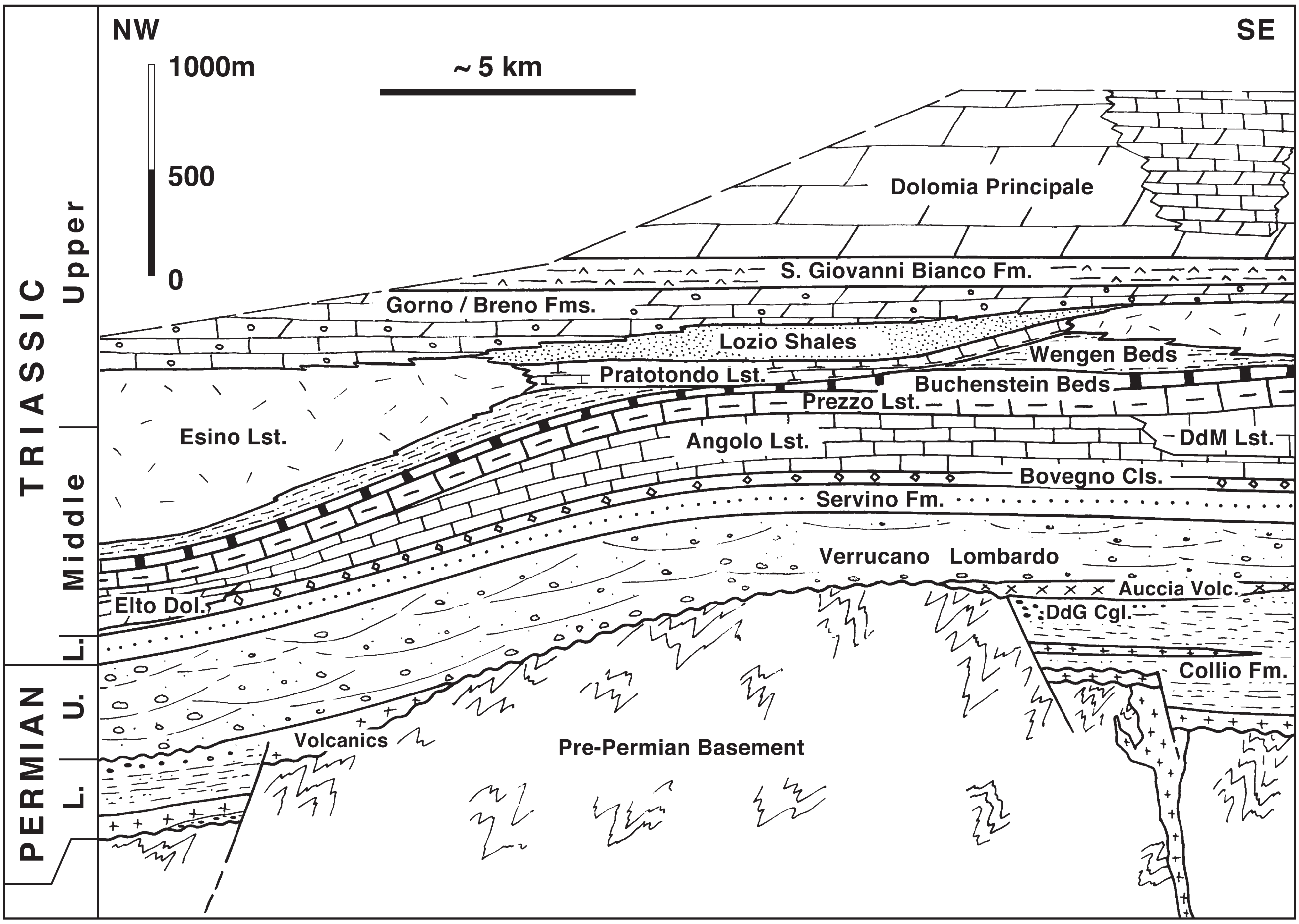


Fig. 5 - Stratigraphy of the Permian and Triassic country rocks around the southwestern rim of the Adamello Batholith. Note the considerable lateral variations of stratigraphic units between northwest and southeast.

CONTACT METAMORPHISM AND AMBIENT CONDITIONS DURING MAGMA EMPLACEMENT

The wide variety of country rock lithologies gives rise to a variety of contact metamorphic minerals in the thermal aureole. The most common mineral assemblages in the various sedimentary rock types are as follows:

Shales - biotite, muscovite, alkali-feldspar, tourmaline, cordierite, muscovite, corundum and andalusite (rare).

Marls and impure limestones - scapolite, calcite, tremolite, anorthite, diopside, grossular, vesuvianite, wollastonite and clintonite.

(Impure) Dolomitic limestones - calcite, dolomite, tremolite, diopside, forsterite, serpentine, clinozoisite, spinel, monticellite (rare), clintonite (rare) and brucite.

These minerals owe their existence to a combination of metamorphism and metasomatism by H_2O-rich fluids derived from the cooling intrusive rocks. Thin metasomatic rinds of calcite, forsterite, serpentine, diopside, tremolite and (pink) clinozoisite are widespread at dolomite/tonalite contacts in the Val Fredda Complex (Frisch & Helgeson 1984).

The various metamorphic mineral parageneses can be used to constrain the pressure and temperature of emplacement. Estimates of metamorphic peak temperature range from 400°C for metasomatic veins in the VFC (Frisch & Helgeson 1984) to 900°C for sedimentary blocks associated with the Blumone Complex (Ulmer 1982). To some extent this wide range in temperature reflects the variation in the composition of the magmas in the southern Adamello. For example, at Passo Blumone, Ulmer (1982) finds blocks of dolomitic marl in which an early assemblage of monticellite-forsterite-clintonite-diopside-spinel is overprinted by a chlorite-serpentine-calcite. The early assemblage to high temperature (800-900°C) metamorphism can be attributed to relatively low X_{H2O} due to emplacement of the very hot Blumone Complex driving decarbonation reactions, and the later assemblage to subsequent emplacement of LVC tonalites at lower temperature 550-650°C and relatively high X_{H2O}.

For the VFC Blundy (1989) finds temperatures of 480-530°C for pelitic and dolomitic sedimentary xenoliths. These values are somewhat higher than the estimates of 400-440°C by Frisch & Helgeson (1984) for metasomatic veins in dolomites from Monte Cadino. Both studies estimate $X_{H2O}\approx 0.96$. The apparent discrepancy in these temperature estimates can be largely attributed to the uncertainty in the estimated pressure. Frisch & Helgeson (1984) use 0.5 kb, while Blundy (1989) uses 1.6±0.3 kb. The true pressure may have been as high as 3.3 kb (see below). Adjusting the above temperature estimates to this pressure yields concordant revised values of: 500-540°C (Frisch & Helgeson, 1984); and 520-560°C (Blundy, 1989).

Estimates of emplacement depth for relatively shallow level rocks are notoriously difficult to obtain, especially when key barometer phases, such as the aluminosilicates, are very scarce. Little mineral geobarometry has been published, however Riklin (1985) identified the following minerals in hornfelsed Permian rocks at the contact with RdC intrusive rocks in Val Daone: quartz, plagioclase (An30), cordierite, andalusite, sillimanite (fibrolite), biotite, muscovite and alkali feldspar. The assemblage quartz + andalusite + sillimanite + muscovite + alkali feldspar + H_2O is invariant. If we assume that the activities of all solid phases are 1.0 (Riklin 1985), then we can estimate the pressure and temperature of emplacement. Assuming $a_{H2O} = 1$, these are 3.5± 0.5 kb and 656±15°C, and 3.8±0.5 kb and 640±15°C for $a_{H2O}=0.8$. The calculated temperatures are in the range cited by Riklin (1985), but the pressure estimates as much as 1.5 kb higher.

The pressures resulting from the application of the experimentally calibrated Al-in-hornblende barometer of Schmidt (1992) to tonalite samples that contain the appropriate buffer assemblage (amphibole + biotite + oxide + sphene + 2 feldspars + quartz), and lack chemical zoning in the amphibole result in calculated average pressures across the Adamello ranging from 2.5 to 5.5 kb (Matile 1996, Caddick & Blundy and Reusser & Brack (unpublished). Moreover the chemical compositions of aplite dikes in the LVC plot close to the composition of the water-saturated minimum in the Ab-Qz-Or-H_2O system at 3±1 kb.

During the emplacement of the Adamello the country rocks outside of the contact aureole were under non-metamorphic or very lowgrade conditions and provide the following constraints on the ambient conditions (for a short discussion and references see Pennacchioni et al. 2006) :

A) A crude lower estimate of the emplacement depth is provided by the total estimated thickness of the Mesozoic sedimentary sequence in the southern Alps, 3-5 km. However this succession was likely thickened tectonically during the period of magmatism.

B) Muscovite and biotite Rb/Sr data from pre- Permian basement rocks west and east of the Adamello, and from Lower Permian intrusions to the east (Val Rendena) and south (Val Trompia), reveal little or no post-Triassic resetting. This indicates ambient temperatures < ca. 350 °C during the Tertiary magmatism.

C) Zircon fission-track data from South Alpine basement schists west of Edolo, and from Permian volcanic rocks in Val Rendena, yielded ages of 94–97 Ma and 107 Ma, respectively and indicate cooling to below 250±50 °C during late Cretaceous, with no significant later re-heating.

D) Illite crystallinity data from Permian sandstones in the surrounding of the Adamello suggest that they underwent, at the most, anchizonal metamorphic conditions.

No evidence for any significant difference in the crustal levels currently visible in the northern and southern Adamello and therefore for a different intrusion depth of the various diachronous plutons of the Adamello. Therefore, the currently available pressure and thermal indicators suggest emplacement conditions for all the Adamello plutons at ambient pressures of 2.5– 3.5 kb and temperatures of about 250 °C, corresponding to a depth range of ca. 9–15 km. This depth of intrusion is in agreement with information on cooling of plutonic rocks in the southern and northern Adamello.

COUNTRY ROCK STRUCTURES AROUND THE RE DI CASTELLO PLUTON

Pre-intrusive structures

The Triassic strata in the western and southern surroundings of the Re di Castello Pluton (Fig. 6) exhibit a pattern of E-W to ENE-WSW striking large-scale folds and overthrusts (Brack 1981, 1984). The thin-skinned tectonic structures are kinematically linked to slices of pre-Permian crystalline basement, which are thrust southwards (Fig. 8). Along the southalpine (Orobic) basement further to the north these slices ramp through Permian to Lower Triassic units and override detachment horizons at the base of the Middle Triassic stratigraphic interval. The structures predate the oldest dated intrusives (i.e. deformation occurred before 43 Ma) and are possibly a result of Early Tertiary continental collision between Europe and the Adriatic (Apulian) microplate.

Along the western flank of Val Camonica, near Breno, Middle Triassic successions occur in two stacks separated by a gently northward dipping thrust (Figs. 6, 7). In an eastern direction the latter stops abruptly at Breno and the internally folded hangingwall portion continues in a series of large-scale folds. To the south of the Badile syncline which links the structures of both valley flanks, remnants of these folds are preserved along the western and southern border of the Re di Castello intrusives. The fold geometries imply a detachment of Middle to Upper Triassic rocks from their original Permian to Lower Triassic substratum. Intense internal folding is observed in the thinly bedded limestone/marl intercalations of the Angolo Limestone, particularly in the cores of large anticlines. The orientation of the metre-scale chevron folds is fairly regular and their axes are parallel to the strike of the large-scale folds across Val Camonica. To the east of Val Caffaro equivalent strata are generally flat lying and show only mild internal deformation. The pattern of large-scale and small-scale folds is cross-cut and in part deformed by the multiple intrusives of the Re di Castello Pluton (Fig. 6).

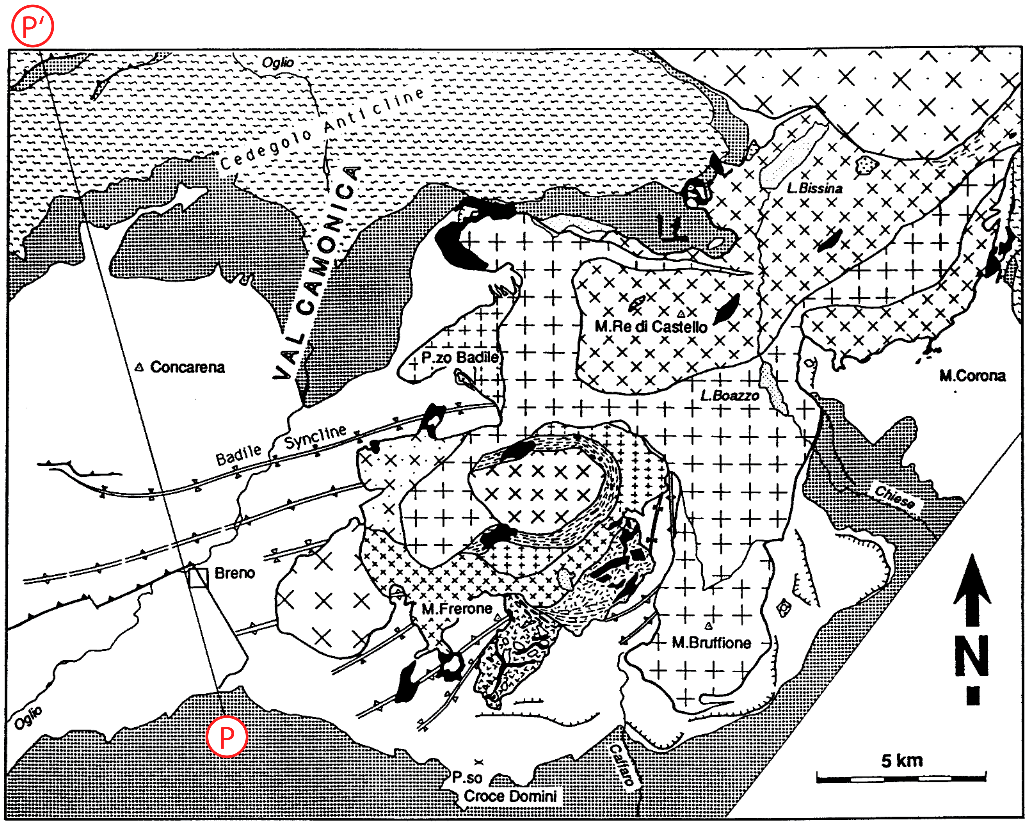


Fig. 6 - Geological overview of the Re di Castello Pluton and its tectonic setting.

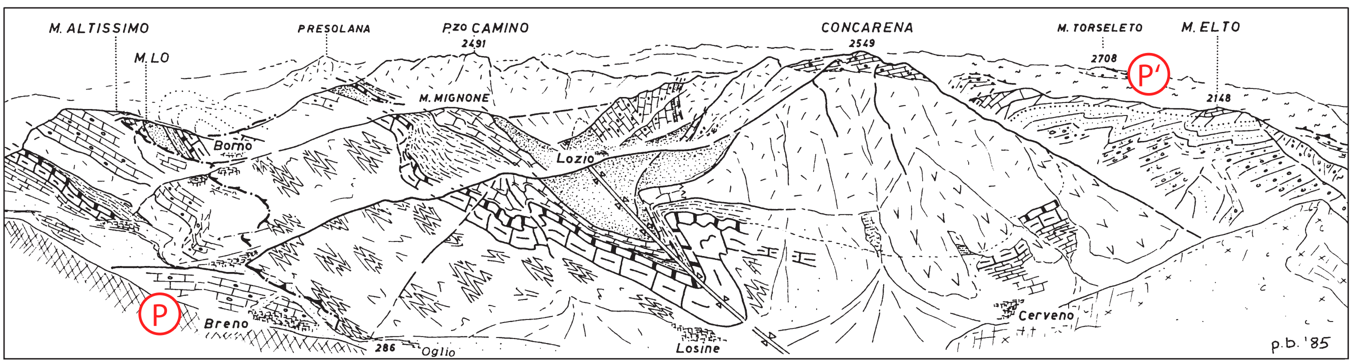


Fig. 7 - View of the western flank of the middle Val Camonica (looking west).

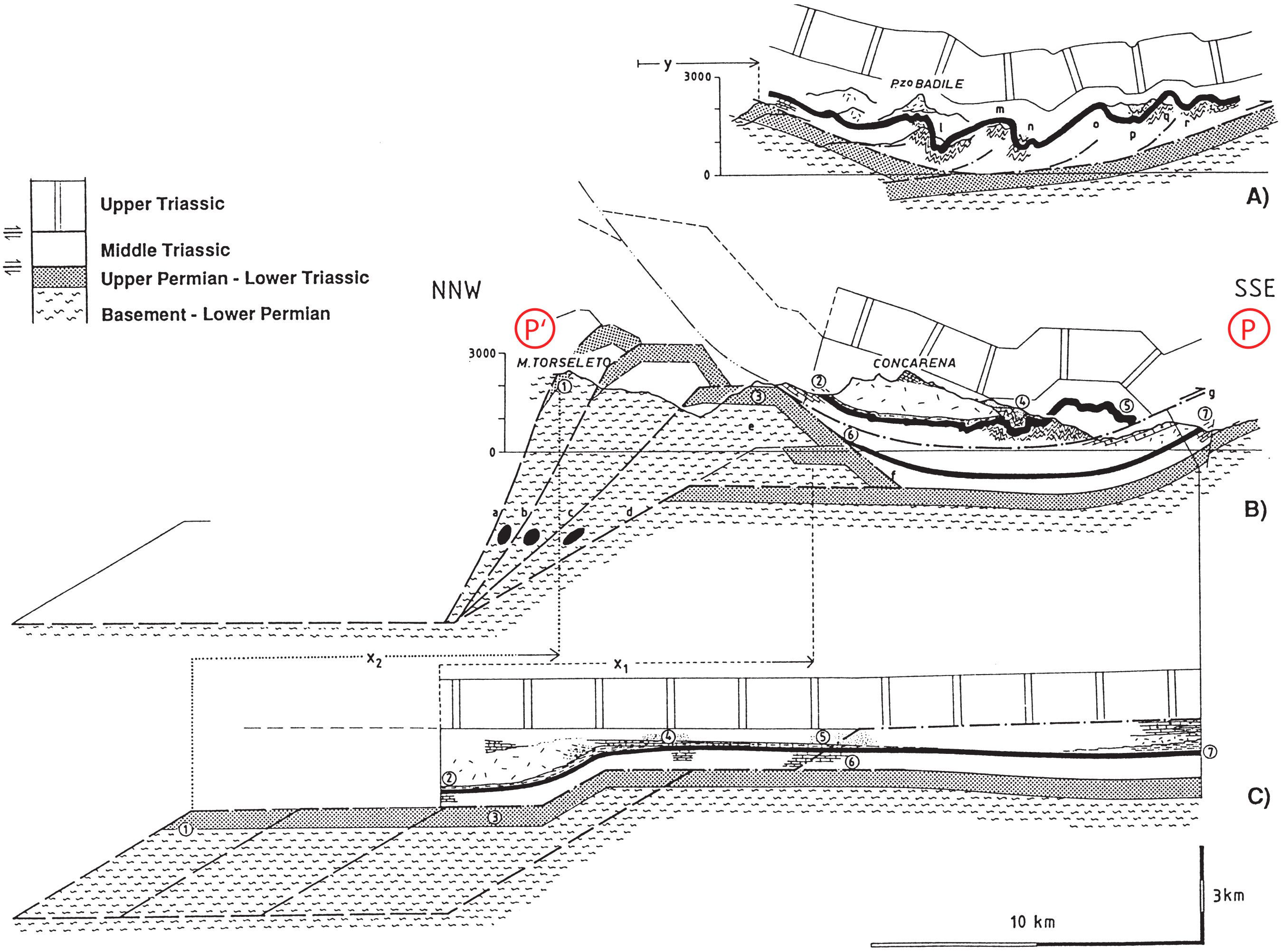


Fig. 8 - Reconstruction of the cross-sectional preintrusive foldpattern (perpendicular to fold axis of the Badile Syncline) along the eastern flank of Val Camonica (A); balanced cross-section (B) and palinspastic restoration (C) of section P - P' (see Fig. 6 for trace of section).

