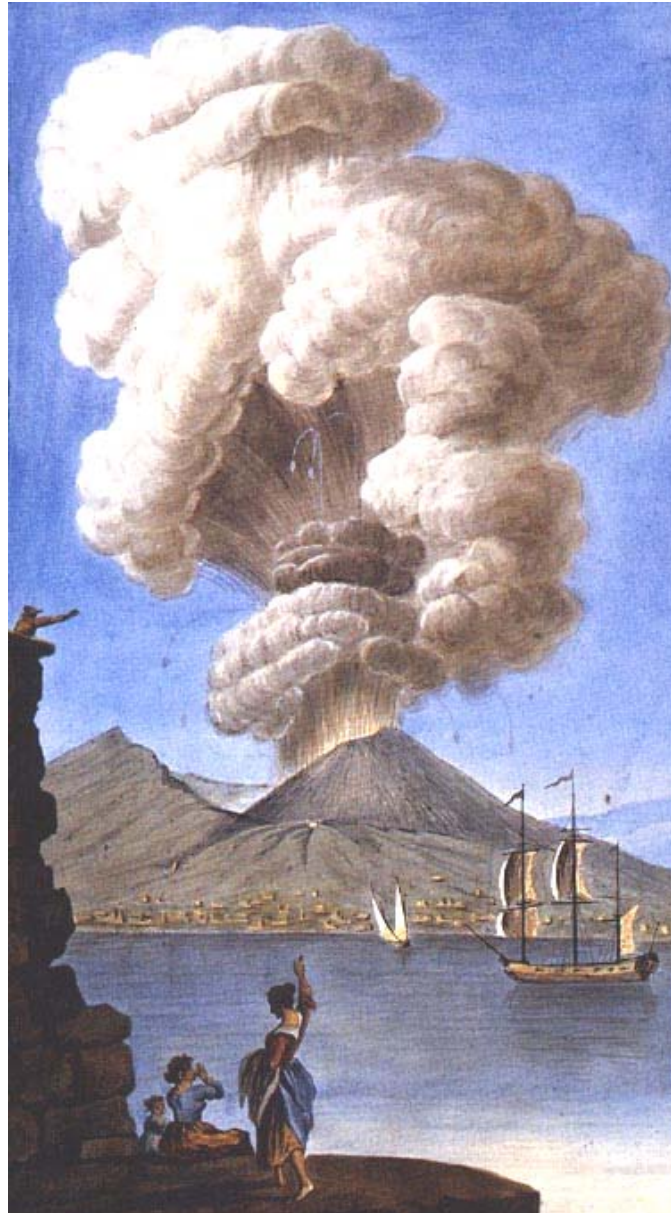# JOURNÉE MAGMATIQUE 2008
ETH-Zürich

January 11, 2008

Program and Abstracts

JOURNÉE MAGMATIQUE 2008
ETH-Zürich, January 11, 2008

Program – Morning Lectures – Lecture Theatre CLA E4

Chairpersons: Peter Ulmer / Max Schmidt

Time	Authors (**Speaker**)	*Title of presentation*
9:30 - 9:40	**Peter Ulmer**	*Welcome and Introduction*
9:40 - 10:00	**Paola Ardia**, Daniele Giordano and Max W. Schmidt	*Pressure effect on the viscosity of hydrous rhyolite: a model*
10:00 - 10:20	**Luca Caricchi**, Luigi Burlini, Peter Ulmer, Manuele Faccenda and Taras Gerya	*The effect of strain localization on the rheology of crystal-rich magmas*
10:20 - 10:40	**Caroline Bouvet de Maisonneuve**	*Eruptive mechanisms of large explosive silicic eruptions: Textural study of Kos Plateau Tuff pumices*
10:40 – 11:00	**Wim Degruyter**	*Permeability, anisotropy and tortuosity measurements of pumices using X-ray computed microtomography*
11:00 - 11:20	**Coffee-Break**	***In front of lecture theatre (CLA E4)***
11:20 - 11:40	**Fabrizio Alfano** and Costanza Bonadonna	*Characterization of tephra particles: influence of the shape on the terminal fall velocity*
11:40 - 12:00	**Celine Longchamp**, Costanza Bonadonna and Olivier Bachmann	*Characterization of proximal tephra deposits: the example of two explosive eruptions at Nisyros volcano (Greece)*
12:00 - 12:20	**Lukas Martin**, Carl Spandler and Thomas Pettke	*Alumina-rich clinopyroxene-spinel-xenoliths Mandraki Beach, Nisyros (Greece)*
12:20 - 12:40	**Ksenia Nikolaeva**, Taras V. Gerya, James A.D. Connolly	*Dynamics of crustal growth in intraoceanic volcanic arcs: Numerical Model*
12:40 - 14:00	**Lunch Break**	**Clausiusbar (CLA) or Main Mensa (MM, Polyterasse) ETH Zürich**

JOURNÉE MAGMATIQUE 2008
ETH-Zürich, January 11, 2008

Program – Afternoon Lectures – Lecture Theatre CLA E4

Chairpersons: Michael Dungan / Othmar Müntener

Time	Authors (**Speaker**)	*Title of presentation*
14:00 - 14:20	**Julien Leuthold**, Othmar Müntener, Lukas Baumgartner, Benita Putlitz, Jürgen Michel	*Emplacement of the Paine Mafic Complex: successive sill injections?*
14:20 - 14:40	**Mathias Dessimoz**, Othmar Müntener, Oliver Jagoutz and Dawood Hussein	*Epidote geochemistry in calc-alkaline rocks*
14:40 – 15:00	**Arjan H. Dijkstra**	*The case for previously (anciently?) depleted peridotites in modern ocean basins and in ophiolites*
15:00 – 15:20	**Arno Rohrbach**, Chris Ballhaus, Ute Golla–Schindler, Peter Ulmer and Dirk Schönbohm	*Experimental evidence for a highly reduced upper mantle*
15:20 - 15:40	*Coffee-Break*	**In front of lecture theatre (CLA E4)**
15:40- 16:00	**Etienne Médard** and Timothy L. Grove	*Water in basaltic melts: effect on liquidus temperatures, olivine-melt thermometry and mantle melting*
16:00 - 16:20	**Sébastien Pilet**, Michael B. Baker and Ed M. Stolper	*Experimental constraints on the origin of OIBs*
16:20 - 16:40	**Carl Spandler**, Greg Yaxley and David Green	*Experimental phase relations and melting of sediments in the upper mantle*
16:40 - 17:00	**Max W. Schmidt**	*The making of the Italian ultrapotassic magmatism: phonolitic melts from carbonaceous pelite melts from the trailing edge of a detached slab traveling through and hybridizing in the mantle to form ultrapotassic kamafugites*
17:00 - ?	*Friday-Beer*	**CLA (Cafeteria, Clausiusbar)**

Pressure effect on the viscosity of hydrous rhyolite: a model

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Viscosity is the single most important property governing the efficiency, rates and nature of melt transport. In geological environments viscosity controls eruption dynamics and rates of physicochemical processes (e.g., degassing, crystallization) in magmas. Composition, volatile content, temperature, pressure, as well as crystal and bubble contents are parameters influencing the viscosity of silicate liquids to various extents. The prediction of viscosity over the range of conditions encountered in nature and, in particular, at conditions relevant to eruptive events, is still challenging. The influence of H_2O-content on viscosity is dramatic (e.g., the addition of 1 wt% of water may decrease viscosity by 6 orders of magnitude). Rhyolitic melt at pressure conditions typical for magma chambers contain up to 10 wt% H_2O and in this sudy we experimentally determined the effect of pressure on the viscosity of hydrous rhyolitic melts.

