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4. Perspectives on batholith formation and evolution in 4D

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4. Perspectives on batholith formation and evolution in 4D

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Swiss National Science Foundation – ProDoc 4D Adamello
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4.1
Piecemeal Assembly of Shallow Crustal Magma Bodies

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The accumulation of large bodies of silicic magma in the shallow crust fuels volcanic eruptions, creates granite plutons and drives hydrothermal ore deposition. Granite batholiths testify to the very large volumes of magma that can accumulate, while caldera-forming eruptions prove that a significant portion of some silicic bodies contains eruptible magma at any one time. An enduring question in igneous geology is the timescales over which such shallow bodies accumulate. A variety of evidence has been mustered to argue for emplacement as large diapirs versus thin sills, for extreme longevity versus ephemerality, for large volumes of convecting eruptible magma versus small pockets of isolated melt. We will use evidence from a variety plutonic and volcanic rocks to argue that the assembly of magma bodies is piecemeal, the presence of eruptible silicic melt is an ephemeral features of such bodies, and that most bodies destined to form plutons rather than erupt.

The key evidence is as follows:

1. Trace element zoning in plagioclase phenocrysts in volcanic rocks is consistent with repeated interaction with magma of similar trace element chemistry, but slightly different temperature.
2. Textural variation in plutonic rocks tends to mask chemical variation suggesting that textural characteristics are imposed at a relatively late stage on melts whose chemistry is established at greater depth.
3. Diffusive timescales of phenocrysts tend to be quite short suggesting that individual pulses either grew shortly before eruption or spent only a fraction of their residence at high (eruption) temperatures.
4. Continuous influx of magma is required in order to sustain shallow magma bodies for substantially longer than is possible with a single large pulse.
5. Melt inclusions trapped at shallow level tend to show much greater diversity in major and trace elements than do the rocks in which they are found, consistent with additions of small volumes of melt to a larger reservoir with which they eventually become blended.
6. Melt inclusions often described curved liquid lines of descent in rocks whose chemical variations are typically linear, due to the prevalence of mixing processes.
7. Both plutonic and volcanic rocks show abundant textural evidence for the cannibalisation of ancestral magma, now preserved as xenocrysts, glomerocrysts and xenoliths.
8. Minerals and isotope systems with different closure temperatures often given quite discrepant timescales.
9. Most granite batholiths contain rocks with very similar bulk rock chemistry to coeval volcanics suggesting that the volumes of melt extracted from batholiths is modest to negligible, such that few batholiths are cumulates.
10. Magmatic fabrics in plutons show radial variations in intensity consistent with pulsed magma emplacement.
11. Few granite plutons appear to have the requisite volumes of complementary dense mafic cumulate rocks required to balance an overall basaltic composition.

In combination these observations can be reconciled with a model of magma differentiation that occurs on at least two discrete levels. In the deep crust differentiation of mantle-derived basaltic magmas generates a range of more evolved rock types on timescales of millions of years. The evolved melts ascend from the deep crustal hot zone (Annen et al, 2006), occasionally pausing en route to undergo further differentiation. Crystal cumulates in arc volcanics testify to such a process (e.g. Tollan et al, 2011). The volumes of ascending melt are small and ultimately accumulate in shallow reservoirs, characterised by repeated mixing of genetically-related magmas to construct large bodies. Textural development is primarily a consequence of these shallow-level processes, which include degassing, mixing and cannibalisation of ancestral plutonic rocks and their residues. Shallow bodies may grow to considerable size without ever containing appreciable volumes of low-crystallinity eruptible melt, or they may erupt frequently. The balance of magmatic addition versus volcanic losses likely reflects stress conditions in the overlying roof rocks, the rate of magma supply, and the non-linear relationship between temperature and melt fraction.

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4.2

The importance of visco-elasto-plastic rheology in numerical modeling of two-phase flow

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We investigate the behaviour of a two-phase system that involves production and percolation of partial melt through a visco-elasto-plastic continental lithosphere and crust under ongoing tectonic deformation. Using two-dimensional numerical simulations we examine the coupled magmatic and tectonic processes leading to intrusive rock formation.

The numerical modeling approach is based on the assumption that the melt fraction is equal to the porosity of the rock and that porosity changes reflects, apart from melting and crystallization, the compaction or dilation of the matrix framework due to visco-elasto-plastic processes. All modes of compaction are connected to the local effective pressure, which can be understood as the volumetric mean stress acting on the solid rock matrix.

The rheology of the solid phase largely determines the mode and efficiency of melt transport. Therefore it is of considerable importance to formulate a realistic visco-elasto-plastic rheology. In the case of two-phase flow modeling, we additionally formulate a volumetric viscosity to consitute compaction/ decompaction deformation along with a standard deviatoric rheology for shear deformation.

First results indicate that melt propagation is strongly related to the regional stress field, and that plastic failure zones (decompaction tubes, dikes and faults) form important conduits for the propagation of partial melt, especially through the more competent parts of lithosphere and crust. Where the partial melt reaches either mechanical barriers or neutral bouancy with respect to the host rock, regions of magma accumulation may quickly evolve into magma chambers with melt content exceeding 50%. There, the melt may either reside until it crystallizes, or fractionate until the more evolved rest melt has obtained new bouancy to force its way further through the crust.

A possible application of such models is to deepen the understanding of the processes involved in, and the geometry and field relations expected from, the emplacement of hydrated slab melts into the overriding continental plate in an ocean-continent subduction setting.

4.3

The thermodynamic properties of saline-rich aqueous fluids at elevated P-T conditions from Brillouin spectroscopy measurements in a diamond anvil cell

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Saline-rich aqueous fluids are of fundamental importance for a large number of geological processes. For instance, at convergent plate margins fluids are released from the hydrated phases present in the subducted oceanic crust through metamorphic devolatilization. These fluids are mainly H_2O- and CO_2 – rich, with different amounts of dissolved ions. As these fluids migrate to the overlying mantle wedge they act as metasomatic agent, modifying the mantle chemical composition. Moreover, the presence of fluid phases lowers the temperature of the mantle solidus, triggering the production of the magma at the origin of arc magmatism, resulting in the formation of batholiths at depth or volcanic arcs.

For a quantitative modeling of fluid-rock interactions at deep geological conditions the thermodynamic properties of the phases involved are a crucial prerequisite. While these data are available for most of the rock forming minerals, this is not the case for aqueous fluids different than pure water. For instance, although the equation of state (EOS) for H_2O-NaCl solutions is valid up to 1000°C, the pressure range is limited to 0.5 GPa. There is therefore a lack of PVTx data of saline-rich aqueous fluids at high pressure conditions.

This work presents the PVTx properties of saline-rich aqueous fluids up to pressure and temperature conditions relevant for the lower Earth's crust and the upper Earth's mantle determined with Brillouin scattering measurements conducted in a diamond anvil cell (DAC).

Brillouin scattering spectroscopy is an accurate technique for measuring the velocity of acoustic waves propagating in a sample. The use of an externally heated membrane-type diamond anvil cell allows the performance of Brillouin measurements up to 500°C and 5 GPa. The densities of the saline-rich aqueous fluids analyzed in this work are inverted from the acoustic velocities measured, and successively fitted with an equation of state (EOS). This EOS is then used for deriving all other thermodynamic parameters, like for example, the coefficient of thermal expansion, the isobaric heat capacity, the isothermal compressibility, etc. Figure 1 shows the fit of the experimentally derived density data of H_2O-NaCl solutions with different concentrations performed with the EOS proposed in this work.

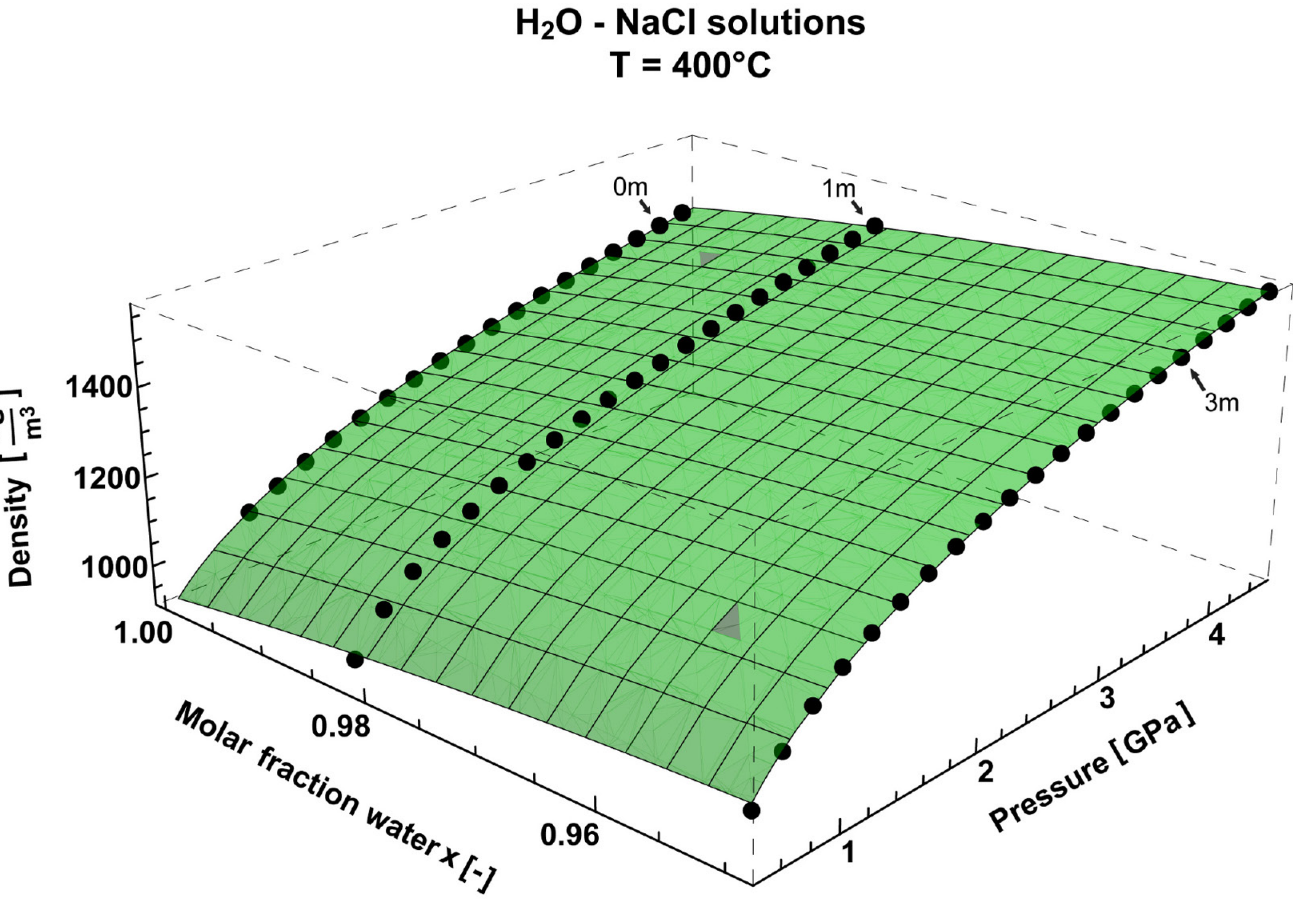

Figure 1. Density of H_2O-NaCl aqueous solutions at 400°C. The black points are density values calculated from Brillouin measurements in the DAC. The surface is a 3-dimensional fit of the data with the EOS proposed in this work.