Syn-intrusive structures

Both, "passive" as well as "forceful" syn-intrusive structures resulting from the emplacement of magmas are found in the border rocks of the southern RdC.

"Passive" structures: Along the western border of the RdC the intrusives simply cut and dismember folded host rocks (Fig. 6). Where mappable over significant vertical relief the dips of intrusion surfaces range between 60-90° (outwards from the intrusion). Only in the area of Pizzo Badile is the southern flank of the Badile syncline strongly squeezed and its eastern end found in a upright position.

Frequently observed features along the southern and eastern borders of the RdC are packages of strata, up to 2 km wide, whose dips progressively increase towards the intrusions. At the contact the strata are often subvertical and at several places high-temperature tear folds are observed in dolomitic marbles. Entire sediment packages are found up to 1.5 km downthrown compared with their position further afield. The packages are bound by faults running approximately parallel to the intrusion borders. The faults dissect folded strata and are in turn crossed by late magmatic dykes. These geometries led Salomon (1903) to propose the ‚ethmolith', a funnel-shaped igneous body. However, the dipping strata rather imply the removal of previously underlying rocks and hence a stepwise downward broadening of the intrusions (Brack 1985). This is in agreement with observed irregular patterns of contact-metamorphic isograds and local occurrences of collapse breccias in the vicinity of Monte Bruffione (Matile & Widmer, 1993).

"Forceful" structures: The preintrusive folds preserved in the limbs of Triassic sediments between the multiple intrusives along the southern border of the RdC-S (area of Monte Frerone, Upper Val Caffaro; Fig. 7) document subsequent syn-intrusive compressions of variable intensity and orientations (Brack 1981, 1984). Syn-intrusive deformations are evident from the following observations in the host rocks or close to the sediment/intrusion interfaces:

a) *Refolding of large-scale fold pattern:* The large-scale fold pattern in the country rocks is disrupted and displaced, and fold-axes curve from an original ENE-WSW-strike to a N-S strike in the uppermost Val Caffaro. The shapes of the originally open folds become isoclinal. Sediment limbs are strongly squeezed and close to their ends they may have undergone substantial uplift. The northern flank of the Val Bona Anticline near Monte Frerone is refolded with a steeply dipping fold-axis (Fig. 9). Dolomite marbles in these folds show ductile behaviour, indicative of high-temperature deformation. In the upper Val Caffaro the curved folds have been cut by the Bruffione intrusives after bending and high-temperature deformation.

b) *Synmetamorphic deformation:* Lithologies have been deformed following an initial contact metamorphic overprint. The original contrast in mechanical behavior between competent carbonate layers and incompetent marls or shales became reversed during contact metamorphism with the formation of ductile marbles and rigid hornfels layers. This is clearly visible in the chocolate-tablet boudinage and disharmonic folding of thin hornfels layers interbedded with calcite marbles in the Angolo and Pratotondo Limestones. Small-scale folds in the former were refolded or further compressed (Fig. 9). In places of ongoing metamorphism the folded coherent hornfels layers were replaced by arrays of mm to cm-sized crystals of garnet and vesuvianite still mimicking the original fold shapes.

c) *Deformed dykes:* Early intrusives (aplitic, various generations of lamprophyres) crossing the sediments are folded and/or stretched (boudinage). Younger undeformed intrusives cross-cut these structures (Fig. 10).

d) *Reorientation of sediment inclusions:* Sedimentary inclusions of various sizes and lithologies in the intrusives east of Monte Frerone are deformed together with the magmatics and show a distinct orientation of their long axes parallel to the intrusive contact. This includes the detached nose of the Frerone anticline, which now occurs as a xenolith rotated by ~90° clockwise relative to the original fold axis (Fig. 14).

In spite of deformation and reorientation these bodies are still arranged in their original stratigraphic succession creating a remarkable ghost stratigraphy throughout the northern part of the Val Fredda Complex. The cause(s) of the ‚forceful' synintrusive deformations in this area can be attributed to the emplacement of the Lago della Vacca Complex to the north (John & Blundy, 1993). Intense deformation of intrusive rocks close to the contact in upper Val Fredda testifies to considerable north-south shortening. Textures in the deformed rocks suggest that deformation occurred in a partially molten state, i.e. before the Val Fredda Complex and the marginal units of the Lago della Vacca Complex had cooled fully below the solidus (John & Stünitz, 1992).

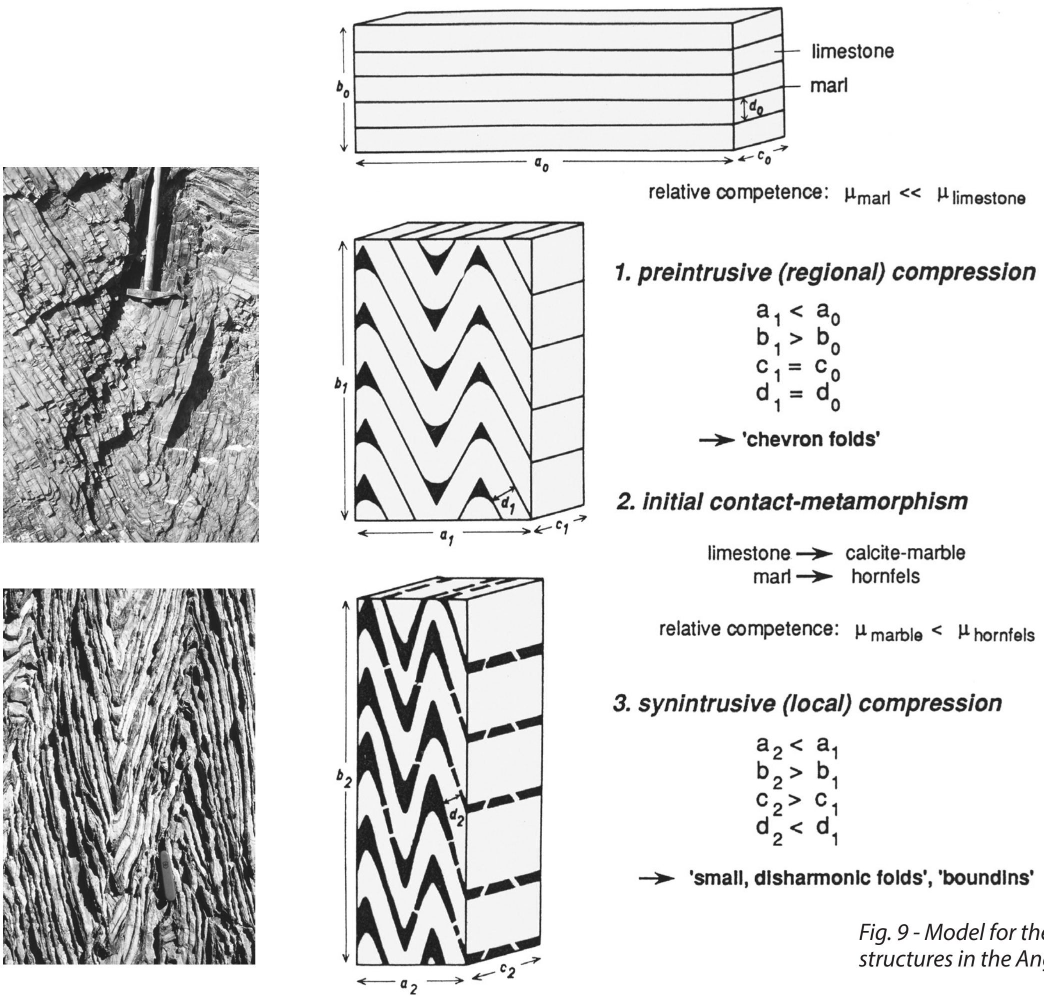


Fig. 9 - Model for the development of small scale structures in the Angolo Limestone (Brack 1981).

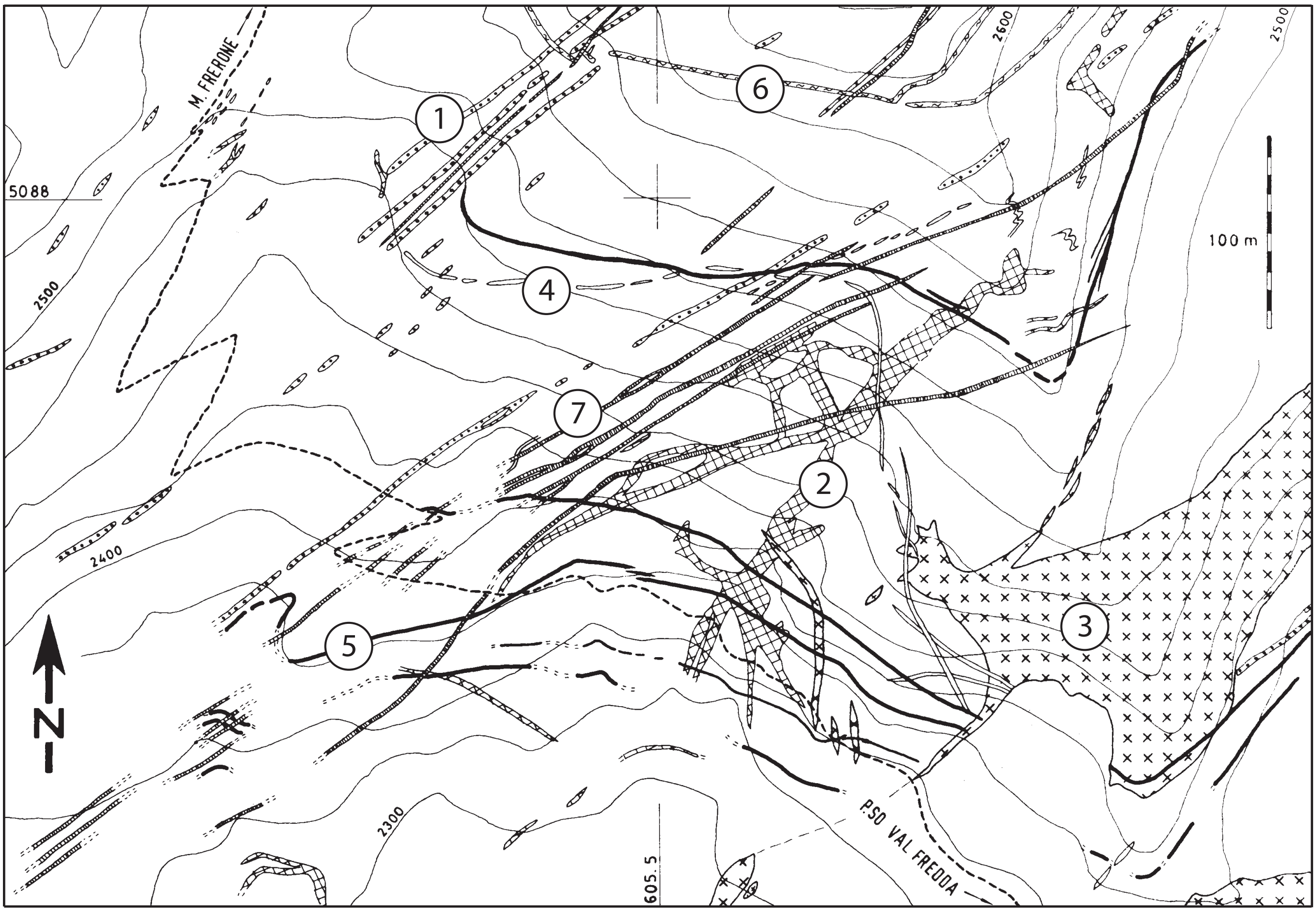


Fig. 10 - Map of the dyke pattern along the southwestern flank of Monte Frerone. Intrusives in chronological order on the basis of cross-cutting relationships: (1) dykes of probable Upper Triassic age; (2) aplites and small granitic masses (including Monte Frerone Granite MFG); (3) Val Fredda intrusives; (4) unclassified mafic dykes; (5) swarm of subhorizontal basic dykes; (6) prominent amphibole-bearing gabbrodiorite dyke; (7) swarm of subvertical basic dykes. Dyke types (1) to (5) are affected by syn-intrusive deformation. From Brack (1981).

Fig. 11 - Compressional structures within the contact-metamorphosed zone in the Monte Frerone area; marble -hornfels interlayers and an early intruded mafic dyke have been deformed by a later intrusion. (Brack 1985).

Fig. 12 - Fragment of Blumone gabbro within Lago della Vacca marginal facies diorites (= Blomone Complex sensu Ulmer/Brack). Note how host rock foliation wraps around xenolith.

An interesting feature of the southern Lago della Vacca Complex (LVC) is the occurrence of bodies of gabbro on the north flank of Monte Stabio that are texturally and chemically identical to gabbros in the Blumone Complex over 1 km to the east. Within the deformed southern margin of the LVC occur numerous small fragments of the same gabbros which map out in a curved pattern linking Stabio and Blumone and lying parallel to the magmatic foliation in this region (Fig. 12). This observation suggests that emplacement of the LVC involved significant dextral displacement of the entire Blumone Complex, possibly along a basal shear at quite shallow depth (Fig. 14). The presence of an anticlinal axis in upper Val Caffaro similar to that at Monte Frerone, only considerably tightened by syn-intrusive compression normal to its axial plane, lends support to this hypothesis.

Post-intrusive structures and uplift

Only few and rather insignificant brittle faults cross-cut the Re di Castello intrusives and their immediate surroundings. However, to the east and south the geometries of the Giudicarie (and possibly also the Val Trompia) fold and thrust belt (Late Miocene, i.e. post-Adamello age) suggest that the tectonic high which is bound by the Giudicarie and Val Trompia Lines and which includes all igneous Adamello units is displaced by several tens of kilometers. Therefore the exposed Adamello intrusives are presumably decoupled from possibly deeper-seated counterparts.

Studies on deformation along the Tonale Line suggest that the first dextral movements along the northern border of the Adamello intrusives occurred after the emplacement of the northernmost magmatic rocks (32-29 Ma cooling ages; Del Moro et al. 1985), but at still elevated temperatures in the contact aureole and before movements along the Giudicarie Line (Werling 1992). Castellarin et al. (2006) present evidence for sinistral movement on the Giudicarie Line as early as the late Cretaceous, while dextral displacement along the Tonale Line is limited to the Neogene. Despite much speculation on possible relationships between the ascent of the Adamello magmas along deeply rooted faults (e.g. Laubscher, 1985, Rosenborg, 2002, Stipp et al., 2002), there remains considerable uncertainty as to the role the Giudicarie and Tonale Lines may have played in permitting the emplacement of the Adamello Batholith. The oldest portion of the Adamello Batholith (i.e., the Re di Castello Pluton) intruded the South Alpine upper crust several tens of kilometres south from the Tonale Line.

In the area of the actually exposed Adamello intrusives the cumulative, postintrusive (<30Ma) uplift and overburden removal as a consequence of tectonism and isostasy are estimated to lie between 7 and 12 km. This is in agreement with pressures of 3-5 kb derived from contact metamorphic mineral assemblages and amphibole barometry at present elevations of around 2000 m.

FIELD RELATIONSHIPS OF THE MAIN IGNEOUS UNITS (SOUTHERN RE DI CASTELLO PLUTON)

The Val Fredda Complex

The Val Fredda Complex (VFC) is a small tonalite-diorite-gabbro intrusion, exposed over ~6 km^2 in Val Fredda, western Val Cadino and on the eastern flanks of Monte Frerone (Figs. 13 and 14). Post-Scythian Triassic rocks bound the VFC on the east, south and west sides, and occur as xenoliths within the tonalitic portions of the intrusion. The VFC is most prominently exposed along the Mattoni-Cadino-Frerone ridge, where the relationships between the principal intrusive rocks of the VFC are clearly displayed, as is the relationship between the form of the VFC and the pre-intrusive structures in the country rocks. The northern margin of the VFC has been deformed by the later intrusion of the Lago della Vacca Complex (LVC). The intrusion was mapped at a scale of 1:5,000 by Blundy (1989) and is shown in Fig. 14.

Emplacement of the Val Fredda Complex: Around the VFC the strata are folded into a series of variable-amplitude folds with sub-horizontal axes striking roughly NNE-SSW. The most prominent country rock structure is the tight, sub-vertical east-vergent Frerone Anticline, in the west of the area. Intense chevron and parallel folds occur in Angolo Limestone in the core of the fold (Bianchi & Dal Piaz 1937b and Brack 1981) and parasitic folding is well developed on both limbs. East of the Monte Frerone anticline, folding takes the form of gentle anticlinal and synclinal flexures, which define the broad Val Cadino Synclinorium in which the VFC is situated.

