

EUG XI



Symposium VPP4

What Is a Magma Chamber?

Convenors

David Pyle
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John MacLennan
Lucy MacGregor

VPP4

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Wednesday PM Session

VPP4 : WEpm25 : G4 Crustal Structure at a Slow Spreading Ridge: Seismic Images from 57°45'N on the Reykjanes Ridge

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The RAMESSES (Reykjanes Axial Melt Experiment: Structural Syntheses from Electromagnetics and Seismics) experiments targeted a section of the Reykjanes Ridge, part of the slow-spreading Mid-Atlantic Ridge extending from the Bright fracture zone to the south-west tip of Iceland. An axial volcanic ridge (AVR) centred at 57°45'N was chosen as the target as it demonstrated seabed features indicative of a recent phase of magmatic activity. The first cruise, undertaken in 1993, adopted a combined wide-angle, controlled-source electromagnetic and magnetotelluric approach to surveying, and imaged an axial crustal mush zone ~8 km in width and 2.5 km below the sea floor, overlain by a small melt lens (Sinha et al., 1998). A follow up survey was undertaken in 1998, during which 37 multichannel seismic profiles were shot over the AVR (5 axis-parallel, 32 cross-axis), with a 5172 in² airgun source fired at 37.5 m intervals and recorded on a 25 m group spacing 96 channel streamer. The aim of this second experiment was to constrain the location and lateral extent of the axial melt body, and its relationship with the structure of the surrounding crust and the morphological expression of the seabed. Using data from the southern end of the survey region, numerous reflection events within the upper 5 km of crust have been mapped. A strong shallow crustal reflection is present over much of the area between ~500 m and ~800 m below the seabed and is identified as representing the layer 2A/2B transition. Two other reflectors have also been imaged. The first is from a planar feature under the western flanks of the median valley which we interpret as a fault plane. The second, closely coincides with the top of the axial melt lens imaged during the first experiment, and is seen almost continuously along the entire length of the AVR.

Sinha MC, Constable SC, Peirce C, White A, Heinson G, MacGregor LM & Navin DA, *Geophys.J.Int.*, **135**, 731-745, (1998).

VPP4 : WEpm26 : G4 Magma Chamber Structure beneath the East Pacific Rise at the 9°03' N Overlapping Spreading Centre

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Models of mid-ocean ridge magma chambers have rapidly evolved in the last decade with the application of waveform inversion to seismic reflection data revealing a magmatic system dominated by a thin pure melt lens, underlain by a thicker, less molten region (Collier & Singh, 1998).

The acquisition of 3D seismic reflection data over a mid-ocean ridge system has revealed a robust magma supply for the overlapping spreading centre (OSC) with melt bodies underlying both limbs and melt present beneath large areas of the overlap basin (Kent et al., 2000). The ARAD (Anatomy of a Ridge Axis Discontinuity) survey allows us for the first time to map the magma chamber structure of a mid-ocean ridge system in three dimensions and enables an investigation of the physical properties within the magma chamber system.

Accurate post-stack 3D depth migration has been achieved using interval velocities from 3D tomographic inversion, providing insights into lateral movement of molten material within the discontinuity and the complex relationships between the molten material and the surrounding lithosphere which can only be truly determined using a 3D depth section.

Waveform inversion has been applied to the multi-channel seismic data in order to determine the physical properties of the magma bodies; producing results which corroborate previous ideas on how we define the geophysical magma chamber from limited seismic data. We present the first application of a 2D wavefield inversion scheme to mid-ocean ridge data.

Both 1D waveform and 2D wavefield inversion schemes have been applied over the propagating eastern limb of the OSC. The 1D inverted solutions have a magma chamber at a depth of ~2 km below the seabed with a melt lens of 30 m thickness laterally changing to a thicker, less molten 60 m thick region within 2 km. The pure melt region is defined by a P-wave velocity of 2.8 km/s and the less molten region is constrained by a P-wave velocity of 4 km/s, after Murase and McBirney's (1973) definition of the relationship between P-wave velocity and basaltic melt. These results are mirrored by the 2D wavefield inversion, which also maps a change in the magma chamber depth from 1.7 km below the seabed to 2.2 km over a lateral distance of 4 km.

Collier JS & Singh SC, *Modern Ocean Floor Processes and the Geological Record*, Geological Society, London, *Special Publication*, **148**, 17 - 28, (1998).

Kent, GM, Singh, SC, Harding, AJ, Sinha, MC, Orcutt, JA, Barton, PJ, White, RS, Bazin, S, Hobbs, RW, Tong, CH & Pye, JW, *Nature*, **406**, 614 - 619, (2000).

Murase T & McBirney AR, *Geological Society Of America Bulletin*, **84**, 3563 - 3592, (1973).

VPP4 : WEpm27 : G4 Geochemical and Geophysical Constraints on the Location of Magma Chambers under NE Iceland

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Magma chambers play an important role in the formation of the oceanic crust and in controlling the composition of magmas erupted at mid-ocean ridges. In recent years several geophysical surveys of active mid-ocean ridges have imaged small, shallow magma chambers under the ridge axis. These observations prompted a series of models of oceanic crustal accretion where magma is supplied directly from the mantle to the shallow melt lens, cooling and crystallisation takes place and then the solid material is advected to depth to generate the oceanic crustal thickness. In contrast, petrological and geochemical observations from the Oman ophiolite are consistent with crustal accretion models where crystallisation takes place in many small magma bodies which occur at a range of depths within the axial crust and uppermost mantle. The Krafla and Theistareykir volcanic systems in NE Iceland provide an excellent opportunity to characterise crustal accretion processes in a place where geological, geophysical and geochemical observations are plentiful. Seismic surveys of the Krafla area prompted by the 1975-84 eruptions revealed the presence of a shallow magma chamber under the Krafla caldera. However, petrological study of basalts and picrites from the Krafla area shows that this magma chamber is not the principal location of crystallisation under NE Iceland. The composition of both clinopyroxene crystals found in the samples and that of the rock samples themselves are not consistent with shallow crystallisation alone and show that crustal accretion took place at a range of depths from sub-Moho (>20 km depth) to upper crustal levels (<10 km depth). The major element trends observed in the lava samples can be explained if the material crystallising in the magma chambers under NE Iceland has a similar mean composition to that of the Oman cumulate gabbro. Material of this composition has similar seismic velocities to that observed for the crust in the seismic survey of Krafla. Therefore, both petrological and geophysical observations from NE Iceland are consistent with crustal accretion at a range of depths. An important implication of this study is that the magma chambers which have been observed by seismic surveys under mid-ocean ridges may not be those where most of the crystallisation under the ridge takes place.

VPP4 : WEpm28 : G4 Identifying Syn-Magmatic Tectonics in Iceland

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Eastern and Western Iceland are composed of Tertiary volcanics cross cut and thickened by various shallow level intrusions, most of them being known as magma chambers under eroded volcanic centres. These intrusions have different shapes, geometries, sizes, textures and compositions. In active Iceland, the emplacement of magmas occurs during seismic activity suggesting interactions between regional tectonics and magmatism. Most of the time, tectonic activity goes on during the cooling of the magmas. Thus, ductile to brittle deformation markers, recording regional strains as cooling proceeds, are expected to be observed within the magmatic rocks of the intrusions. However, in Icelandic rocks such evidences of deformation during crystallisation or solidification have never been described. The ability of a magmatic rock to record ductile deformation depends on several factors such as magma composition, temperature, crystal content and size, amount and rate of deformation. It also strongly depends on the time scale ratio between deformation and cooling. In shallow level intrusions undergoing rapid cooling, the probability of an intrusion to record regional strains becomes low, especially where country rocks suffer substantial thermal softening. In addition, the amount of displacement along faults during an eruption are rather small, which further reduces the probability to record associated strains within Icelandic magmatic rocks. Furthermore, the magma cannot record strain associated with a rapid tectonic event (earthquake) as long as the melt-crystal ratio is high. On the other hand, the intrusion can induce strain and thermal softening of older host-volcanics. As temperature increases and strain rate decreases, the ductile behaviour is favoured as the host-rock approaches its glass transition.

Among a variety of samples both from intrusions and their host-rocks in off axis areas, evidences of brittle deformation are common at different scales. However, they could indicate post-magmatic tectonics. In contrast, ductile deformation which provides evidence for syn-magmatic tectonics, have been observed only within few cases of host-volcanics. For example, some crystal-rich basaltic host-rocks display shear bands reorienting plagioclase microlites, whereas no deformation features were observed in the adjacent intrusion. This emphasises that syn-magmatic strain record are more likely to be found within country rocks of shallow level intrusions rather than within the intrusion itself.