The Newtonian viscosity of synthetic rhyolitic liquid (HGG) containing 0-5.25 wt% dissolved water was measured at pressures from 4 to 26 kbar. The combined use of a high T concentric cylinder and the high-T, high-P falling sphere techniques allowed viscosity measurements in the interval from 10^2 to 10^7 Pa s, pertaining to eruptive conditions. No previous experimental work has investigated such a wide range of viscosity. Concentric cylinder measurements were performed on dry melts up to 1650 °C. The falling sphere technique on static and centrifuging piston-cylinders allowed to measure viscosities between 580 to 1350°C at different pressures. The increased acceleration field (50-1000g), applied to the sinking sphere, enabled us to measure viscosities below the solidus temperature. As to be expected, viscosity decreases with water contents and with increasing temperature. The viscosity response of hydrous melt to pressure increase is different: as expected at high T the viscosity decreases, whereas at low T the viscosity doesn't indicate strong effects. For dry compositions a decrease of viscosity is observed in the entire T-range, indicating that in the presence of H_2O, T and P-induced speciations and structural variations significantly affect melt rheology.

A combination of our and previous studies on rhyolitic melts were employed to calculate an empirical model reproducing the experimental data and predicting the viscosity of rhyolitic melts in the full range of T-P-H_2O-X space for which data are available. The model is based on the Vogel-Fulcher-Tammann (VFT) equation. Our model reproduces the viscosity of about 500 viscosity data obtained on both synthetic and natural silicic melts from peraluminous to peralkaline with RMSE values of less than 0.25 log-units and less than 5% relative error on a logarithmic scale.

The effect of strain localization on the rheology of crystal-rich magmas

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The rheology of magmas containing more than 40 vol. % of crystals is of particular interest to constrain the physical conditions of magmas during the extrusion of volcanic domes and necks.

In this study we have conducted series of simple shear experiments on synthetic crystal-bearing hydrous rhyolitic material and on natural rocks from the Monte Nuovo eruption (Phlegrean Fields, Italy) in a Paterson-type internally heated rock-deformation apparatus. The experiments covered a wide range of crystallinities (50-80 vol. %) and strain rates (10^{-6}-10^{-3} s^{-1}). All experimentally deformed samples lack yield strength but they exhibit a tendency to non-Newtonian and Binghamian behavior at relatively high ($>10^{-4}$ s^{-1}) strain rates. The experiments have been performed under temperature and strain rate conditions where the melt phase behaves Newtonian. Moreover, in the range of strain rates applied, viscous heating is unable to account for the observed shear thinning effects (decrease of viscosity with increasing strain rate). Consequently, the non-Newtonian effects must be due to the presence of crystals in the magma. In experiments were shear weakening was indeed observed, the samples exhibit macroscopic localization features that are oriented at around 30° with respect to the shear plane. In all the other experiments, microstructural observation of cross-sections of the samples revealed melt-enriched planes and crystals alignments with an orientation identical to the localization features observed in the samples that experienced shear thinning.

Numerical simulations have been conducted that were designed to reproduce the experiments and were, therefore, computed with identical stress and strain rate conditions as the experiments. Samples from both, the experiments and the numerical simulations reveal the generation of melt-enriched bands oriented at around ±30 ° with respect to the direction of flow. The melt enrichment induces localization of the strain in these regions and leads to a geometrical redistribution of melt and particles that is responsible for the complex rheological behavior of crystal-rich magmas.

Eruptive mechanisms of large explosive silicic eruptions: Textural study of Kos Plateau Tuff pumices

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Silicic pumices formed during explosive volcanic eruptions are faithful recorders of the state of the magma in the conduit, close to the fragmentation level, as viscosity is generally high enough to limit their post-fragmentation deformation to a minimum. Pumice textures are therefore of great interest to shed light into bubble nucleation, growth and coalescence in silicic magmas ascending in a volcanic conduit, which ultimately controls the style of eruption. In this study, we have characterized the pumices produced by the rhyolitic 161 ky Kos Plateau Tuff (KPT) eruption, Aegean Arc, Greece. Four types of pumices were distinguished macroscopically in the non-welded deposits, and have been characterized using thin section observation, SEM imagery, porosimetry, and permeametry. We show that the types of pumices defined are confirmed by distinct petrophysical characteristics, and the measured differences in porosity and permeability are the result of either conduit processes, differences in crystallinity or magma mixing. We also show that permeability does not depend solely on porosity, as implied by the percolation theory. Size of pore aperture, tortuosity and pathway wall rugosity also play a fundamental role in the flow of gas through the permeable magmatic foam.

Permeability, anisotropy and tortuosity measurements of pumices using X-ray computed microtomography

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X-ray computed micro-tomography (μCT) has become a widely-applied technique to obtain density maps of heterogeneous media; it allows gathering non-destructively qualitative observations as well as quantitative information on the 3D geometries of multi-phase samples. In this study, we obtained 3D images of different pumice types found in the rhyolitic Kos Plateau Tuff (KPT) deposits (161 ky, South Aegean Arc, Greece), and combined anisotropy and (geometrical) tortuosity measurements of these scans with permeability data to gain insights into the development of pathways through magmatic foam and how it affects syn-eruptive degassing.

The rhyolitic KPT pumices are particularly prone to textural analysis because (1) the deposits are non-welded, (2) the high viscosity of the magma helped preserving information on the state of the magmatic foam in the conduit immediately prior to fragmentation (i.e., disruption of magma into pyroclastic fragments) and (3) pumices display variable macroscopic textures including tubular and near-spherical networks of bubbles.

The stacks of grey-scale μCT images were cropped and segmented to obtain 3D binary volumes. These volumes were submitted to anisotropy and tortuosity measurements using existing software. Results suggest a significantly more convoluted path through the spherical bubble networks than the tubular bubble networks. To complement this geometrical characterisation of pumices, permeability values on the same binary volumes will be acquired using a numerical code (using the Lattice Boltzmann technique).

Characterization of tephra particles: influence of the shape on the terminal fall velocity.

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Tephra fall deposits represent the result of the accumulation of volcanic material produced during an explosive eruption, ejected into the atmosphere and, finally, sedimented on the ground. The grain size distribution of these deposits usually shows a very wide dimensional range, with particles ranging from block size (>64 mm), which fall relatively near the vent, to ash size (<2 mm), which can stay suspended into the atmosphere for long time and fall very far from the vent. The distribution on the surface of tephra particles is linked to the dynamics of the eruption process and to the characteristics of the volcanic products. The main parameters that control the areal distribution are: the plume height; the velocity and direction of the wind; the settling velocity of the particles. Among these three parameters, the third one is linked to the characteristics of the particles ejected. It is defined as the balance between gravitational and drag forces acting on the object, and represents the maximum velocity that it can reach during its fall through the atmosphere.