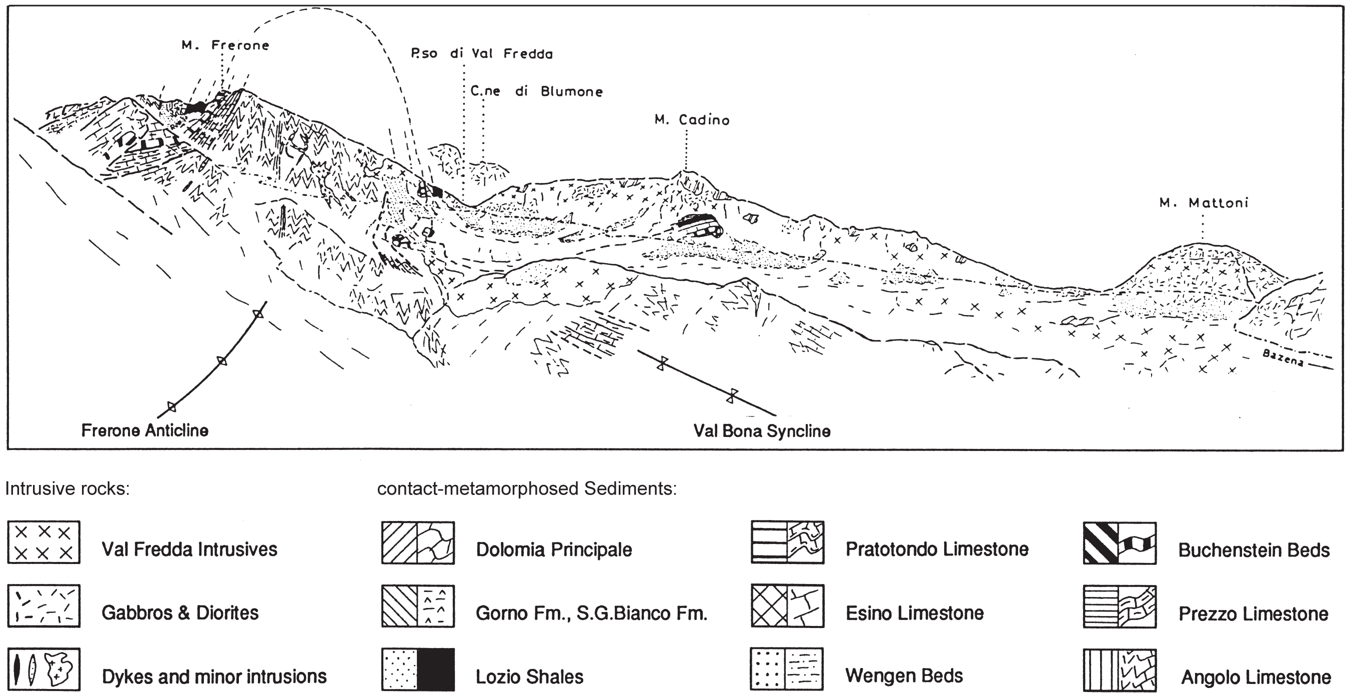


Fig. 13 - View of the M. Frerone - M. Cadino - M. Mattoni ridge with indicated traces of the major folds.

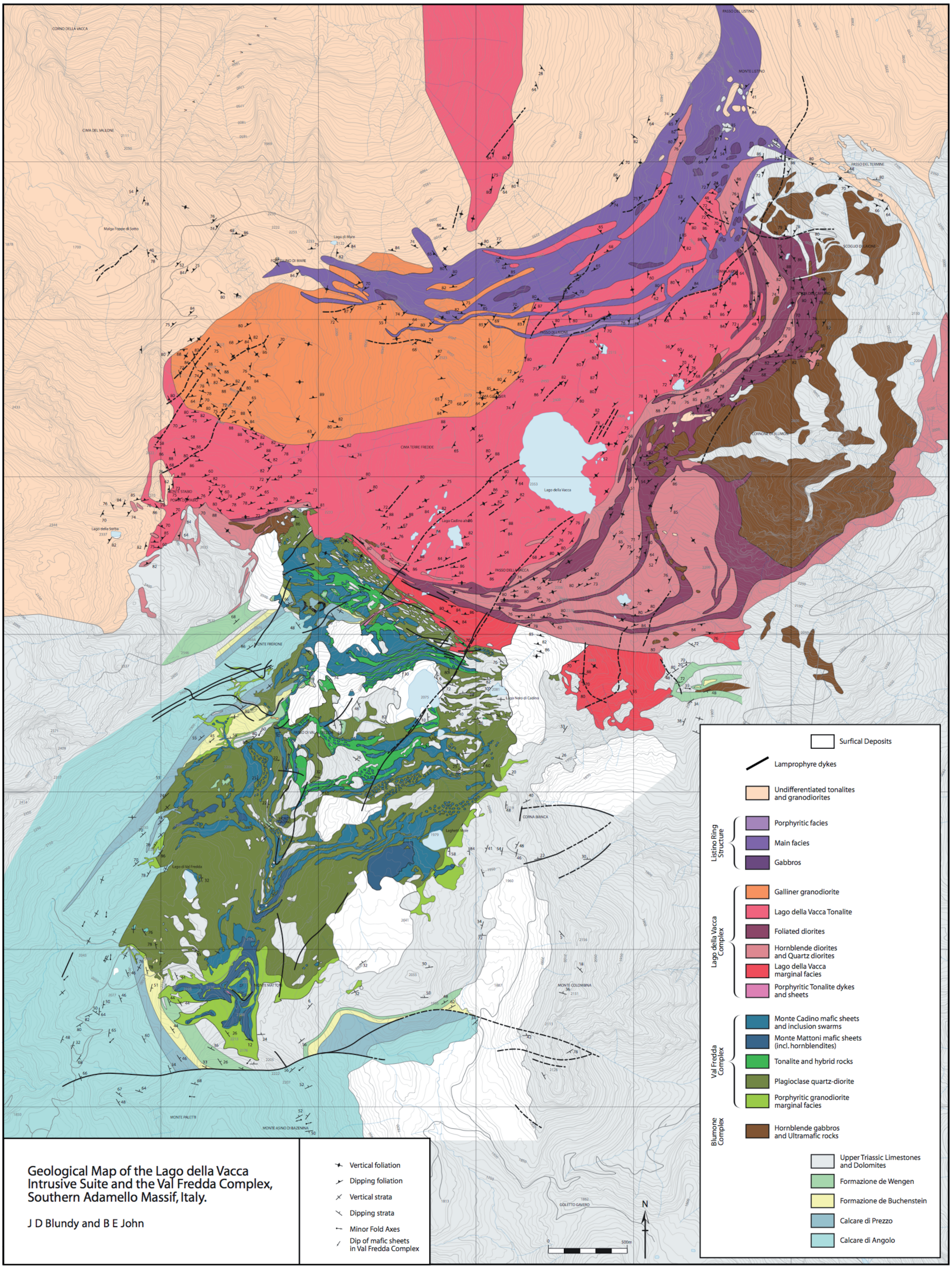


Fig. 14 - Preliminary geological map of the southern part of the Re di Castello pluton.

The location of the VFC within a broad synclinorium, bound to the west by a steep anticline, suggests that its emplacement was influenced by the pre-intrusive geometry of the country rocks. The roof of the intrusion apparently dips at a shallow angle eastwards from Monte Cadino, parallel to bedding in the adjacent dolomite. The steep western bounding-wall of the intrusion is marked by the sub-vertical eastern limb of the Frerone anticline. At its southern extremity, south of Monte Mattoni, the VFC consists of two parallel intrusive sheets separated by a 30-40m thick screen, or „septum", of dolomite. Both sheets wedge out southwards.

Xenoliths of country rocks, predominantly sugary, recrystallized dolomite up to 300 m across, are abundant throughout the VFC. Xenoliths are most notable on Monte Cadino where they occur as pendants in a giant roof breccia (Fig. 15). Elsewhere xenoliths of other Triassic lithologies are of obvious local derivation and can often be restored in jigsaw fashion to their original position in the wall or roof of the intrusion (Fig. 14). Above Passo di Val Fredda there is evidence of blocks of wall rock essentially frozen in the process of stoping and detachment by the magma. There is also evidence that magma exploited bedding planes or other lithological weaknesses in the country rock. For example, to the west of Corna Bianca, an exceptional „lit-par-lit" structure can be recognized, wherein beds of dolomitic limestone dip northwards at steep angles as they are split apart and fragmented by thin sheets of tonalite.

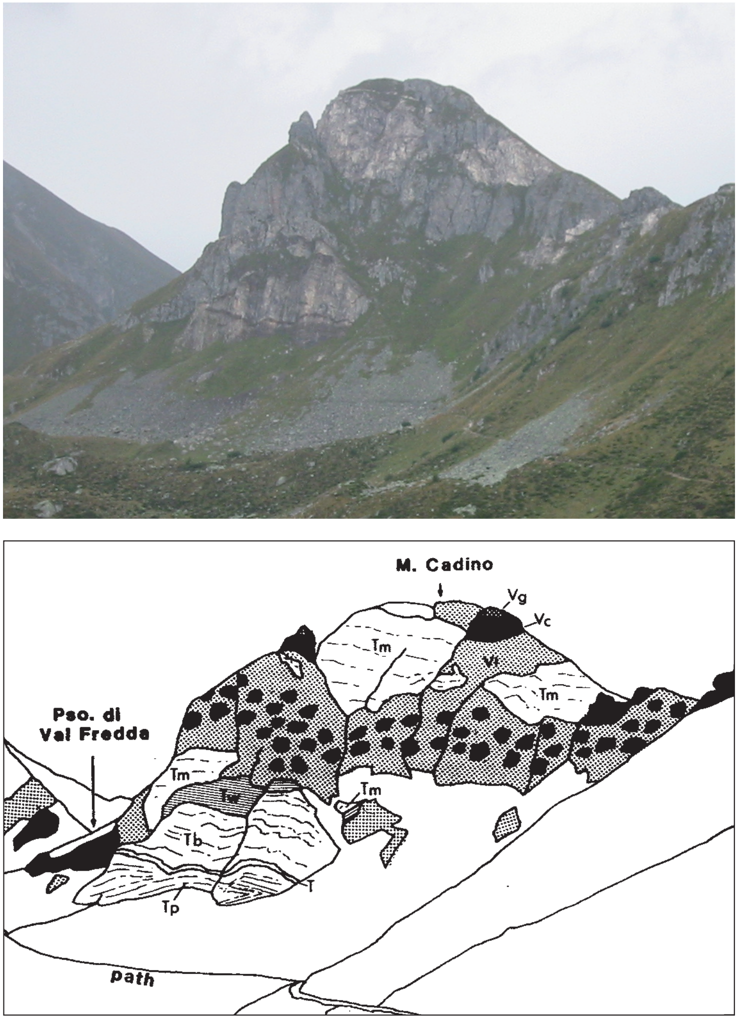


Fig. 15 - Large country-rock xenoliths of Triassic strata (Tm, Tw, Tb, Tp) in mafic-inclusion rich Val Fredda tonalities on Monte Cadino.

It is apparent that the VFC was emplaced into an essentially monoclinal structure, at a stratigraphic level slightly below the base of the Dolomia Principale. Emplacement was predominantly passive, resulting in minimal disruption of the pre-intrusive structure and the preservation of a remarkable „ghost stratigraphy" within the VFC, similar to that described by Pitcher (1972) for parts of the Donegal Batholith. In essence the VFC may be a laccolith, exposed close to its roof and of probable limited vertical extent.

Intrusive relationships in the Val Fredda Complex: The VFC consists of granodiorites, tonalites and quartz-diorites intruded by several sub-horizontal mafic sheets ranging in thickness from 0.5 to over 100 m. The bulk of the felsic rocks are equigranular to slightly porphyritic tonalites, with a small volume of quartz-diorites in the central and northern part and a marginal facies of porphyritic granodiorite, predominantly at the southern extremity.

The mafic sheets can be divided into two varieties. The first type (the Monte Cadino mafic rocks) consists of hornblende gabbros to quartz-diorites with equigranular to weakly plagioclase-phyric textures. They are characterized by elongate prismatic to acicular hornblende (up to 8 mm in length) in a matrix of plagioclase, quartz and minor biotite and rare alkali-feldspar. The margins of the sheets are conspicuously finer grained than the interior with an increase in the aspect ratio of hornblende from prismatic to highly acicular.

The second type (the Monte Mattoni mafic rocks) consists of hornblende-phyric pyroxene-bearing gabbros with minor plagioclase-phyric varieties. The principal Mattoni rock type contains equant prismatic hornblende phenocrysts (~8 mm) in a matrix of poikilitic plagioclase enclosing 1-2 mm hornblende and cpx, with conspicuous groundmass sphene and subordinate quartz and alkali feldspar. A decimetric sub-horizontal layering is defined by variations of hornblende phenocryst abundance (Fig. 16). Hornblendite (or cortlandite) occurs as blocks and bands in Mattoni rocks and is notable for the presence of olivine, opx, cpx and Cr-spinel inclusions in the hornblendes. Monte Mattoni rock types occur in the cores of the mafic sheets and are without exception separated from the felsic rocks by variable thickness selvages of Monte Cadino mafic rocks.

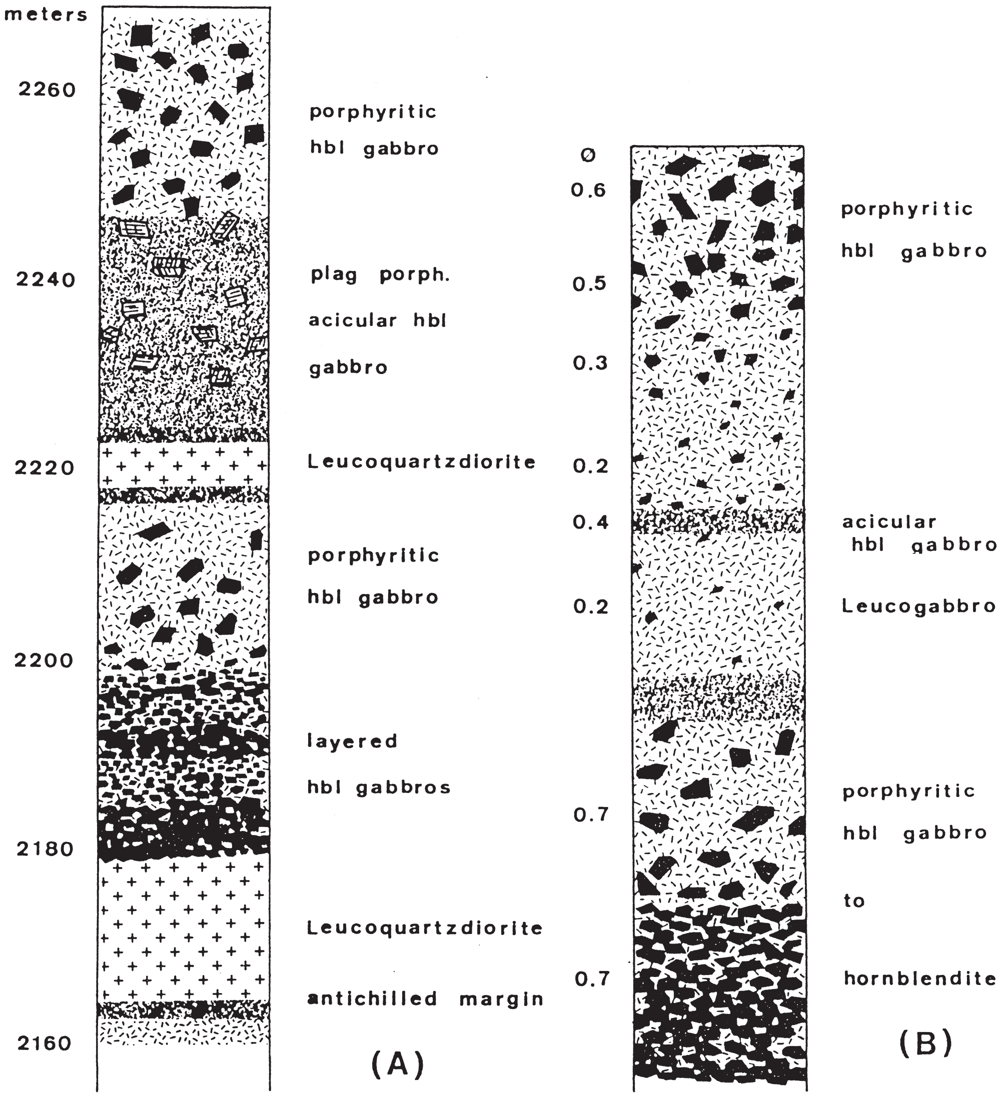


Fig. 16 - Schematic lithological profile of the western slope of M. Mattoni. Numbers indicate the altitude. (B) Rock succession of the layered gabbro sequence at M. mattoni on a mesoscale. Numbers indicate the average diametre of amphibole crystals (after Sonder-egger, 1980).

Coarse gabbro pegmatites occur throughout the mafic sheets as concordant horizontal pods parallel to layering and as discordant veins and pods. Layering-parallel pegmatites typically occur near the tops of mafic sheets. The abundance of hornblende and calcic plagioclase together with the ubiquity of gabbro pegmatites all indicate that the VFC mafic rocks crystallized from hydrous basaltic magmas. The form and distribution of pegmatites suggest that they formed during contraction of the cooling host magmas.

The mafic sheets have irregular, complex boundaries with surrounding felsic host rocks and degenerate laterally into dense swarms of inclusions (Figs. 14, 15). The upper and lower margins of the sheets are typically lobate and mafic inclusions can be observed frozen in the act of detachment from the margins. The outer margins of sheets and mafic inclusions are fine-grained and cuspate (Fig. 17). Both are characterized by acicular, randomly oriented hornblendes. The sheets are sometimes back-veined and brecciated by felsic pegmatite and aplite. Most inclusions are in the size range 5 to 50 cm and are typically ellipsoidal with weakly prolate form, except where flattened in the deformed northern VFC. Occasionally selvages of hornblende and/or biotite occur at the contact with the felsic host and there may be a thin zone (≤l cm) of noticeably leucocratic felsic rock around inclusions.

Mixing textures between tonalite and mafic magmas are apparent in the field. Crystals and crystal aggregates (notably plagioclase, biotite and quartz) from the host tonalite can be seen in various stages of assimilation and reaction into the mafic inclusions and sheets (Fig. 17). Many inclusions are texturally and compositionally heterogeneous due to variable assimilation of tonalite, giving them a distinctly „xenoporphyritic" texture. Reaction of quartz xenocrysts with mafic inclusion magma produces coronas of hornblende. Banding of tonalite and diorite/gabbro on a decimetric scale can be observed at some localities. In areas of high inclusion density the host tonalite also shows signs of hybridisation. Disaggregation of inclusions yields thin stringers and schlieren of fine-grained mafic material that are heterogeneously distributed through the tonalite. Reaction of quartz phenocrysts in the tonalite with fine-grained mafic material produces similar coronas to those in the mafic inclusions.

Fig. 17 - Mafic inclusions of Cadino-type gabbro and diorite with chilled margins against host Val Fredda tonalite. Note partial assimilation of tonalite by mafic magma in lower two inclusions and mafic schlieren within tonalite. Casinetto dei Dossi.

