

# *EUG XI*



Symposium MS03

Magmatic Inclusions in Minerals –  
A Source of Key Information  
about the Mantle Processes

Convenors

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## MS03 Magmatic Inclusions in Minerals

### Tuesday PO Session

#### MS03 : TUp01 : PO Boron Concentration and Isotopic Composition (i.e. B&B Systematics) of Olivine Hosted Primitive Melt Inclusions from Mt. Shasta, California

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Primitive melt inclusions occur in high-Mg olivines in basaltic andesites from Shasta. They represent the closest approach for studying melting and melt migration processes beneath Cascades (Shimizu et al., 1998). The Shasta subduction zone is one of the hottest and youngest subducting slab on Earth and therefore constitute an endmember case study.

The  $\delta^{11}\text{B}$  variations for several melt inclusions from a single sample span from -21.3‰ to -0.9‰ and are much larger than what has been previously reported (Gurenko and Chaussidon, 1997; Hauri et al., 1999). The overall range of  $\delta^{11}\text{B}$  values (from -23.5 to +3.5‰) suggest the heterogeneity of the source of the melts. Although we can not decipher between direct slab melting and/or fluid triggered mantle wedge melting, for the origin of the melt inclusions, the B&B systematics allows us to propose a most likely two step process consisting in: (1) a severe dehydration due to subduction metamorphism followed by (2) melting/fluid triggered melting of the slab/mantle wedge, respectively. This interpretation is furthermore supported by the Rare Earth Element and Trace Element patterns measured in the same melt inclusions.

Melt inclusions in these samples display contrasting trace element patterns. Those in 85-44 and 82-81 are flat with abundances around 10 times Cl, and whereas those in 95-15 are strongly depleted in HREE and enriched in LREE with high Sr/Y (up to 230). The REE variability in the melt inclusions are accompanied by large variations in  $\delta^{11}\text{B}$ . Melt inclusions in 85-44 display variations from -13.9 to -4.0‰ and from -23.5 to -9.3‰ in 82-81. These  $\delta^{11}\text{B}$  variations overlap with the  $\delta^{11}\text{B}$  values of 95-15.

The highly variable and mostly negative  $\delta^{11}\text{B}$  of primitive melt inclusion raises the question of the magmatic processes that allows melt inclusions from a single mineral to be so different. In addition these primitive melts have low B concentrations (from 0.18 to 4.64 ppm) which suggests that there is probably less fluid-induced melting in the Shasta subduction zone system than in any other subduction zone.

Shimizu N & Grove TL, *EOS*, **79**, F1002, (1998).

Gurenko A & Chaussidon M, *Chemical Geology*, **135**, 21-34, (1997).

Hauri E, Tomascak P & Lassiter J, *Goldschmidt Abstract*, **1**, 118, (1999).

#### MS03 : TUp02 : PO Koolau and Mauna Loa Primitive Melts: Investigation of Melt Inclusions in Olivines

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Koolau lavas were shown to represent the end-member component within the Loa trend of Hawaiian volcanoes enriched in recycled material of oceanic crust, including oceanic sediments (e.g. Hauri, 1996). However, so far available data on Koolau is restricted to lavas, which are significantly affected by magma mixing, alteration and crystal fractionation and thus may not represent primary melts. Moreover high-Mg olivines in Koolau lavas were proposed to represent disaggregated mantle xenoliths rather than phenocrysts (Takahashi et al. 2000).

Here we report results of comparison of compositions of melt inclusions (MI) trapped in high Mg olivine phenocrysts in picritic lavas from Koolau (2 samples) and from Mauna Loa (4 samples covering more than 100 ky of volcanic history, Sobolev et al., A.V., 2000). Crystallized MI in olivines were heated till full homogenization under optical control and quenched while naturally quenched glassy melt inclusions were not treated experimentally. Major and trace element compositions of experimentally or naturally quenched MI and host olivines were studied by electron probe and by ion microprobe respectively. Compositions were corrected for Fe-Mg exchange and crystallization of olivine up to equilibrium with host olivine (corrected melts) and up to equilibrium with most magnesium olivine Fo 90.8 (primary melts).