VPP4 : WEpm29 : G4 Melt Distribution in a Partially Molten Crust: Some Insights from the Central Andes

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Geophysical observations point to the present existence of huge amount of melts in the crust below the central Andes (Schilling et al., 1997; Schmitz et al., 1997). The central Andes are an ideal place to study melt distributions in a continental crust. Because an enormous amount of geophysical studies were carried out in the framework of a Special Research Project (SFB 267, Deformation processes in the Andes) including seismic velocity by refraction and reflection studies, Vp-, Vs-velocities and wave absorption studies by seismological tomography, as well as electrical conductivity observations by magneto-telluric experiments, and gravity observations. Laboratory studies and model calculations were performed in conjunction with the field measurements to study the effect of partial melts on the physical properties of rocks. The melt distribution/melt structure were optically determined in the laboratory on quenched samples. Laboratory experiments on the electrical conductivity and elastic properties of partially molten rocks are used in combination with melt structure observations to get a detailed insight into the dependence of physical properties on the melt structure. The observations were

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modeled and different model approaches are tested. The interrelation of different properties allows to distinguish between melt isolated in pockets (magma chambers) and interconnected melt along grain boundaries or grain edges. The aim of this contribution is to use the interrelation of different physical properties to get a more detailed insight into the melt distribution of large areas, which have been inferred to be partially molten (Partzsch et al. 2000). The field observations are interpreted with respect to the laboratory experiments, while taking the scaling problem into account. The main results are: (1) Thermal modeling indicate, that most of the described melts are crustal melts, whereas ascending basic magmas from the mantle wedge seems to trigger crustal anatexis. (2) The field observations lead to the conclusion that most of the assumed partial melts in the central Andean crust are interconnected and not located in isolated magma chambers. (3) A stable solid network of rock is necessary to describe geophysical and geodynamic observations.

Acknowledgment: The financial support by the Deutsche Forschungsgemeinschaft (German Science Foundation) is gratefully acknowledged.

Partzsch GM, Schilling FR & Arndt, *Tectonophysics*, **317**, 189-203, (2000).

Schilling FR, Partzsch GM, Brasse H & Schwarz G, *Physics of the Earth and Planetary Interior*, **103**, 17-31, (1997).

Schmitz M, Heinsohn Wand Schilling FR, *Tectonophysics*, **270**, 313-326, (1997).

VPP4 : WEpm32 : G4

Determining Sr Isotope Systematics of Feldspar Crystals to Track Petrogenetic Pathways and Timescales

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Sr-isotope variations among and within single feldspar grains, particularly when combined with textural and elemental data, can be used to track open system magma evolution and crystal provenance, since the core-rim record of ⁸⁷Sr/⁸⁶Sr reflects the progressive change in ⁸⁷Sr/⁸⁶Sr of the magma from which the crystal grew. Sr isotope data can be obtained via microdrilling, chromatography, and standard TIMS, which provides high precision and accuracy but is time-consuming. Alternatively, laser ablation multi-collector ICP-MS can be used to determine ⁸⁷Sr/⁸⁶Sr on feldspars with comparable spatial resolution and precision, but only if Sr contents are high (>500 ppm) and Rb/Sr ratios low (<0.1). We have found that;

1. At Chaos Crags, CA, the provenance of feldspar crystals in quenched magmatic basaltic andesite inclusions and their dacitic hosts can be traced using core-rim ⁸⁷Sr/⁸⁶Sr data. The feldspars originate in the dacite (⁸⁷Sr/⁸⁶Sr ~ 0.7041) and are mechanically transferred into the mafic magma which now forms the inclusions. Consequently, a lower ⁸⁷Sr/⁸⁶Sr rim in equilibrium with the basaltic andesite, is grown on the ⁸⁷Sr/⁸⁶Sr = 0.7041 core. At El Chichin volcano, Mexico, plagioclases are characterized by consistent core-rim ⁸⁷Sr/⁸⁶Sr decreases, with core ratios considerably higher than those of bulk rocks. The observed core-rim decreasing ⁸⁷Sr/⁸⁶Sr, coupled with increasing Sr, can be explained by repeated recharge and cannibalization of plagioclase cumulates previously formed from a contaminated magma.

2. In the Rum layered intrusion of NW Scotland, cumulate minerals in a gabbro near to a unit boundary are not in isotopic equilibrium. Here, plagioclase cores have lower ⁸⁷Sr/⁸⁶Sr than rims, suggesting growth in from a progressively contaminated primitive magma.

3. In the Taylor Creek rhyolite of New Mexico, a core-rim record of increasing then decreasing ⁸⁷Sr/⁸⁶Sr, reflecting contamination then recharge, is found in the largest sanidine crystals, with smaller crystals retaining truncated records. This suggests that the crystals grew in a common magma system, with smaller crystals nucleating later and recording only later stages of evolution. The high Rb/Sr, low Sr of the sanidines preclude analysis by laser multi-collector ICP-MS, and demand chromatographic separation of Sr from Rb to generate precise and accurate ⁸⁷Sr/⁸⁶Sr.

We note that in addition to elucidating petrogenetic pathways, the single crystal Sr isotope data can be used to help constrain the timescales of magmatic processes. For instance, the mere existence of isotopic differences over 1-2 mm in single feldspar grains in the plutonic Rum rocks precludes them being held at high temperatures for long times. Given well-constrained Sr self-diffusion coefficients we should be better able to constrain cooling histories. Similarly, the length scale over which ⁸⁷Sr/⁸⁶Sr changes in volcanic plagioclases is diffusion-limited and might be used to obtain residence times of crystals in a magma reservoir.

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Volcanic Power Outputs and U-series Age Constraints: A Link between Crystallisation Processes and Magma Differentiation

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The development of improved analytical techniques for U-series isotopes, and in situ trace element measurements have provided powerful incentives for further investigation of the time scales of magma differentiation processes. Crystals preserve high resolution records of changing magma compositions. However, while the ages of crystals can be determined, and in a number of cases these have been shown to be significantly older than the age of eruption, it is difficult to link the ages of crystals with the time scales of magma differentiation. An alternative approach is to consider U-series isotope ratios in the magma, and how these may change with degree of magma evolution. In one such study, on the island of Tenerife, it has been shown differentiation from basanite to phonolite, by up to approx. 80% fractional crystallisation, may have taken ~200 ky (Thomas et al., in prep). In detail, differentiation took place at depths equivalent to pressures of 6-10 kbars and then 2-3 kbars, and the average rate of differentiation was significantly slower at the greater depths. A model is explored in which fractional crystallisation is driven by the falling temperature of the magma, and the apparent rate of fractional crystallisation implied by the U-Th isotope data can be linked to the thermal power output from the magma chambers. At least until alkali feldspar becomes a fractionating phase, the temperature of Tenerife liquids is linearly related to the amount of fractional crystallisation. For average power outputs in the range 0.1 to 1 GW, the model implies a deep chamber fractionating basalt to intermediate magmas with a volume of order 103 km³ and a shallow chamber fractionating intermediate to evolved magmas with a volume of order 102 km³, over a total period of ~200 ky. Such time scales will be compared with those that might be inferred from the rate of change of magma composition with stratigraphic position.