Our interpretation of these field relationships is that the mafic magmas were emplaced into hot tonalite mush still containing some interstitial melt. The fine-grained margins and the acicular texture result from chilling of mafic magma on contact with the adjacent cooler tonalites. These must have been coherent enough to allow the mafic magmas to intrude as sub-parallel sheets close to the roof of the intrusion, but hot enough to remobilize it causing the sheets to disintegrate laterally into inclusion swarms and locally to mingle intimately with tonalite. Mixing textures indicate that the tonalite was crystal rich, but could be mobilized with sufficient ease to allow partial hybridization. Mobilization was facilitated by the transfer of heat to the tonalites from the cooling mafic magmas. Exsolution of volatiles from the mafic sheets, as evinced by the ubiquitous gabbroic pegmatites, would have facilitated host rock mobilization. Where host tonalite was sufficiently remobilized it was injected back into the solidified mafic rocks to produce the net-vein breccias and, locally, small cross-cutting dykes or sheets of porphyritic tonalite. In essence the sheets and rounded inclusions show all the classic features of syn-plutonic intrusions and net-veined complexes where silicic and mafic magmas are incompletely mixed together.

The Blumone Complex

The present day outcrop of the Blumone Complex owes its form to disruption by the Lago della Vacca Suite (s.l.), which effectively rent the original Complex in two, with the largest segment located around Cornone di Blumone (2843m) and Scoglio di Laione (2670m), and a much smaller segment situated below Monte Stabio, to the west of Monte Frerone (Fig. 14). As noted above, fragments and xenoliths of the Blumone Complex in the LVC mark out arcuate trains, which reveal the original contiguity of the two Blumone fragments. The Blumone Complex is a spectacular example of polyphase intrusion, wherein an early, layered ultrabasic/basic cumulate body has been disrupted by later magma pulses ranging in composition from (qtz-)gabbro to trondjhemite. Consequently the Complex is host to a wealth of dykes and intrusive breccias showing many different age relationships. Mapping of the Complex is made very difficult both by the heterogeneous nature of the rocks and by the inaccessible nature of Cornone di Blumone, in particular the sheer south face. Some of the best rock samples are to be found in talus south of Cornone di Blumone and to the east of Lago della Vacca. The most comprehensive description of the geology is given by Ulmer (1986; see Fig. 18a for his map).

Of the early cumulate sequence relatively little remains. The original layering is locally preserved on the south flank of Cornone di Blumone, where it can be seen to dip 50-60° to the northwest. Many primary features of the layered complex have been overprinted by intrusion of later, hydrous magma. In particular, early cpx-bearing assemblages have been extensively amphibolitized. Magnetite is a ubiquitous component of all Blumone rocks, while primary orthopyroxene is (nearly) lacking. Ulmer (1986) and Pimenta Silva et al. (2023a) identified the following rock types of the layered sequence: coarse-grained wehrlites (augite+Fo_{88}) with or without plagioclase (An_{85-98}) that only occur as inclusions in younger gabbroic rocks; olivine-gabbros; cpx-bearing anorthosites and anorthositic gabbros; magnetite-hornblende cumulates. Where preserved, the layering follows the sequence ol-gabbro - cpx-magnetite-gabbro - anorthosite in alternating bands up to 1m thick, locally developing cumulate textures, including comb layering (Fig. 19) and modal grading. The best examples occur ~600 m northeast of the Cornone di Blumone peak at an elevation of ~2550 m. Samples of the stratified sequence may also be found as xenoliths enclosed in younger intrusives. Based on textural and chemical evidence, Ulmer (1986) interprets the Blumone Complex as the shallow cumulate relict of a former feeder channel, which supplied basaltic to basaltic andesitic magmas to shallow depth (and possibly even to the surface?).

The Complex was disrupted by a number of coarse-grained hornblende-cpx-magnetite-gabbros and medium-grained-diorites to tonalites. The latter are considered the marginal facies of the Lago della Vacca Complex by John & Blundy (1993), but as part of the Blumone complex s.l. by Ulmer (1986). The abundance of hornblende and magnetite at the expense of olivine and clinopyroxene suggests that hydration and oxidation of the cumulate rocks accompanied disruption. There is also evidence of high temperature deformation of the layered rocks, e.g. bent twin planes in primary calcic plagioclase.

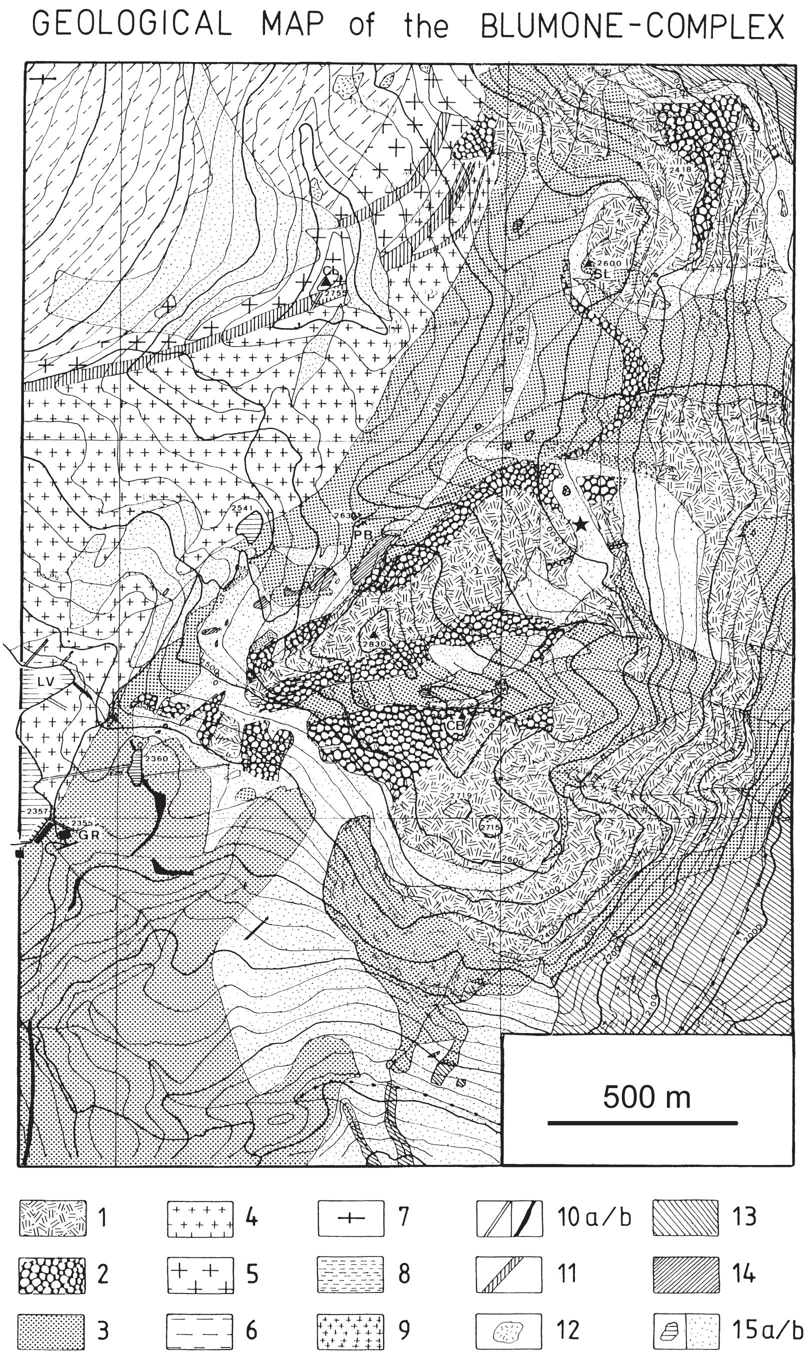


Fig. 18a - Geologic map of the Blumone Complex (Ulmer 1986)

Abbreviations:
CB – Cornone di Blumone;
CL – Cima di Blumone;
GR – Rifugio Gabriele Rosa (now the Guardian´s house at the dam of L. della Vacca);
LV – Lago della Vacca;
PB – Passo del Blumone;
SL – Scoglio di Laione

1	stratified gabbros and anorthosites of the Blumone Complex
2	brecciated gabbros of the Blumone complex
3	quartz-gabbros to tonalities of the Blumone Complex
4	Lago della Vacca tonalite
5	unnamed leuco-tonalite
6	“Schlieren-zone” of the Listino Ring structure
7	M.ga Listino tonalite
8	strongly oriented tonalities of the Blumone Complex (upper Caffaro Valley)
9	biotite-leucotonalite to trondhjemite of the Blumone Complex (small stock 200m NE of Cornone di Blumone)
10a	basaltic – andesitic dikes (subvertical dip)
10b	olivine-tholeiitic to picrobasaltic dikes (subhorizontal dip)
11	andesitic to dacitic dike rocks related to the Listino ring structure
12	hornblendite macro-enclaves in the Listino Ring structure
13	contact metamorphic sediments of upper Val Caffaro (Dolomia Principale, S. Giovanni Bianco Fm.)
14	high-temperature contact metamorphic skarns related to the intrusion of the Blumone Complex
15	a: lakes; b: talus scree

The Complex is cut by a number of discrete dykes, including, in order of decreasing age (Fig. 18b):

(i) Pegmatitic hornblende gabbros with plagioclase laths up to 5 cm and hornblendes up to 30 cm. The dykes are 20-80 cm across and frequently occur in sheeted swarms, predominantly sub-vertical with N-S trend.

(ii) Microdiorites, similar to synplutonic dykes in the LVC.

(iii) Tuffisite dykes, characterized by abundant large xenocrysts and xenoliths derived from the Blumone Complex set in a fine-grained hornblende-magnetite-plagioclase groundmass. The dykes are oriented in a roughly radial fashion, normal to the margins of the Complex. The dykes have chilled margins against adjacent gabbros and probably represent magmatic microbreccias formed by explosive disruption of the layered sequence. These dykes exhibit unusual compositions, i.e. nepheline-normative alkaline magmas that can be attributed to partial melting of amphibole-bearing cumulates by invasion of and interaction with qtz-dioritic magmas (Pimenta Silva et al., 2023a).

(iv) Rare aplite and trondhjemite dykes, some of which are possibly related to the Vacca Tonalite.

(v) Subhorizontal and subvertical spessartite dykes as described from other parts of the S-Adamello.

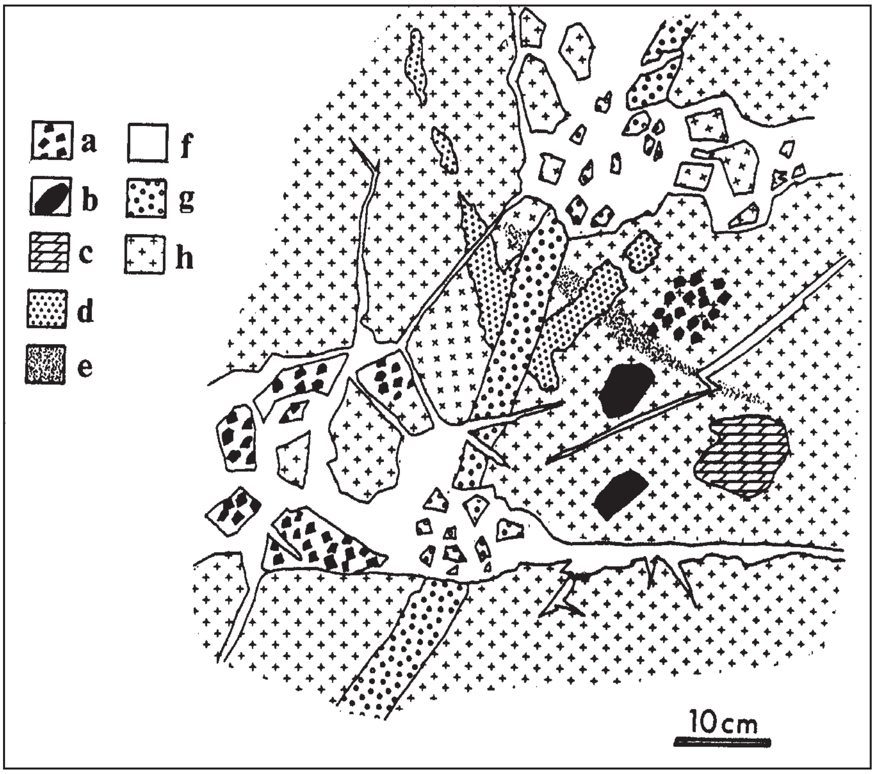


Fig. 18b - Field sketch of cross-cutting intrusive relationshipseast of Passo Blumone. (a) Blumone Gabbro; (b) hornblende megacrysts derived from (a); (c) clintonite-bearing marbles; (d) disrupted syn-plutonic microdiorite dykes; (e) mafic schlieren; (f) aplite; (g) tuffisite; (h) low-K hornblende diorites

Fig. 19 - Folded comb layering in plagioclase-rich cumulate rocks of the Blumone Complex, north-west flank of Cornone di Blumone.

The Lago della Vacca Complex

The Lago della Vacca Complex (LVC) forms a small semi-circular intrusion, roughly 4.5 km by 4.7 km, centered about Lago della Vacca, extending eastwards to the upper Caffaro Valley and westwards to Lago della Sorba. The extension of the LVC is, however, a subject of debate between Jon Blundy/Barbara John and Peter Ulmer/ Peter Brack respectively that put the boundaries and, thus, associated lithologies at different identifiable contacts. Ulmer/Brack associate the foliated diorites and hornblende diorites and quartz-diorites with the Blumone Complex s.l. whereas BlundyJohn associte them with the LVC. The LVC was emplaced into folded Late Triassic sedimentary rocks and precursor Tertiary intrusives, including the Val Fredda and Blumone Complexes (Fig. 14). The LVC is truncated to the north and west by younger intrusive rocks. These include fine-grained tonalites and associated basic rocks around Monte Stabio to the west, medium to coarse-grained tonalites to the north of Lago di Mare, and coarse-grained granodiorites to the northeast near Passo del Termine (Fig. 14). The northern margin of the LVC is further dissected by a subcircular intrusive structure, designated the "Listino Ring Structure" by Brack (1985) and Verberne (2013).

Internal structure and syn-intrusive deformation.The Lago della Vacca Suite is divided into four units based on texture and mineralogy (using the Blundy/John definition, Fig. 14): two outer or marginal units of quartz diorite to tonalite, and two inner or core units of tonalite to granodiorite (the Vacca and Galliner units). U-Th zircon age dates of LVC rocks range between 42.1 ±0.1 and 41.7 ±0.1 Ma (Schaltegger et al. 2009; Schoene et al. 2012; Broderick et al. 2015; Verberne (unpublished)). These data imply that the LVC was emplaced and cooled to temperatures of ≤400°C between 42.1 and 41.7 Ma , i.e. in a very narrow time interval, but entirely consistent with field relations.

The external contact of the Lago della Vacca Complex, between the marginal units and surrounding country rocks, varies in nature and orientation, depending on host rock type. Essentially two types of contact can be observed: discordant contacts that dip outwards, often at quite shallow angles, and truncate pre-existing structures; and deformed contacts that are sub-vertical to steeply inward-dipping and are associated with a strong planar fabric in both intrusive rocks and country rocks. Discordant features are locally re-oriented by forceful structures, indicating that the style of emplacement changed during the evolution of the LVC.

The overprinting of early discordant features by later forceful features is well preserved in the northern VFC. The contact between the VFC and LVC is marked by a network of thin dykes and sheets of marginal facies LVC rocks in VFC tonalite. Subsequent forceful emplacement of younger LVC magmas rotated the sheets parallel to the steeply outward-dipping contact, oriented WNW-ESE, and produced a strong planar fabric in both the LVC and the VFC. Within approximately 200-400 m of the LVC contact, VFC mafic sheets develop a steeply northward to subvertical dip, mafic enclaves and stoped dolomite fragments are flattened in a plane parallel to the contact, and a xenolith of folded mid-Triassic marls and limestones has been rotated by some 70° clockwise (Fig. 14).

In contrast, deformation of the Blumone Complex by intrusion of the LVC is almost exclusively brittle in character. Subvertical dikes and apophyses of marginal quartz diorite apparently exploited fissures in the Blumone Complex, stoping blocks of coarse-grained gabbro, which are now widespread in the southern and eastern parts of the suite (Fig. 12). These marginal magmas may have rent in two the original Blumone Complex (see above), a proposal borne out by the occurrence of trains of brecciated gabbro and rare calc-silicate blocks extending southwest of Cornone di Blumone towards Monte Frerone. The arcuate trend of these trains suggests that they were displaced and rotated by later, forceful emplacement of the core units or the Listino Ring Complex (depending on interpretation). The contrast in styles of deformation between the Val Fredda and Blumone Complexes is attributed to differences in their composition, grain size, and possibly initial temperature, which permitted relatively easy fracture of the coarse-grained, quartz-poor Blumone Complex.

Sedimentary rocks around the LVC have undergone both plastic and brittle deformation in response to emplacement. Plastic features associated with emplacement include refolding and tightening of folds, deformation of earlier formed porphyroblasts and the development of chocolate-tablet boudinage (Brack 1981).

In contrast to external relations, contacts between the marginal and core units are typically vertical or steeply inward dipping (>60°) toward the center of the suite, and are associated with well-developed foliations (Fig. 20). Irregular, penetrative contacts between core and marginal units, though only rarely observed, indicate that the core units are younger than the marginal units. Forceful emplacement of the core units or the Listino Ring Complex (see below) might be responsible for the observed reorientation (steepening) of the outermost contacts of the marginal units. Contacts between units in the LVC are sharp in some places and in others are marked by diffuse mineralogical and textural changes over a distance of several meters indicating that successive magma pulses (units) were emplaced before the precursor pulse had fully solidified.

The dominant fabric in LVC intrusive rocks is planar. Magmatic foliations, defined by the planar alignment of igneous plagioclase, amphibole and biotite, and by mafic enclaves, are developed to varying degrees in all units of the LVC. Linear mineral fabrics are very rarely observed: where present, as in the westernmost parts of the Vacca tonalite near Monte Stabio, they are subvertical. Foliations define steeply inward-dipping (or funnel shape) concentric trajectories that roughly parallel the marginal contact and, in general, show a crude decrease in intensity towards the core of the pluton. A similar trend is observed in the axial ratios of mafic enclaves, which also tend to decrease towards the pluton core (Fig. 21). The concentric pattern of foliations, with subordinate or absent lineation, suggests that forceful emplacement involved a significant component of radial expansion.