The obtained data suggest the following conclusions  
1. Koolau olivine phenocrysts (Fo 84-89.5) have crystallized from different primary melts significantly distinct from Mauna Loa primary melts in higher Si, Na, and lower Ca, Ti and HREE.

2. The recorded range of primary melts composition suggests mixing of at least two components: relatively low-Si Mauna Loa end-member and extremely high-Si Koolau component depleted in Ti, Ca, and HREE.

3. Both Mauna Loa and Koolau components show strong evidence for garnet in the residuum.

4. The high Si content of Koolau component suggests melting of olivine free source in the garnet stability field below oceanic lithosphere.

Hauri EH, *Nature*, **382**, 415-419, (1996).

Takahashi E et al., *Abstract, Plume 3, Hawaii*, 77-79, (2000).

Sobolev AV, Hofmann AW & Nikogosian IK, *Nature*, **404**, 986-990, (2000).

#### MS03 : TUp03 : PO Implications of Melt Inclusions Study in Geodynamics: Some Tough Questions about Exotic Inclusions

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Primary melts are the only direct witnesses of processes in the convecting part of the Earth mantle. However after extraction from the mantle source these melts could be easily modified either by reaction en route or by mixing in plumbing system. Thus the only available option to find primary melts in nature before they have been modified is the study of melt inclusions in early minerals. The published data on the compositions of exotic melt inclusions in high Mg olivines, which might represent such a melts, seem to support this approach (Sobolev & Shimizu, 1993; Gurenko & Chaussidon, 1995; Sobolev, 1996; Kamenetsky et al. 1998; Sobolev et al., 2000). However from these data is not directly evident how representative are those inclusions and, in particular, what amount of melt do they represent. This question becomes really tough for any geodynamic implication of exotic inclusions composition considering possibility that such inclusions represent only locally existing reactive melts trapped nearly simultaneously with their production. Moreover the fact that in many cases exotic inclusions coexist with normal ones in the same olivine crystals on the hundred micrometers scale seems to strongly support this alternative.

In this paper I will try to access this problem by using the following approaches: 1. The mass balance estimations of amount of exotic melts assuming them as pure end members in the mixed bulk lava or assuming known composition of mantle source and melting regime. 2. The comparison between PT conditions of trapping and melt origination. 3. The detail reconstruction of trapping history for compositionally variable inclusions coexisting in one olivine grain.

The following results have been obtained so far: 1. It is shown that the ultra-depleted melt inclusions from both mantle plume and mid-oceanic ridge and Sr-rich melt inclusions from mantle plume should likely represent significant original amount of melt in particular plumbing systems (more than 10% of total). 2. Almost all 500 melt inclusions in olivines from different Hawaiian volcanoes studied by SIMS clearly indicate their high-pressure origin in the presence of garnet (thus more than 30 kbar pressure). In contrast, data on C concentrations in the melt inclusions,

low densities of coexisting fluid inclusions and high Ca contents in host olivines all suggest low pressures of trapping (less than 6 kbar). This rules out common simultaneous production and trapping of melt at least for Hawaiian volcanoes. 3. The detail data on the composition of coexisting melt inclusions and host olivines show that variable in composition melt inclusions were trapped sequentially at different depths. This suggests complicated multistage crystallization and trapping process rather than nearly simultaneous trapping of locally heterogeneous melts.

The obtained arguments seem to support application of inclusion data in geodynamics. However because they are not general, each case should be considered individually.

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Sobolev AV & Shimizu N, *Nature*, **363**, 151-154, (1993).