VPP4 : WEpm34 : G4

Magma Chamber Processes Reflected in Major, Minor and Trace Element Plagioclase Zoning (Parinacota Volcano, Chile)

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Parinacota volcano (Chile, Central Volcanic Zone of the Andes) is characterized by five volcanic stages: Chungara Andesite and Rhyolite Plateau (264-110 ka), Old Cone (53-18 ka), cone collapse (18 ka), Healing Stage (<18 ka), where the cone was rebuilt, and recent satellite cones (Ajata, ~ 6km). Rock compositions range from mafic andesites to rhyolites. Two types of almost phenocryst-free parent mafic andesites (high-Sr and low-Sr) are found in Ajata. We investigated major, minor and trace element zoning patterns in plagioclases from the three last volcanic stages. Al, Si, Ca, Na, K, Fe, Ti, Ba, Sr, Mg were analyzed with electron microprobe and major element zoning patterns documented by back-scattered electron images. Plagioclase phenocrysts are characterized by oscillatory zoning and various forms, degree, and frequency of resorption. Minor and trace elements zoning patterns show following features: Whereas Fe, Ti, Mg are very well correlated with whole rock silica content in Parinacota samples, these elements are correlated with An content only in some oscillatory zoned plagioclases from the Old Cone, reflecting differentiation of the melt. In the other cases

(Healing Flow, Ajata and resorbed crystals from the Old Cone), the absence of correlation indicates variable control by other parameters (temperature, pressure, water content and oxygen fugacity) either on plagioclase An-content or on partition coefficients. Sr and Ba partition coefficients allow calculation of their melt concentration and provide evidence for the type of the parent magma (high/low Sr) and recharge events. Old-Cone samples show at most one major recharge event. A dacite has mainly plagioclase grown from the Sr-poor parent showing differentiation without significant recharge. A basaltic andesite shows initial plagioclase growth from the high-Sr parent followed by recharge with mafic low-Sr parent magma. Plagioclase phenocrysts in a typical andesite are only inherited, rhyolitic crystals (very low Sr, Ba, K, Fe, Mg Ti) with resorption at the rim and regrowth in the mafic, Sr-rich magma. Healing Stage and Ajata andesites, by contrast, show multiple resorption and larger ranges in Fe/Sr. This indicates frequent recharge events with both high-Sr and low-Sr mafic magmas. Trace element zoning patterns in plagioclase thus reflect changes in style and rates of magma chamber processes (recharge, eruption): Old Cone evolution suggests protracted magmatic differentiation at low magma production and eruption rate. Young Cone lavas (Healing Stage and Ajata) are characterized by high magma eruption and recharge rates. The two mafic end-members (equivalent to Ajata stage) played a role throughout the history of the volcano.

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Magma Dynamics beneath Piton de la Fournaise Volcano, Reunion Islands, as Inferred from U-series Disequilibria

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Magma chamber residence time and transfer time of magma under active volcanoes can, in favorable cases, be estimated from U-series nuclides. Several historic and prehistoric lava flows from Piton de la Fournaise have been analyzed for U and Th abundances and Th isotope ratios. The radioactive disequilibria ²³²Th-²²⁸Ra and ²³⁰Th-²²⁶Ra-²¹⁰Pb have been measured in a few lavas as well. The samples have uniform Th/U value of 3.95 ±0.03 (2SE, n=33) and identical Th isotope ratio (0.934 ±0.006; n=10) and, therefore, a constant 20% excess of ²³⁰Th over ²³⁸U. All analyzed samples are in ²²⁸Ra-²³²Th radioactive equilibrium, but the (²¹⁰Pb/²²⁶Ra) values at the time of eruption range from 0.75 to 0.39. Lava flows erupted through the summit craters or the rift zones during the last three centuries, have uniform (²²⁶Ra/²³⁰Th) ratios of 1.30±0.01 (n=13). The eccentric craters northwest of the volcano erupted basalts of a more primitive compositions with (²²⁶Ra/²³⁰Th) values identical to those of the 20th century oceanites, or 1.40±0.01 (n=9). Crystal fractionation and accumulation have caused the Th and U abundances to vary by a factor of 2 from oceanites to the most evolved basalts. Basalts with a Th content lower than 2.25 ppm have only been produced in eruptions outside the Enclos caldera, whereas more evolved basalts are predominantly observed close to the summit, inside the caldera. The more primitive basalts with higher (²²⁶Ra/²³⁰Th) could represent the mantle derived magma entering a central reservoir. The constant (²²⁶Ra/²³⁰Th) ratios of 1.30 could then correspond to a steady-state value, and the residence time for this central magma reservoir can be estimated as a few hundred years. Taking into account the present day lava production rate, a liquid reservoir volume of a few km³ is derived. Several lines of evidence indicate that this magma reservoir is most probably located at a depth greater than 6 km beneath the volcano.

The steady-state basalts can be assumed to leave the deep reservoir with ²¹⁰Pb-²²⁶Ra in radioactive equilibrium. This magma enters the dyke and sill complex that has been inferred at sea level or 2500 m beneath the summit craters. Vigorous degassing of water is expected at this depth and if ²²²Rn escapes quantitatively from the magma, unsupported ²¹⁰Pb decay would indicate the transfer time through the shallow reservoir. The measured deficiencies of ²¹⁰Pb suggest a decreasing transfer time through the dyke complex from approximately 30 years in 1961 to 10 years in 1998.

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²³⁰Th-²³⁸U Disequilibrium in Zircons from the Post-Caldera Sequence at Taupo Volcano, New Zealand: Constraints on Pre-Eruptive Processes

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What is a rhyolite magma chamber - a large, long-lived fractionating liquid body, or a 'sleepy' crystal mush that gets kicked into life every so often, re-mobilizing existing material? What do crystals really represent - phenocrysts vs. xenocrysts - and what 'memory' do they retain? Related to these issues are questions such as does crystal growth and dissolution reflect protracted fractionation of a single magma body or remobilization and dispersal of crystal mush during injection of fresh magma into the subvolcanic system?

Recent work using ⁴⁰Ar/³⁹Ar, Rb/Sr or U-series isotope data has led to the suggestion that rhyolite magmas in the Long Valley system are stored, following differentiation, for long (10⁵-10⁶ yr.) time scales. This contention has been disputed principally on the basis that it would be difficult to keep a body of magma thermally viable for such long periods, even if >500 km³ volume. Alternative physical models have been proposed, such as remobilization of juvenile plutons or cumulate materials and ion microprobe work on zircons has variously upheld or contested the claims for long magma residence times.

We address these contentious issues through a study of ²³⁸U-²³⁰Th disequilibrium systematics in zircons from young eruptive sequences from Taupo volcano in North Island, New Zealand. Zircon is particularly useful for dating <350 ka crystallisation events since it strongly fractionates U from Th and thus precisely constrains isochrons on the equiline diagram. Use of TIMS techniques here yields high precision (±2-5%) and an ability to date zircons as young as 16 ka, while analysis of various crystal size fractions has yielded information on the variability of the zircon age population.

At Taupo, U-Th isochrons from, and modelling of Zr-saturation in, eruptives following the climatic ~530 km³, 26.5 ka Oruanui eruption imply that part to all of the zircon derives from remobilisation of older (but still <350 ka) silicic intrusives. This 'xenocrystic' fraction has been overgrown in Zr-saturated magmas by material crystallised over a short period (e.g., 4-10 ka) prior to the eruption. On this basis, generation of rhyolites erupted after the caldera-forming event must be extremely rapid.

Comparisons between chemical/isotopic characteristics and volume/frequency relationships of Taupo post-caldera rhyolites imply that although the former result from AFC processes, generation of particular magma volumes for eruptions must involve large-scale remobilisation of older, sub-solidus silicic intrusives.

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Short-Lived Radioactive Disequilibrium (²¹⁰Pb, ²¹⁰Bi, ²¹⁰Po) in Volcanic Gases at Merapi, Central Java, Indonesia: Constraints on the Magma Chamber Dynamics and the Eruptive Behavior

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Merapi volcano is one of the most active and dangerous Indonesian volcano. Its volcanic activity is characterized by the slow growth of an andesitic lava dome that ultimately collapses during pyroclastic events. This lava extrusion is associated with continuous degassing at two high-temperature fumarolic fields and through cracks crossing the lava dome emplaced within the summit crater. For 20 years, volcanic aerosols and gases have been collected at intervals of a few years at both fumarolic fields and summit crater, and analyzed for short-lived radionuclides (²¹⁰Po, ²¹⁰Bi, and ²¹⁰Pb). These three nuclides are considerably enriched and fractionated in volcanic gases according to their specific