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4.4
Andesite production in a deep crustal hot zone

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Andesites represent the major proportion of eruptive product at the convergent margins and are considered a major component in the formation of continental crust. Several hypotheses of andesite petrogenesis have been developed, based on field observations and experimental studies, including, partial melting of peridotite under hydrous conditions (e.g. Wood & Turner, 2009), assimilation of plutonic roots of arcs by silicic magmas (Reubi& Blundy, 2008), and crystal fractionation of mantle-derived basalts (e.g. Muntener et al., 2001, Grove et al., 2003). However, all hypotheses have their weaknesses.

Andesitic magmas usually contain considerable volumes of crystals showing disequilibrium characteristic of magma mixing, assimilation, and fractional crystallization. Melt inclusions are considered as an essential source of information of magmagenesis, as they represent unequivocal liquid compositions. However, andesitic compositions in melt inclusions are very rare raising questions as to the mechanism by which andesites are produced (Reubi and Blundy, 2008). Here we present a plausible scenario for origins of pure andesitic melts (not magmas) in the deep crust based on a combination of high pressure phase equilibrium experiments and numerical simulations.

The compositional evolution of melts derived from the crystallisation of a primitive calc-alkaline basalt from St Vincent (Lesser Antilles) were investigated experimentally at 0.7, 1 and 1.3 GPa frpm liquidus to solidus temperatures with initial water contens of 2.3 and 4.5 wt%. The experiments show that the relationship between melt fraction (F) and temperature (T) is variously non-linear and varies with pressure (P) and H_2O content. The experimental T, P, F and melt compositions were used as input into numerical simulations of a deep crustal hot zone (Annen et al, 2006) where sills of basalts are periodically injected at the base of the crust. Basalt accretion rates of 2.5, 5, and 10 mm/yr were tested. The sills thermally equilibrate with the surounding crust at temperatures that progressively increase with time. First melts to be generated are low temperature, low melt fraction and higly silicic. As the crust thermally matures the system produces higher melt fraction, lower in silica, melts.

Since a large proportion of crystals precipitates over a relatively small temperature interval, melt compositions become bimodal as the system matures when we have 2.3 wt% of initial water. The time needed for bimodalism to emerge at this water content varies between less than 0.5 to more than 8 millions years depending on the basalt emplacement rate. In a thermally mature deep crustal hot zone, 3 types of melts can coexist: a high melt fraction-low silica melt and a low melt fraction-high silica melt, both residual from basalt crystalisation and a crustal melt generated by partial melting of the preexisting crust. In marked contrast to the results at 2.3 wt% H_2O we do not see bimodalism developing if we have 4.5 wt% H_2O in the system and the sill emplacement takes place below 0.7 GPa. At such crustal pressures truly intermediate (andesitic) liquids emerge in a very short geological period, between 0.5 and 2 millions years (Figure 1), again depending on emplacement rate.

The numerical simulations are consistent with production of andesite liquids in deep crustal hot zones. The scarcity of andesitic melt inclusions could be that they are trapped at low pressures (< 0.5 GPa), following significant crystallisation and degassing.

Our preliminary results suggest that if there is more available water than 2.3 wt% in the parental liquid (melt) at low crustal conditions in the crustal hot zone truly andesitic liquids could be produced in considerable volume. Conversely, drier parental magmas tend to give rise to more bimodal melt compositions.

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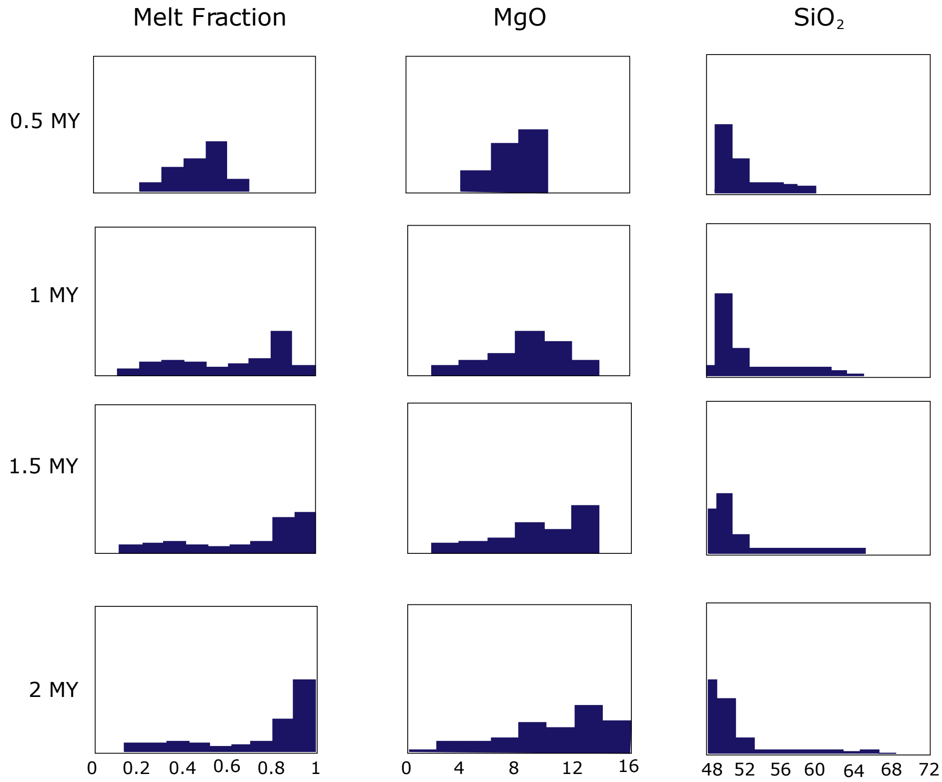

Figure 1. Simulation results at 1 GPa with 4.5 wt% of initial H_2O. Sill emplacement rate is 10 mm per year.

4.5

Physical controls and depth of emplacement of sills and plutons

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Emplacements styles and rates of magma bodies within the crust have fundamental implications for magma differentiation, country rock metamorphism and assimilation, as well as magma chamber formation. The formation and growth of magma bodies are now recognised as involving the amalgamation of successive, discrete pulses such as sills. Sills would thus represent the building blocks of larger plutons (sensu lato). Mechanical and thermal considerations on the incremental development of these plutons raise the issue of the crustal levels at which magma can stall and accumulate as sills. A critical analysis of the mechanisms that could a priori explain sill formation shows that principal physical controls include: rigidity contrast, where sills form at the interface between soft strata overlaid by comparatively stiffer strata; rheology anisotropy, where sills form within the weakest ductile zones; and rotation of deviatoric stress, where sills form when the minimum compressive stress becomes vertical. Comparatively, the concept of neutral buoyancy is unlikely to play a leading control in the emplacement of sills, although it could assist their formation. These different controls on sill formation, however, do not necessarily operate on the same length scale. The length scale associated with the presence of interfaces separating upper stiffer layers from lower softer ones determines the depth at which rigidity-controlled sills will form. On another hand, the emplacement depths for rheology-controlled sills is likely determined by the distribution of the weakest ductile zones. Whereas the emplacement depth of stress-controlled sills is determined by a balance between the horizontal maximum compressive stress, which favours sill formation, and the buoyancy of their feeder dykes, which drives magma vertically. Ultimately, the depth at which a sill forms depends on whether crustal anisotropy or stress rotation is the dominant control, i.e. which of these processes operates at the smallest length scale. Using dimensional analysis, it is shown that sill formation controlled by remote stress rotation would occur on length scales of hundreds of meters or greater. This therefore suggests that crustal heterogeneities and their associated anisotropy are likely to play a larger role than remote stress rotation in controlling sill emplacement, unless these heterogeneities are several hundred meters or more apart. This also reinforces the role of local stress barriers, owing to interactions between deviatoric stress and crustal heterogeneities, in the formation of sills.

4.6

Petrologic consequences of variations in metamorphic reaction affinity

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The extent to which kinetic barriers to nucleation and growth delay the onset of prograde metamorphic reaction, commonly known as overstepping, is related to the macroscopic driving force for reaction, termed reaction affinity. Reaction affinity is defined in the context of overstepping as the Gibbs free energy difference between the thermodynamically stable, but not-yet-crystallized, products and the metastable reactants. Mineral reactions which release large quantities of H_2O, such as chlorite-consuming reactions, have a higher entropy/volume change, and therefore a higher reaction affinity per unit of temperature/pressure overstep, than those which release little or no H_2O. The former are expected to be overstepped in T or P less than the latter. Different methods of calculating reaction affinity are discussed. Reaction affinity 'maps' are calculated that graphically portray variations in reaction affinity on equilibrium phase diagrams, allowing predictions to be made about expected degrees of overstepping. Petrologic consequences of variations in reaction affinity include: (1) metamorphic reaction intervals may be discrete rather than continuous, especially in broad multivariant domains across which reaction affinity builds slowly; (2) reaction intervals may not correspond in a simple way to reaction boundaries and domains in an equilibrium phase diagram, and may involve metastable reactions; (3) overstepping can lead to a 'cascade effect', in which several stable and metastable reactions involving the same reactant phases proceed simultaneously; (4) fluid generation, and possibly fluid presence in general, may be episodic rather than continuous, corresponding to discrete intervals of reaction; (5) overstepping related to slowly building reaction affinity in multivariant reaction intervals may account for the commonly abrupt development in the field of certain index mineral isograds; and (6) pressure-temperature estimation based on combined use of phase diagram sections and mineral modes/compositions on the one hand, and classical thermobarometry methods on the other, may not agree even if the same thermodynamic data are used. Natural examples of the above, both contact and regional, are provided. The success of the metamorphic facies principle suggests that these kinetic effects are second-order features that operate within a broadly equilibrium approach to metamorphism. However, it may be that the close approach to equilibrium occurs primarily at the boundaries between the metamorphic facies, corresponding to discrete intervals of high-entropy, dehydration reaction involving consumption of hydrous phases like chlorite (greenschist-amphibolite facies boundary) and mica (amphibolite-granulite facies boundary), and less so within the facies themselves. The results of this study suggest that it is important to consider the possibility of reactions removed from equilibrium when inferring the P--T--t evolution of metamorphic rocks.