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#### MS03 : TUp04 : PO Exceptionally Carbon Rich Silicate Melts Included in Olivine from Pyroxenite Xenoliths (West Eifel, Germany)

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Here we report the discovery of the natural high pressure melts exceptionally enriched in C. They have been found as a melt inclusions in cumulative olivine pyroxenite xenolith (DW-905) occurring in the ash-tuffs of the Dreiser Weiher maar-type volcano, West Eifel, Germany (Witt-Eickchen & Kramm, 1998). The inclusions were treated by high temperature experiments both at 1 atm, and 10-12 kb pressures. Quenched melt inclusions were analyzed by electron probe (major elements and C), nuclear probe (C) and by ion probe (trace elements, H<sub>2</sub>O and C) techniques.

Silicate melts, high density CO<sub>2</sub>, sulfide melt and their combinations occur as inclusions in well-defined planes along healed intragranular fractures in olivine and clinopyroxene and were interpreted as pseudosecondary inclusions trapped in xenolith minerals before its transportation. T-P conditions of formation of xenolith minerals estimated from the compositions of Cpx inclusions in olivine and from the partial and full homogenization of melt inclusions and density of CO<sub>2</sub> fluid inclusions are as following: T=1200-1250 C; P more than 10-15 kb. The absence of garnet in the assemblage constrains upper limit of pressure at 25 kbar.

Compositions of melt inclusions corrected for quench olivine crystallization on the walls of cavity correspond to alkali rich highly silica undersaturated melts. They show significant range in respect to silica contents (SiO<sub>2</sub>=33-41 wt.%), concentration of alkalis, Ca and P covering and exceed (toward lower Si and higher Ca, P and alkalis) all entire compositional range of reported Eifel magmas (Mertes & Schmincke, 1985). All inclusions show extreme enrichment (up to 1500X chondrite for Ba) by highly incompatible elements (light REE, Ba, Nb and Sr) and are relatively depleted in HREE (10-25 X chondrite for Yb). Similar to major elements, trace elements concentrations cover all entire range reported for Eifel magmas (Mertes & Schmincke, 1985) and exceed it toward higher concentrations of all highly incompatible elements. Carbon concentrations in quenched melt inclusions were studied by 3 independent techniques: nuclear probe, electron probe and ion probe. All methods show consistent results and suggest that the original concentration of C in the tapped melts was

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in excess of 15000-20000 ppm. This corresponds to up to 5.5-7.5wt% of CO<sub>2</sub> in the melt. H<sub>2</sub>O concentrations in melts were lower than 0.50 wt%. Chlorine varied in the range of 0.2-0.4wt%, sulfur in the range of 0.10 to 0.30 wt%.

The composition of studied inclusions correspond to the melts coexisting with olivine and clinopyroxene, CO<sub>2</sub>-rich fluid and sulfide melt at temperature 1200-1250 °C and pressure range between 15-25 kbar. Low viscosity of these melts and their extreme enrichment in highly incompatible elements make them efficient agents of cryptic metasomatism in lithospheric mantle.

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### MS03 : TUp05 : PO Carbonates in Ultramafic Xenoliths from the Kerguelen Archipelago (Southern Indian Ocean): Evidence for Carbonate Magmas in the Mantle