The values of the terminal velocities for a generic particle falling through the atmosphere are linked to the characteristics of the air (viscosity and density), and to the characteristics of the particle itself (density, size and shape). The shape of a particle is a very important parameter in determining its terminal velocity, because of the great influence that it has on the aerodynamical drag forces acting on it. Irregular-shaped particles, like those of volcanic origin, are characterized by a higher aerodynamic drag than regular-shaped particles. This aspect represents the main problem in studying the settling dynamics of tephra particles, whose irregular shape cannot be quantified easily. For this reason, to avoid the problem of the univocal definition of complex shapes, the first studies tried to define a physical model based on the assumption of a spherical shape: in this case it is possible to estimate the terminal velocities in relation only with the mean radius of the particles. This approach cannot be totally satisfying because it does not take in account the extreme variability of the shape shown by a particle produced during a volcanic eruption. Therefore, these models do not give any information about the influence of the shape on the settling process of tephra particles.

The last studies on this issue tried to define physical models for the settling process of generic irregular-shaped particles, using shape parameters like sphericity, circularity, length of the axis, projected surfaces, surface area, etc. Therefore, with these models it is possible to evaluate how the shape affects the settling process, and to determine the drag coefficient of the particles in relation with the Reynolds number.
In this work we try to characterize tephra particles erupted by different volcanoes (Soufrière Hills Volcano, Montserrat W.I.; Pululagua, Ecuador; Kilauea, Hawaii; Cerro Negro, Nicaragua), in order to investigate the influence of composition, grain size distribution and shape on the settling process.

Characterization of proximal tephra deposits: the example of two explosive eruptions at Nisyros volcano (Greece)

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The volcanic island of Nisyros is located at the eastern part of the quaternary calc-alkaline volcanic arc of the Aegean Sea. Nisyros had known two main explosive eruptions that have deposited the Lower Pumice (LP) and the Upper Pumice (UP) units on the north and northeast of the island respectively. After those two phases, the two third of the crater were filled by lava domes and the Lakki plain is the theater of hydrothermal activity. Our research objectives were to characterize the two explosive events that produced the UP and LP units. These deposits were already studied by several authors (e.g. Limburg and Varekamp,1991, Volentick et al, 2005), but crucial physical parameters were not well constrained due to the limited exposure of the deposits (i.e. erupted volume, column height, mass eruption rate, eruption duration). We have mapped the deposits again and applied state-of-the-art methods for the characterization of tephra deposits. In particular, we have compiled isopach and isopleth maps for the two eruptions considering two possible locations of the vent (one in the north rim of the caldera and the other in the south). Isopleth maps were used for the calculation of the wind speed, the height of the eruptive column and the mass discharge rate (MER). We found a column height of about 15 km above sea level based on the method of Carey and Sparks (1986) for both eruptions and a MER of 1.6×10^7 kg/s for the LP and 1.5×10^7 kg/s for the UP. Isopach maps were used for volume calculations with three different methods (Pyle 1989, Legros 2000 and Bonadonna and Houghton 2005). We found a volume between 6×10^5 m^3 and 1.4×10^6 m^3 for the LP and between 4.6×10^5 m^3 and 1.3×10^6 m^3 for the UP. The resulting duration for both eruptions is around 50 seconds, which is probably underestimated due to the underestimation of erupted volume derived from proximal field data (within 5.5 km from the vent). Proximal outcrops are predominantly coarse grained with $\geq$ 90wt% between -6ϕ and 0ϕ (64-1mm). Componentry data show a predominance of juvenile material in all outcrops investigated. These new results are important for the characterization of proximal deposits and the application of field-based techniques and for the hazard assessment of potential future eruptions at Nisyros volcano that could serious affect Nisyros island as well as the surrounding islands in the east part of the Aegean Sea.

Alumina-rich clinopyroxene-spinel-xenoliths Mandraki Beach, Nisyros (Greece)

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This project examines magma evolution beneath the Nisyros island arc volcano, located in the eastern-most section of the Hellenic arc close to the mainland of Turkey. Nisyros is a very young volcano, likely younger than 161'000 years, emplaced in the caldera having formed in response of the giant Kos Plateau Tuff eruption. Most of the volcano comprises andesitic to rhyolitic volcanic lithologies, although mafic lava flows occur throughout the stratigraphic succession. The petrology and geochemistry of most of these mafic rocks have not previously been investigated in detail. Here, we examine the earliest mafic unit that outcrops at Mandraki Beach (NW Nisyros Island) in order to gain insights into the earliest magma evolution of this volcano. Special focus is given to ultramafic xenoliths of this unit, because these provide important insights in processes and reactions that occur beneath island arcs. This information is critical for understanding the evolution and chemistry of island arc magmas and, hence, the generation of new crust.

The host-rocks: The Mandraki Beach unit consists of pillow lavas and hyaloclastites, which are the first witnesses of this evolving volcano. They are of basalt-andesitic to andesitic composition (Buettner et al., 2005). The rocks contain abundant (30%) phenocrysts of clinopyroxene (augite and diopside), plagioclase and, rarely, orthopyroxene. Olivine has only been found as xenocrystic relicts. The earliest crystallised clinopyroxene is zoned with a Mg-number of between 92 and 83. It is followed by the crystallisation of more evolved, unzoned clinopyroxene, with $Mg\#_{86-72}$. Some zoned clinopyroxene crystals are associated with orthopyroxene ($Mg\#_{82}$) on their rim. Plagioclase (An_{74-60}) first occurs in contact with zoned clinopyroxene ($Mg\#_{82-79}$) and, afterwards, small plagioclases (An_{79-60}) are formed in the matrix in association with orthopyroxene and clinopyroxene.

The xenoliths: Hosted within the mafic lavas are xenoliths that may be up to 10 cm in size. The xenoliths are clinopyroxenites, which consist mainly of alumina-rich clinopyroxene and alumina-rich spinels. The alumina-rich clinopyroxene crystals have euhedral to subhedral forms, are Mg- ($Mg\#_{82-77}$) and Ca-rich and contain between **12 to 15 wt% Al_2O_3**! They are classified as fassaites. The spinels [$(Fe^{2+}_{0.14} Mg_{0.86})$ $(Fe^{3+}_{0.21} Al_{1.79}) O_4$] are mainly aligned along cracks, show a euhedral texture and seem to have crystallised in alumina-rich melt pockets. The spinels are chromium free.
The fassaites and their associated spinel are not stable with the host rock and, hence, feature a reaction rim consisting of diopside ($Mg\#_{85-79}$) and anorthite (An_{100-95}).
At the current stage of research we consider four possible origins for these unusual xenoliths**:**

a)   **Deep origin:** Clinopyroxene of deep origin (>1.5 GPa) are rich in alumina and sodium. The sodium content of clinopyroxene from the xenoliths is relatively low, in the range of 0.1 to 0.2 wt%. Moreover, the crust below Nisyros is not expected to

exceed 27 km in thickness (Makris and Stobbe, 1984). Therefore, these xenoliths are unlikely to represent samples of deep lower crust.