4.7

Rheology of Volatile-rich Crystal Mush

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Large bodies of granite and their corresponding large eruptions have a dual nature: homogeneity at the large scale and spatial and temporal heterogeneity at the small scale (Burgisser and Bergantz, 2011). Such magma batholiths are commonly highly crystalline (> 50 vol%; crystal mush, Bachmann and Bergantz, 2008a) and possible modes of mobilization and emplacement have been intensively discussed in the last decades. Recently, it has been proposed that a stiff mushy batholith must be reheated to mobilize; this produces a reduction in crystallinity that leads to an increase of the magma buoyancy (Burgisser and Bergantz, 2011). Another way of batholith mobilization in the crust can be caused by addition of volatiles (mainly H_2O and CO_2) released by ascending hydrous mafic magmas coming from the mantle (Bachmann and Bergantz, 2008b). The enrichment in volatiles induces a drastic decrease of the bulk viscosity of the granitic body and, thus, in the rheological properties of the batholith. The rheology of such very crystal-rich highly viscous systems is still a matter of debate. To provide some additional experimental constraints relevant to this discussion, we deformed hydrous (2.52 wt% H_2O) haplogranitic magmas containing variable amounts of quartz crystals (from 55 to 65 vol%), and fixed volume of gas-pressurized CO_2-bubbles (9-10 vol%), in simple shear using a HT-HP Paterson-type rock deformation apparatus. Strain rates ranging between $1 \cdot 10^{-5}$ s^{-1} and $4 \cdot 10^{-3}$ s^{-1} were applied at temperatures between 823 and 1023 K (subsolidus conditions) and constant confining pressure of 200 MPa (8 km depth). The results suggest that three-phase suspensions are characterized by strain rate-dependent rheology (non-Newtonian behavior). Two kinds of non-Newtonian behaviors were observed: shear thinning (decrease of viscosity with increasing strain rate) and shear thickening (increase of viscosity with increasing strain rate). The first effect dominantly occurs because of crystal size reduction and shear localization, enhanced by the presence of gas bubbles in the weak shear bands. However, when the solid crystal framework induces an internal flow blockage due to crystal interlock, the second effect becomes dominant. Comparing our results with previous ones for the rheology of crystal-bearing systems (Caricchi et al., 2007), the presence of limited amount of gas bubbles (12 vol% maximum) favors an evident decrease in viscosity; e.g., at about 70 vol% crystals a decrease of about 4 orders of magnitude in relative viscosity is caused by adding only 9 vol% bubbles. These experiments suggest that magma rheology is strongly controlled by the simultaneous presence of bubbles and crystals in the melt phase and their interactions during deformation. The localization in strain favors granite mobilization in the crust and the occurrence of large eruptions; in contrast, the crystal interlocking halts the batholith in the crust.

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4.8

The tonalitic lamellae along the Giudicarie fault system: a multidisciplinary study

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Numerous large and small magmatic bodies are exposed along the Periadriatic line (PAL) or close to it (e.g. Becke 1903; Rosenberg 2004). This study concentrates on small intrusions along two important faults of the Giudicarie fault system (GFS), the Northern Giudicarie (NGF) and the Meran-Mauls fault (MMF), summarised under the term tonalitic lamellae (Dal Piaz 1926).

Magnetic fabric analyses in combination with structural field data indicate dextral strike slip deformation along the NE-SW striking northern part of the GFS, the Meran-Mauls fault, overprinted by younger top-SE thrusting (Pomella et al. 2010). The regional stressfield was constantly oriented approximately NNW-SSE during Tertiary times. The distinctive change in deformation along the MMF from dextral strike slip to top-SE thrusting may be caused by a rotation or bending of the fault after the intrusion of the tonalites and the formation of their horizontal magnetic foliation.

U/Pb data on zircon (Pomella et al. 2010) show that some of the lamellae are of Oligocene (Rupelian), others of Late Eocene (Priabonian,) age. An amphibole-gabbro lens occurring on the Meran-Mauls fault provides a Middle Eocene (Bartonian) age. Among the major Periadriatic plutons, only the southern units of the Adamello batholith also intruded in the Eocene which suggests a strong correlation between the tonalitic lamellae and the Adamello batholith.

New zircon fission track data (Pomella 2010) show a corridor of young, Miocene zircon fission track ages from the tonalitic intrusions along the Northern Giudicarie fault. This corridor connects Early Miocene (17-23 Ma) Zircon fission track ages of the NE-Adamello with the Miocene (23-9 Ma) zircon fission track ages of the Meran-Mauls basement and the Tauern window. To the SE the narrow corridor is bounded by Southalpine sediments characterized by only partially reset zircon fission track ages and towards NW by Oligocene zircon fission track cooling ages found in the Austroalpine units.

This multidisciplinary study provides evidence for a polyphase deformation along the Giudicarie fault system:

Oligocene (Fig. 1(a)): Intrusion of the northeastern units of the Adamello batholith adjacent to the straight, dextral strike-slip PAL. Late Oligocene / earliest Miocene (Fig. 1(b)): The NNW-ward movement of the Southalpine indenter leads to a bending of the fault, material from the northeastern part of the Adamello batholith is squeezed to the NE along the bent part of the fault. Early Miocene (Fig. 1(C)): The brittle Passeier fault, Northern and Southern Giudicarie fault dissect the bent part of the PAL. Along the northern part of the bend (MMF) a nearly continuous tonalitic body persists, whereas along the NGF only small boudinaged bodies rotated during brittle faulting are present

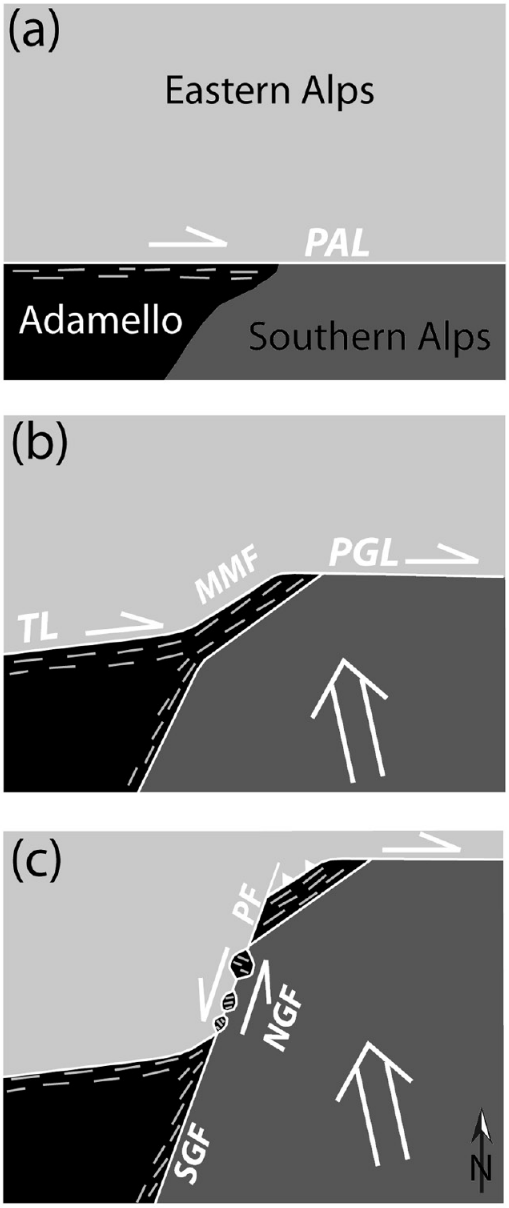

Figure 1. Schematic illustration of the emplacement of the tonalitic lamellae along the Giudicarie fault system (Pomella et al. 2010). PAL = Periadriatic line, MMF = Meran-Mauls fault, TL = Tonale line, PGL = Pustertal Gailtal line, NGF = Northern Giudicarie fault, SGF = Southern Giudicarie fault, PF = Passeier fault.

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4.9

Tectonic exhumation and relief development of the Alps: constraints from the Adamello Complex

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The Adamello Complex is the largest of the Periadriatic intrusions, situated as a wedge between the Periadriatic Fault System (locally called the Tonale line), the South Giudicarie line and the Val Trompia thrust. A minimum of 5 kilometers of overburden has been removed since its emplacement in the late Eocene-early Oligocene and modern overall relief is over 2 km. Major rivers which dissect the complex flow into overdeepened valleys inferred to be areas of maximum incision from the Messinian Salinity Crisis (MSC). This makes it an ideal location to determine the role and magnitude of tectonic events (Giudicarie phase shortening in the late Miocene) and superimposed erosional events driven by climatic or other external environmental conditions (MSC and Neogene glaciation) as drivers of near surface exhumation.

Low-temperature thermochronometers, such as, apatite (U-Th-Sm)/He dating (AHe) and apatite fission-track dating (AFT), constrain near-surface (<5 km) exhumation rates that can be used to characterize climate or tectonic forcing. In this study we present AHe and AFT ages for samples collected in the three of the largest valleys of the Adamello Complex. The ages determined in this study span the Miocene and display a normal age-elevation relationship (AER), where age increases with elevation. All AFT ages along with high elevation AHe samples (3600-2700 m) record early to mid-Miocene ages, while samples located below 2300 m record nearly identical AHe ages, within error, of 6.5±1 Ma. This pattern reveals the base of an exhumed AHe partial retention zone located at a modern elevation of ~2300m, which indicates 2-3 km of exhumation has occurred since ~8.5 Ma, and a minimum of 2 km of exhumation between 29 Ma and 8 Ma, as constrained by pluton emplacement age and depth. We use this data to calculate average exhumation rates and compare to those determined from AER and numerical modelling.

4.10

Timescales of pluton emplacement – insight from high-precision U-Pb dating

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Calibrating the timescales of magma generation, transport, and storage in the crust is important for building robust models for the thermal, rheological and geochemical evolution of the lithosphere. Models need to quantify volumes and rates of magma flux into the middle and upper crust, degrees of liquid-crystal separation, syn-intrusive deformation, degree of magma mixing and crustal assimilation and the fractionation paths of major and accessory minerals.

High-precision U-Pb geochronology has become an invaluable tool for calibrating the tempo of eruptive and intrusive igneous processes. The high closure temperature for Pb diffusion in zircon suggests that zircon U-Pb dates record the time of crystal growth in the magma. Age scatter of individual zircon grains suggest that large plutons are assembled over more than million year timescales by the amalgamation of small pulses of magma, thus downplaying the importance of large magma chambers in the generation of batholiths. As a result of increased age precision beyond the 0.1% level in U-Pb ID-TIMS geochronology of single- to sub-grain zircons, it is becoming increasingly common in plutonic rocks to find populations of zircons on the hand sample scale that record zircon growth over 10^4-10^6 years. Lead loss can be excluded as a source of scatter, since "chemical abrasion" techniques were used for the pre-treatment of analyzed zircons. Such data present difficulties because a zircon date does not necessarily represent the age of the intrusion of a magma or the eruption of a volcanic ash any more. On the other hand, the capability of such minerals to record crystal growth despite prolonged or subsequent exposure to magmatic temperatures can be used to our advantage because these minerals contain a geochemical record of the liquids from which they crystallized which can potentially provide information about the geochemical evolution of a magmatic system with time.