emanation coefficients ϵ . Because Po is more volatile than Bi and Pb ($\epsilon_{Po}=100\%$, $\epsilon_{Bi}=10-20\%$, and $\epsilon_{Pb}=1\%$ for basalts; 50-85%, 5%, and 1%, respectively, for andesites), ²¹⁰Po/²¹⁰Pb and ²¹⁰Bi/²¹⁰Pb activity ratios may be used to decipher primary magmatic gases signature. ²¹⁰Po/²¹⁰Pb ratios measured on the growing lava dome are lower than 1 and are interpreted to result from the secondary degassing of a magma that previously degassed its polonium. On the other hand, medium to high ²¹⁰Po/²¹⁰Pb ratios recorded at both fumarolic fields and in the summit crater main plume correspond to a primary magmatic vapor. However, at fumarolic fields, very high ²¹⁰Bi/²¹⁰Pb ratios suggest that, besides the magmatic component, ²¹⁰Bi atoms formed by Pb-sublimates decay contribute to the gas. Consequently, the main plume represents the most primary and unaltered magmatic gases. Based on the idea that radionuclides degassing takes place in a shallow steady-state chamber fed by deep undegassed magma in ²¹⁰Po-²¹⁰Bi-²¹⁰Pb radioactive equilibrium, we propose a model accounting for the time-variation of activity ratios in this main plume. Due to the radioactive properties of the three nuclides, this model allows characterization of both the escape time of gases from the reservoir and the magma chamber residence time. Escape time is estimated at about one week in 1995, longer than usual values for basalts (usually a few hours), which reflects higher magma viscosity preventing rapid gas escape. Magma turnover also appears slower than at basaltic volcanoes with magma residence times varying from 500 days in 1995 to 5.5 years in 1978-79 and 14 years during the 1984-92 period. Combined to a deep magma supply beneath Merapi in the range 0.07 - 0.7x10⁶ m³/month, these residence times yield a volume of about 10⁷ m³ for the degassing reservoir. The dynamical parameters inferred from the model are correlated with the eruptive activity at the surface. We suggest that eruptive cycles observed at Merapi strongly depend on the magma dynamics and can be explained by sudden departure from steady-state behavior followed by continuous pressure increase beneath the lava dome.

VPP4 : WEpm38 : G4

Self-Mixing in Magma Chambers

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A central aspect of defining magma chambers is the understanding of the processes that occur within them. We present work to suggest that self-mixing of material within magma chambers may play a major role in producing the textural variation seen in igneous rocks on a local scale. If mafic material is intruded into the base of a more silicic magma body, the siliceous material adjacent to the intrusion will become heated. With time this material will become unstable as its density decreases, thus convection can be initiated which occurs solely within the silicic magma. Hot boundary layer magma stirred into the chamber interior will be quenched, resulting in crystallisation of anomalously high temperature minerals as overgrowth rims and microphenocrysts. Convection mixes together parcels of magma with the same composition, but with large variations in thermal history, resulting in disequilibrium textures, and diverse mineral compositions. Our study shows that it is not necessary to explain disequilibrium features in magmas by mixing of different magmas. These concepts can be applied to interpret the origin of the Soufriere Hills andesite, Montserrat, hornblende microlites found in Mount Unzen eruptive products, and rapakivi textures in granites. We estimate that the convection could be initiated in the order of tens of days for the Soufriere Hills andesite, Montserrat. We conclude that magma chambers can be perceived as near-solid bodies, which are reactivated and heated by influx of hotter material and processes such as self-mixing.

Wednesday PO Session

VPP4 : WEpo01 : PO

Evolution of Magmatic Melts of the Volcano Elbrus and Problem of the Magma Chamber

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The volcano Elbrus is located on the Central uplift of the Greater Caucasus. The volcanic activity began in Eopleistocene and consisted of 6 phases, lasted up to 2000 years ago. The Elbrus near surface magma chamber is situated at the depth about 1 km relative to the sea level. The lower part of the magma chamber is situated at the -10 km depth. In accordance with geophysical studies there are some 'waveguides' (6.8-6.9 km/sec) in the depths 20-25 km. This 'waveguides' can be explained by existing intracrustal magmagenation zones with high temperature, developing leake and partial melting of the rocks. Volcanism is represented by calc-alkaline series and had antitropical nature to evolutions from rhyolites to dacites. All types of volcanites are characterized by the low concentration of Ti, Fe, Y, Cu, Zn, Ni, Cr, heavy REE and high concentration of Al, Na, K, Rb, Sr, Ba, Nb, Zr, light REE. Porphyric structures with phenocrysts of feldspats, augite, hypersthene, biotite, hornblende, quartz, magnetite are typical. Elaborate study of phenocrysts chemical composition, forming glomeroporphyric aggregates in the Elbrus dacites, has allowed to find PT conditions evolution, the melt had been before its appearance on the day surface. The most early parageneses Amf+Pl, Amf+Cpx+Pl point to minimum temperatures of the melt (T=750-780°C), whereas later ones - Opx+Pl, Opx+Pl+Bi - to high temperatures (T=850-1150°C). At first there was increasing of both as temperatures as pressures. Then the pressure, having reached maximum (1.42 MPa) of T=1000°C, began to fall, but the temperature had risen up to 1150°C. That was accompanied by changing of melt chemical composition - toward the more alumina and less calcium. Taking into consideration the design pressure of primary magmas generations (1.02 MPa), it is possible to draw a conclusion that the silicate melt undergone the additional extra pressure (over lithostatic one) 0.4 MPa, stipulated by continental collision process. The silicate melt is capable to bear a surplus comparatively for a long time, sufficient for crystallisation of phenocrysts. High internal pressure, overheat and low viscosity of magma ensure a quick transport it to surfaces. The increasing of the fluid pressure on melt has stipulated also processes of liquation marked in Holocene Elbrus eutaxitic dacites. Volcanic rocks, forming different colour parts, differ in contents of Ti, Cr, Mn, Ni, Na, K, P and normative ratios of albite, orthoclase, pyroxenes, corundum and quartz as well. The melt exfoliation comes about under the influence of the pressurised fluid flow. It confirmed by abundance of ignimbrites in the Elbrus volcanic rocks and highexplosion volcanism type.

VPP4 : WEpo02 : PO

Qz-Syenites in Ignimbrites on Gran Canaria (Canary Islands, Spain): Long-Living Felsic Magma Chambers on Ocean Islands

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A long-lived felsic magmatic system on Gran Canaria produced >300 km³ rhyolitic-trachytic volcanic rocks in the period 14 to 13 Ma. Qz-syenite fragments in ignimbrites record processes inside this system that are not preserved in the extrusive volcanic rocks. Large feldspar crystals in the syenites forming an interlocking framework or dispersed in fine-grained matrix of ternary minimum composition show the following features: (1) euhedral plagioclase with symmetrical normal zonation (An40-6), (2) asymmetrical zonation and fragmented shape, (3) highly irregular to alternating zonation of both 1 and 2, (4) turbid albite to minimum feldspar overgrowth rims on 1 to 3, and (5) variable subsolidus exsolution of 1 to 4. While crystals 1 may represent comagmatic cumulus phases, crystals 2 and 3 reflect a complex crystallization history involving repeated recycling of older feldspar crystals. Overgrowth records late intrusion of highly evolved melt into the cumulate mush pile. Spatially variable cooling rates and quenching temperatures in the system are suggested by great differences in crystal size and exsolution features (5) between syenite fragments. Incompatible trace element ratios and

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REE-patterns are identical to the host ignimbrites; syenites relatively enriched in trace elements document extended differentiation during extended cooling whereas relatively depleted syenites record escape of up to 40% of interstitial melt from the cumulate mush. Though all syenites are comagmatic in as much as they are derived from the same long-lived system, variations in chemical composition, crystalline textures, and proportions of feldspar types 1 to 3 show a complete range from comagmatic to recycled feldspar crystals and from syenites almost entirely coeval to the ignimbrite host magma to syenites almost entirely composed of recycled feldspar material from earlier evolutionary stages of the system.

VPP4 : WEpo03 : PO Constraints on U-series Nuclides on the Magma Plumbing System beneath Galunggung Volcano (Sunda Arc, Indonesia)

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The 1982-83 activity at Galunggung volcano (Sunda arc, Indonesia) produced magmas ranging in composition from andesites to rather primitive basalts at the end of the eruption. Such compositional variations are commonly explained by the presence of a density stratified magma chamber, where density decreases with magma differentiation. The timescale of magma differentiation can, in principle, be estimate from U-series nuclides. The Galunggung lavas show small but significant ²³⁸U excess over ²³⁰Th (8-15%) and ²²⁶Ra excess over ²³⁰Th. The (²²⁶Ra/²³⁰Th) ratio decreases with differentiation: the values ranges from 2.30 to 1.77 with Th content increasing from 0.756 ppm to 2.01 ppm. Most samples have ²¹⁰Pb in radioactive equilibrium with ²²⁶Ra, except one phreatomagmatic bomb.