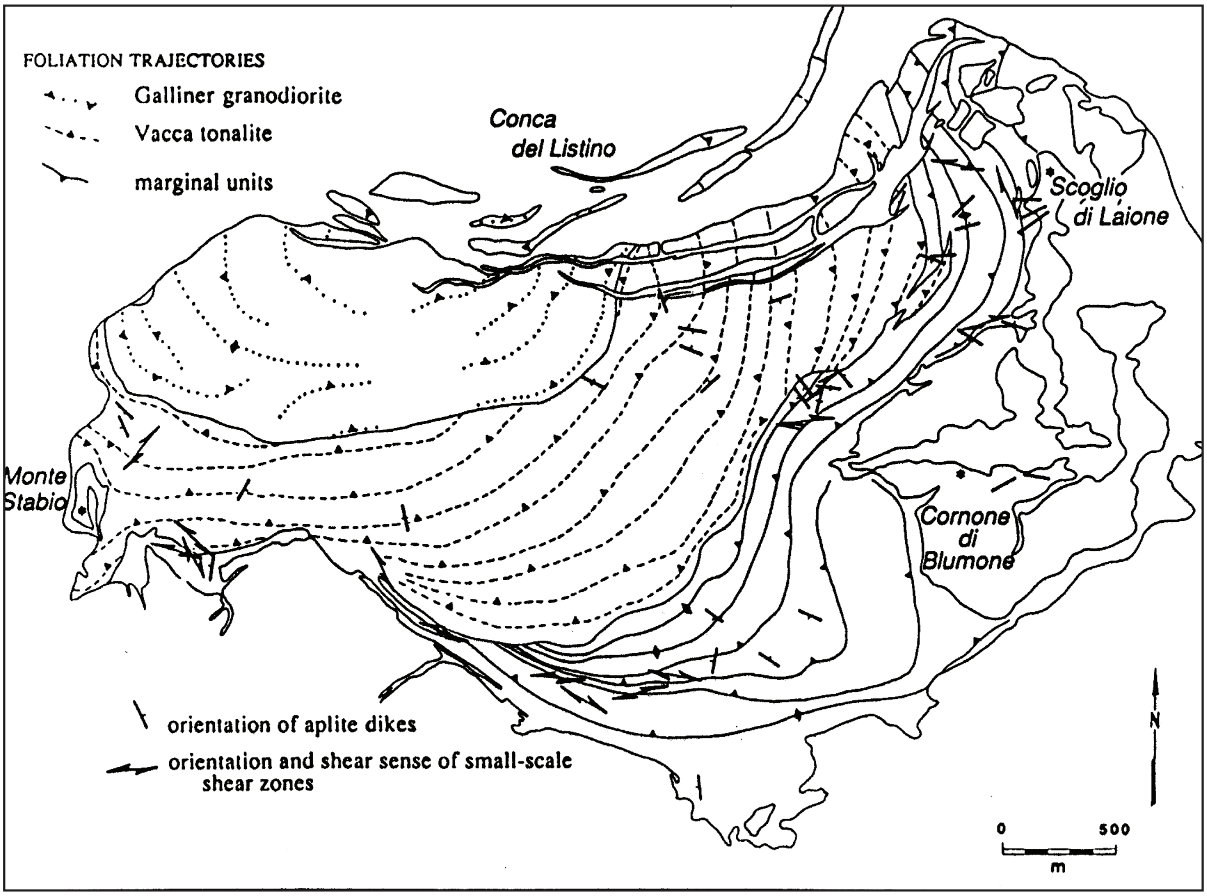


Fig. 20 - Map of magmatic foliation trajectories, aplite dykes and shear fabrics within the LVC, from John & Blundy (1993).

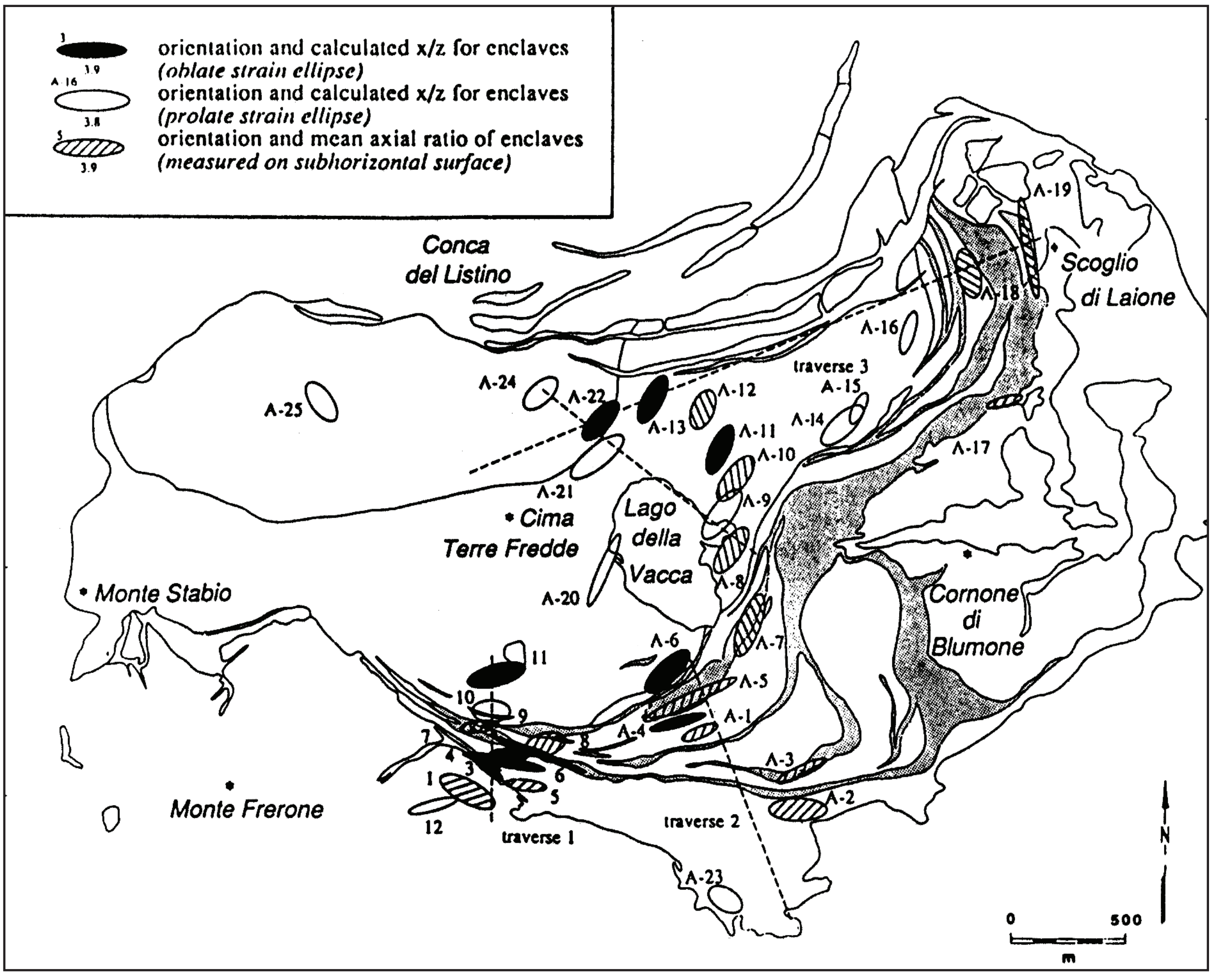


Fig. 21 - Variation in mafic inclusion strain ellipsoids in the LVC from John & Blundy (1993).

The orientation of magmatic foliation trajectories along the margins of the pluton (Fig. 20) can be related to the rheology of the surrounding country rocks at the time of emplacement. Foliation is deflected around the Blumone Complex southeast of Lago della Vacca to form a prominent bulge, suggesting that the Blumone Complex acted as a rigid bulwark. Conversely, a concordant foliation is developed against the northern margin of the Val Fredda Complex which we interpret as having been thermally soft (i.e. close to or above its solidus) at the time of LVC emplacement. Adjacent to the southern and eastern borders of the Vacca tonalite, foliation trajectories are oblique to the contact between the tonalite and the surrounding marginal units (Fig. 20). This relationship is particularly evident where the contact is irregular (as NW of Cornone di Blumone), and suggests that fabric development and magma intrusion occurred synchronously throughout emplacement (i.e. early formed fabrics were repeatedly truncated and reoriented by subsequent magma pulses). Foliation trajectories in the LVC are truncated (or locally reoriented) by the younger intrusives to the north, including the Listino Ring Structure (Figs. 14, 20).

Although there is a general increase in magmatic foliation intensity toward the margin of the intrusion, the most intensely foliated rocks occur as sinuous, anastomosing, concentric zones of fine-grained diorite and quartz diorite within the marginal units. These zones, described as „deformed marginal units" (Fig. 22), are characterized by aligned grains of plagioclase, hornblende and, rarely, biotite in a fine-grained foliated matrix, that vary in width from centimeters to hundreds of meters, extending for tens to hundreds of meters along strike. These zones are also characterised by relatively high concentrations of mafic enclaves. The contact between more and less deformed rock is marked by relatively abrupt changes in grain-size, although at least locally, both rock types may have similar chemical and modal composition.

Synplutonic mafic dikes and enclave swarms occur throughout the LVC (Blundy & Sparks 1992), but are typically concentrated at the margins of each pulse, notably within the Galliner and Vacca units against their slightly older host. West of Cornone de Blumone there is abundant evidence that synplutonic dikes pass along strike into enclave swarms.

Aplite dikes 1-20cm wide, are widespread in the LVC (Fig. 20). They are predominantly subvertical, intersecting the foliation at high angles, even in the deformed marginal rocks. This distribution is consistent with expulsion of evolved interstitial melt along radially propagating fractures during deformation and cooling. Locally, aplite dikes develop a fabric oblique to their margins indicating that deformation continued after dike formation. There compositions are consistent with late stage (near-solidus) melts in the cooling tonalite plutons (Marxer & Ulmer, 2019) at 2 – 3 kbar.

The marginal units of the LVC (= Blumone Complex sensu Ulmer/Brack) are cut by numerous small-scale ductile shear zones cross-cutting the main foliation trajectories and zones of intense fabric development at angles of 10-40° (Figs. 20, 22). Several of these shear zones are filled with thin aplite veins indicating shearing in the presence of melt. Truncation of the dominant foliation by these shear zones suggests that in many localities simple-shear was a relatively late form of strain accommodation. Overall, small-scale shear indicators show bilateral symmetry: minor shear zones west of Lago Cadino Alto have a sinistral shear-sense, whereas those to the east have a dextral sense of shear.

Emplacement mechanisms. John & Blundy (1993) interpret the intrusive relations in the LVC in terms of a progressive transition from an early passive style of emplacement by stoping, to later forceful emplacement of the core units. Field and chemical data indicate that the LVC evolved as a series of hydrous magmatic pulses in the sequence: high-potassium marginal unit; low-potassium marginal unit; synplutonic microdiorite dikes; Vacca Tonalite; and finally Galliner Granodiorite at the core. Diffuse contacts between units suggest that each pulse was emplaced before the precursor pulse had completely solidified consistent with the very limited age range of the various lithologies (<400 ky). The early, marginal units were emplaced principally by stoping of denser country rocks, while the later, core units were emplaced forcefully, radially

Fig. 22 - Sheared and flattened mafic inclusions in LVC marginal diorites close to the contact with the VFC in upper Val Cadino.

flattening their carapace of partially molten marginal rocks and the thermally softened aureole marginal units. Mineralogical and textural data indicate that the flattening deformation occurred predominately in the magmatic or submagmatic state, close to the granitoid solidus (~660°C). Flattening strains in the marginal units are strongly partitioned into arcuate anastomosing fine-grained foliated zones. Although some textural features of these zones resemble mylonites, there is no evidence of extensive shear displacement across these zones. John & Blundy (1993) attribute the heterogeneity of strain patterns in the marginal rocks to the presence of mobile interstitial melt during deformation. Thus, the complexity of the observed strain patterns reflects the temperature-, time- and composition-dependent rheological properties of magma. Over the short timescales of shallow-level pluton emplacement (~40-60ka), such variations can result in substantial differences in finite strain. For recent age determinations and additional details see Figure 35 (at the end of the guide) where you also find a simplified intrusion model (Fig. 36) for the Lago della Vacca complex based on Schoene et al. (2012).

The Listino Ring Structure

The Listino Ring Structure (LRS), was first recognized by Peter Brack and Peter Ulmer in 1983. It was mapped by Brack (1984) and subsequently re-mapped in greater detail by John & Blundy (1993) and Verberne (2013). The LRS comprises a sub-circular zone of intrusive rocks, approximately 3.4 km in external diameter and between 200 and 700 m wide (Figs. 23, 24). In detail the LRS is composed of several interlocking arcs of intrusive rocks, containing screens of older intrusives. Marginal apophyses splay off the LRS, often at high angles to the outer contact. The western extremity of the LRS is truncated by a series of gabbroic breccias and tuffisites, the Forcellino di Mare Complex, which may be related to the LRS. The LRS clearly post-dates the LVC as well as the quartz-rich granodiorites exposed near Passo del Termine.

The structure of the LRS comprises at least three separate intrusive pulses, in order of intrusion:

(i) Plagioclase-phyric tonalites, with relatively mafic matrix and widespread evidence of magma mingling.

(ii) Synplutonic (?) hornblende-gabbros forming dykes and small masses.

(iii) Hypabyssal plagioclase-phyric granodiorites containing alkali-feldspar oikocrysts - the "Listino Porphyry" - best exposed around Cima Laione.

The chemistry of the LRS rock types overlaps with the chemistry of other Re di Castello Pluton rocks (see below). In detail the LRS is highly heterogeneous with widespread evidence of syn-intrusive deformation and magma mingling. LRS intrusive rocks contain abundant xenoliths of Mattoni- and Blumone-textured gabbros and sedimentary rocks, as well as large screens of LVC intrusive rocks and, near Monte Listino, granodiorite. While many of the xenolith lithologies occur locally, the LRS is some 3 km north of the nearest Mattoni gabbros, suggesting that this rock type occurs at depth and was brought up by the LRS magmas. A magmatic fabric is well developed in LRS intrusive rocks, especially facies (i). The fabric runs subparallel to the steeply inward-dipping outer contact and at a high angle to fabrics in the LVC, which in places are re-oriented parallel to the LRS fabric. Locally, however, contacts between LRS and LVC rock types cross cut the fabrics in both rock types, indicating that the contact is faulted. The presence of amphibole+biotite+feldspar+quartz along the contact indicates that faulting occurred in the magmatic state.

Brack (1985) interpreted the LRS as a compressive deformation zone produced by radial expansion of tonalite intrusives in the core of the LRS. Conversely, John & Blundy (1993) proposed that the LRS represents a composite shallow-level ring complex, emplaced along a series of ring fractures into partially molten rocks of the Lago della Vacca suite. In their view, the LRS intrusive rocks form a polyphase ring dyke, possibly underlying a sub-volcanic magma chamber. The form and fabric of the LRS is remarkably similar to a structure in the Mount Givens Granodiorite, Sierra Nevada, interpreted by McNulty et al. (2000) as the result of sinking of a plutonic body into underlying, unconsolidated magmas.

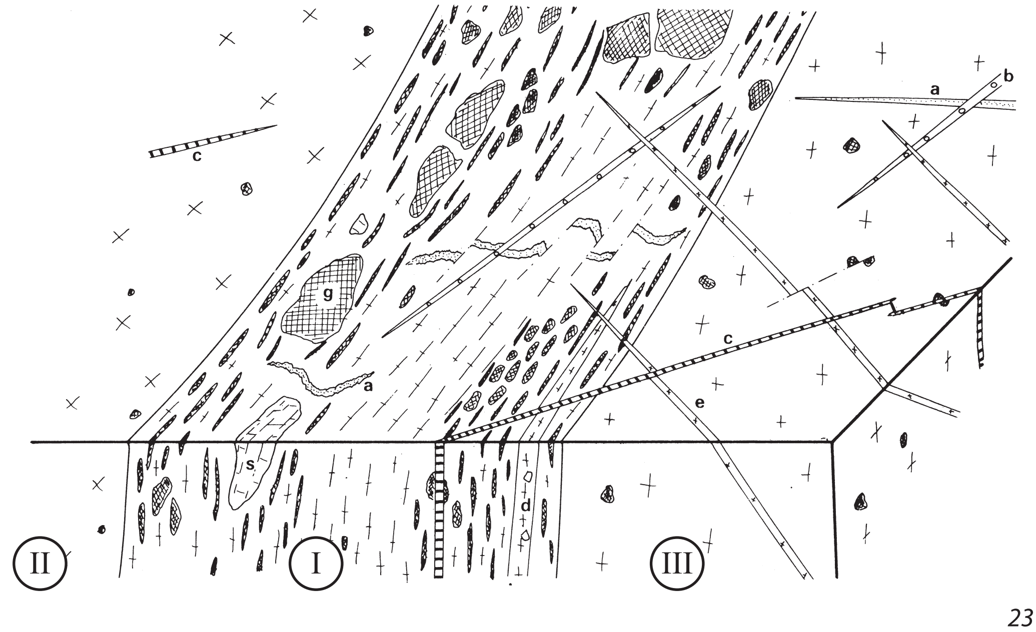


Fig. 23 - Schematic diagram of the structural features in the Listino ring structure (I); (II) M.ga Listino Tonalite (core); (III) external tonalite area; a, b, c: mafic dykes of different generations; d, e: granitic and aplitic dykes; g: gabbros; s: sediments. From Brack (1985).

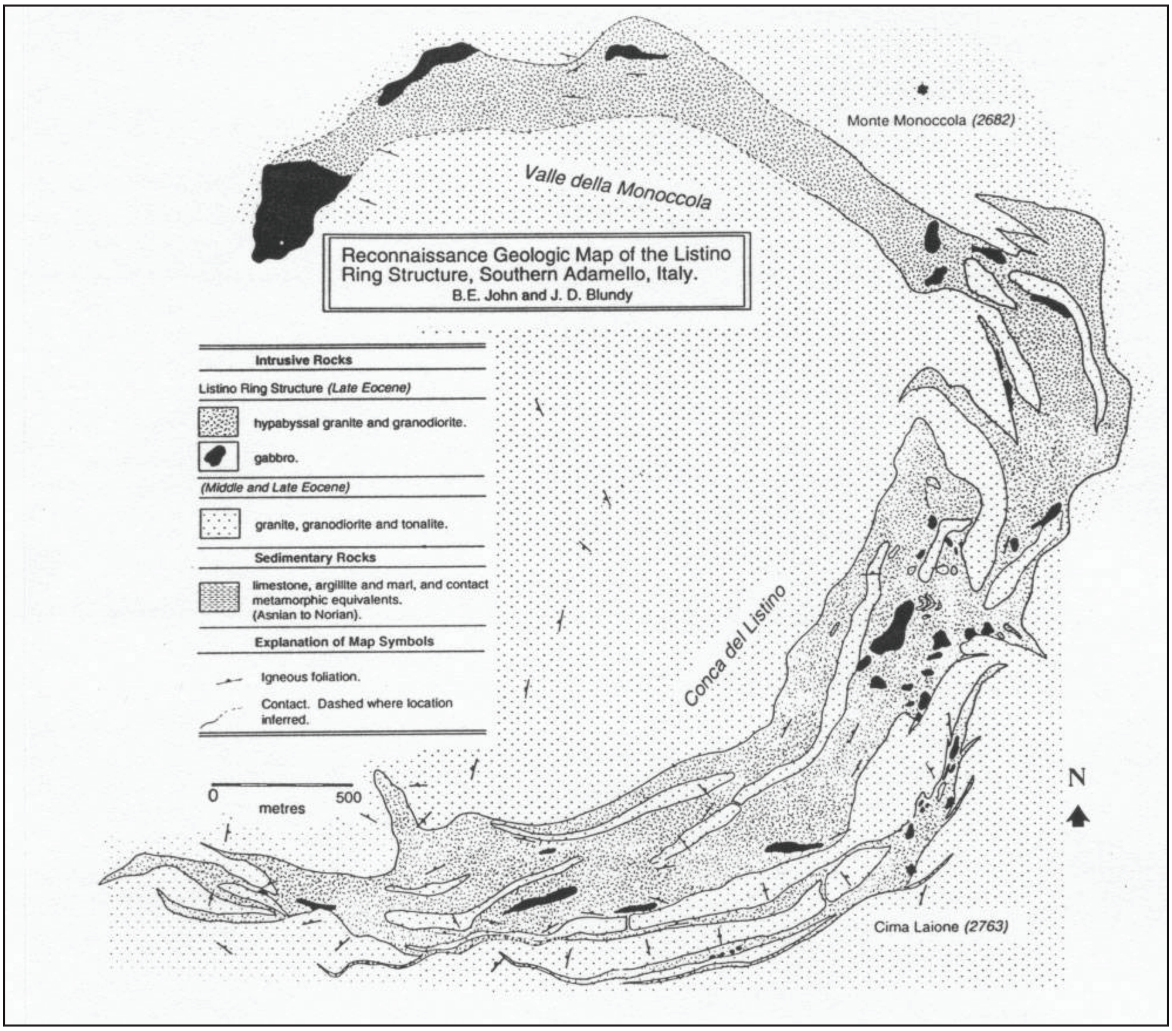


Fig. 24 - Reconnaissance geological map of the Listino Ring Structure showing main plutonic units. The southern end of this map overlaps the northern edge of Fig. 10.