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The ultramafic xenolith collection from Kerguelen archipelago has provided the greatest diversity of xenoliths ever observed in an oceanic setting. Beyond them, Peridotites can be subdivided into mantle harzburgites, dunites and associated composite xenoliths that represent mantle wall-rock. Furthermore, some xenoliths are rich in volatile-bearing minerals (amphiboles, micas, carbonates - Calcite, dolomite, magnesite-) which study has been led simultaneously with that of phlogopite and amphibole megacrysts from peralkaline silica-undersaturated lavas have also been examined. This study shows that percolating fluids in peridotites are mantle-derived and related to the latest alkaline magmatic activity which characterizes the Kerguelen plume, with the final stage represented by silicate and carbonate melts, such as those observed within trapped inclusions (Schiano *et al.*, 1994). Carbonate melts have physical and chemical properties which enhance migration along grain boundaries within mantle peridotites. In contrast, silicate melts seem to be confined to veinlets and the vicinity of the wall-rock (on mm to cm scale). Solid-liquid reactions between silica-undersaturated melts and orthopyroxene, can produce Cr-Na-rich clinopyroxene and both alkali-rich silica oversaturated melts and carbonate melts. Clinopyroxenes, amphiboles, micas, Fe-Ti oxides, Fe-Ni sulfides, carbonates and phosphates are the new mineral phases occurring within magma percolation channels during multi-stage mantle metasomatism. These new mineral phases have preserved their "primary" stable isotopic mantle signatures (C, H) which are relatively homogeneous. The  $\delta D$  values of micas and amphiboles of xenoliths and megacrysts lie within the accepted mantle range, but the  $\delta D_{H_2O}$  values calculated in equilibrium with amphiboles and micas at the same temperature, exhibit a bimodal distribution that could indicate the existence of two different mantle fluids. Carbonate within lavas and peridotites show mantle isotopic compositions (O, C) and provide no evidence about recycled lithospheric components. Metasomatic clinopyroxene and amphibole display trace element patterns suggesting that these minerals are in equilibrium with highly alkaline silicate melts and occasionally with carbonate melts. Trace element patterns in carbonates from amphibole-bearing dunites are characterized by low alkali content; high Mg/(Mg+Fe) ratio; high Sr, Ba content, appear unusual in their high LREE enrichment. From microstructural features and chemical composition, it is deduced that carbonates inclusions suggest that they are quenched carbonate liquids rather than crystal cumulates from carbonate-rich melts as observed by Lee *et al.*, (2000) in other setting. Moreover, trace elements in carbonates (<0.5% in mode) control the trace element signature of the

whole-rock. These patterns are similar to those found in carbonate peridotites from different setting such as Mongolia and Spitsbergen Islands (Ionov, 1998).

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Ionov D., *Journal of Petrology*, **39**, 1931-1941, (1998).

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### MS03 : TUp06 : PO Melt Inclusions and Interstitial Glasses from Anhydrous Spinel Peridotite Xenoliths in Pliocene Basanites of the Vitim Volcanic Field

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Three series of anhydrous peridotite xenoliths from the Pliocene basanites of the Dzhilinda river were determined: (1) high-T garnet and spinel lherzolites, (2) low-T spinel lherzolites and harzburgites, and (3) low-T titaniferous spinel lherzolites (Litasov *et al.*, 2000). We studied melt inclusions, interstitial glasses and melt pocket assemblages from all the peridotite groups to describe the evolution of small fraction melt in the mantle and interaction of this melt with primary peridotite minerals. Both heated (up to homogenization temperature) and unheated secondary melt inclusions in silicate minerals of peridotites were inspected. Temperature of homogenization in the inclusions was not less than 1150-1250°C. Cryometric study of CO<sub>2</sub>-bearing fluid inclusions indicated pressure ranging within 3-9 kbar. Host basanite (1.8 Ma) has Mg# = 55-57 and contain (wt.%) TiO<sub>2</sub> = 2.4-2.7, Na<sub>2</sub>O = 3.8-4.5, K<sub>2</sub>O = 2.4-2.7. We recognized two major types of melt inclusions in the minerals: type I is obviously related to the host basanites according to high K<sub>2</sub>O contents and low Mg# of glasses, and type II probably reflects partial melting of peridotites at 10-15 kbar. Heated glasses from inclusions of the type II are very similar in composition to those reported by Schiano *et al.* (1998) and to the composition of small fraction melts from experimental studies of lherzolites (Baker *et al.*, 1995; Robinson *et al.*, 1998). These primitive glasses were found in peridotites of group 1 and 2 and contain (wt.%) SiO<sub>2</sub> = 50-57, Al<sub>2</sub>O<sub>3</sub> = 14-19, CaO = 7-15, Na<sub>2</sub>O = 2.5-5, K<sub>2</sub>O = 0.3-0.7, Cr<sub>2</sub>O<sub>3</sub> = 0-0.2 and have Mg# = 78-91. Glasses from Ti-rich peridotites of group 3 correspond to both types of inclusions: heated glasses of type II contain 1.6-3.2 wt.% of TiO<sub>2</sub> and 0-0.5 wt.% of K<sub>2</sub>O. Unheated glasses of melt inclusions in minerals from harzburgite xenolith are most enriched in SiO<sub>2</sub> (up to 71.5 wt.%). Interstitial glasses in lherzolites are also enriched in SiO<sub>2</sub> (60-67 wt.%) and mainly correlate with unheated inclusions of type I. Melt pockets are commonly located around spongy-rimmed clinopyroxene grains and consist of plagioclase, glass, olivine, spinel and rare ilmenite needles in glass. Olivine microclots have composition similar to primary lherzolitic olivine with Mg# = 88-92, however they contain higher CaO (0.15-0.4 wt.%), and lower NiO (0.15-0.3 wt.%). Spinel in melt pockets contain 20-25 wt.% Cr<sub>2</sub>O<sub>3</sub>. The results support the idea that Si-rich melt (of basalt to andesite compositions) may coexist with peridotite at shallow mantle level and can be produced by very small partial melting of anhydrous peridotite. In contrast, in case of small degree of hydrous partial melting of peridotite containing amphibole/phlogopite, Si-undersaturated alkaline basaltic melt is formed. This is clearly supported by the composition of both melt inclusions and interstitial glasses from hydrous xenoliths (Newmann and Wulff-Pedersen, 1997) and from the composition of OIB magmas (Kinzler and Langmuir, 1995).