Several studies have shown that ²²⁶Ra is more compatible in plagioclase compared to olivine, pyroxenes, and oxides which are the other phenocryst phases in Galunggung lavas. The decreasing (²²⁶Ra/²³⁰Th) might therefore in part be related to plagioclases differentiation before the 1982 eruption. We can compare the Ba and ²²⁶Ra which are supposed to have an analogue behaviour during fractional crystallisation. In contrast to the regular decrease of (²²⁶Ra/²³⁰Th) with increasing Th content, the Ba/Th values show two different correlations. Moreover, Ni contents decrease faster between basaltic andesites and andesites compared to the much slower Ni depletion between Mg-rich basalts and basaltic andesites (Gerbe et al., 1991). Fractional crystallisation from a single parental magma is therefore excluded. On the other hand, two-stage magma mixing can explain the geochemical results. These stages emerge from Ba/Th versus 1/Th and (²²⁶Ra/Ba versus (²³⁰Th)/Ba diagrams where two distinct correlations are observed, clearly suggesting two independent mixing series. The first suite is defined by the basalts, whereas the second one is composed of basaltic andesites to andesites. The presence of these two series suggests that the 1982-83 Galunggung magmas evolved in spatially separated but interconnected magma chambers.

This study shows that decreasing (²²⁶Ra/²³⁰Th) with differentiation are not always related to the duration of magma evolution. In the case of Galunggung, the timescale of differentiation appears to be very short compared to the half-life of ²²⁶Ra (<< 1600 years).

Gerbe MC, Gourgaud A, Sigmarsson O, Harmon R, Joron JL, Provost A, *Bull. Vol.*, **54**, 284-298, (1991).

VPP4 : WEpo04 : PO Layering in the Fongen-Hyllingen Intrusion, Norway

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The 160 km² Fongen-Hyllingen Intrusion (FHI) is situated 60 km southeast of Trondheim. It was synorogically emplaced about 426 Ma ago, close to a lithological contact between metabasalts and metapelites. The mineralogy of the contact metamorphic aureole indicates that intrusion took place at 3-4Kb. There is a total thickness of ca.5.5 km of modally-layered cumulates which range in composition from olivine gabbros (with Fo73 and An65) to quartz-bearing syenites with low temperature end-member minerals at the roof. Numerous compositional reversals reflect repeated magma replenishment. The overall composition of the intrusion is dioritic, implying a broadly andesitic parental magma. Abundant raft-like country rock inclusions (dominantly of metabasaltic hornfels) are a major feature in the lower part of the layered series. The intrusion was emplaced before regional deformation and metamorphism in amphibolite facies. Deformation of the intrusion has resulted in exposure of the entire layered series from the floor to the roof so that reconstruction of the shape of the chamber is possible. Primary igneous features are extensively preserved despite the synorogenic timing of emplacement.

Studies of layer-forming processes were started in 1999 when field observations and sample collection were carried out in two areas immediately north of Fongen summit. Karin Josephsen is studying a 6.5 m-thick representative profile with ca. 50 well-developed cumulate layers to determine the nature of the processes responsible for layer-formation. Individual modal layers generally vary from 2-30 cm in thickness and are defined by variations in proportions of cumulus plagioclase, olivine, two pyroxenes and FeTi-oxide. The grain size is usually between 1 and 3 mm. Layer types vary from isomodal to reverse- and normally graded. Samples have been collected to determine the detailed modal and grain size variation as well as the mineral chemistry. Four orientated samples will be studied to determine if there is a lineation. It is hoped that the possible roles of processes including crystal settling, current deposition and in situ crystallisation will be able to be assessed. Dorthe Holm is studying a huge metabasaltic inclusion with a total thickness of more than ca. 500 m. The lower contact is concordant to modal layering in the FHI cumulates. The inclusion is dominated by granular metabasaltic hornfels, but shows a wide textural variation including ultramafic segregations, alternating mafic and felsic bands (a type of modal layering) and globular patches of granoblastic metabasalt in a gabbroic matrix. The aim is to determine the nature of the processes that were responsible for the development of the modal layering within, and apparent partial melting of, the metabasaltic inclusion.

VPP4 : WEpo05 : PO Evolution of Vesuvius Magma Chamber-Wall Rock Interface as Constrained by Fluid Inclusion Study

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Previous works have shown that the Vesuvius system is characterized by the constant presence of shallow reservoirs, hosted within the carbonate Mesozoic basement and periodically supplied through discrete K-basaltic to K-tephritic mafic magma batches. It has been suggested that the growth with time of these magma chambers is accompanied by changes in aspect ratio and compositional layering: (1) initial stage, high aspect ratio 1906-1944-type chamber, moderate volume (0.01-0.1 km³), almost homogeneous mafic melt downward enriched in crystals; (2) young stage, medium aspect ratio 'Pollena-type' chamber, medium volume (0.1-0.5 km³), gradual, almost continuous gradient from mildly evolved to felsic melt; (3) mature stage, low aspect ratio 'Pompeii-type' chamber, large volume (0.5-5 km³), twofold layering with stepwise gradient separating the lower, mildly evolved

portion from the upper felsic portion. The protracted stagnation of magma at shallow crustal levels implies chemical reactions, metasomatic and thermometamorphic transformations inducing the formation of variously complex, roughly stratified shells between magma and country rocks. The outer portion of the magma body is formed by a highly crystallized margin, expanding with time, while changing its composition from glass-bearing fergusonite to foid-bearing K-syenite. From this, the transition to the country rocks occurs throughout a skarn shell, resulting from reciprocal diffusion metasomatism between carbonates and magma, and thermometamorphic marble. In the case of a high-T early magma chamber, the thin both magmatic and skarn shells record a nearly direct magma-carbonate contact with formation of contaminated melts by the addition to magma of Ca and Mg (deriving from decarbonation reaction and/or melting of host rocks). These melts are the main metasomatizing agents forming the complex skarn shell consisting of layers cooling outwards: melilitite- and phlogopite-bearing skarns. With increasing size of the chamber and thickness of its highly crystallized margin, a direct magmatic melt-carbonate contact is progressively prevented and high-T modified melts have more and more difficulty to form and to act as skarn-forming carriers of elements. The presence of melt and hypersaline fluid inclusions in xenoliths testifies of the fluid exsolution at the peripheral portions of the young Vesuvius magma chambers and of the changed metasomatizing carrier. The magmatic brines provide in fact the reactive solutes for the skarn-forming reactions with carbonate rocks. The brines temperature is lower than that of modified melts and this is reflected by the disappearance of melilitite-bearing skarn. In a further mature stage of evolution (Pompeii chamber), multiphase hypersaline fluid inclusions evidence a not uniform composition of the exsolved fluid phase, which can be either chloride- or fluoride-bearing. The Cl and F melt/fluid partition coefficients suggest that the Cl-brine was produced by early exsolved fluids, while a F-brine may represent the latest fluids released from the crystallizing magma.

VPP4 : WEpo06 : PO Study of a Triassic Shallow Magma Chamber: The Subvolcanic Bodies of Montecampione (Southern Alps, Northern Italy)

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The study of shallow magma chambers of deeply eroded ancient volcanoes allows to understand their feeding system and the stress field influencing volcanic edifices, and then to apply these information in different geodynamic and tectonic settings in order to better understand active volcanoes, where these shallow magma chambers are revealed only indirectly by geophysical methods. Coherent intrusion complexes are seen in all major eroded volcanoes (Walker 1992), and it's estimated that they intruded under the volcanic edifice at depths that range from less than 1 km to 4 km (Borgia et al. 1992, Mudge 1968). Walker (1992) proposes two main typologies for them (dyke complexes and sheet complexes) in relation to the possibility or not for the volcanic edifice to freely expand laterally on a basal décollement (as in the case of M. Etna, Borgia et al. 1992): this possibility or its lack determine the direction of extension (horizontal or vertical) accommodating magma injections.