GEOCHEMISTRY OF THE MAIN PLUTONIC UNITS

General geochemical character of Adamello rocks

The Adamello rocks clearly belong to the medium- to low-K calc-alkaline trends typical for subduction-related magmatism at active continental margins (e.g. Müntener et al., 2021). The overall trends observed for plutonic and dyke rocks (Figs. 26 and 27) are consistent with extensive fractional crystallization of MgO-rich mantle derived magmas. Fractionation involves an initial olivine-dominated assemblage, with plagioclase saturation producing a marked inflection in Al_2O_3 at ~51-55 wt% SiO_2. With the exception of the Blumone Complex rocks, which are demonstrably cumulate in texture and chemistry, there is a striking overlap between the Adamello rocks and for example the Cascade volcanics (represetning a typical Volcanic suite of an active continental margin). Significantly both datasets (Adamello and Cascades) cover a very similar range of SiO_2 and MgO contents. The dyke rocks from Adamello describe the same fractionation trend as both the plutonic and volcanic rocks; thus, they are rather good proxies for liquid compositions in such a plutonic system.

Within the Adamello Batholith itself, subtle differences can be discerned between the different plutons, most noticeably in terms of Na_2O and MgO. Rocks of the northern superunits of Avio and Presanella have lower Na_2O and Sr at a given MgO. They also contain rather fewer mafic bodies that are found in the southern plutons. Adamello plutonic rocks share many chemical characteristics with the RdC plutons (North and South). In addition to these subtle chemical changes from South to North, there are also systematic changes in Sr and Nd (and O and Hf) isotope composition, from mantle-like values in the South, to radiogenic values in the North (Fig. 25). This is consistent with increasing involvement of radiogenic Sr-bearing (crustal) rocks in the petrogenesis of northern Adamello magmas.

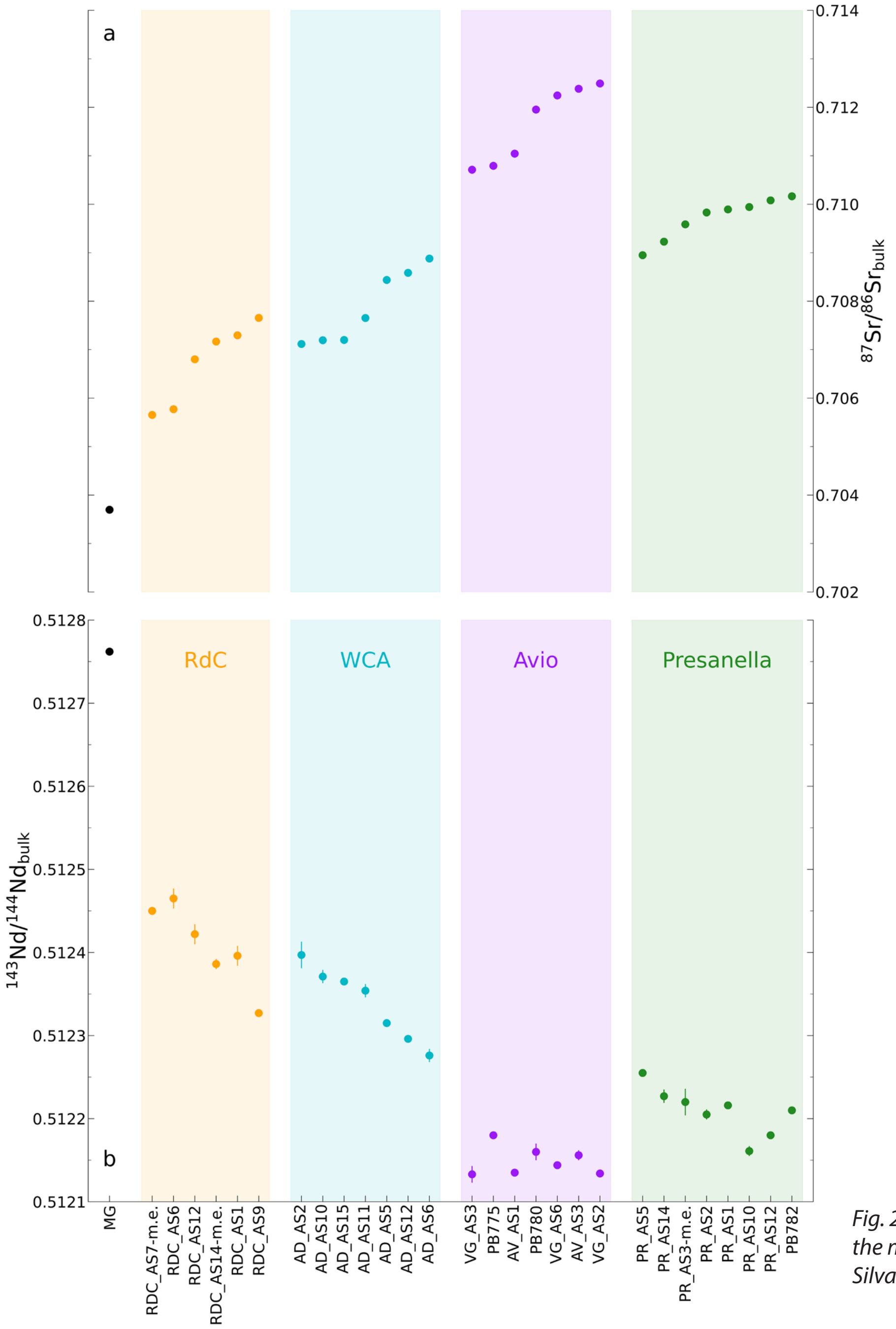


Fig. 25 - $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ bulk rock ratios of the main Adamello units (compilation by Pimenta Silva et al., in review).

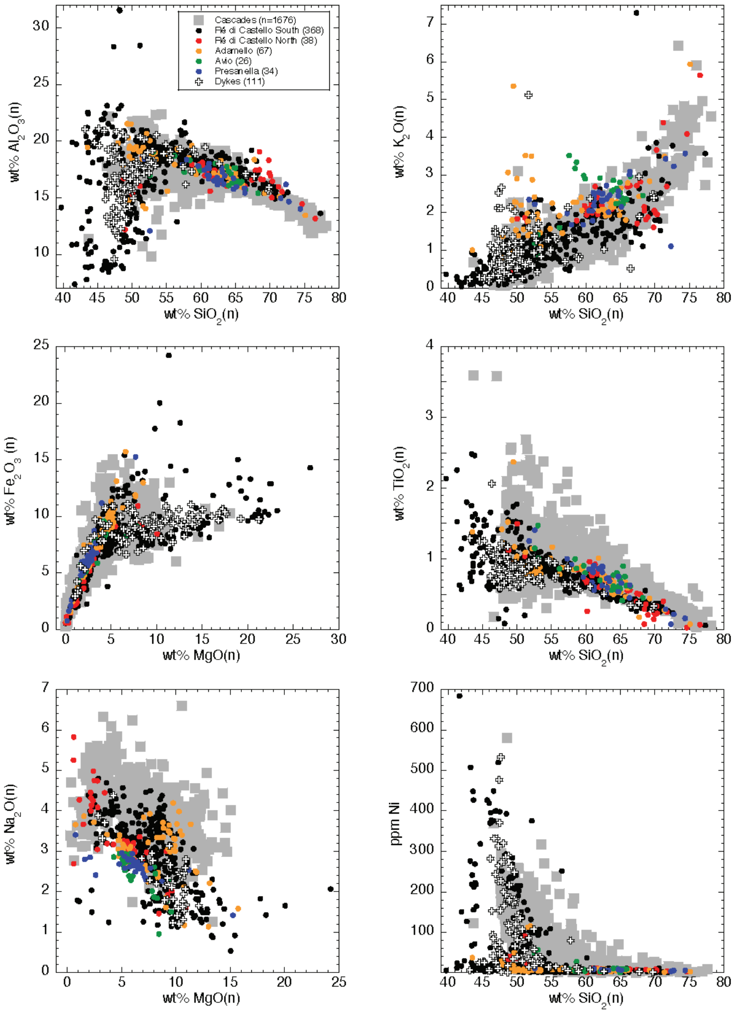
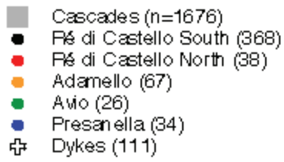


Fig. 26 - Major element (and Ni) variation in Adamello plutonic rocks and dykes compared to over 1670 analyses of Cascades volcanic rocks taken from the literature. Adamello data are taken from Bianchi et al. (1970), Dupuy et al. (1982); Macera et al. (1983); Ulmer et al. (1983); Ulmer (1986); Blundy (1989); Blundy & Sparks (1992); John & Blundy (1993); Kagami et al. (1991) and unpublished data from Blundy, Ulmer and several ETH Diploma students.



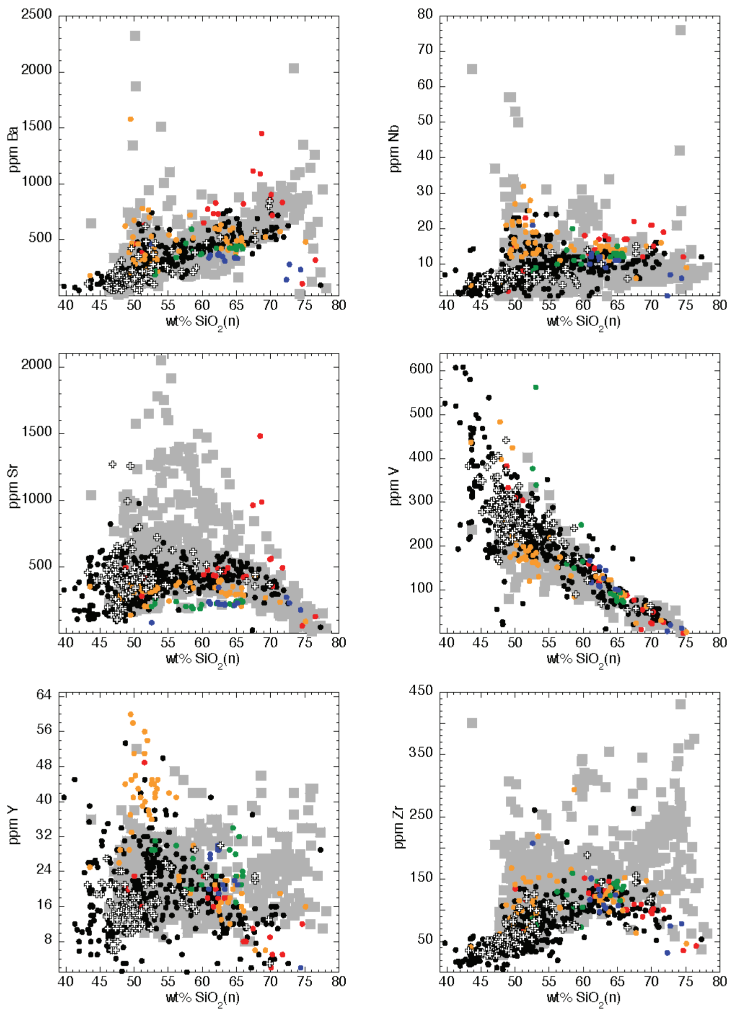


Fig. 27 - Trace element variation in Adamello plutonic rocks and dykes compared to Cascades volcanic rocks. Data sources and symbols as in Fig. 20.

Lago della Vacca Complex

For the purposes of comparison, the LVC, Blumone Complex and dyke suite are plotted together for major elements (Fig. 28) and trace elements (Fig. 29). The LVC / younger Blumone Complex intermediate rocks (marginal high-K diorites, marginal low-K diorites, deformed marginal rocks, Vacca tonalite and Galliner granodiorite) exhibits an overall crude concentric compositional and temporal zonation from pyroxene-bearing hornblende and biotite quartzdiorites at the southern margin, through tonalite in the Lago della Vacca area (Vacca Tonalite) to granodiorite (Galliner Granodiorite) at the core, in which age decreases and silica content increases inward from the margins. These units form a chemically related suite of granitoid rocks, which define smooth linear trends on Harker plots for most major and trace elements (Kagami et al. 1991). The overall chemical similarity of the rocks emphasize the need to use textural criteria (such as mafic mineral habit, grainsize, inclusions etc) when mapping them. This is the basis for different igneous units shown in Fig. 14. Nonetheless, the various mapped units do show subtle chemical differences between each other. The quartzdiorite and tonalite from the marginal units are divided in the field into low- and high-potassium members, based on the modal proportion of biotite present. Those with appreciable biotite (>10 vol%) form the high-potassium marginal units (K_2O ≥1.3 wt%), which are confined to the upper reaches of the Val Cadino, close to the contact with the VFC (Fig. 14). This unit defines subtly different trends from the Vacca Tonalite and Galliner Granodiorite in terms of K_2O, Ba and Rb, due to an increased proportion of crystallizing biotite. There is in addition a negatives trend of Zr versus SiO_2 (Figure 29) due to saturation in zircon at lower SiO_2 (52 wt% compared to 60 wt% in Vacca Tonalite). The calculated zircon saturation temperature for the least evolved high-K marginal rock is 705 °C, indicating that chemical variations within this unit were generated by crystal-melt segregation at low, near-solidus temperatures, presumably during emplacement. In contrast, marginal units with amphibole in much greater proportion than biotite form the low-potassium units (K_2O ≤1.3 wt%), which are situated along the southeastern margin of the Vacca Tonalite, where they demonstrably intrude and disrupt the Blumone Complex (assigned to Blumone s.l. by Ulmer). Attenuated outcrops of deformed low-K marginal units also intrude the high-K marginal unit close to its contact with the VFC. The low-K marginal units range in SiO_2 content from 51 to 64 wt%. The younger Vacca and Galliner units form the core of the suite, and show a small range in SiO_2 (58-64 wt%), high K_2O, and modal biotite in slight excess of hornblende. These bodies lie at the evolved end of the trend defined by the low-K marginal units in terms of both major and trace elements. Even the most evolved rocks do not show evidence for zircon saturation on a Zr-SiO_2 plot (Fig. 29), suggesting higher emplacement and differentiation temperatures than the high-K marginal units. Deformed rocks of the marginal units have composition that overlap completely those of the undeformed low-K units, indicating that deformation, albeit in the magmatic state, involved very little physical extraction of residual melts on hand specimen scale. However, some scatter on the Zr-SiO_2 plot (Fig. 29) may testify to movement of low-temperature zircon-saturated melts during deformation.

Dykes

The dyke rocks show a very wide range in composition from MgO-rich picrobasalts, through high alumina basalts to andesites, dacites and aplites. The fine-grain size and chilled margins of many of the dykes are strongly suggestive of melt composition, although some entrainment of cumulus phases, such as olivine and plagioclase is evident from major element data, notably Al_2O_3 and MgO (Fig. 28).

Ulmer (1986) and Hürlimann et al. (2016) ascribe the dyke trends to fractional crystallization of a picrobasaltic parent, with ~48 wt% SiO_2 and 16 wt% MgO, at crustal pressures of 2 to 10 kb. The early crystallizing assemblage is dominated by olivine ± pyroxenes, leading to an increase in Al_2O_3 and sharp fall in MgO and Ni. The inflexion in the Fe_2O_3-MgO trend (Fig. 28) marks the relatively late appearance of magnetite as a fractionating phase. Plagioclase joins the fractionating assemblage at ~ 53 wt% SiO_2 to produce a trend of falling Al_2O_3 and CaO that is consistent with the LVC intrusive rocks. This strongly suggests that the intermediate and silicic rocks of the LVC were generated by fractional crystallization of basaltic parents. Mafic inclusions in the LVC rocks match the compositions of dykes, consistent with their formation by disruption of synplutonic dyke magmas. However, in detail the differentiation processes are complex, polybaric and additional processes must have been involved (mixing, mingling, primocryst entrainment/retention, e.g. Marxer et al., 2023).

Blumone Complex

The Blumone Complex (s.s.) rocks have a clear cumulate character, ranging in composition from olivine clinopyroxenites and gabbros, with or without amphibole, to magnetite-rich gabbros and anorthosites. The spectrum of cumulate compositions is consistent with the fractionation assemblage that drives the compositional variation in the dykes. Blumone Complex cumulates show textural evidence for relatively late appearance of amphibole, after plagioclase, which Nimis & Ulmer (1998) attribute to fractionation at relatively low pH_2O ≈ 1-4 kb. Intrusive relationships between the various dyke rocks and cumulates in the Blumone Complex strongly suggest fractional crystallization of magmas in dykes and shallow magma chambers beneath an andesitic stratovolcano. Although the LVC intrusives could be generated by a similar process of shallow fractional crystallization, it is clear that this process did not occur at the present level of exposure. The relatively early appearance of amphibole as a phenocryst in LVC rocks accounts for the more rapid fall in Y with increasing SiO_2 than is observed in the dykes (Fig. 29). This suggests that the LVC intrusives originated by fractional crystallization at somewhat higher pH2O than the Blumone cumulates.