The example of the Adamello batholith shows that very different timescales are involved in its construction: 10-12 Ma for the intrusion of the whole Adamello batholith (Skopelitis et al. 2011) , 1-2 Ma for the assembly of one pluton or unit (such as the Re di Castello unit; Schaltegger et al. 2009), 250-300 ka for the accretion of one intrusion series (such as the Val Fredda or the Lago di Vacca intrusion), 20-40 ka for the crystallization of a single magma batch (Broderick et al. 2011). Applying high-precision chemical abrasion – isotope dilution – thermal ionisation mass spectrometry techniques, using a double isotope EARTHTIME tracer solution for both Pb and U, lowest-blank chemical separation of Pb and U, and precise isotope ratio analysis on high-linearity secondary electron multiplier and high-precision (10^{12}Ohm) Faraday cups, we are able to achieve <0.1% uncertainty at 95% confidence level for individual analyses. For the Adamello batholith, we therefore can reconstruct crystallization processes at the ±20'000-30'000 years level (see Fig. 1). With this unprecedented precision we are able to distinguish between *autocrystic zircon* (crystallized very late in the magmatic history in the lithology we see today), *antecrystic zircon* (crystallized earlier, in a magma but that broadly originated in the same magmatic system). Xenocrystic zircon is inherited from fully crystallized country rock.

By analyzing trace element ratios (e.g., Th/U, Gd/Yb, Eu/Eu*) and initial Hf isotopes of the same dated zircon volume (Schoene et al., 2010), we trace the geochemical evolution of the magmas during crystallization of zircon, involving assimilation, fractional crystallization, and magma mixing processes, which then can be resolved within high-precision time.

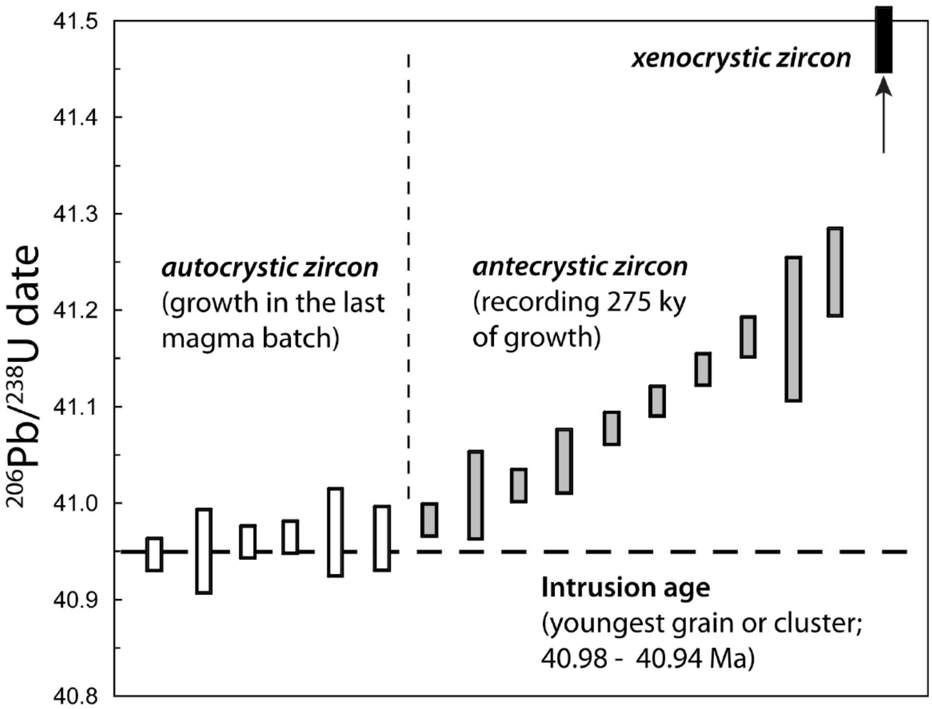

Figure 1: Example how to interpret plutonic zircon U-Pb ages

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4.11

Injection of Mafic Magma as Trigger for Felsic Intrusion Processes

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Plutons grow by melt transfer from a deep source to a higher emplacement level. However, the mechanisms leading to felsic magma transport through the crust is still a point of discussion (e.g. [1]). Geochronological data of exposed rocks in the Ivrea Zone, northern Italy, indicate a close spatially and temporally relation between intrusions of mantle derived mafic magma into the lower crust and crustal scale silicic volcanism [2].

Following up such observations on the correlation of mafic and felsic magma we used numerical modeling to identify potential physical mechanisms for the initiation of felsic magma ascent by injection of mafic material. The code I2ELVIS [3] has been used to study the emplacement of granitic intrusions into the upper crust in a self-consistent way including strong mechanical interaction between the ascending melt and the crustal rocks. It includes a visco-elasto-plastic rheology of the crustal rocks and it is possible to handle strong contrasts in the material properties between magma and crustal material. As initial setup we assume a region of high temperature in the lower crust where partially molten felsic magma is present and a mantle reservoir of mafic melt at a depth of 100km. This reservoir is connected to the bottom of the lower crust via a magmatic channel. We do not apply an initial stress field in the crust in order to get results independent from predefined stresses.

With our numerical experiments we show that the influx of mafic magma from a mantle source into a partially molten region in the lower crust is able to trigger the ascent of felsic material from the lower crust to a higher emplacement level. Furthermore, our study indicates which parameters determine timescale and final shape of upper crustal felsic intrusions and how they influence the development of the ascent and emplacement process.

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4.12

Fluid evolution of the Monte Mattoni mafic complex, Adamello Batholith, northern Italy

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The fluid evolution of the Monte Mattoni mafic complex (John & Blundy 1993) in the southern Adamello batholith was reconstructed by combination of fluid inclusion studies (microthermometry and LA-ICPMS analysis of individual fluid inclusions) and fluid-mineral equilibria modeling. The Monte Mattoni complex consists of two main magmatic units, the Monte Mattoni and the Cadino gabbro, which both show textural evidence for fluid saturation. In the Mattoni gabbro, fluid saturation was likely reached due to rapid magma ascent and pressure decrease. The exsolved fluid phase is trapped in ocelli (miarolitic cavities of subcentimeter size) and segregated fluid pockets that formed from a more evolved, fluid-rich residual melt. In the Cadino gabbro, progressive crystallization and fractionation induced fluid saturation. Fluid inclusions are preserved in miarolitic cavities forming in the center of local pegmatitic pods. Five distinct fluid inclusion types (A to E) that are present as texturally and compositionally consistent assemblages (with clear relative chronology) were observed. The fluid evolution is characterized by several consistent features, most importantly changes in salinity, CO_2 concentration and the Ca/Na ratio. Fluid inclusion types A to C are aqueous-carbonic, and show a systematic decrease in salinity (from 7.8 to 5.5 wt%), coupled with a decrease in CO_2 concentration. The salinity in later aqueous fluid inclusion types D and E increases again (to 9.5 and 27.1 wt%), while the CO_2 concentration drops to very low values. The Ca/Na ratio in the aqueous fluids increases, and the late-stage type E fluids are concentrated calcic-sodic brines.

The initial decrease in salinity and CO_2 content is likely related to fluid-melt partitioning during successive stages of fluid exsolution (Cline & Bodnar 1991). Conversely, the substantial increase in salinity observed in late-stage aqueous fluids is the consequence of water-consuming fluid-rock reactions (formation of epidote and chlorite) at low fluid/rock ratios. This conclusion is strongly supported by fluid-mineral equilibria modeling in the system Si-Al-Fe-Mg-Ca-Na-K-C-H-O-Cl, using a Gibbs energy minimization approach that combines aqueous fluid speciation with nonideal mineral solid-solutions (Dolejs & Wagner 2008). The simulations predict the texturally observed mineral transformations and the chemical evolution of the fluids largely within their analytical uncertainties. The modeling does also predict the continuous decrease in CO_2 concentrations in the late-stage aqueous fluids resulting from calcite precipitation. From isochores constructed for the different fluid inclusion types an approximate pressure-temperature path has been derived. This path shows near isobaric cooling for the early aqueous-carbonic fluid inclusion types, followed by a substantial pressure decrease that resulted in entrapment of moderately saline aqueous inclusions. The late stage calcic brine inclusions were probably entrapped at temperatures as low as 250 °C. The concentrations of ore metals (Cu, Pb, Zn, W, and Mn) in the aqueous-carbonic fluid inclusions in the Monte Mattoni complex are rather low, both in comparison with mineralized intrusions and more differentiated barren plutons (Audetat et al. 2008). By contrast, the late-stage low-temperature calcic brines contain high concentrations of Pb and Zn which are comparable to base metal concentrations found in ore stage fluids of major sediment-hosted Pb-Zn deposits (Stoffell et al. 2008; Wilkinson et al. 2009).

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4.13

Hybridization processes in a partially crystallized magma chamber (Austurhorn intrusion, SE Iceland): Multiple magma mixing scenarios

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The Tertiary Austurhorn intrusive complex in SE Iceland is believed to represent a large exhumed magma chamber with an extensive history of magma mixing and mingling. The basal part of the intrusion consists of granophyric host rocks which have been intensively intruded by different pulses of more mafic rocks. The association of granophyres, basic and hybrid rocks at Austurhorn are known as “net-veined complex” in the literature, but field relations suggests a much more complex history. Different mafic pillows can be distinguished in the field and morphologies range from near-ideal pillow shapes to fragmented pillows incorporated into intermediate rocks. Rapid quenching of some mafic pillows results in chilled margins, whereas others do not seem to follow the same thermal history. In pillows which lack a chilled rim plagioclase phenocrysts are randomly distributed and can be identified extending all the way to the outer rim compared to an absence of phenocrysts in outer parts of the quenched pillow margins. Complex cross-cutting correlations between different hybrid generations can be distinguished in numerous exposed outcrops. Trace element compositions of hybrid rocks suggest multiple replenishment events of mafic magma into a felsic host reservoir. Mixing proportions in different hybrid generations obtained from Rare Earth Element bulk partition coefficients show that in the beginning of magma mixing hybrid compositions are dominated by the felsic magma but with time hybrids get more mafic in composition as a result of an inversion of mixing endmember proportions. Plagioclase phenocrysts in hybrid rocks often display reverse and oscillatory zoning indicating replenishment events of mafic magmas. Distinct plagioclase zonation patterns represent the mixing history of a single hybrid generation and suggest in case of Austurhorn that magma mixing occurred between mafic, felsic and previously formed hybrid magmas. Near the contact of the intrusion the granophyric magma display brittle deformation indicated by the presence of sharp and blocky enclaves separated by mafic veins. The complexity of the mixing increases towards the center of the intrusion, where chaotic hybrid rocks dominate the lithology.