The study of the subvolcanic bodies belonging to the group of Montecampione (Corazzato et al., in press), located in the Southern Alps, is an approach to the comprehension of shallow magma chambers related to ancient eroded volcanoes. These subvolcanic bodies are mainly laccolithical bodies and sills, intruded into an upper carboniferous-lower triassic sedimentary sequence. The radiometric age of these bodies (Cassinis & Zezza 1982) sets them in the scenery of the middle-upper Triassic (Ladinian-Carnian) volcanism, which products are widespread through the Southern Alps. Coeval pyroclastic fall layers interbedded in the sedimentary succession (Pasquare & Rossi 1969) and volcanoclastic deposits (Arenarie di Val Sabbia) were related to the presence of volcanic edifices (Cassinis & Zezza 1982) in the studied area. The intrusion depth of the subvolcanic bodies can be estimated 1.5 km, basing on the thickness of the sedimentary overburden measured in adjacent areas where preserved sections crop out. The area interested by these intrusions is 10 km², and the minimum volume we

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Thursday AM Session

VPP4 : THam01 : G4 Glimpses into the Crystallization History of Carbonatitic Melts – An Isotopic Approach

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Although most of the isotopic information about the mantle has been obtained from oceanic basalts, carbonatites provide a valuable alternative into monitoring the chemical evolution of the sub-continental mantle. Not only are most young carbonatites similar in Nd, Sr and Pb isotopic compositions to many OIBs, but the isotopic ratios of some are similar to end-member compositions that characterize some mantle components. Most measurements from carbonatites have been made of whole rocks rather than separated mineral grains, which means that their isotopic compositions represent a weighted average of the individual minerals and of the melt from which they crystallized, assuming that all of the minerals crystallized at the same time. In a preliminary attempt to evaluate the isotopic composition of carbonatites on a grain by grain basis, a laser-ablation ICP-MS study was undertaken of several carbonatites and associated silicate rocks from Canada, East Africa, Finland, Namibia and Russia. Analyses were made of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from both calcite and apatite at the University of Quebec in Montreal, Canada. Apatite, on the basis of these findings, shows considerable promise for ICP-MS work. It is not only rich in Sr but provides runs just as, or more, stable than those from calcite. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for both apatite and calcite from carbonatites were measured with uncertainties of about 0.01%, some closely approaching those of conventional thermal-ionization mass spectrometry (TIMS). The apatite analyses reported here are the first from igneous rocks using ICP-MS. Isotopic equilibrium between co-existing apatite and calcite has been found in some carbonatites (e.g. Siilinjärvi, Finland; Dicker Willem, Namibia), and their average values are in excellent agreement with those obtained by conventional TIMS. Some complexes, however, such as Sukulu (Uganda), and Oka (Canada), are not in isotope equilibrium and isotopic differences from grain to grain on the scale of a thin section can be as much as 4 parts in 7000. These isotopic differences are found not only in apatite, but also in calcite. Of even more significance is the finding that even individual grains show significant isotopic differences (e.g. apatite, Oka, 0.7031-0.7035). To change the Sr isotopic composition of carbonatitic melts by simple assimilation is difficult because of their unusually high Sr contents. One way of producing isotopic disequilibrium from grain to grain involves magma recharge with carbonated melts of different isotopic compositions, coupled with precipitation of apatite and calcite crystals that then behave as cumulus phases. Isotopic similarities from grain to grain might thus provide a means of correlating grains that formed under similar conditions of crystallization, and might even help to evaluate the relative timing of crystal formation.

VPP4 : THam02 : G4 Magmatic Structures in the Lower Proterozoic Orogenic Mäntsälä Mafic-ultramafic Intrusions, Southern Finland

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Most of the Finnish Svecofennian (1.9-1.8 Ga) mafic-ultramafic intrusions are layered. This is the case of the Hyvinkää-Mäntsälä Gabbroic Belt (HMGB) in southern Finland. The HMGB consists of tholeiitic syn-orogenic (1.88-1.87 Ga) intrusions, representing island-arc magmatism, intruded into the 1.9 Ga volcano-sedimentary Häme Belt. The Mäntsälä region has nine different sized (4 to 50 km²) gabbroic, hornblenditic and anorthitic intrusions, which are all layered. The most important are the Hirvihaara and the Soukkio Gabbros. Both intrusions are concentric and differentiated, surrounded by metavolcanic rocks and granitoids.

Layering in the mafic-ultramafic rocks at Soukkio is well developed along the western border of the intrusion, whereas along the eastern and southern margins the mafic

rocks are mingled and mixed with the Soukkio Granite. Layering of the western part occurs within a sequence of anorthosites and pyroxenites as cross-stratification, trough-structures, slumps and scour-and-fill structures. These structures represent dynamic processes at a margin of the magma chamber, where cumulates collapsed, fell down and flowed to the floor of the magma chamber in density currents. Above this sequence there are massive and layered mafic-ultramafic cumulates with irregular anorthosite lenses. Anorthosite lenses are remnants of less-dense anorthosite diapires that swelled into the mafic magma from the crystallized layers below, where such upwelling structures are found. Overlaying the mafic cumulates is a layer with abundant xenoliths of volcanic rocks that are oriented parallel to the border of the intrusion, likely due to a magma flow. This part of the Soukkio intrusion also includes various layered alternations of mafic, ultra-mafic and felsic ribbon-like layers, dykes and pipes. Thin (0.1 to 15 m) mafic layers are fine grained, and represent chilled mafic magma against felsic magma. Pressure-release structures are found in the eastern margin of the Soukkio intrusion. These structures probably indicate intrusion of late-magmatic melts through the mafic cumulates. The layering and many of the mingling features of the Soukkio complex are similar to the structures described within the Mafic-Silicic Layered Intrusions from Coastal Maine, USA, where mafic magma was injected into a silicic magma chamber and trapped.

The Hirvihaara gabbro was formed by both dynamic and non-dynamic magmatic processes. Layering is well developed in the northern part of the intrusion whereas in the southern border it is absent. Mafic cumulate layers have suffered syn- to post-cumulative processes, are disrupted and occur sometimes as autoliths.

The Svecofennian HMGB mafic-ultramafic intrusions prove that orogenic gabbros include well developed layering comparable to the classic layered intrusions emplaced in cratonic settings.

VPP4 : THam03 : G4 The Workings of a Magma Chamber: The Fongen-Hyllingen Layered Intrusion

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The 160 km² Fongen-Hyllingen Intrusion (FHI) is a synorogenic layered mafic intrusion of Caledonian age located 60 km southeast of Trondheim, Norway. Lateral correlation along 40 km of strike length through ca. 6 km of layered cumulates has allowed reconstruction of the form and evolution of the magma chamber. The chamber has the form of a double-bottomed bowl with an asymmetrical wide extension to the south. The northern (Fongen Series) part of the intrusion occupies the deepest part of the chamber. The southern (Hyllingen Series) part occupies the southern extension. The FHI, which has a dioritic bulk composition, has been divided into four evolutionary stages on the basis of the mineral chemical evolution in profiles normal to layering.

Stage I comprises a basal reversal in the Hyllingen Series. Stage II has fairly constant compositions and is characterised by the presence of numerous, large, raft-like, dominantly metabasaltic, inclusions. Stage III consists of a major compositional regression, ending with the most primitive assemblages in the intrusion (with olivine Fo75, plagioclase An63). Stage IV comprises a sequence showing strong normal fractionation, ending with quartz-bearing syenites with low temperature end-member mineral compositions at the roof. A major feature in the Hyllingen Series is the presence of systematic lateral compositional variations in mineral chemistry, with more evolved compositions along the strike of modal layering approaching the southern margin. For example, over a distance of ca. 6 km the mineral compositions vary from Fo73:An61:Mg#cpx79 to Fo13:An42: Mg#cpx38 along strike. These discordant relations between modal and cryptic layering developed as a result of the crystallization of compositionally zoned magma along an inclined floor. These features imply that wide scale convection did not take place and that cumulus crystals formed from the magma in contact with the local floor and were not transported far before deposition.

The basal reversal of Stage I in the Hyllingen Series formed as a result of crystallisation during gradual elevation of compositionally zoned magma up an inclined floor in response to the influx of relatively dense, primitive magma. Away from the leading edge of the expanding chamber

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modally layered cumulates of Stage II formed at the same time as the basal reversal; their constant compositions reflect balance between the rates of influx and crystallisation. At the same time, relatively primitive cumulates were forming in the deepest part of the chamber where new magma was being emplaced. Different mineral assemblages were therefore crystallising simultaneously in different parts of the magma chamber.

VPP4 : THam04 : G4

New Insights into the Crystallization History of the Skaergaard Intrusion from Zoning in Plagioclase Overgrowths and Occurrence of Quartz

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The Skaergaard intrusion, East Greenland is the best known example of extreme fractionation of basaltic magma. Because of the relatively slow cooling rate, plagioclase is the only cumulus mineral which preserved primary zoning, down to ~5µm. Cumulus plagioclase shows cryptic variation from the margin to the centre of the intrusion in rocks from the floor (Layered Series: LS), walls and roof (Upper Border Series: UBS), compositions varying from ~An₇₀ to ~An₃₀. In the LS, average An of cumulus crystals decreases nearly linearly with stratigraphic height, whereas Or increases from 1.5 mol% Or in the LZ to 3 mol% in the MZ and UZ.