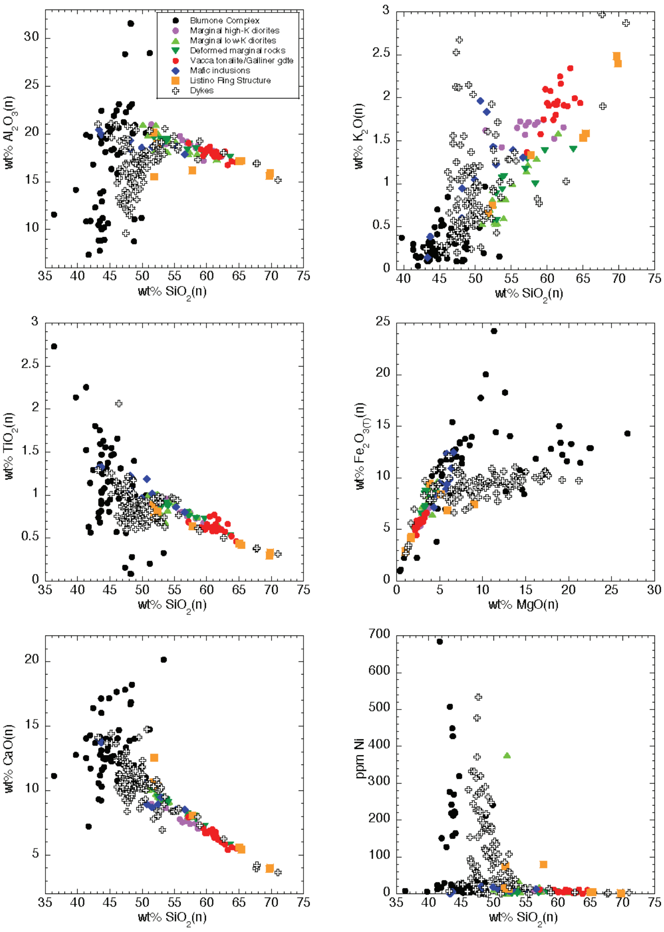


Fig. 28 - Major element (and Ni) variation in rocks of the LVC, Blumone Complex and dykes.

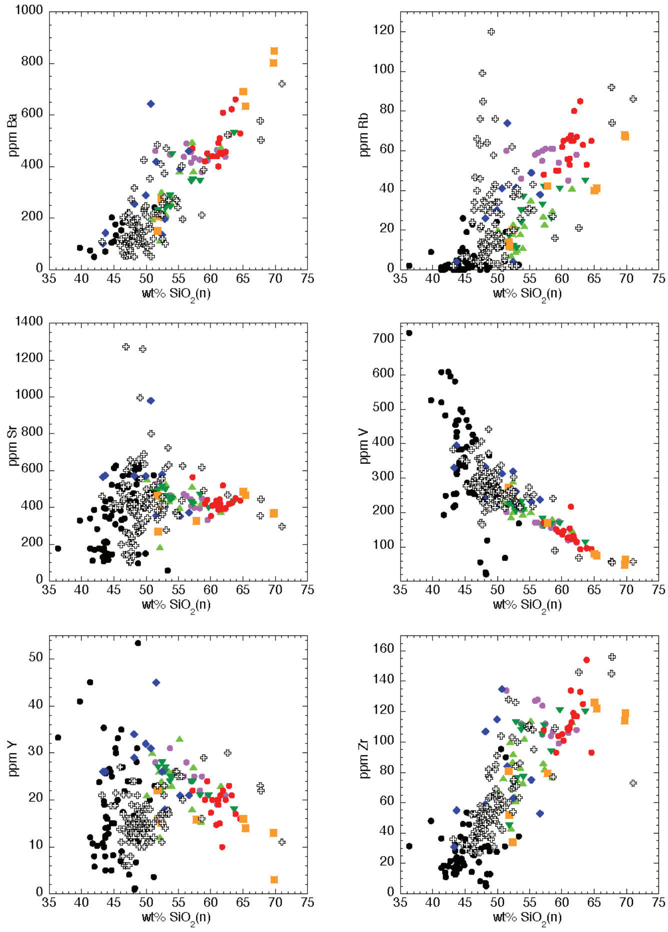


Fig. 29 - Trace element variation in rocks of the LVC, Blumone Complex and dykes. Symbols as in Fig. 22.

The Listino Ring Structure

The Listino Ring Structure, although not extensively sampled, shows a wide range of compositions from gabbros, through the main tonalitic phase, to evolved granodiorite dyke rocks (Listino Porphyry). Compared to the LVC, some subtle differences emerge, with the Listino tonalities and granodiorites having slightly lower K_2O and Rb, and showing evidence for zircon fractionation in the most evolved samples. The zircon saturation temperature in the main Listino tonalite is 740 °C (800-820°C according to Marxer & Ulmer, 2019).

Val Fredda Complex

As a suite the rocks of the VFC (Figs. 30, 31) show broadly similar trends to the LVC and Blumone Complex rocks described above. However, there are some significant differences. In contrast to cumulate rocks from the Blumone Complex, gabbros and hornblendite rocks from Monte Mattoni are displaced to slightly higher SiO_2, overlapping with the compositions of MgO-rich dyke rocks. Evidently, the fractionating assemblage, which gave rise to these rocks was SiO_2- and Al_2O_3-poor compared to that responsible for the differentiation of the Blumone Complex. This feature can be attributed to the very late appearance of plagioclase as a crystallizing phase at Monte Mattoni, after olivine, pyroxenes and amphibole. The delayed appearance of plagioclase is a likely result of higher pH_2O and higher pressure in general during fractionation (Nimis & Ulmer, 1991), consistent with the P-T phase diagram derived experimentally for high-Mg basaltic dykes by Ulmer (1989) (Fig. 32) and general phase relations of differentiating, hydrous (high-Al) basaltic magmas (Fig. 33 and 34, Marxer et al., 2023).

The mafic rocks of Monte Cadino, in addition to the mafic inclusions, lie at the SiO_2-rich end of the Mattoni trend, consistent with their derivation by fractional crystallization of the same parent magmas. On the basis of experiments and clinopyroxene crystal chemistry, Nimis & Ulmer (1991) propose that the mafic rocks of Mattoni and Cadino were generated by fractional crystallization at pH2O≈7-10 kb, i.e. well below the present level of exposure and close to the base of the crust.

The aphyric high-Mg basaltic lamprophyre dykes (~48 wt% SiO_2 and 12-16 wt% MgO) have compositions similar to those of the most basic Monte Cadino sheets and some Monte Mattoni hornblende-phyric gabbros, and are considered to represent optimal starting liquid compositions (Ulmer et al. 1985; Ulmer 1988; Kagami et al. 1991; Ulmer et al. 2018). The similarity of some hornblende-phyric gabbros to the dyke rocks, coupled with the occurrence of quartz, alkali feldspar and sodic plagioclase in the interstices of these rocks, suggests that despite their highly porphyritic character the bulk compositions of these gabbros represent magma compositions that have undergone near closed system in situ differentiation. Still more basic rocks types, including hornblendites and other Mattoni gabbros, are cumulates or cumulus-enriched, apparently formed by in situ accumulation processes.

The Val Fredda felsic rocks fall into three chemically distinct groups: the main Val Fredda Tonalite, the biotite-rich porphyritic marginal granodiorite facies, and amphibole-plagioclase-rich diorites from northern Val Fredda. The three groups show a clear fractionation link between each other, with the granodiorites representing the evolved melt composition and the diorites the residual assemblage. The texture of these diorites is not consistent with them being a true melt composition, as can also be seen from their slight offset relative to the evolved Cadino diorites in terms of lower K_2O and Ba. We suggest that chemical variation within the Val Fredda felsic rocks was generated by in situ processes occurring at the present level of exposure. The trend of decreasing Zr with increasing SiO_2 suggests that zircon was a fractionating phase, which limits the temperature to ~830°C. The spatial distribution of felsic rock types within the VFC suggests that differentiation occurred during southwards directed flow of magmas into a shallow laccolithic body. This chemical differentiation pre-dates the emplacement of the Mattoni and Cadino mafic sheets, which patently re-heated the felsic magmas and may have lead to further fractionation due to remobilization and migration of evolved melts. Some hybridization of mafic and felsic magmas is evident from plots that show marked fractionation peaks, such as P_2O_5 (apatite) and Sr (plagioclase): mixed rocks lie below the peaks in both cases.

On the basis of trace element variations in plagioclases from all rock types of the VFC, Blundy & Shimizu (1991) propose that all magmas shared a common parentage and represent a fractional crystallization sequence, but one that occurred a significant greater depths than the current exposure level. This is in accord with the conclusions of Kagami et al. (1991) and Nimis & Ulmer (1991). Blundy & Shimzu (1991) reconstructed the Ba and Sr composition of the parental magma to the VFC and conclude that it is a good match for some of the high-Mg basaltic dykes dykes found in the area.

Blundy & Sparks (1992) modelled the major element evolution of the VFC rocks using a simple fractionation model with a southern Adamello high-Mg basaltic lamprophyre as parent. Three stages of fractionation were chosen to reproduce the observed sequence of crystallization in the VFC mafic rocks:

(1) Co-precipitation of spinel, olivine, orthopyroxene and clinopyroxene in the weight proportions in which they occur in hornblendites

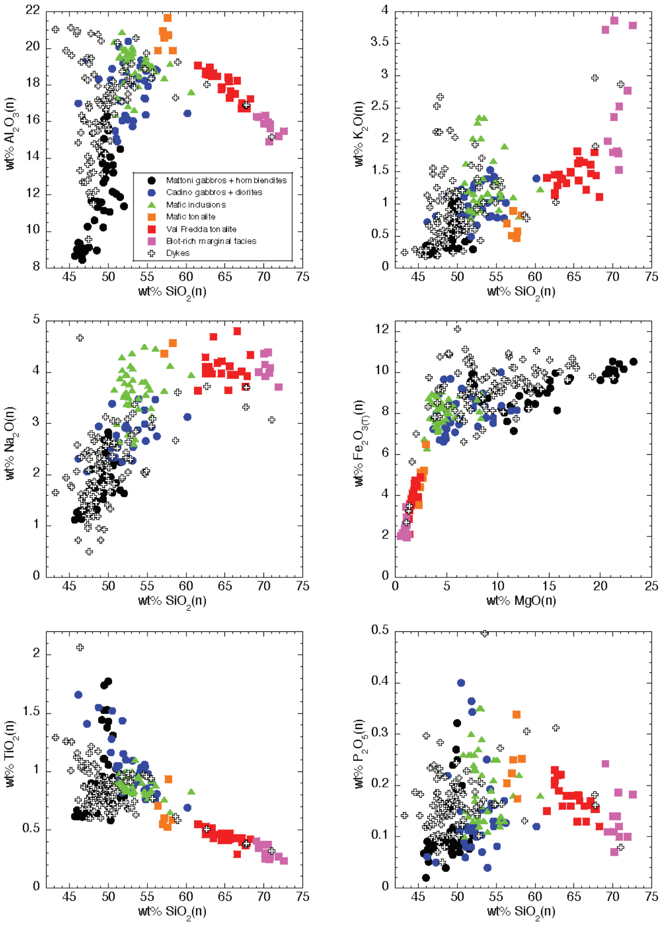
(2) Fractionation of hornblende to produce hornblendite cumulates. Minor magnetite (~5 wt%) accompanies hornblende, as observed petrographically, with the effect of suppressing iron-enrichment in the residual liquids

(3) Co-precipitation of hornblende and calcic plagioclase to produce the early formed phases of the Mattoni gabbros and some Cadino mafic rocks. The delayed precipitation of plagioclase also serves to suppress iron-enrichment in the residual liquids.

The model satisfactorily reproduces the major element compositions of the intermediate rocks (53% SiO_2) after 44% fractionation of the lamprophyre parent and the compositions of the felsic rocks (65% SiO_2) after 75% fractionation. Subsequent in situ fractionation of this fractionated melt generated the observed chemical variation in the VFC felsic rocks. This model was confirmed by subsequent experimental simulations of fractional and equilibrium crystallization at 7 kbar (Nanadedkar et al., 2014).

The low initial $^{87}Sr/^{86}Sr$ ratios (Sr_i at 40Ma) of the VFC rocks (Del Moro et al. 1985b; Blundy 1989; Kagami et al. 1991; Pimenta Silva et al. 2023b) rules out large-scale assimilation of radiogenic strontium during fractionation. However, there is a progressive increase in Sr_i from the basic rocks (0.7036-0.7043) to the felsic rocks (0.7042-0.7057) indicating that some contamination by radiogenic Sr affected the most evolved rocks. Kagami et al. (1991) argue that this contamination occurred at depth during fractionation from high-Mg-basalt through gabbro to quartz-diorite and tonalite and has not had a substantial influence on the major element chemistry of VFC rocks.

Although the model gives good agreement with the overall chemical evolution of the VFC, there are a number of mafic inclusions and sheet margins, which display significant geochemical anomalies. Enrichment in K_2O and a number of trace elements, including Rb, Ba, Y, Mn and Zn and the middle and heavy REE, are difficult to reconcile with either fractional crystallization or magma mixing as some mafic inclusions are richer in these elements than their host granitoids. Similar trace element enrichments have been observed in mafic inclusions from several other granitoid plutons, including the Western Adamello Tonalite. Blundy & Sparks (1991) interpret these anomalous trace element enrichments as the result of prolonged chemical interaction between crystals in the partially solidified mafic inclusion and the large volume of silicic magma in the host granitoid. In effect the inclusion scavenges trace elements from the host until such time as (a) inclusion minerals and host silicic melt attain chemical equilibrium or (b) the pluton becomes completely solidified.



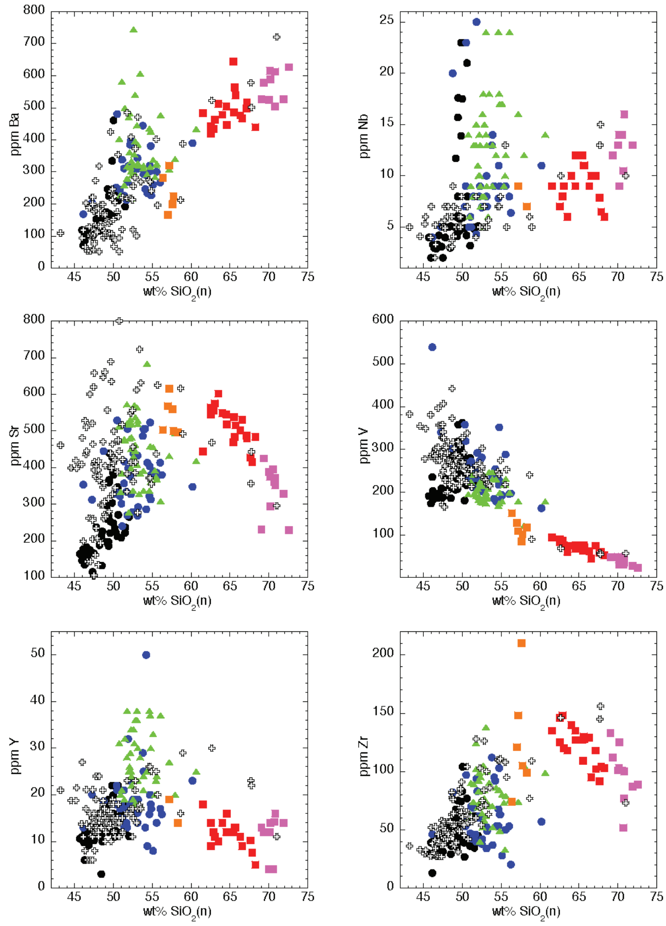
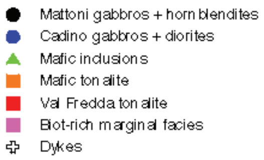


Fig. 30 - Major element variation in rocks of the VFC and dykes. Data sources as Fig. 23.

Fig. 31 - Trace element variation in rocks of the VFC and dykes. Symbols as in Fig. 24..



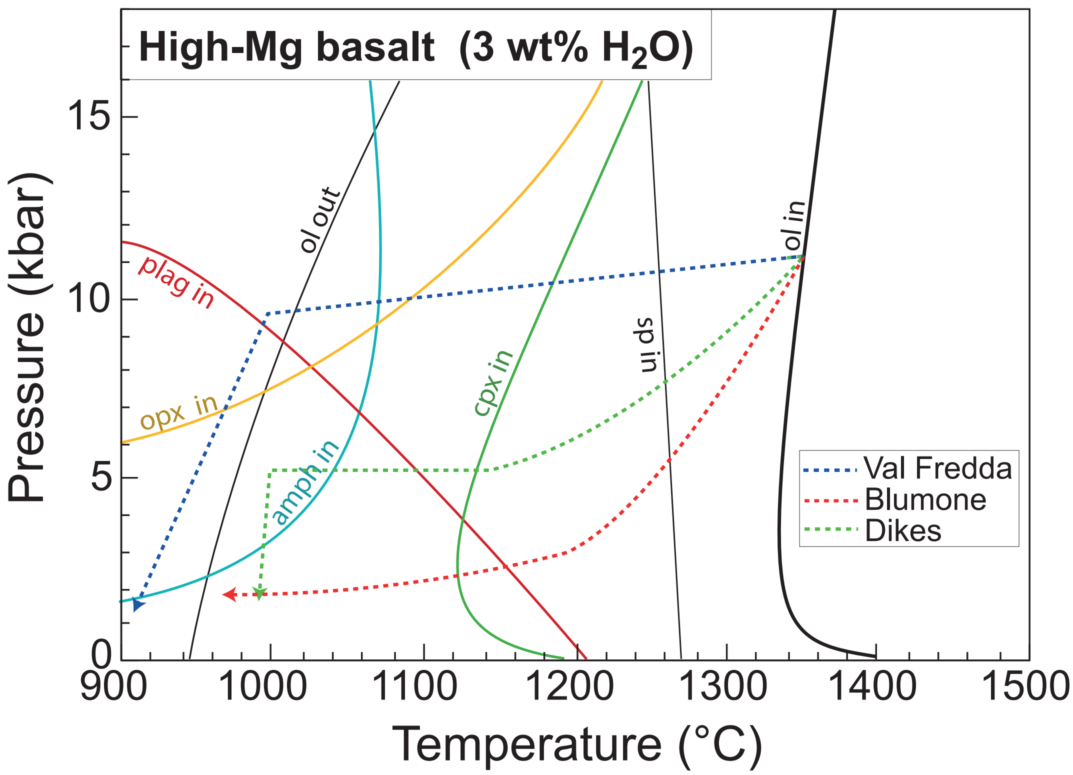


Fig. 32 - Mineral stabilities in a picrobasaltic dyke. possible cooling paths for different mafic rocks of the southern RdC rock suite are indicated.