New magma input locally increases the host temperature and changes the rheology of both the felsic and basic magma. Repeated reheating episodes due to multiple magma injections decrease the viscosity of the granophyres and promote chemical diffusion. Compared to previous studies on the petrology of the Austurhorn intrusion our 65 bulk rock samples show linear trends suggesting mixing between the mafic and silicic end-members as well as mixing between different hybrid magmas. Textural observations in the field and bulk rock analysis suggest that hybrid rocks, in case of Austurhorn with andesitic composition, are formed by several mafic replenishment events into the basal part of an already partially crystallized felsic magma chamber.

4.14
Magma Emplacement Tectonics: What can we learn from the oceans, ophiolites and arcs?

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Magma migration and emplacement remain the fundamental means by which large volumes of heat and mass are added to the lithosphere, ultimately resulting in crust formation. For example, the ~ 170x10^{6} km^{2} Pacific Plate represents the quantum result of magma emplacement, solidification and crustal generation at the fast-spreading East Pacific Rise (EPR). Crustal accretion at the EPR occurs over a vertical region no more than ~6 km thick, perhaps as narrow as 50-500 m perpendicular to the strike of the ridge, and along 10's to 100's of km's of ridge strike length, indicating an extremely focused and efficient melt extraction and collection system. Island arcs and their plutonic underpinnings are considered the primary building block of continental lithosphere. The construction of large batholiths and the eruption of voluminous ignimbrite deposits point to the complex interaction of physical and chemical processes that lead to focused point sources for magma collection and/or eruption. Yet, there remains an incomplete understanding of the mechanisms of magma migration, emplacement, and solidification in the lithosphere. Are there similar operative processes in these diverse environments? If so, what insights may be gained by comparing these two systems?

From new data as well as an incomplete survey of the published literature a number of important paradigms in magma emplacement studies may be documented. These paradigms illuminate our understanding of "magma emplacement tectonics" in arc systems and oceanic spreading centers (OSC's) and provide a template for future studies.

1) Field, geophysical, textural, theoretical, and geochronological studies indicate that the construction of magma chambers may occur by the emplacement of successive batches of magma, the size of which vary by several orders of magnitude in *either* setting. Complexities arise when batches of different composition overlap in time and space.

2) The plutonic portions of these systems generally reflect an incomplete cumulate residue (gabbroic in OSC's vs. dioritic to mafic granodiorite in arcs) from which high-level, more evolved igneous rocks (or their eruptive equivalents) are derived.

3) Structural fabrics (hypersolidus foliations, lineations, folds, etc.) preserved within these systems form diachronously by i) strain associated with magma emplacement; ii) strain associated with regional deformation; and iii) a combination of the above. However, without an external kinematic reference frame (i.e., host rock configuration and structural orientation; regional displacement field orientation, etc.), these fabrics are difficult to interpret at best, and unintelligible, at worst.

4) Crystallographic, field, and geochemical data may be used to quantify near-solidus magma rheology. These studies point to the ability of magmas to undergo hypersolidus deformation at low melt fractions (e.g., < 10% melt in gabbroic systems), without preserving appreciable crystal-plastic deformation. Thus, the notion of a rheological transition (30-50% remaining melt), below which the magma behaves as a solid, must be called into question. Field and microstructural studies imply that low melt-fraction strain may be the norm in arc plutons. Such low-melt fraction (i.e., near-solidus) conditions may govern the formation of the final fabric patterns observed.

5) The thermal evolution of a given pluton may traverse the solidus multiple times due to cooling and reheating by subsequent intrusion of new batches of magma. Such "defrosting" may occur repeatedly and may be observed texturally in the form of resorbed crystals, truncated zoning profiles and new crystal growth.

6) "Traditional" magma emplacement mechanisms such as stoping, ductile flow (e.g., ballooning), roof uplift/floor down-drop (by rigid rotation/translation or by ductile flow) occur in both OSC's and arcs. However, field and mass-balance considerations indicate that the predominant displacement direction of the host material is downward in an integrated arc column, toward the region of magma generation by a combination of the above processes. In contrast, OSC's involve lateral material transfer parallel to transform faults; a transfer mechanism generally unaccounted for in arc systems. However, both roof uplift and floor down-drop have been documented in the plutonic portions of the Josephine and Oman ophiolites, indicating that vertical displacement also occurs.

Instead of focusing on various models for magma migration (e.g., dikes vs. diapirs), we suggest a method of defining the operative deformation mechanisms attending magma migration and emplacement. These include hypersolidus flow, dislocation creep, diffusion creep (both of which facilitate viscous flow), and elastic and inelastic failure (e.g., ductile fracturing, rigid body rotation/translation). The dominance of one mechanism over the other is primarily a function of the heat budget of the magma batch, host material temperature (viscosity), strain rate, and degree of melt overpressure. The observation that the plutonic sections of arcs, ophiolites, and in situ oceanic cores preserve evidence for multiple deformation mechanisms attending the emplacement of a *single magma batch* indicate that heat budget, strain rate, and degree of overpressure may vary in space and time during the emplacement of a single magma batch. The onus remains to establish testable predictions and thoughtful models that integrate the above paradigms to illuminate the nature of magma emplacement tectonics in these environs.

P 4.1

A detailed reconstruction of emplacement and crystallization sequence in the Southern Adamello Batholith, N. Italy using the potential of accessory minerals

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Recent advances in U-Pb zircon geochronology have revealed the complexities of pluton construction, by multiple injections on 10-100 ka to Ma timescales (Michel et al., 2008, Schaltegger et al., 2009). Using high precision U-Pb dating we are potentially able to describe the duration and evolution of magmatic systems, their crystallization and emplacement within the crust. The potential exists to better understand these processes by detailed study of accessory minerals. The trace element and isotopic characteristics of accessory minerals makes them important information carriers for tracking changes in a magma through time. High precision U-Pb dating, using CA-ID-TIMS and employing the ET2535 tracer solution for <0.1% precision and accuracy on $^{206}Pb/^{238}U$ zircon and titanite dates, and trace element analyses of zircon and titanite, combined with Hf isotope analysis of zircon are presented for the investigation of a complex magmatic system.

This study focuses on the Val Fredda Complex (VFC) in the southern tip of the 43 to 32 Ma Adamello batholith, N. Italy. The VFC displays complex relationships among mafic melts that were injected into solidifying felsic magmas. The mafic units crystallized potential autocrystic zircons over a duration of 100 ka, with the majority of zircons co-crystallizing with titanite. The TIMS-TEA method (Schoene et al., 2010) allows us to analyze trace elements on the same volume of zircon/titanite used for U-Pb dating. Mafic zircon and titanite trace elements (e.g., Eu/Eu* and Sr) suggest that these accessory minerals crystallized prior to plagioclase fractionation. Based on experiments (Ulmer et al., 1983) and the trace element data from this study, we suggest that the mafic zircons and titanites do not represent in situ crystallization and therefore are more likely antecrystic.

Data from the VFC felsic units show more complex zircon populations, including xenocrystic, antecrystic and autocrystic zircons. These felsic units have apparent autocrystic zircon growth over 100 to 200 ka, with zircons co-crystallizing with titanites during the final 20 to 50 ka. While zircon/chondrite normalized REE patterns do not vary with differentiation, titanite REE patterns reveal changes with differentiation, mostly within the LREEs and Eu/Eu*. Based on trace elements fractionation we suggest that felsic zircons and titanites crystallized in situ and represent autocrystic growth. The oldest autocrystic zircon may approximate the injection of the respective magma pulses into the host rock, whereas the youngest zircon and titanite indicate final crystallization at the solidus in a stagnant interstitial melt.

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P 4.2

2D numerical modelling of fluid and melt percolation in the subduction zone

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Subducting slab dehydration and resulting aqueous fluid percolation triggers partial melting in the mantle wedge and is accompanied with the further melt percolation through the porous space to the region above the slab. This problem is a complex coupled chemical, thermal and mechanical process responsible for the magmatic arcs formation and change of the mantle wedge properties.

We have created a two-dimensional model of a two-phase flow in a porous media solving a coupled Darcy-Stokes system of equations for two incompressible media for the case of visco-plastic rheology of solid matrix. Our system of equation is expanded for the high-porosity limits and stabilized it for the case of high porosity contrasts. Melting process is implemented according to the model of Katz (2003) where melting degree is a function of pressure, temperature, composition and water content. We use a finite-difference method with fully staggered grid in a combination with marker-in-cell technique for advection of fluid and solid phase.

We performed a comparison with a benchmark of a thermal convection in a porous media in a bottom-heated box to verify the interdependency of Rayleigh and Nusselt numbers with a theoretical one. We have demonstrated the stability and robustness of the algorithm in case of strongly non-linear visco-plastic rheology of solid including cases with localization of both deformation and porous flow along spontaneously forming shear bands.

We have checked our model for the forming of localized porous channels under a simple shear stress (channelling instability).

Current work includes implementation of non-liner viscous rheology and elaboration on the setup of self-initiating subduction. Later we plan to include solid elasticity and fluid/solid compressibility.

Also we have developed a full complexity system of equations for visco-elastic case and currently are working on numerical realisation of it to verify our simplifying assumptions for the general model.

Ultimate goal is to simulate in a realistic self-consistent manner fluid and melt generation and transport in subduction zones including fluid/melt focussing phenomena above slabs.

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P 4.3

Thermal evolution of the Western Adamello contact aureole

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The Western Adamello pluton (WAD, Northern Italy) intruded into the South Alpine basement and its permotriassic cover around 38 Ma ago. The thermal effects of the tonalitic intrusion on the host rock are (among other mineral reactions) a) partial melting of basement rocks and sediments up to 0.3 km from the contact due to breakdown of muscovite, b) garnet re-growth at 1.7 km from the contact and c) growth of andalusite at 2.4 km from the contact.

The occurrence of partially molten host rock requires temperatures >650 °C at 300 m from the contact and Grt/Bt thermometry of a sample at the same distance produced 637 ± 18 °C. Heat flow models can be used to describe the Temperature-time evolution in the contact aureole. For these, several parameters are crucial: A) initial host rock temperature, B) presence or absence of hydrothermal systems in the host rock, C) convection in the magma chamber, D) the emplacement style and E) the intrusion temperature. An initial attempt with a two-dimensional, thermal model (non-convecting) single batch intrusion with T_{int} = 800 °C and T_{host} = 300 °C yield temperatures at least 150 °C lower than those from the above petrologic evidence.