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Kinzler RJ & Langmuir CH, *Nature*, **375**, 274-275, (1995).

### MS03 : TUp07 : PO Melting Processes in the Sub-Continental Antarctic Mantle-Constraints from Melt Pockets in Spinel-Lherzolitic Xenoliths, Seal Nunataks, West-Antarctica

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Our study on Upper Mantle xenoliths in Antarctic Peninsula volcanics based on whole-rock geochemistry and petrology of mafic minerals give a new insight in the thermal upper mantle conditions below the Antarctic Peninsula. Our focus was to determine the origin of the xenolith bearing host magma. In here we compare the characteristic of melt pockets and the host magma. The Seal Nunataks - a group of alkali-basaltic volcanic outcrops - were formed in an glacial environment. Volcanological descriptions are still insufficiently described in the literature. The geochemistry is well reported by Hole (1990), but petrological and geochemical description of mantle-xenoliths are still missing. On the base of an influence from mantle flow from south Pacific induced Magmatism in the Antarctic Peninsula region emphasised by Veit and Miller (1999), the young volcanics show a common magma source. Samples were taken from the lower unit of Bruce Nunatak (the only xenolith bearing location in the Seal Nunataks). Different nodules of spinel-lherzolitic type have been examined by thin section and fluid-inclusion techniques. The main mineral phase is olivine (forsteritic composition). In the medium grained olivine matrix rare clin- and ortho-pyroxenes can be found. Spinel occur in the intergranular veins which are mostly filled with basaltic melts. The pyroxenes show reaction rims (between ortho-pyroxenes and clinopyroxenes and between clinopyroxenes and spinel respectively basaltic melt). The geochemistry of the fluid trails in olivine and pyroxene had been measured by Electron Microprobe techniques. Three types of basaltic melts were compared: one is an alkali-basaltic host magma, second the hawaiitic to mugearitic glass rim and melt pockets. The hawaiitic to mugearitic glass rim and melt pockets are not correlated with the alkali basalt. The alkali basalt is generated through extension of the Antarctic Peninsula back-arc lithosphere. The glass rim and melt pockets are influenced by the flow of a fluid through the subantarctic upper mantle. This implies that the fluid induced the melting of the mineral phases in the upper mantle. In mayor and trace element patterns of Antarctic Peninsula volcanics the back-arc signature - on the one hand - is well defined but on the other hand the influence from the downgoing slab is only slightly present. Whole rock isotope geochemistry of host magma and xenolith support these undergone effect of slab derived melts. The mantle flow is in a superposition with extensional intraplate melting in a back-arc setting.