We studied zoning in the postcumulus overgrowths between cumulus plagioclase crystals in all subzones in the three Series. The zoning is much more extensive than previously described: in a rock from the lowest zone in the LS (LZa), it ranges from An₆₂ to An₂₇, whereas it ranges from An₃₂ to An₁₄ in a rock from the highest zone (UZc). Overgrowths in rocks from the UBS are broader and zoning extends to more Ab-rich compositions (An₆₂ to An₃ in UBZα and An₁₇ to An₂ in UBZγ). The range of composition in the overgrowths from the three Series covers more than the remaining range of the cryptic variation in the intrusion, suggesting that the postcumulus overgrowths result from a more-complete liquid line of descent than the exposed LS.

Quartz is common in contact with the postcumulus overgrowths in meladiorites. It occurs even in gabbros in LZa containing olivine Fo₆₅, but is not found at distances <~0.5-1 mm from olivine, suggesting that the length scale for local equilibrium decreases strongly as the temperature drops during intercumulus crystallization. Quartz occurs as discrete crystals between plagioclase from LZa to UZb, whereas it occurs almost exclusively in granophyric intergrowths with plagioclase from UZb to UZc of the LS and in the whole UBS. Orthoclase contents decrease steadily towards the rim of the overgrowths and the granophyric intergrowths, and numerous micropores occur in them; this indicates that the last stages of crystallization occurred under water saturation, hence explaining the strong decrease in Or. The presence of quartz and the fact that the range of plagioclase overgrowth compositions in the upper LS and UBS rocks extends well beyond that in the cumulus crystals, imply the probable existence of now-eroded granophyric rocks (Vanished Zone).

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Trace Element Evidence for In-Situ Crystallization of Poikilitic Clinopyroxene from the Skaergaard Intrusion

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Large poikilitic Ca-rich clinopyroxenes enclosing plagioclase and olivine characterize the rocks of the Hidden Zone and Lower Zone a of the Skaergaard Intrusion, East Greenland. Understanding the physical and chemical conditions under which these crystals grew is important for constraining the history of these rocks, in particular for distinguishing preserved magmatic features from potential secondary redistribution. We have therefore begun a systematic study of the textures and compositions of these large pyroxenes, as well as the minerals they enclose.

Analyses of major elements (e.g. Fe, Mg) and a series of minor divalent cations (e.g. Ni, Co, Mn) show no systematic variation as a function of position within single crystals. On the other hand, within single pyroxene grains, chromium contents are found to be highly variable, from 2500 ppm to below the detection limit (100 ppm).

Furthermore, chromium content is a systematic function of position within the grain, with a central region of high chromium content, and a regular decrease in concentration towards the grain edge. Using an ion probe we have also determined rare-earth element (REE) patterns of the same pyroxene grains. We find the central region of the grains to be relatively poor in REE, with little or no obvious europium anomaly. With increasing distance towards the grain edge REE contents increase, and a significant europium anomaly is present.

The observed variations of the compatible element Cr and the incompatible REE may both be quantitatively accounted for by precipitation of cotectic proportions of clinopyroxene, plagioclase and olivine from the intercumulus liquid. This interpretation of in-situ crystallization of the intercumulus liquid is also consistent with measured relative modal proportions of the principal silicate minerals. The fact that concentration gradients are observed for trivalent cations, but not for the divalent cations may be simply explained by the fact that diffusion coefficients for the former are significantly greater than those of the latter. Thus, on the time scale of cooling of the Skaergaard Intrusion, sufficient time was available for significant redistribution of the divalent, but not of the trivalent cations.

VPP4 : THam08 : G4

The Contrast between Oman Ophiolite and Skaergaard Stratiform Intrusion

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In spite of very distinct origin and mode of functioning, the gabbros crystallized in the Oman Ophiolite Magma Chamber (OOMC) or in the Skaergaard Stratiform Intrusion Magma Chamber (SSIMC) have some striking similarities related to the large magmatic flow taking place in both. The SSIMC was a bowl-shaped cavity with a stable floor and upward a large liquid-mush interface; in contrast, the OOMC had a large and moving floor with tent-shaped walls through which the solidifying gabbros were drifting; the liquid-mush interface at the top was only 1-2 km wide and the melt lens, is only about 50 m thick. The gabbros in both situations are magmatic tectonites developing structures similar to those classically described in metamorphic rocks (foliations and lineations, tectonic banding, boudinage, shear zones, rotated folds and sheath folds). In the OOMC, the strain is induced by subsidence from the melt lens and by mechanical coupling with the solid mantle below; in the SSIMC, the strain results from avalanches from the wall where the mush crystallize toward the center of the intrusion. The spectacular layering developed in both situations is essentially due to this tectonic history and not to gravity-controlled, static magmatic settling.

VPP4 : THam09 : G4

Differentiation and Contamination Processes in the Grachou Paleo Lava Lake, Cézallier, French Massif Central

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The Grachou paleo lava lake is presently 200 m-wide and up to 30 m-high. Partly eroded, its internal structure comprises a vertical feeder dyke and two adjacent paleo convective cells (M.J. Le Garrec 1988).

The porphyritic alkali basalt lava is cut by numerous variably textured pegmatoid veins. The basalt also shows numerous ocella (mm size) only formed by small prismatic clinopyroxene (with minor oxides) resulting from centripetal growth. Diopside-augite of the ocella is Si-rich (up to Si = 2.00 per unit cell) compared to that of the lava (Si = 1.88 to 1.77), and Si content increases from the rim (Si = 1.78) to the core (Si = 2.00) of the ocella. This has been interpreted as the result of interaction between basalt and quartz xenocrysts, which were totally dissolved during the reaction. Unlike lava flows, where quartz xenocrysts within pyroxene rims are often partially preserved, cooling of Grachou lake has been long enough to lead to total xenocrysts dissolution: pyroxene ocellae provide the only evidence effective silica contamination.

Pegmatoid cm- to m-thick veins are made up plagioclase, olivine, clinopyroxene, oxides, sanidine and an altered foidic phase. Systematic paragenetic variations, rock crystallinity and crystal shapes are observed from walls to vein centre: (i) zoned plagioclase has grown from the vein walls and were progressively replaced by anorthoclase, sanidine and foid toward the centre of the veins; (ii) according to its chemical evolution, plagioclase shape evolved from large tabular to skeletal and dendritic rims in a groundmass of dendritic-curved anorthoclase-sanidine crystals; (iii) olivine, oxides as well as pyroxene are typically skeletal. Clinopyroxene and calcic plagioclase display progressively a granophyric texture, indicating they ultimately grew simultaneously and rapidly at eutectic temperature.

Pegmatoid veins are the result of residual liquid extraction by filtre-press process. Moreover, mineral chemical evolutions evidence that the residual liquid itself evolved to phonolite, despite silica contamination of the parent magma. Rapid variations of nucleation and growth rates of feldspars are mainly controlled by two parameters: chemical trend from calcic to sodi-potassic feldspar (G. Lofgren 1974) and sudden decrease of the internal pressure during crack opening and degassing at the quenched surface of the lake. Mixing calculation shows that 41% of basaltic magma must crystallize to produce such a residual liquid, the small volume of pegmatoid veins (a few% in volume) shows that the extraction process was poorly achieved.

VPP4 : THam10 : G4

Crystallizing a Rhyolitic Magma – Insights from the Permocarboniferous Halle Volcanic Complex, Germany

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The mode of emplacement (intrusive vs. extrusive) of felsic magmatic bodies in different regions of Permocarboniferous magmatism in Europe, e.g. the Midland Valley, the Oslo Graben, the Saar-Nahe Basin, the Saxonian Volcanic Complex, and the Halle Volcanic Complex, remains a much debated topic. The Halle Volcanic Complex is situated in the late Paleozoic Saale Basin (Schwab, 1965, Romer et al., in press). In this area, 60 km³ of rhyolitic magma were emplaced 307±3 to 294±3 Ma ago (Breitzkreuz and Kennedy, 1999). Large thicknesses (partly >1000 m), thin (dm or cm) chill zones, dome and bowl shaped flow textures, and steeply dipping sedimentary rocks of older age in between the different units indicate the rhyolitic bodies to be shallow-level laccoliths intruded into unconsolidated terrestrial sediments.