b)   **Island-arc cumulates:** Cumulate pyroxenites below island arcs typically contain between 2 to 3 wt.% Al_2O_3. The fassaites have much higher alumina-contents. Melt compositions in equilibrium with the fassaites calculated using the partition coefficient of (Muntener et al., 2001) would have between 25 to 100 wt% Al_2O_3. Such aluminous melts are clearly not likely to exist in island arc environments, rendering the cumulate hypothesis improbable.

c)   **Breakdown of Gabbro:** The spinels are interpreted to have crystallised in melt pockets with relatively low-Si and high-Al compositions. Such compositions are more or less similar to aluminous gabbros in lower crust. The breakdown of such gabbros may lead to the formation of locally high-alumina melt (Dellapasqua et al., 1995). In this process, water and the stability of anorthite-rich plagioclase might have played a significant role.

d)   **Assimilation of carbonates:** Underneath Nisyros, there is a basement of limestone and thermometamorphosed marble. Also, skarns are found as xenoliths in some units. A recent experimental study (Marziano et al., 2007) examined clinopyroxene compositions as a function of carbonate content in the melt. Increasing carbonate in the melt was found to cause crystallisation of Ca- and Al-rich clinopyroxene. This could have lead locally to the formation of the fassaites. Furthermore, fassaites are usually associated with metamorphosed limestones and dolomites.

Determining the origin of these xenoliths is of great importance to understanding the crystallisation and geochemistry of arc magmas and might provide insight into processes that occur in deeper parts of island arcs. Based on our field and petrographic observations and preliminary geochemical work, we expect that these xenoliths derive either from breakdown of aluminous gabbros (c) or due to magmatic interaction with limestones (d). In the case that these xenoliths are the result of assimilated limestones, it should be investigated if this is not a commonly occurring phenomenon beneath island arcs volcanoes that develop on carbonate platforms. Subsequent work is planned to determine the bulk-rock and mineral major- and trace-element geochemistry of these rocks in order to resolve the origin and evolution of the Mandraki Beach mafic volcanics and their xenoliths. This will hopefully unravel the processes responsible for the genesis of this small post-caldera volcano in the Kos volcanic center.

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Dynamics of crustal growth in intraoceanic volcanic arcs: Numerical Model

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We have created a new coupled geochemical-petrological-thermomechanical numerical model of retreating intraoceanic subduction associated with volcanic arc development. The model includes spontaneous slab bending, subducted crust dehydration, aqueous fluid transport, mantle wedge melting, and melt extraction resulting in crustal growth. This model allows us to investigate the dynamics of subduction, mantle wedge plumes development and magmatic arc growth and displacement. Our numerical experiments show that subduction rate varies strongly with time and plays a crucial role in a plume development and consequent arc growth. In all our models, this rate slows (from 4-7 cm/a to 1-2 cm/a) in a few Myr after the beginning of subduction and then rises to 4 cm/a. Subsequently two scenarios can be distinguished: (1) decay and, ultimately, the cessation of subduction, (2) increase in subduction rate (up to 12 cm/a) and stabilization of subduction. In several numerical experiments with slowing subduction an intra-arc extension is observed. The extension which is triggered by the rheological weakening of the overriding plate due to its serpentinization in the fore-arc region leads to the splitting of previously formed crust and favors continuation of subduction process. Composition of magmatic arc strongly depends on the way of subduction evolution, i.e. through which scenario it goes. Newly formed arc crust is composed of rocks that are derived by melting of hydrated mantle and subducted crustal lithologies. Crust formed by mantle melting is predominant in the intraoceanic magmatic arc in all numerical experiments. The contribution from melting of subducted crust is only significant after the cessation of subduction (scenario 1), which allows thermal relaxation and melting of the slab. Rate of crust production correlates positively with subduction velocity. The volume of crust produced in the course of subduction process depends on both the efficiency of melt extraction and the slab age. Intermediate extraction efficiency (melt extraction threshold from 2 vol.% to 6 vol. %) and slab age (70 My) maximize crustal growth. The loci of magmatic activity and intensity of crustal growth is strongly dependent on the dynamics of hydrous partially molten upwellings (cold plumes) rising from the slab.

Emplacement of the Paine Mafic Complex: successive sill injections ?

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The Torres del Paine Laccolith in Patagonia/Chile is part of a chain of isolated Miocene intrusions which intruded into the eastern foothills of the southernmost Patagonian Andes (13-12 Ma, Michel et al. submitted) and is possibly emplaced in a transpressional-transtensional regime change due to the opening of the Chile Ridge slab window (Altenberger et al., 2003). It is composed of a ~400m-thick Mafic Complex, overlain by a ~1000m-thick granitic laccolith, emplaced at pressures of ~0.1 GPa. The Paine Mafic Complex (PMC) has been built up in a short time, by emplacement and crystallization of several pulses of high K calc-alkaline basaltic to andesitic magmas. Igneous structures of the PMC are vertical in the Western most part while internal structures and major contacts were found to be sub-horizontal in the central and Eastern most parts of the PMC. Detailed field work on four crucial outcrop, rock textures and chemical analyses are used to tentatively reconstruct the 3-D intrusive stratigraphy of the PMC.

The major mass of the PMC consists of two 100-150m thick gabbroic units that are mainly composed of sills locally displaying normal modally graded layers of 1-5m. In many places the internal stratigraphy is disrupted and crosscut by smaller (10-20m thick) gabbroic and dioritic sills. The intraplutonic contacts frequently display diffuse transitions and cuspate-lobate structures indicating supersolidus conditions during most of the emplacement history. Some diorites are later emplaced as indicated by fractures cutting the gabbroic rocks and by the local formation of 1-5 m long evolved granodioritic diapirs intruding surrounding mafic sheets. The youngest intrusive rocks are porphyritic granitic dikes, which may contain up to 50% of dioritic and granodioritic enclaves. They form small, up to decametric (about 40 x 40 x 5m) magma bodies. Some of the dioritic enclaves show chilled margins suggesting that the emplacement of porphyritic granites is probably triggered by replenishment of mafic magma at depth.

Field criteria and microscopic observations permit to distinguish up to three different types of mafic cumulates within the gabbroic units: (i) some cumulates consisting of olivine, pyroxenes and hornblende show reaction relationships within the gabbroic sills indicating that they formed in the source and are later transported as mafic lenses; (ii) some are formed in-situ by crystal settling processes and (iii) the most spectacular ones are formed by accumulation of dm-scale layers rich in subhedral Mg-silicates in the center of a sill, where the emplacement velocity is highest.

We tentatively propose that the Torres del Paine mafic complex forms a sheeted sill complex, fed by the source region in the Western part of the Paine massif.

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Epidote geochemistry in calc-alkaline rocks

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Epidote is commonly accepted as magmatic mineral in intermediate plutonic rocks after the work of Zen and Hammerstrom (1984). Over the last years, the occurrence of primary epidote in TTG was confirmed by numerous experiments performed at different pressure, temperature and $X-fO_2$ (review of Schmidt and Poli, 2004). These experiments establish a minimum pressure of crystallisation of epidote around 0.3-0.7 GPa depending mainly on the bulk composition and on the oxygen fugacity. However, few data are available on epidote stability in gabbroic rocks at H_2O-undersaturated conditions and in volcanic dykes.