We varied, where appropriate, the above critical parameters to gain a better understanding of emplacement style by reproducing the observed temperatures in the contact aureole. A) The host rock temperature before intrusion is constrained to a maximum of 300°, since there was no post-Triassic resetting of Biotite Rb/Sr data outside the contact aureole (Pennacchioni et al. 2006) and Illite crystallinity from samples outside the contact aureole suggests, at most, anchizonal conditions (Riklin 1985). B) Significant convection in a large hydrothermal system in the host rock can be excluded in the inner aureole due to the low amount of partial melt observed in the proximity of the intrusion. C) Convection within the pluton is strongly depending on the intrusion geometry. The presence of a large batch of magma resulting in convection is often used to increase temperatures in the host rock. Bea (2010) showed that convection would only last in the order of a few thousand years for a single batch intrusion of a similar size to the WAD. The observed temperatures in the WAD contact aureole require the pluton to convect for at least 5 to 10x longer, unless intrusion temperatures are above 950°C.

Therefore, convection could contribute to higher contact metamorphic temperatures but cannot account for the entire temperature mismatch. D) Continuous or pulse-wise feeding of the magma chamber at the contact will significantly raise the temperatures in the contact aureole. The WAD (5 km) is mainly non-foliated, and non-layered with exception of a small marginal zone (500 m), showing a contact-parallel foliation and sub-vertical orientation of hornblendes. Structural elements in the host rock (foliation, boudinage, folding and microtextures) suggest a significant compressional component during the WAD emplacement.

Therefore, a scenario of a continuously growing pluton, fed over an extended period of time is favored. The emplacement has to be rapid enough to result in a large batch, allowing convection. More structural, petrographic and geochronologic data is needed to further constrain the emplacement style.

In any case, the intrusion temperature needs to be in excess of 800 °C to lead to the observed temperatures in the WAD contact aureole (E).

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P 4.4

Trace-element partitioning in post-plutonic dike-suites S-Adamello (N-Italy)

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Mineral-melt trace-element partition coefficients are used to model the evolution of trace-element concentrations such as the rare earth elements (REE) in magmas through fractional crystallization. Recently, such mineral-melt coefficients were mainly determined by experiments. These partition-coefficients vary as a function of pressure, temperature and bulk composition. Here we present an approach to directly determine the partition coefficients from natural subvolcanic rocks where bulk composition for the primary magmas and pressure in the form of the emplacement level are confined. This is in the context of post-plutonic dike-suites from the S-Adamello, which is part of the batholith that emplaced during the late stage of the Alpine collision in N-Italy. Dike rocks generally closely approach liquid compositions, in particular mafic compositions, relative to plutonic rocks and thus are suitable to model the chemical evolution of magmas. The present case study explores the links of magma sources that formed the plutonic units and the later dikes.

A laser ablation study was carried out to determine the trace-element composition of the aphyric fine-grained matrix along the chilled margins representing the liquid, and the microphenocrysts such as pyroxene, hornblende and plagioclase to eventually calculate the partition coefficients between crystals and liquid. The aphyric matrix was analyzed by scanning with LA-ICP-MS. For performing the quantification of this analysis the whole rock composition was corrected for large crystals with their overall mineral chemistry and through detailed textural analysis to achieve a major-element composition for the aphyric-matrix. This in turn gives an internal standard for calculating liquid trace-element concentrations of the matrix scans with LA-ICP-MS.

Dike rocks display variation in cooling rates, which are very rapid at margins and decreases towards the center. Our calculations have to take into account the potential of increasing disequilibrium growth of the crystals towards the rapidly cooled dike margins due to kinetic effects (Mollo et al. 2011). Further the determined partition coefficients are assessed with the crystal structure lattice-strain model (Blundy & Wood 1994) for their consistency.

The range of different magma compositions of the Adamello dike-suites shows mingling or mixing of different magma sources for more evolved compositions through crystal textures. Different magma sources appear to have evolved along different liquid lines of descent. Differences in the crystallization sequence are revealed by mineral trace-element chemistry. Clinopyroxene in basalts has REE-patterns indicating co-crystallization with plagioclase through an Eu anomaly. Olivine occurs as pseudomorphs with spinel-inclusions in these basalts. Hornblende in basaltic andesite has generally lower concentrations in REE than hornblende in basalts. The slightly steeper light-REE patterns implies hornblende crystallizing after olivine rather than clinopryoxene. While in basalts olivine appears to have followed by clinopyroxene and plagioclase. These preliminary results imply that larger crystals from basaltic-andesites formed from a water-rich magma source in deep crustal reservoir. Such a water-rich magma source seems to have mixed with less differentiated drier basalts.

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P 4.5

Trace elements geochemistry and experimental petrology as novel approaches to understand reactive flow through the Rum layered intrusion: preliminary results and perspectives

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The well studied Rum Isle layered intrusion has built up by emplacement of a series of 16 macro-rhythmic units. Magma intruded 60.53±0.08Ma (Hamilton *et al.*, 1998), at a pressure <0.5 kbar (Holness, 1999). Units are composed of feldspathic peridotite at the base, overlain by troctolite and gabbro. Layering is induced by fractional crystallization from picritic magma (Upton *et al.*, 2002; Holness *et al.*, 2007). Rum magma liquid line of descent is complicated by reactive melt percolation within crystal mushes, either originating from continuous cumulate pile compaction or from a newly injected reactive picritic magma (Figure 1). Field evidence is numerous: some troctolites, that display gabbroic enclaves, result from clinopyroxene primocryst dissolution from a gabbroic crystal mush, when intruded by subsequent clinopyroxene undersaturated peridotite dykes or protrusions. They are associated with a clinopyroxene-rich band in the overlying gabbroic mush. This horizon is wavy. In poikilitic gabbros, clinopyroxene occurs as cumulus grains, as interstitial crystals and as coronae around olivine cumulus grains. A distinct decrease in the Mg# and an increase in Ti content are observed between clinopyroxene primocrysts and oikocrysts (Holness *et al.*, 2007). Due to disequilibrium between crystals and invading magma, clinopyroxene is dissolved from the mush, leading progressively to saturation of the percolating magma (Holness *et al.*, 2007). After transport along grain boundaries, it is re-precipitated interstitially.

Rum is ideally suited to study interstitial melt migration through magmatic mushes. We are developing a novel approach to understand infiltration metasomatism, by coupling trace element geochemistry and experimental petrology. Appearance temperature for all mineral phases will be determined using (a) water-saturated, 200bar, f_{O2} at QFM experiments on aphyric picrite in TZM pressure vessel, and (b) anhydrous, one-atmosphere, f_{O2} at QFM in Gas-mixing furnaces, using a picritic starting material. Results will be used to define a relative timescale for infiltration processes, based on temperature. We will acquire high precision and space resolution microanalyses on natural samples and experiment run products, using FEG-probe, LA-ICP-MS and nanoSIMS. Equilibrium liquid composition with natural cumulus grains, thin rims and interstitial crystals will be determined, using calculated partition coefficients. The objectives of studying crystal zoning and mineral generations are to check if different infiltration episodes have occurred and to make precise timescale estimations using chemical diffusion through crystals. In a second stage, we will use a novel approach to study infiltration metasomatism process by producing synthetic mixes of crystals with reactive percolating melt.

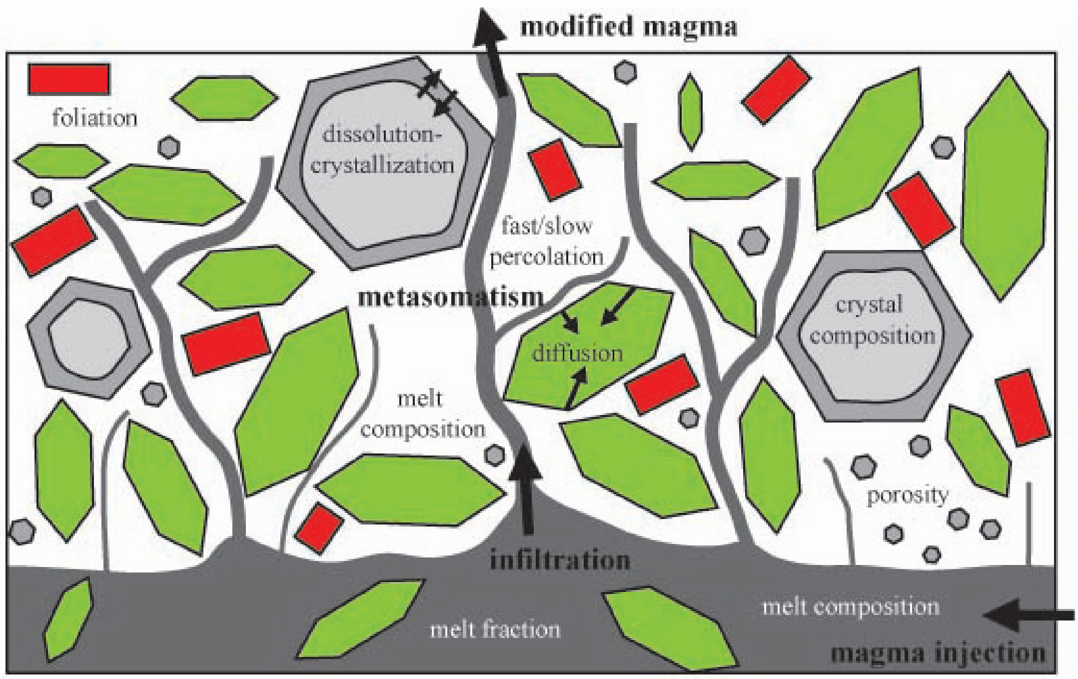

Figure 1. Schematic representation of reactive flow of residual interstitial melt through crystal mush.

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P 4.6

Cordierite growth textures in the Permian sequence of the Adamello contact aureole, Italy

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Metamorphic Permian rocks display different cordierite textures in the Adamello contact aureole in northern Italy. These rocks are pelitic sandstones of the Verrucano Lombardo unit and experienced low P/high T contact metamorphism due to the emplacement of the Adamello batholith, a Tertiary instrusion of mostly granodioritic to tonalitic composition (Callegari & Dal Piaz, 1973). The Adamello batholith is located between Lombardy and Trentino in the Southern Alps. The metamorphic overprint results in different metamorphic zones. With increasing grade these are (see also Ricklin, 1982): a) the biotite zone, which is characterized by the first appearance of small biotite and muscovite flakes growing around and into old detritic quartz, K-feldspars, deformed muscovites and biotites, or they form fine grained aggregates within the matrix; b) the cordierite zone, which is marked by the growth of cordierite around and within the biotite aggregates as well as the recrystallisation of K-feldspar in the matrix; c) the andalusite zone, which is characterized by the growth of andalusite at the margins of detritic quartz crystals and in many cases within the K-feldspar and muscovite rich zones between the cordierites; d) the sillimanite zone, with fibrolitic sillimanite occurring as aggregates, mostly replacing muscovite and biotite but rarely andalusite.