As a physically volcanological approach to resolving the crystallization history of the laccoliths, crystal size distributions (CSDs) of the felsic phenocrysts K-feldspar, plagioclase and quartz have been determined. The CSD-plots obtained are linear, show influence of textural coarsening or resorption (for quartz), and suggest a batch crystallization model without significant accumulation or fractionation (Marsh, 1998). Resorption of quartz is also indicated by rounded phenocrysts. This is presumably related to growth of K-feldspar at the expense of quartz under conditions of decreasing pressure, i.e. during the ascent of the magma (Holtz et al., 1992). The CSDs reveal differing initial nucleation density (n₀) and growth rate * growth time (Gτ) of K-feldspar for fine-grained and coarse-grained varieties, respectively. Relative modal proportions between the three phenocryst types do not show significant difference. Residence times calculated from the CSDs for the above mentioned phenocrysts range from several weeks to centuries depending on different growth rates (Cashman, 1990). The residence times differ significantly among the phenocrysts. So far, no systematic vertical or horizontal variations of Gτ and n₀ have been observed within the laccoliths.

Exact shapes of phenocrysts and true 3D-CSDs are currently determined by serial sectioning. By comparing CSDs of sills and laccoliths of varying thickness, we want to distinguish post-emplacement cooling effects from inherited signatures. Also, the change of CSD characteristics in different positions within the magma body is being investigated further.

VPP4 What Is a Magma Chamber?

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VPP4 : THam11 : G4 A Numerical Model for the Thermal Evolution of the Vesuvius Magma Chamber

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A physical model has been developed to investigate the thermal evolution of the Vesuvius magma chamber over periods of time ranging from years to centuries. The chamber is assumed to be periodically supplied by hot fresh melt, increasing its volume without changing height, therefore decreasing its aspect ratio. The historical activity of Vesuvius records eruptions of widely variable magnitude that have been referred to the emptying of the chamber of quite different age and volume. The 1906 and 1944 eruptions testify the involvement of small (0.01-0.1 km³), young (tens of years), high aspect ratio chamber, while the AD 79 Pompeii or 3,500 BP 'Avellino' eruptions result from the emptying of large (0.5-5 km³), old (centuries), low aspect ratio chamber. In this model the deformation of country rocks due to the chamber volume increases is treated with a simple scheme of rock displacement at constant mass and enthalpy content. The cooling of magma is modelled as a conductive loss into the host rock through an effective conductivity, considering the melt in the chamber both in a state of conduction and convection. The conservation equation of enthalpy for the chamber and rocks is solved on a large domain using a FEM code. The latent heat of crystallization is taken into account by means of an effective dependence of enthalpy on temperature as calculated with the MELTS code (Ghiorso, 1995) for the typical Vesuvius magma compositions. A parametric study is performed on the thermal conductivity. Results on temperature, thermal gradients close to the chamber walls and thickness of heated country rocks are discussed in terms of their evolution with time, and compared with petrological data shown by Marianelli et al. (this volume).

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VPP4 : THam12 : G4 A Model for the Collapse of Piston Calderas during Ignimbrite Eruptions

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We investigate the mechanics of caldera collapse into a reservoir of volatile-rich silicic magma. We present a scaling analysis of the collapse of a coherent piston into an underpressured cylindrical or elliptical reservoir with a flat roof. The analysis gives the underpressure required to trigger coherent collapse along a vertical or outward-dipping ring fault as function of the roof aspect ratio (R =thickness/width).

Laboratory experiments confirm the analysis and serve to define the transition, at increasing R , between regimes of (i) coherent (piston) collapse and (ii) no collapse or non-coherent (chaotic) collapse. Coherent collapse occurs along outward-dipping faults, which propagate from the reservoir edges through the roof. In non-coherent collapse, the first reverse faults form at deeper levels, then join underground, and collapse proceeds in a chaotic fashion; underground collapse then triggers surface subsidence (thin residual or mechanically weak roof) or creates a cavity overlain by a stable roof (thick and strong residual roof). The failure criterion obtained from the scaling analysis is used to calculate the fraction of a volatile-rich silicic magma reservoir that must be erupted in order to trigger coherent caldera collapse. We consider a two-stage model, with an initially overpressured chamber that becomes underpressured as the

eruption proceeds. The main input parameters are the chamber depth and vertical extent, the magma water content, and the ring-fault dip. The results show that, in case of an homogeneous roof, and of a single large eruption, the erupted volume fraction required to trigger coherent collapse increases with R , until the chamber is totally emptied at $R \sim 1-1.4$, the exact value depending mainly on the ring-fault dip. This suggests that collapse into reservoirs with $R > 1-1.4$ probably cannot collapse in a coherent manner and, if a surface caldera forms at all, collapse is more likely to occur non-coherently.

Data for the onset of caldera collapse during seven well documented ignimbrite eruptions for which pre-eruptive magma water content and reservoir depth are known are in good agreement with the model. We infer that the collapses at Crater Lake, Long Valley, Santorini, and Aira calderas may be of piston type, whereas those at Somma-Vesuvius (AD 79) and Pinatubo (1991) calderas are more likely to be non-coherent.

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VPP4 : THam13 : G4 Garnet as a Marker of the Dynamics of Deep Crustal Magma Chambers

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In many cases, minerals are the only markers of the dynamics of geological processes whose time constants can be very long (from thousands to millions of years). In volcanic products, plagioclase crystals commonly display compositional zoning, growth or resorption features that are used to characterize fractional crystallization, magma mixing or decompression, within shallow magma chambers.

In partially molten crustal systems, garnet displays rather unusual and interesting behaviour: (1) it is often present in the crustal protolith that undergoes melting, (2) it grows during partial melting since melting reactions are of the type $A + B = \text{Grt} + \text{melt}$, (3) in case of interactions between mafic and felsic magmas, garnet may continue to grow. In addition, diffusion of elements in garnet is particularly slow as a consequence of its compact structure. This means that garnet has great potential to preserve information about processes that occurred within magma chambers in the deep continental crust.

A more or less complete section of the continental crust, as left after the Hercynian orogen, outcrops in the Pyrénées. Rather unusual deep plutons or magmatic complexes can be observed and show remnants of interactions between mafic and felsic magmas.

A detailed study of major and trace element distribution in garnets of these magmatic complexes has been undertaken using a Cameca SX100 microprobe and ICP-MS (laser ablation). Complex compositional zoning features are identified on calcium, titanium, aluminium, phosphorus, hafnium, and heavy REE (e.g. Yb, Lu). They allow identification of both growth and resorption features.

On the basis of these element distributions, the $\delta^{18}\text{O}$ in these garnets have been measured in situ using the IMS1270 ion microprobe at CRPG (Nancy). Variations between $\delta^{18}\text{O} = +11\%$ and $\delta^{18}\text{O} = +15\%$ relative to SMOW are observed within a single garnet crystal and can be correlated with major and trace element variations.

From core to rim, these chemical variations are interpreted in terms of (1) metamorphic stage, (2) crustal partial melting, (3) chemical exchange with magmas of mantle origin, (4) final stage of recrystallization. It is thus demonstrated that garnets are excellent markers of both the nature of the processes occurring in deep magma chambers and their succession in time.

VPP4 : THam14 : G4 Cognate Xenoliths and the Crystallising Boundary Layer

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Vesicular and glassy xenoliths have been found at a number of active volcanoes. Their physical state indicates that they were both partially molten and volatile-saturated at the time of sampling by an eruption. They have the potential to record the processes operating in the crystallising boundary layer of a magma chamber.

We report results of studies on xenoliths from Santorini, Greece, and Mt Mayon, Philippines. Quantitative analysis of crystal-size distributions provide important constraints on the textural development of the boundary-layer samples. Distinct grain size and textural differences between xenoliths and host-rock can be interpreted in terms both of nucleation and growth of one population of crystals within the boundary layer; coupled with the capture and continued coarsening of a second population of crystals supplied by sedimentation within the magma chamber. The two populations may be recognised petrographically and chemically, by their different styles of zonation and discrete core compositions.

Analysis of trace element zonation within plagioclase feldspar crystals, using both electron microprobe and laser-ablation ICP MS, places first-order constraints on the physical conditions within the sub-volcanic magma chamber at the time of crystallisation. In additions, the patterns of coupled variation of Sr, Ba, Pb and LREE concentrations in regions showing oscillatory zonation of feldspar. An content, can be used to understand the nature and timescales of the development of this zonation.