Rare examples of epidote phenocrysts in volcanic rocks of dacitic to ryhodacitic composition are known from Sutter Buttes, California and Boulder, Colorado in the USA (Evans and Vance, 1987; Dawes and Evans, 1991). The phenocrysts show complex and fine oscillatory zoning with a general decrease in allanite components towards the rim. Many dissolution and recrystallization border could be observed in a single crystal indicating that epidote is a near-liquidus phase in dacitic to rhyodacitic compositions. The core of the phenocryst is often composed by a nucleation centre associated with a complex irregular zoning pattern. Relics of quartz in the core and the vermicular aspect of the zoning resemble to what could be observed in epidote found in plutonic rocks.

Magmatic epidote in mafic rocks is widespread in the Kohistan Arc Complex in Northern Pakistan. In the Jijal complex which is interpreted as the crust mantle transition (Burg et al., 1998) field evidence such as magmatic layering, garnet and hornblende cumulates strongly indicate that the magmatic origin of the complex is preserved. Hence the Jijal Complex is one of the few places in the world to study epidote bearing mafic plutonic rocks (P around 1.5 GPa) in a K-poor natural system and to understand the phase relations involving epidote in gabbroic rocks. Epidote occurs as primary phase in garnet hornblende bearing gabbros and in some pegmatites together with quartz rutile and paragonite. The vermicular texture of epidote and quartz is similar to the cores of volcanic epidote and strongly support a magmatic origin.

We will present first results on magmatic epidote in volcanic rocks. The other point is to evaluate the potential peritectic reactions using trace element geochemistry that form epidote in a gabbroic system.

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The case for previously (anciently?) depleted peridotites in modern ocean basins and in ophiolites

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When referring to oceanic 'mantle heterogeneity', most people have in mind a heterogeneous mantle consisting of normal, 'ambient' depleted mantle (DMM) containing enriched domains of various scales including the well-known isotopically defined mantle reservoirs such as HIMU, EM1 and EM2. Ultimately, these enriched mantle heterogeneities are thought to represent recycled crustal material. Although it is relatively early days yet, there are some indications that another type of mantle heterogeneity needs to be added to the list: anciently depleted mantle.

Recent studies of abyssal peridotites, most notably at the Fifteen-Twenty Fracture Zone region at the Mid-Atlantic ridge, at Gakkel Ridge between 3 and 20°E, and at Macquarie Island in the South Tasman Ocean Basin, have reported on the presence of ultra-depleted peridotites, whose compositions can be modelled as residues of >20% of near-fractional melting of a typical depleted MORB-source mantle. In all cases, the regional degrees of melting, estimated from spreading rate, the composition of overlying crustal rocks, or the composition of peridotites from nearby regions, are much lower than 20% near-fractional melting. Therefore, these ultra-depleted peridotites are thought to have preserved a record of a previous melting event. Similarly, within ophiolite massifs, large variations in calculated degrees of melt depletion in peridotites on the scale of a few kilometers also point to the presence of previously depleted mantle domains.

The difficulty in interpreting the melting record of these pre-depleted peridotites lies in the fact that they all have a significant imprint of recent melt-rock reaction processes as well as metamorphic subsolidus reequilibration within in the thermal boundary layer underneath the ridge systems at which they are found today. The Macquarie Island samples were extensively equilibrated at temperatures around 1000°C within the thermal boundary layer after melting but before melt-rock reaction. Only by 'looking through' these late-stage processes, for instance by combining textural analysis with geochemistry, and by looking at compatible or weakly incompatible elements which are not easily affected by melt-infiltration processes, does their unusual character become apparent. The most commonly used isotope systems, which use highly or moderately incompatible elements, are generally strongly affected by these late-stage processes. As a result, the timing of the melting events which led to the highly depleted character of these rocks, remains obscure. The Re-Os isotope system, which can potentially look through the late-stage melt-infiltration events as Os is a compatible element in mantle peridotites, gave ancient model depletion ages as old as >1 Ga for the peridotites from the Fifteen-Twenty Fracture Zone. These results suggest that anciently depleted mantle may survive for long times without being mixed with normal DMM mantle, and that anciently depleted mantle may be another 'flavour' of mantle with a global significance.

In my presentation I plan to summarize the main arguments used for proposing the presence of previously depleted mantle at the ocean floor. I will focus on the example of the Macquarie Island peridotites, complemented with some observations on peridotites from the Fifteen-Twenty Fracture Zone and from the Pindos and Othris Ophiolites in Greece.

Experimental evidence for a highly reduced upper mantle.

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At the time of core formation, the Earth's silicate mantle was presumably in redox-equilibrium with the metallic iron core, which means—assuming an olivine composition of Mg# 0.9—an oxygen fugacity (fO_2) of about 2 logarithmic units below the iron–wüstite equilibrium (IW–2) [1]. On the other hand, samples representative for the modern upper mantle such as abyssal peridotites or melts that originate in the upper mantle (MORB, OIB, IAB) are considerably more oxidized with fO_2s around the fayalite–magnetite–quartz equilibrium (FMQ) [2]. Questions arising are: Which process may have caused secular mantle oxidation? Is the entire upper mantle as oxidized as the shallow mantle, or are there systematic changes in relative fO_2 with increasing depth in the upper mantle, leaving parts of the upper mantle in redox equilibrium with the metallic core?

There is evidence for reduction with depth. Thermodynamic model calculations and analysis of natural garnet peridotite samples indicate that fO_2 in the upper mantle decreases with increasing pressure [3,4]. In addition, experiments have shown that phases stable in the transition zone (400 to 670 km) and the lower mantle (670 to 2900 km) can incorporate so much Fe^{3+} that an Fe–rich metal phase is likely to be stable [5,6].

To investigate the redox evolution of the upper mantle with increasing depth we performed experiments in Fe° capsules from 1 to 14 GPa and 1220 to 1650°C with a modified fertile mantle composition. We subtracted 30 wt% olivine from the composition in order to increase the amount of potentially Fe^{3+}-rich phases like pyroxene and garnet. The starting composition was enriched in FeO (Mg# of 0.5) to raise the FeO content of the minerals, which results in more precise counting statistics during EELS measurements. fO_2 at run conditions, approximated from the FeO content of the silicates, are IW –0.5 to –2. Analysis of pyroxene and garnet with Electron Energy Loss Spectroscopy (EELS) show that above 7 GPa, subcalcic pyroxenes and majoritic garnets incorporate so much ferric iron that a mantle composition with 8 wt% FeO and 2000 ppm Fe_2O_3 will be within metal saturation. Hence, the Earth's upper mantle at depth greater than 250 km is likely to be saturated with an (Fe,Ni) metal phase [7]. We interpret therefore the oxidized nature of the Earth's upper mantle as a direct consequence of mantle convection: Downward convection (compression) results in relative reduction, upward convection (decompression) results in relative oxidation.