Cordierite growth textures show variable morphologies from egg-shaped, almost spherical porphyroblasts to irregular, dendrite- or tree-like patterns. Most of the cordierites were replaced by fine-grained pinnite increasing the contrast and therefore making the textures easily visible to the naked eye. Roundish, poikilitic cordierites vary from about 2 mm to 30 mm in size. Small crystals are typically spherical with well defined, straight margins, whereas larger crystals are more egg-shaped with rather lobate boundaries. Dendrite textures are up to 30 mm in size with more or less complex limbs. The overall shape of the dentrites is spherical and the geometry suggests a radial growth. They are either finely branched or thicker and less complex with thickened bifurcations. All different morphologies can occur with or without halos, which have variable sizes and shape. The halos are biotite-free, but contain otherwise the same mineralogy as the matrix (muscovite – K-feldspar – quartz – oxide – plagioclase). In most of the collected samples, the cordierites are randomly distributed throughout the rock but in some cases the textures are aligned within or even grow across the bedding. Thin section investigations suggest that the cordierite-producing reaction was muscovite + biotite + quartz = K-feldspar + cordierite + water.

Different morphologies were observed within a single outcrop, which experienced a unique temperature-time trajectory. Hence, the rate of temperature is not the major factor discriminating between the textures. We propose that differences mainly in whole rock chemistry and/or fluid composition were responsible for the generation of differences in textures.

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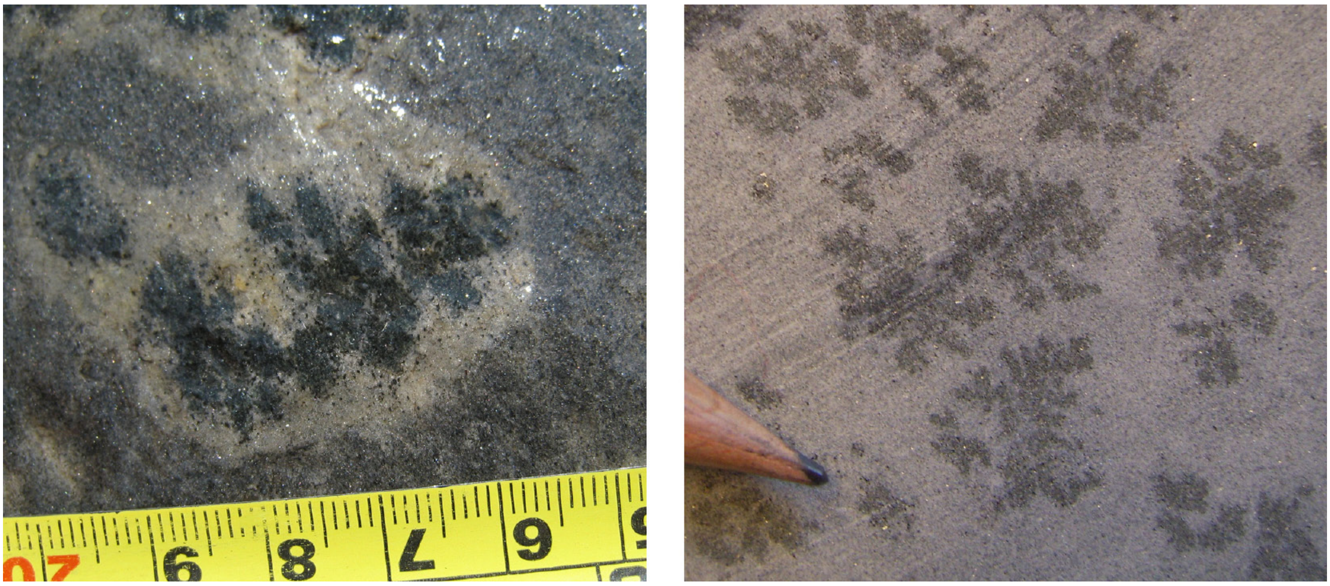

Figure 1 : Examples of dentritic cordierite growth with depletion halo (left) and without (right).

P 4.7

Liquid line of decent from olivine-tholeiite to granodiorite at 0.7 GPa

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The isobaric fractional crystallization history of a cooling hydrous, primitive, calc-alkaline, basaltic magma at lower to intermediate crustal levels is investigated by this experimental study of the liquid line of decent. An end-loaded piston cylinder apparatus was used to perform these experiments at 0.7 GPa. The composition of an olivine-tholeiitic dike from the Adamello batholith (Northern Italy), was used to synthesis a synthetic equivalent containing 3 wt.% of water and 32 trace elements at 40 ppm level. Glass compositions, which represent the liquid composition in equilibrium with solid phases, were subsequently synthesized from oxides, hydroxides and silicates and used as new starting material for the following experiment conducted at 30°C lower temperature. Analyses were performed upon the recovered experimental charges using EPMA and LA-ICP-MS. Liquidus temperature of the synthetic equivalent of the natural olivine-tholeiitic dike has been found at 1165°C (±5°C). The experimentally obtained liquid line of decent follows a calc-alkaline fractionation trend as anticipated. The generated intermediate to granitic compositions closely resemble plutonic and volcanic rocks that compose arc-related igneous complexes (e.g. Adamello batholith, northern Italy). The following crystallization sequence has been determined: olivine (ol) => clinopyroxene (cpx) => plagioclase (plg), spinel (sp) => orthopyroxene (opx), amphibole (amph), magnetite (mag). The liquid line of decent evolves towards corundum-(Al_2O_3) normative (peraluminous) compositions at 780°C with a silica content of 68 wt.%. Comparing the study of Kägi (2000) on a similar initial starting material, it's noticeable that liquid compositions remained diopside-normative (metaluminous) down to 990°C at 1.0 GPa. Plagioclase fractionation, which occurred only at 0.7 GPa (this study), is not supposed to be responsible for this contrasting behavior. However, we state that a "branching" peritectic encompassing the amphibole stability field is causing the meta- versus peraluminous derivative liquids when respective phase equilibria are inspected: At 0.7 GPa, phase relations evolve from cpx+opx+plg+mag to amph+opx+plg+mag without cpx. In contrast, Kägi (2000) reported the coexistence of cpx+amph+mag at 1 GPa. This could be related to an inferred decrease of the amph stability field towards lower temperatures at 0.7 GPa or/ and a larger amount of opx compared to cpx crystallizing before amph at 1.0 GPa, driving the derivative liquids towards the other branch of the diverging peritectic point.

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P 4.8

Textures and chemistry of zircons: implication on the interpretation of U-Pb zircon ages from observations of the Chaltén Plutonic Complex (Argentina)

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The subject of this presentation is the high precision U-Pb dating of zircons from the Chaltén Plutonic Complex (CHPC) in Argentina. The CHPC is a mafic to granitic intrusive suite situated in a backarc position in Southern Patagonia. We could show that the precise absolute geochronology of this small plutonic complex has important consequences for the geodynamic interpretation, i.e. arc migatione pattern in Patagonia (Ramirez et al. 2011). Here, we explore in more detail the textural and chemical characteristics of zircons from the different plutonic units of this composite intrusion to gain insights on the growth of zircons in magmas with variable degrees of differentiation. These features are of interest for the geological interpretation of zircon ages, escpecially since increasing precision of ages can be obtained (Schaltegger et al. 2009, Schoene et al. 2011).

The calc-alkaline gabbroic to granitic rocks of the CHPC were emplaced over a short time-span of 530 ky between 16.90 ± 0.05 Ma and 16.37 ± 0.02 Ma. The zircon ages are consistent with the relative geochronology inferred from field relations (8 plutonic units were distinguished). Where undulating ductile contacts are observed, the age difference between units cannot be resolved. In the case of brecciated contacts a minimum age difference of 80ky was obtained, which is at the limit of the obtained precission (±40ky). The petrographic textures of zircons in mafic rocks indicate crystallization in isolated pockets, i.e. interstitial. The application of the Ti-in-zircon thermometer yields consistently low temperatures (~760°C). This indicates that (most) of the zircons from these mafic samples might have crystallized near solidus temperatures, and consequently post-date the emplacement.

In contrast, the textures of zircons from divers granitic rocks indicate a more protracted crystallization. The chemistry (LA-ICP-MS analysis) of zircons from granitic rocks displays systematic variations of U/Th and U/Ta ratios between core and rim. This pattern can be correlated with the variation of temperatures and Ce^{III}/Ce^{IV} ratios. These observations suggest that several episodes of zircon crystallization at different temperatures exist in granitic melts. The calculated temperatures are 100°C to 200°C higher than the solidus, which would imply that many zircons crystallized prior to the emplacement (antecryst).

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P 4.9

Tracing episodic magma accretion by U-Pb dating and $^{18}O/^{16}O$ isotopes in zircon: the case of the Adamello batholith, Italy

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Styles and timescales of batholith formation still remain a matter of debate. There is growing evidence that batholiths are not formed by a single ascent of magma but by accretion of multiple batches. In the latter case, are they derived from the same source or different ones, and do they suffer similar degrees of contamination?

In order to answer these questions, we study tonalites from the Adamello batholith (33-43 Ma) localized in the northern Italian Alps. Previous studies mainly based on cooling ages highlighted a younging of magmatic activity towards the north (Callegari & Brack 2002; Schaltegger et al., 2009; Del Moro et al., 1983) which is confirmed by our new U-Pb zircon LA-ICP-MS dating (Fig.1). Isotopic compositions of both Sr and O indicated increased contribution from higher $\delta^{18}O$, more radiogenic supracrustal sources in the same direction (Cortecci et al., 1979). We present new data from a $^{18}O/^{16}O$ isotope study on small quantities of freshest and refractory separates of quartz, amphibole, titanite and zircon, and best estimate $\delta^{18}O$ magma values (Bindeman 2008). The data confirm increasing crustal contamination towards the north indicated by elevated $\delta^{18}O$ values up to 7‰ in zircon. H isotope ratio is strongly negative (-97‰) for the amphibole in the most northerly sample suggesting an assimilation of hydrothermally-altered rocks or an assimilation of marine sediment. We will quantify the contamination by AFC modelling using geochemistry, whole rock and mineral isotopes. As a preliminary conclusion, the Adamello batholith was formed by different pulses over ca 10 m.y. coming from different in $\delta^{18}O$ magma reservoirs with contrasting oxygen isotope compositions, due to their different depth in a $^{18}O/^{16}O$ zoned crust.