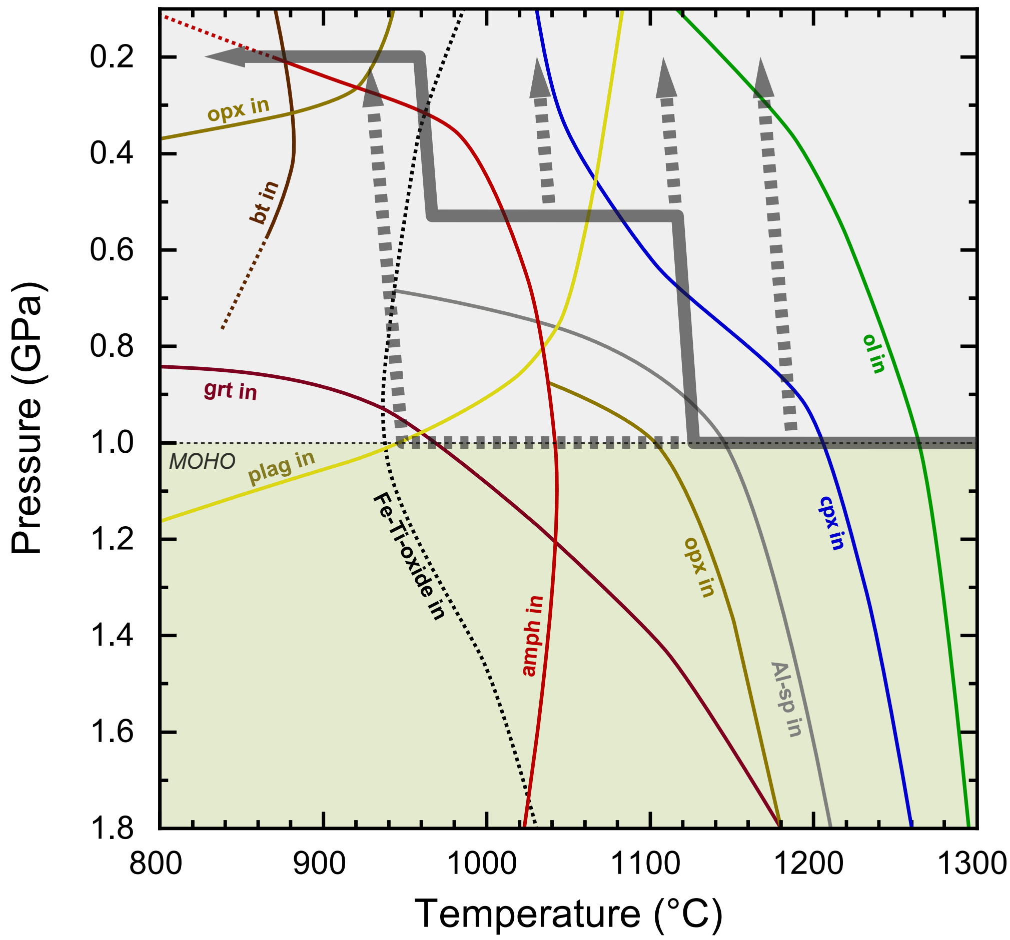


Fig. 33 - P-T diagram for equilibrium crystalllization of high-Al basalt with arrows indicating possible magma ascent paths Marxer et al. (2023).

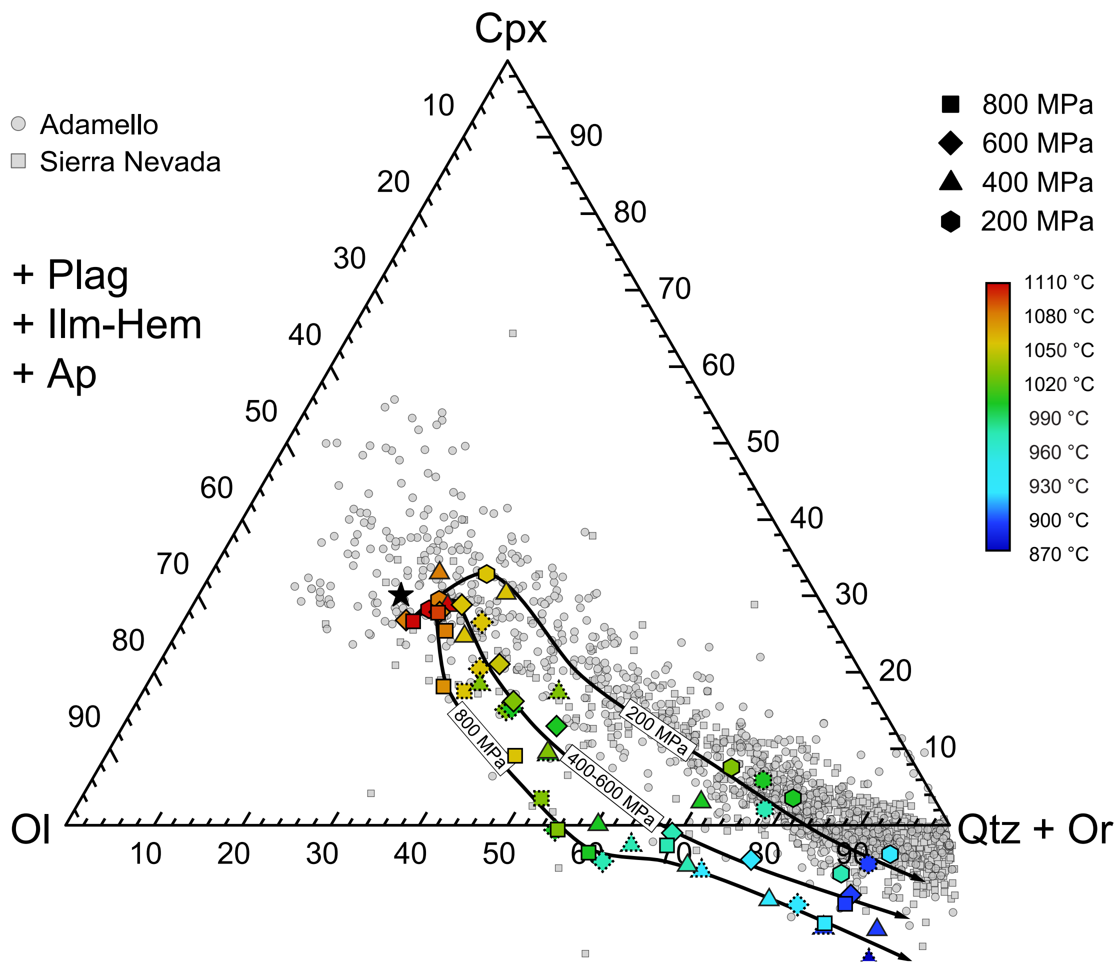


Fig. 34 - Liquid lines of decent for fractional and equilibrium crystallizaton in a normative ternary phase diagram (modified after Marxer et al. 2023).

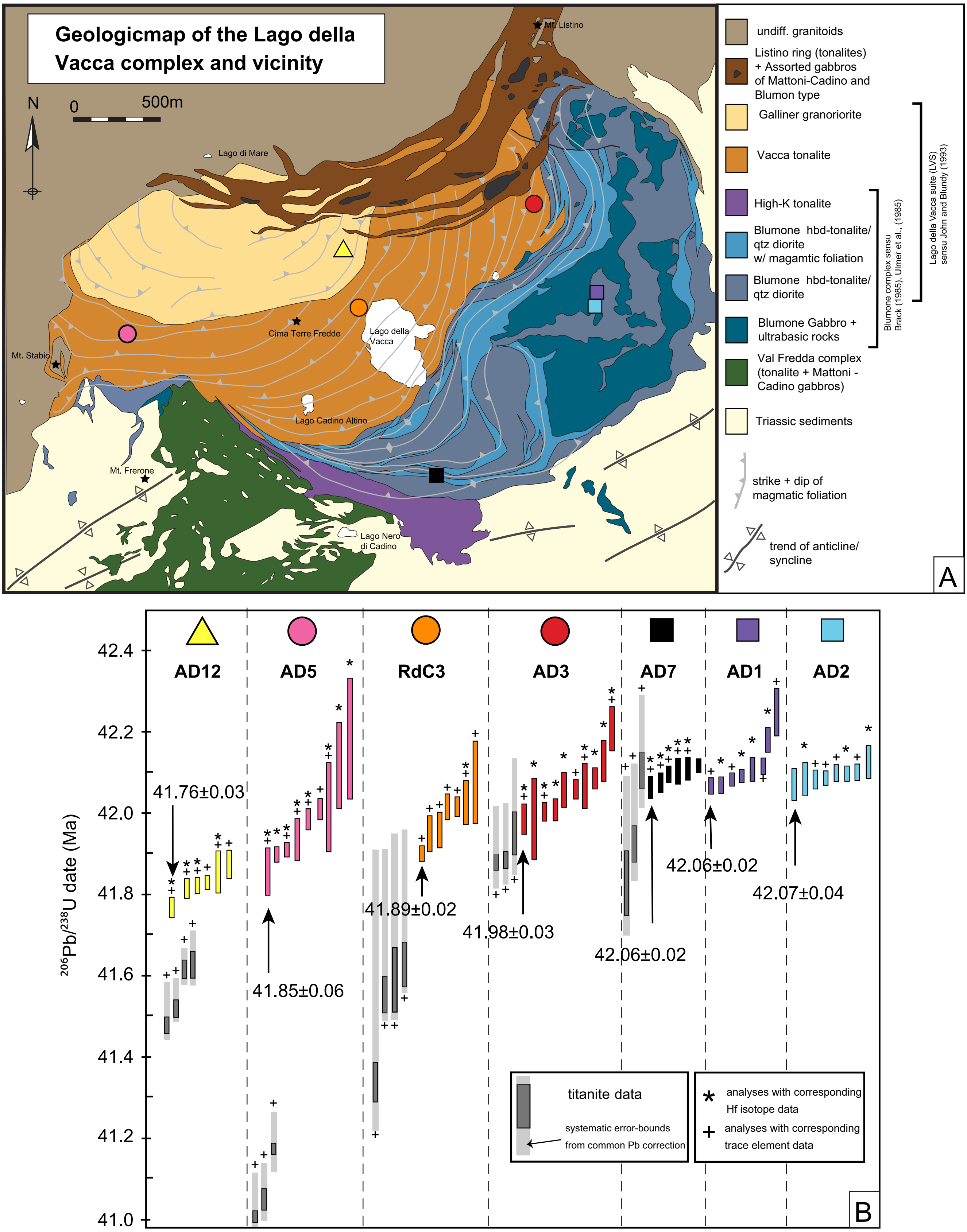


Fig. 35 - (A) simplified geologic map of the study area after John and Blundy (1993). Sample locations indicated by symbols. (B) U–Pb geochronology showing 206Pb/238U dates for individual zircon and titanite. Each bar is an individual analysis and the size of vertical bars are 2-sigma. Crystallization age and uncertainty of youngest zircon from each sample is written out for reference. Colors match sample locations in (A) and samples also separated by vertical dashed lines. All titanite analyses are gray, but correspond to samples within the same vertical dashed lines. The systematic uncertainty in titanite dates arising from unknown common Pb composition produces a systematic error, estimated here by the light gray bars that represent changing the composition estimate by the Stacey and Kramers (1975) Pb evolution model between 0 and 200 Ma, from 42 Ma that was used to reduce data in dark gray. From Schoene et al. (2012).

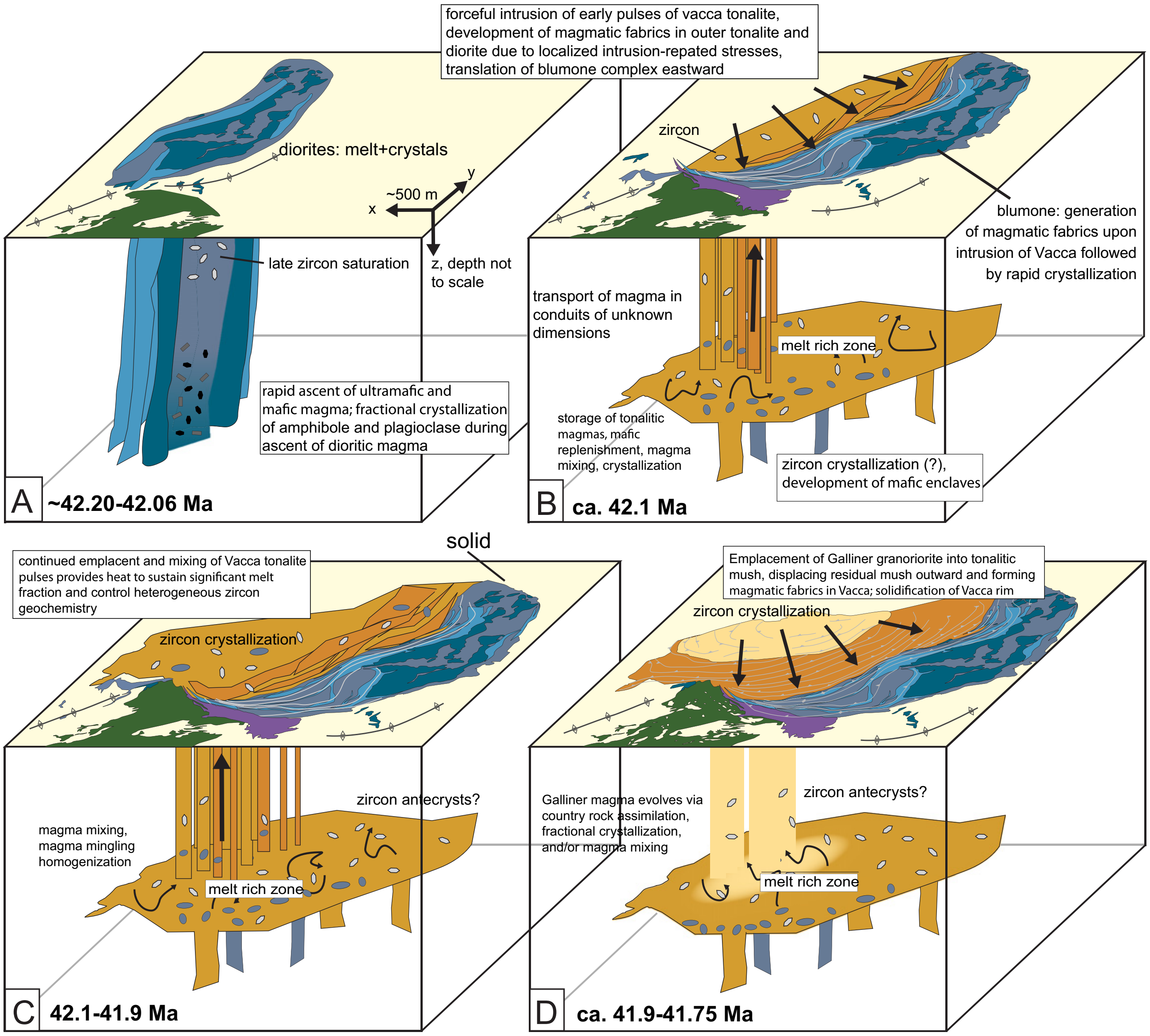


Fig. 36 - Simplified intrusion model for the Lago della Vacca complex. A–D represent a pseudo-3D time series for the sequence of intrusions determined by U–Pb TIMS-TEA. Top of the cube represents the outcrop pattern, and the depth is not to scale. Feeder conduits and geometry of magma reservoirs at depth is not well constrained, as discussed in the text. Conduits are drawn as thin dikes simply to remove clutter from the 3D cartoon. (A) Ultramafic to mafic mantle melts ascend rapidly through the crust to emplacement level. Fractional crystallization during depressurization results in dioritic magmas with little to no crustal assimilation. Late gabbroic pegmatites form in Blumone complex, mixing with crustal-derived fluid. (B) First stage of pulsed intrusion of Vacca tonalite. Development of margin parallel magmatic fabrics in Blumone diorites and tonalites due to forceful intrusion of Vacca tonalite. (C) Continued magmatic activity in tonalitic magma reservoirs and intrusion of Vacca tonalite. Mixing and mingling of magmas at depth and/or at level of emplacement result in evolving zircon geochemistry and source of zircon antecrysts. Tonalitic pulses also provide additional heat to slow down cooling of Vacca at level of emplacement. (D) Lower magma reservoir undergoes crustal assimilation, continued fractional crystallization and development of granodioritic magma, which intrudes central Vacca as crystal mush. Forceful intrusion of the Galliner granodiorite provides "ballooning" related stress causing concentric magmatic fabrics in Vacca tonalite and Galliner granodiorite. Final stage includes the intrusion of units directly to the north (see map Fig. 37), and continued fluid migration and growth of subsolidus titanite until ca. 41 Ma. From Schoene et al. (2012).

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Legend to geological map by Brack & Ulmer (in Brack, 1984) of the Re di Castello Pluton and its surroundings (Fig. 37)

Tertiary intrusive rocks:

- Western Adamello Tonalite

Re di Castello Pluton:

- Acidic differentiates
- Re di Castello Tonalite s.l. (composite)
- Bruffione Granodiorite , L.Boazzo - Arno Leucotonalite
- Badile Granodiorite
- M.ga Listino Tonalite
- Listino Ring
- unnamed tonalites
- Alta Guardia Tonalite
- L. Vacca Tonalite
- Val Fredda Tonalite
- Blumone Complex
- Gabbro / Diorite

- post-tonalitic mafic dykes
- aplites / pegmatites
- mafic dykes
- acidic intrusions

Dip of strata:

- 85°- 90°
- 0° - 5°
- 5°- 25°
- 25°- 45°
- 45°- 65°
- 65° 85°

Small-scale folds:

- 0° 5°
- 5°- 20°
- 20°- 40°
- > 40°

Border rocks:

Dolomia Principale	TRIASSIC	upper
undifferentiated Carnian sediments	TRIASSIC	upper
S. Giovanni Bianco Fm.	TRIASSIC	upper
Argillite di Lozio	TRIASSIC	upper
Gorno Fm.	TRIASSIC	upper
Breno Fm.	TRIASSIC	upper
Pratotondo Lst.	TRIASSIC	upper
Esino Limestone	TRIASSIC	middle
Wengen Fm.	TRIASSIC	middle
Buchenstein Fm.	TRIASSIC	middle
Prezzo Limestone	TRIASSIC	middle
Dosso dei Morti Lst.	TRIASSIC	middle
Angolo Limestone	TRIASSIC	middle
Elto / Serla Dol.	TRIASSIC	middle
Bovegno Carnieules	TRIASSIC	middle
Servino	TRIASSIC	lower
Verrucano Lombardo	PERMIAN	upper
Volcanic rocks	PERMIAN	lower

- Crystalline basement (Edolo Schists)

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