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Water in basaltic melts: effect on liquidus temperatures, olivine-melt thermometry and mantle melting

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We designed and carried out experiments to investigate the effect of H_2O on the liquidus temperature of olivine-saturated primitive basalts. The olivine-melt equilibrium is of critical importance for the understanding of magmatic processes: (1) since olivine is the low-pressure liquidus phase in mantle-derived magmas, thermometry based on the olivine-melt equilibrium provides the primary evidence for estimating melting temperatures in the mantle; (2) the effect of water on the olivine-melt equilibrium can also be used as a first approximation to parameterize hydrous melting models, olivine being the dominant phase in the upper mantle of the terrestrial planets. Previous quantitative estimates are scarce and often incompatible with each other. This is a consequence of the experimental difficulties inherent in carrying out hydrous experiments, including the ability to maintain a constant H_2O content, and to quench water-rich hydrous melts to analyzable glasses.

Our experimental approach has been to measure the dry liquidus temperature, and liquidus temperatures for various amounts of added H_2O, on the same basaltic bulk composition (a high-alumina tholeiitic basalt from Medicine Lake Volcano, California). This method allows us to separate the effect of H_2O from other potential influences (e.g., melt composition, pressure). Most of the H_2O-bearing experiments were performed under water-saturated conditions and the water contents were analyzed using a variety of methods (SIMS, by-difference and oxygen analysis with electron microprobe).
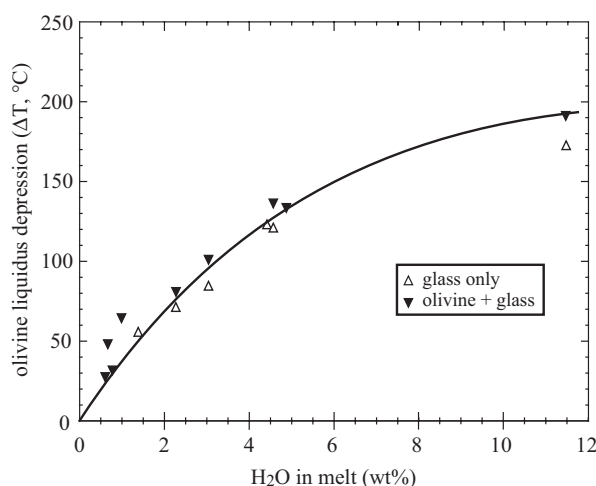

Fig. 1. Experimental determination of liquidus depression for tholeiitic basalts. For each experiment, the difference between the dry liquidus temperature and the experimental temperature is plotted as a function of H_2O concentration. Olivine-free and olivine-bearing experiments bracket the liquidus depression curve. The black curve is a thermodynamic model based on the data.

The experimental data indicate a stronger effect of water at small water concentration, which progressively weakens at higher water concentration. The non-linear effect of H_2O indicates that incorporation of H_2O in silicate melts is non-ideal, and involves interaction between H_2O and other melt components. A non-ideal solution model that

treats the effect of H_2O addition as a positive excess free energy can be fitted to the data to describe the effect of melting point lowering (Figure 1). Results from the thermodynamic model can be approximated by the purely empirical polynomial fit (H_2O in wt%):

$$\Delta T \left(^\circ C \right) = 39.2 \cdot \left(C_{H_2O}^{melt} \right) - 2.84 \cdot \left(C_{H_2O}^{melt} \right)^2 + 0.0772 \cdot \left(C_{H_2O}^{melt} \right)^3$$

Additional experiments on an alkali-rich olivine-leucitite, and comparison with other experimental data on MORB (Almeev et al., American Mineralogist 92, 670-674, 2007) indicate that there is no compositional dependence and that this equation is valid for any basaltic composition, within uncertainty. This equation can be added to existing "dry" olivine-liquid geothermometers to calculate equilibrium temperatures for primitive, mantle derived basaltic magmas. This equation can also be combined with mineral/melt H_2O partition coefficients, and melt fraction / temperature relationships for dry melting to calculate melt fraction / temperature relationships for water-undersaturated melting.

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Experimental constraints on the origin of OIBs

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The trace-element and isotopic ratios of mafic alkaline magmas (e.g., basanites and alkali basalts) from oceanic islands and continental alkaline massifs are often explained by the presence of subducted/recycled oceanic crust in their sources [1]. Alternatively, these ratios could reflect oceanic or continental lithosphere-bearing sources into which amphibole- and/or pyroxene-rich metasomatic veins have been emplaced [2-3]. The major-element compositions of alkaline magmas provide important tests of these hypotheses and constraints on possible source compositions and their petrologic evolution. To date, high-pressure melting experiments on peridotites, eclogites, and peridotite/eclogite mixtures have not fully reproduced the major- and trace-element compositions of basanites and the spectrum of composition from basanite to alkali basalt observed in alkaline massifs worldwide.

We conducted melting experiments on natural amphibole-rich veins and on their dehydrated equivalents at 1.5 and 2.5 GPa to test the metasomatic hypothesis for the origin of recycled components in OIB sources. These experiments demonstrate that melting of metasomatic veins can reproduce key features of the major and trace element compositions of many nephelinites and basanites from both oceanic and continental settings; moreover, these experiments show that reaction of partial melts of amphibole-rich veins (or their dehydrated equivalents) with surrounding lherzolite can explain the observed compositional trends from nephelinites to alkali basalts.

Our results indicate that partial melting of metasomatized lithosphere (i.e,. peridotite + amphibole-bearing veins) could generate liquids similar to alkaline lavas in continental settings. The presence of amphibole xenocrysts similar in composition to the amphibole observed in metasomatic veins and metasomatized peridotite xenoliths in continental alkaline magmas is a strong argument in favor of the hypothesis. Moreover, the recycling (e.g., via subduction or/and delamination) and partial melting of such veined lithosphere after its transformation into silica-deficient garnet pyroxenite could likewise contribute to the compositional characteristics of oceanic alkaline lavas. The same source types could also explain compositional trends from basanite to alkali basalt observed in both oceanic island and continental massif settings provided that reaction occurs between basanitic liquids and the surrounding peridotite (most likely during the melting process, but perhaps during transport to the surface). Furthermore, the isotopic characteristics of alkaline HIMU and EM-type OIBs are consistent with models of amphibole-bearing vein formation and resultant element fractionations [3]. Our results are thus consistent with the hypothesis that alkaline OIBs are dominantly produced by large degrees of melting of small volumes of trace-element-rich and volatile-rich material (e.g., originally metasomatic veins) present within the upper mantle rather than less enriched but volumetrically more abundant recycled oceanic crust. We conclude that partial melting of amphibole-bearing veins in metasomatized lithosphere can account for the major-element, trace–element, and isotopic compositions of alkaline OIBs and should be considered a

testable alternative to more widely accepted models of their formation that invoke recycling of oceanic crust ± sediments.

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Experimental phase relations and melting of sediments in the upper mantle

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Plate subduction over Earth history is expected to have transported significant volumes of sedimentary rock into the mantle. Sedimentary components in the mantle have been proposed as a source for mantle-derived diamonds and many distinctive oceanic magma suites including ocean island basalts (OIB) and some mid ocean ridge and continental flood basalts. Moreover, processing of sediments in the mantle may lead to significant geochemical refertilisation of the mantle.

Despite the importance to magmatism, there is a conspicuous lack of data on the melting behaviour of sedimentary rocks under upper mantle conditions. We have performed a series of piston-cylinder experiments examining the anhydrous phase relations and compositions of a synthetic pelite starting material over a pressure and temperature range of 3.0 to 5.0 GPa and 1100 to 1600 ºC. Complete parageneses, phase compositions and phase proportions were determined for almost all experiments.