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### MS03 : TUp08 : PO Two Rock Series within Single Alkaline Ultrabasic Complex - Derivatives from Two Primary Magmas?

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Two coexisting series, strongly calcium melilite-bearing rocks and more common melilite-free alkaline-ultrabasic rocks were found to compose the alkaline-ultrabasic association in the massifs Kovdor and Cape Turii, Kola Peninsula, and 6 massifs of Maimecha-Kotui Province, NW Siberian Platform, including the largest in the world Guli massif (Kravchenko, Rass, 1985). Also two series, different in Ca content, were later described in Oldoinyo-Lengai and Shomboly volcanoes (Peterson, 1989) and in Gardiner complex (Nielsen, 1994). Both authors think the two series are comagmatic, i.e., derivatives from the single magma.

The primary magma composition was determined in melt inclusions in olivine from meimechites, the Guli massif (Sobolev *et al.*, 1992), and the composition of this melt was

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apriori accepted as a single primary magma which provides in all rocks which compose alkaline-ultrabasic complexes, including melilite-bearing rocks also.

However, differences of compositions and zoning of accessory and rock-forming minerals, affiliated to melilite-bearing or melilite-free rock series, dependent on parent melt compositions, rare element distributions in carbonates, within ring complexes with or without melilite-bearing series, and different fractionation parameters for REE, Sr, Zr, P, during formation of the two series suggest that an other primary magma, rich in Ca, should exist.

The only technique which could currently provide direct samples of early magmatic stages are magmatic inclusions in minerals. The first preliminary results on the compositions of melt inclusions in olivine (Fo=86-93) from kugdite (Ol+Mel), the Guli massif (Rass, Plechov, 2000) demonstrate their essential dissimilarity from that of melts analyzed in inclusions in olivine of commensurable Mg/(Mg+Fe), which represent phenocrysts in meimechite (Sobolev et al., 1992). These melts are high in CaO (Ca/Si ratio is 0.45, contre 0.32), in Na<sub>2</sub>O up-to 11.6 wt%, and in Al<sub>2</sub>O<sub>3</sub> up-to 15.5 wt%. The daughter minerals in primary, completely crystallized, inclusions are monticellite, clinopyroxene, nepheline, perovskite, Cr-spinelide. The thermometric experiments were conducted at 1221 and 1320 C. The re-homogenized inclusions consisted of glass and a gas bubble, with crystals of chill monticellite on the walls of some inclusions.

The problem of the existence of Ca-rich magmas formed in a carbonatized mantle matter is related to the kimberlite problem. IB kimberlites (Smith et al., 1985) and Ca-rich ultrabasic primary magmas may be derived by different degrees of partial melting. Experiments on the melting of natural calcium rich kimberlite at 7 kb have revealed a possibility of melilite crystallization (Rass et al., 1996). The necessary condition for the differentiation of Ca-rich kimberlite-like or kimberlite magma to reveal melilite is the existence of an intermediate magma chamber under pressures at least as low as those within the melilite field.

The author thanks RFBR for a financial support (N 98-05-65017).

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### MS03 : TUpo09 : PO Inclusions in Apatite and Olivine as Indicators of the Evolution of Mineral-Forming Solutions in the Kovdor Massif, Kola Peninsula, Russia

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The Kovdor carbonatite massif comprises rocks of phosphorite series (olivinites, turjaite-pegmatites, ijolites, phlogopite complex) and phoscorite-carbonatite series. In this study, we investigated, using an analytical SEM, inclusions in two of the rock-forming minerals, apatite and olivine.