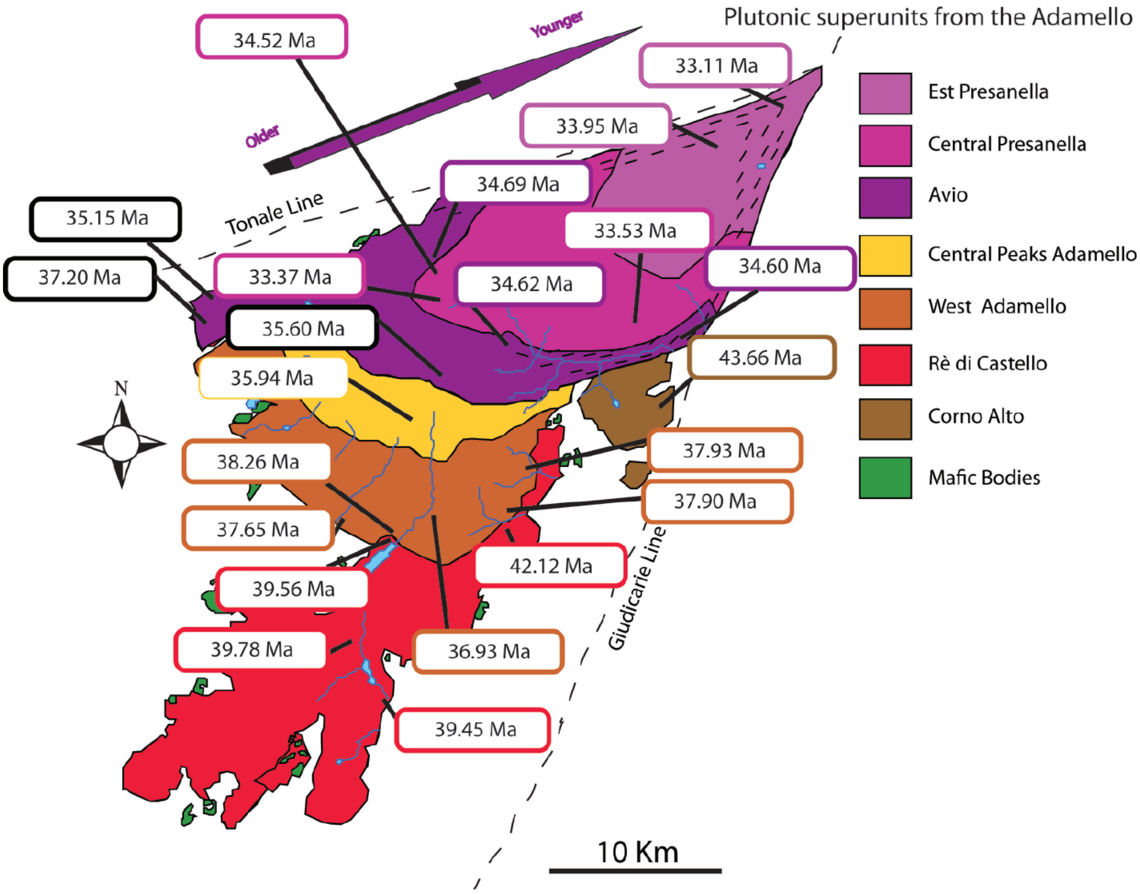

Figure 1. Simplified geological map of the Adamello batholith with the different superunits. New U-Pb ages analyzed by LA-ICP-MS on zircons.

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P 4.10

Experimental determination of the hydrous basalt liquidus: The Grenadan perspective

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A series of experimental liquidus determinations have been carried out on a hydrous primitive basalt at a range of pressures pertaining to ≤ 60 km depth. The starting composition replicates the major element chemistry of a picrite from South East Mountain, Grenada, Lesser Antilles with 15.4 wt % MgO and whole rock Mg# = 73. The island of Grenada is known for erupting primary mantle melts and post-Miocene products of the arc volcanism yield evidence for magmatic water contents of ≤ 6.4 wt % H2O (Bouvier et al. 2010).

The ultimate aim of this experimental series is to map out the topology of the hydrous basalt liquidus in P-T space. The position of the liquids relative to a mantle adiabat determines the amount of superheating experienced by magma as it ascends to lower pressures. This in turn has implications for the manner in which mantle-derived melts interact with the crust.

Equilibrium experiments have been conducted using both piston cylinder and TZM apparatus at pressures ≤ 1.7 GPa at an fO2 corresponding to NNO. Both anhydrous and water-undersaturated conditions have been explored and the starting material is nominally carbon-free. All experiments have been conducted using the double capsule technique of Hall et al. (2004).

The 3.0 wt % H2O liquidus is found to be parallel to the anhydrous liquidus and has a temperature gradient of ~60ºC/GPa, increasing from 1260ºC at 1kbar to 1355ºC at 1.7 GPa. At the lowest pressures the liquidus phase is Cr-rich spinel; at P > 6kbar the liquidus assemblage becomes olivine + spinel. Clinopyroxene-in occurs 50-100ºC from the liquidus.

All experimental glasses have been analysed for CO_2 using SIMS. Significant carbon infiltration (< 1.2 wt %) has occurred in hydrous piston cylinder experiments but TZM run products remain relatively carbon-free (<500ppm), thus isolating graphite furnaces in the piston cylinder assembly as the source of the carbon. We discuss mechanisms for carbon diffusion and investigate techniques for limiting carbon contamination in piston cylinder experiments.

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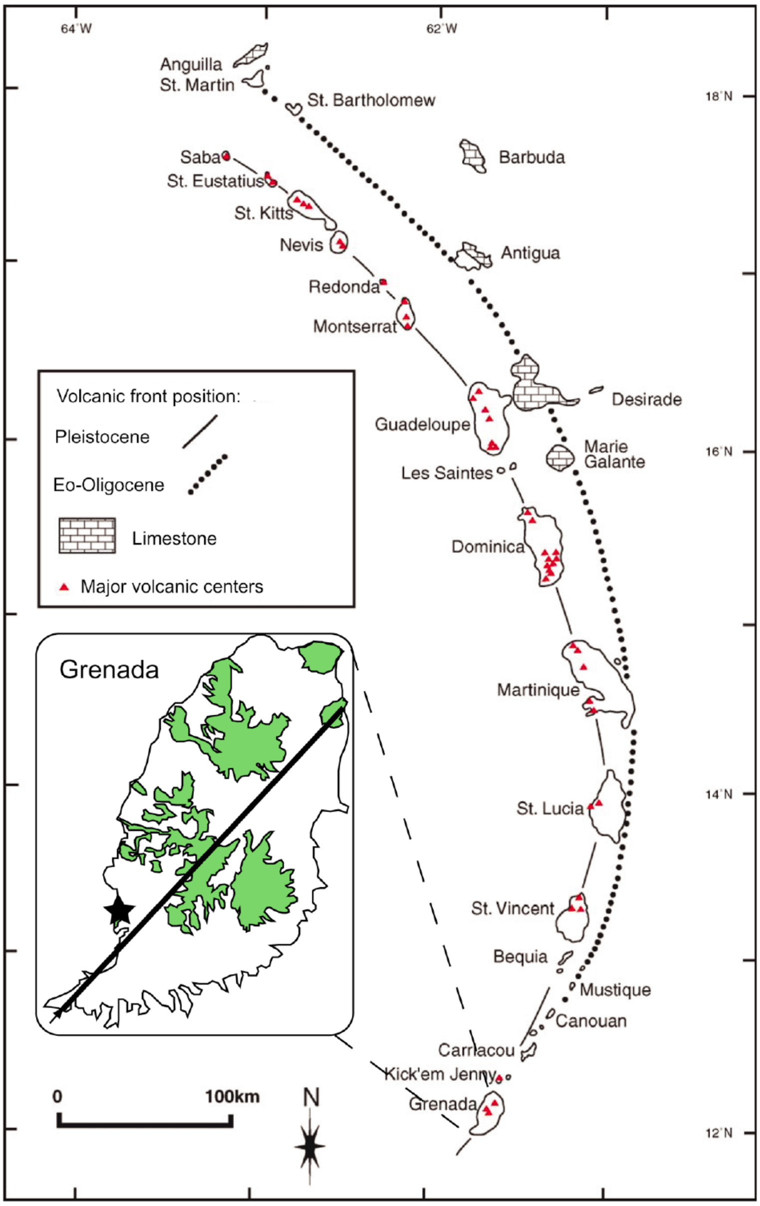

Figure 1. Position of Grenada within the island arc of the Lesser Antilles. Major volcanic centres on Grenada are shaded in green (Bouvier et al. 2010).

P 4.11

Field relations and consequences for emplacement of the Listino Ring Structure, Adamello Massif, N-Italy

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First described by Brack (1984, 1985), the Listino Ring Structure (LRS) in the tertiary Southern Adamello massif (Italy) consists of a 300-500 meter wide zone of well foliated, subvertical to steeply inwards dipping tonalite containing a large amount of elongated, mainly gabbroic, mafic enclaves, surrounding a core of fine-grained tonalite approximately 2.5 km in diameter. This zone itself is surrounded by fine- to medium-grained tonalites and is truncated by a granodiorite intrusion in the west. Deformation within the ring is mainly hyper-solidus (i.e. magmatic), although steeply dipping sub-solidus shears and joints are also present. The LRS is crosscut by several phases of syn- to post-plutonic dikes varying in composition from leucogranite to basalt. Recently, a more detailed study into the internal structure of the LRS, combining cross cutting and structural relations of the magmatic phases present has been made.

Cross cutting relationships found on the northeastern side of the LRS indicate the external tonalites (Monocola tonalite) are intruded by a gabbroic magma before they have completely crystallized. The resulting gabbroic enclaves can be up to several meters wide, have fine grained margins and form several 'enclave trains' parallel to the foliation in the tonalite. The tonalite within and immediately around these 'trains' contain coarse porphyritic plagioclase crystals and have diffuse margins with the Monocola tonalite. The tonalite in between the enclave trains is intruded by basalt dikes, which have been sheared into boudins. These are subsequently crosscut by diorite dikes, which form boudins in the tonalite between the enclave trains, but occur as enclaves within the enclave trains and can be found as nearly undeformed dikes outside of the LRS, giving insight into the localization of deformation around the LRS at the time of their intrusion. Two sets of tonalite dikes at right angles with each other crosscut all of these phases, still showing syn-magmatic deformation within the enclave trains of the LRS. These phases are crosscut by two-phase leucogranite dikes that appear to cut the LRS at right angles (radiating pattern) and may still record some syn-magmatic deformation. Plagioclase phyric granodiorite dikes that are closely associated with the LRS, but do not show any evidence for syn-magmatic deformation finally crosscut all of these.

As such, results from this study show an intricate relation between the relative timing, deformation and appearance in and outside of the LRS of magmatic phases present. At the conference, we will present geological models that may explain the development and evolution of the Listino Ring structure.

REFERENCES

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