The anhydrous pelite solidus is located at between 1150 and 1200 ºC at 3.0 GPa and close to 1250 ºC at 5.0 GPa; temperatures that are around 50-150 ºC lower than anhydrous MORB solidus (Pertermann and Hirschmann, 2003; Spandler et al., 2007). By contrast, the liquidus for anhydrous pelite is likely to be over 1600 ºC at all investigated pressures, giving a large melting interval of over 400 ºC. The subsolidus phase assemblage consists of quartz/coesite – feldspar – garnet - kyanite – rutile ± clinopyroxene ± apatite. Above the solidus, feldspar, rutile and apatite are rapidly melted out, with the feldspar stability field shrinking with increasing pressure. By contrast, clinopyroxene stability is greatly enhanced with increasing pressure. Garnet and kyanite are stable to high melt fractions (70-90%), but quartz/coesite is the sole liquidus phase over an interval of at least 150 ºC. Feldspar compositions vary with pressure from sodian sanidine at 3.0 GPa to nearly pure orthoclase at 5.0 GPa. Clinopyroxenes are jadeite and Ca-eskolaite rich, with jadeite contents increasing with pressure and decreasing with melt fraction. Garnets are dominated by almandine and pyrope components, with increasing pyrope and decreasing grossular with increasing melt fraction.

Melt compositions at all investigated conditions are alkaline dacites with SiO_2 and Al_2O_3 contents varying little from 66 wt% and 16 wt%, respectively. FeO and MgO are compatible, whereas TiO_2 and P_2O_5 behave incompatibly. At 3.0 GPa, initial melting is rapid and is controlled almost exclusively by feldspar and quartz, giving melts with $K_2O/Na_2O \sim 1$. At 4.0 and 5.0 GPa, low-fraction melting is controlled by jadeite-rich clinopyroxene and K-rich feldspar, which leads to compatible behavior of Na and melts with $K_2O/Na_2O \gg 1$.

The determined phase and melting relations and compositions may have important implications for production of mafic magma suites. Sedimentary protoliths in upwelling heterogeneous mantle source regions may undergo melting at greater depths than mafic lithlogies to produce ultrapotassic dacitic melts. Such melts are expected to react rapidly with surrounding peridotite to produce metasomatic pyroxenites (e.g., Yaxley and Green, 1998), which may melt at shallower levels to produce primitive, but compositionally distinct, magma types. This scenario can account for many of the distinctive isotopic and alkaline element characteristics of EM1- and EM2–type OIBs (e.g., Samoa, Society, Azores, Pitcairn, Marquesas, and Austral-Cook suites).

Another important implication of extensive melting of sedimentary rocks in the mantle is the production of SiO_2 as a residual phase. Pure SiO_2 (quartz, coesite, or stishovite) in the mantle has melting temperature over 2000 ºC, meaning these residues may be preserved for very long timescales in the mantle, and hence may be the cause of some seismic discontinuities that occur beneath hotspot, island arc and oceanic ridge (?) volcanic regions (Williams and Revenaugh, 2005).

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The making of the Italian ultrapotassic magmatism: phonolitic melts from carbonaceous pelite melts from the trailing edge of a detached slab traveling through and hybridizing in the mantle to form ultrapotassic kamafugites

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The ultrapotassic magmas from the Intra-Apennine and Roman provinces constitute worldwide end members in terms of K_2O/Na_2O, K_2O content and CO_2 degassing, SiO_2 of potentially primitive melts ranges from 45-54 wt%, and some are also associated with carbonatites (see Pecerillo, Springer, 2005). They are found in a geotectonic situation where plate convergence has slowed down to less than a few mm/a, the slab now tearing off leading hot asthenospheric mantle to flow in between the trailing slab and the crust (Spakman and Wortel, The Transmed Atlas, 2004).

A successful recipe for ultrapotassic magmas requires K/Na fractionation at some previous stage. Melts from fluid-absent melting of carbonaceous pelites at ≥ 3 GPa constitute such ultrapotassic (phonolitic) melts with an SiO_2 near 64 wt% and have a K_2O/Na_2O up to 9, because of residual cpx with compositions around jadeite$_{80}$. With respect to CO_2-free pelites, CO_2 stabilizes residual jadeite, lowers the SiO_2 content, and increase K_2O/Na_2O ratios (CO_2 free pelite melts at 4 GPa are highly siliceous granites with a K_2O/Na_2O of 1-3 and $SiO_2 = 73-77$ wt%). The phonolitic melts were experimentally equilibrated with a fertile, a refractory but cpx bearing mantle, and with a wherlite. At sufficient pressures (3.5 GPa) and X_{CO2} in the volatile component, hybridization of these slab melts produces highly subsilicic kamafugites, with K_2O/Na_2O only slightly lowered, MgO contents of up to 27 wt%, and X_{Mg}'s > 0.75. The essential role of CO_2 during the hybridization stage in the mantle is to reduce the olivine saturation volume and to shift the olivine-cpx-opx cotectic to lower SiO_2. The extreme MgO contents and X_{Mg}'s found in the experimental melts can be mitigated by 7-25 wt% of olivine fractionation, which then yields MgO concentrations and X_{Mg}'s as observed in the Italian melts. However, a prerequisite to allow for any significant olivine fractionation is that the experimental primitive CO_2-rich melts are low in SiO_2 (on a volatile including basis down to 43 wt.%). Many Italian kamafugites are also ultracalcic ($CaO/Al_2O_3 = 1.2-1.4$), and although carbonaceous pelite melts have < 2 wt% CaO and 20 wt % Al_2O_3, the assimilation of cpx and precipitation of aluminous opx in the mantle leads to ultracalcic compositions when equilibrated with refractory peridotite or wherlite, but not with a pyrolitic fertile mantle.

Temperatures necessary for the fluid absent carbonaceous pelite melting are 1050-1150 $^{\circ}$C, far above any reasonable subduction geotherm. Hybridization in the mantle requires 1300-1370 $^{\circ}$C (at 3.0-3.5 GPa). The proposition is, that the phonolitic slab melts only form in thermally relaxing slabs typical for an ending subduction. Slab break off causes inflow of hot asthenospheric mantle, which further heats the trailing edge of the slab. In this model, the phonolitic melts travel into the overlying mantle, which does not need any previous metasomatism (i.e. pre-existing phlogopite and magnesite or dolomite are unnecessary). In the particular Italian situation,

temperatures of the trailing slab edge and the asthenosphere are apparently sufficient to keep the carbonaceous slab melts liquid during hybridization in the mantle, leading to MgO-rich kamafugites which fractionate olivine during decompression when traveling to the surface. Different extents of melting in the mantle wedge in combination with different degrees of depletion of the wedge mantle produces a spectrum of primitive melts which is wider than what is observed at the surface. In this model, the chemical variation in possible primitive melts indicates that it is futile to search for a single parental magma for the entire Italian ultrapotassic magmatism. The short longevity of the ultrapotassic magmatism (800 ka) collaborates the concept of a one-time event, i.e. the one-time melting of the trailing slab edge during it's break-off.

Map of City Center with ETH-Buildings

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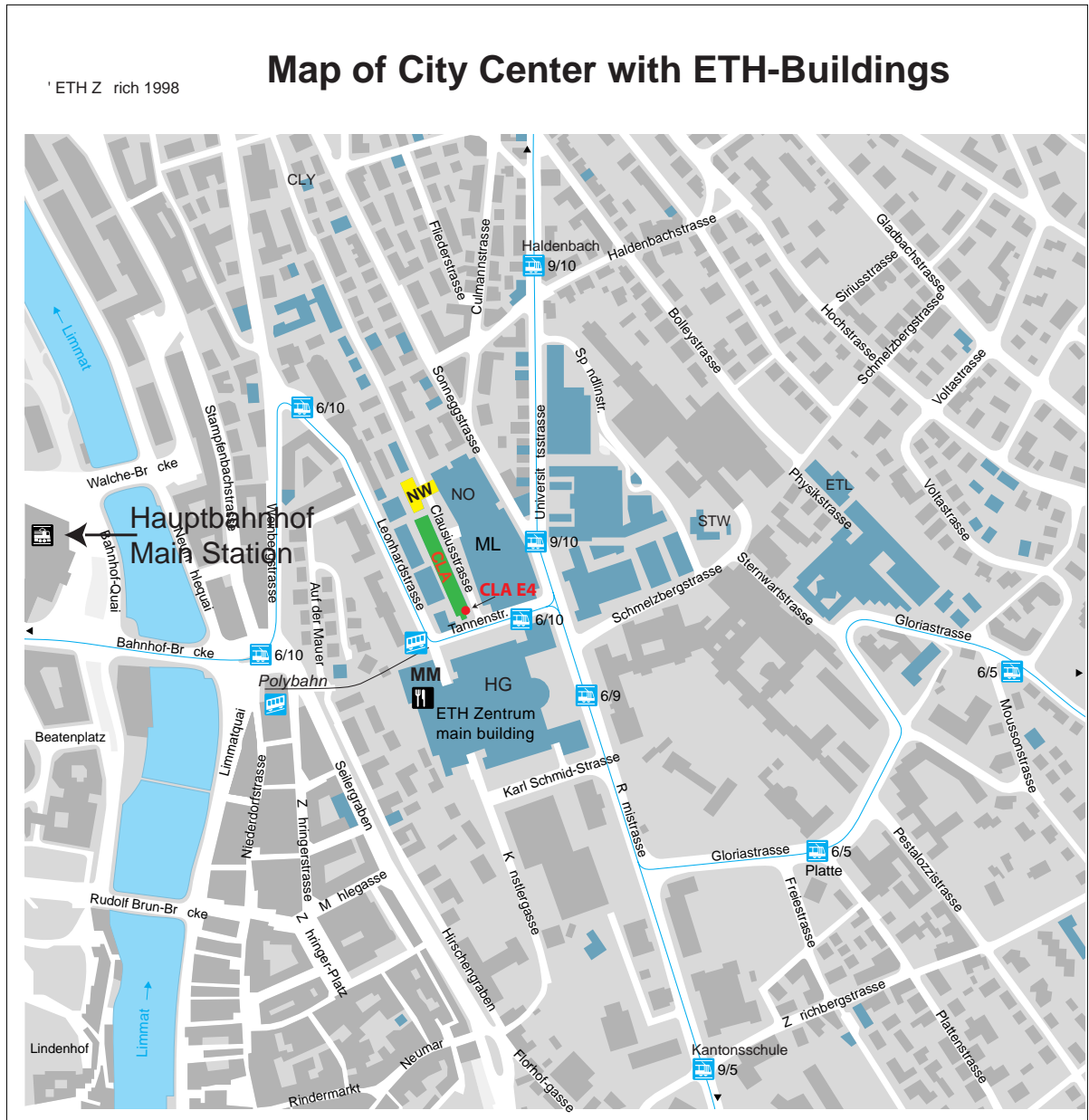
Map of ETH Zentrum
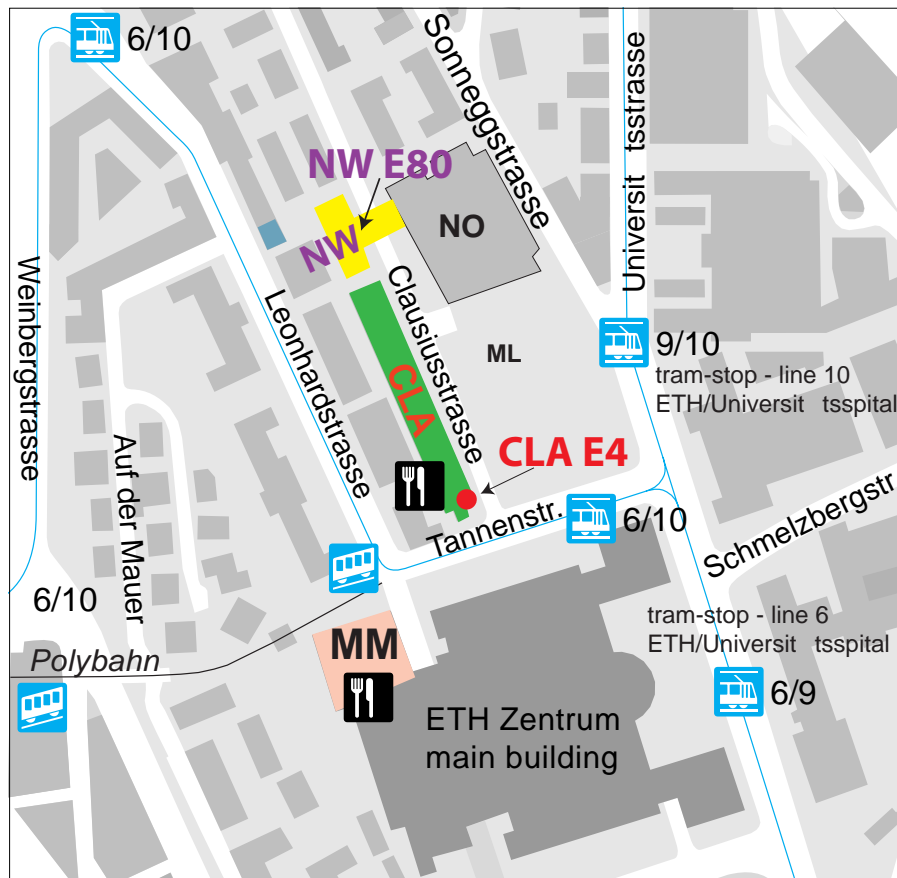
CLA - Building Clausiusstrasse (opposite ETH-Zentrum main building)
Lecture Theatre **CLA E4** (E-floor, directly on the right at the entrance from the Tannenstrasse before the stairs leading down to the Mensa/Cafeteria (Asian Mensa)

NW - Naturwissenschaften West: Part of Earth Science Department - **Welcome Coffee** at 8:30 in E 80 (Entrance under the Passarelle(gangway), 2 1/2 floors up directly oposite the stair

MM - Main Mensa: Lunch at Main Mensa or Clausiusbar (Asian Mensa directly under