In olivine, two types of inclusions were observed: Type I - magnetite-silicate intergrowths (exsolution structures); Type II - solid primary inclusions, some are crystallised melt, with a range of daughter minerals. Type I inclusions occur only in the pre-phoscorite rock series (with the exception of ijolite where they are absent). Diopside is present in exsolution structures in olivine from olivinites, rocks of the phlogopite deposit, and monticellite, and in olivine from turjaite and olivine-monticellite rock-types. Homogenisation of these inclusions shows that diopside begins to disappear at temperature of 1050°C.

Type II inclusions are typical for olivine from all investigated rock types. In the pre-phoscorite rocks, the included minerals are diopside, phlogopite, tetraferriphlogopite, apatite and magnetite. These inclusions reflect an accumulation, as residual liquids, of those components which subsequently form the major rock-forming minerals during formation of phlogopite and phoscorite-carbonatite complexes. Olivine from rocks of phlogopite complex contains calcite, shortite, barite, pyrite and other minerals which are characteristic of the late-stage rocks. Forsterite from the phoscorite-carbonatite complex contains only Type II inclusions with compositions depending on the host rock-type. Daughter minerals in these inclusions are either very similar to that of rock-forming minerals from their corresponding rock-types, or are minerals (e.g. Fe-bearing dolomite, Na,Ca carbonates, bradleyite, Na,Ba phosphate, pyrrhotite, pyrite) typically associated with the late-stage rock-types.

Apatite contains a larger diversity of inclusions, both solid and fluid, than olivine. In rocks of the phlogopite complex, daughter minerals in apatite include serpentine, pyroxene, phlogopite, calcite, thorianite and zirconolite. Apatite inclusions from phoscorites and carbonatites typically comprise barite, dolomite, magnesite, sylvite, and Na,Ca carbonates. Some co-existing multi-phase inclusions from single grains vary significantly in the proportions of solid, fluid and gaseous phases which attest to the micro-scale heterogeneity of the mineral-forming solutions during the crystallisation process. Temperatures of homogenisation of the apatite inclusions range from 500-920°C (phlogopite complex); from 470-700°C (phoscorite complex), and 380-420°C (carbonatites).

This study of inclusions in olivine and apatite from rocks of the Kovdor massif contain information about the initial magmatic melt, as well as the mineral-forming solutions of the subsequent stages of magmatism. The study has been supported by INTAS Grant No 97-0722.

### MS03 : TUpo10 : PO Quantification of Major to Trace Element Concentrations of Single Melt Inclusions in Various Host Phases using LA-ICP-MS

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Thanks to significant progress in the development of new analytical techniques in recent years, analyses of melt inclusions have provided new insight into igneous processes that occur in magma chambers or during volcanic activity. One significant limitation of most of the currently used techniques (EMPA, SIMS) approaches for the quantification of melt inclusion chemistry is the prerequisite that inclusions are compositionally homogeneous (not devitrified) and representative of the inclusion melt, i.e., they have to be homogenized at the appropriate temperature prior to analysis. Moreover, inclusions need to be exposed to the sample surface.

Laser-ablation ICP-MS provides a novel technique by which heterogeneous bulk inclusions can be analyzed, thus avoiding these prerequisite conditions (Halter et al. 2001). Because host mineral is ablated with the inclusion, quantification of the melt inclusion composition necessitates deconvolution of this mixed signal. This can be achieved in various ways, including (1) determination of the volume ratio between the inclusion and total ablated volume of the mixed signal, (2) a fixed, pre-determined, concentration of a given element; (3) a constant distribution coefficient between the host and the inclusion melt and (4) whole rock differentiation trends in a given igneous suite. We applied the latter approach to melt inclusions in various minerals from the high-K Farallon Negro Volcanic Complex (FNVC), Argentina.

The FNVC records a continuous differentiation trend from basaltic andesites, through andesites and dacites, to rhyolites. Assuming that melt inclusions represent melt compositions in this suite, laser-ablation ICP-MS analyses were quantified by constraining their Al/Fe ratio to that of the differentiation trend in the whole rocks. This approach was applied to inclusions from pyroxenes, amphiboles, plagioclases and quartz. The resulting compositions of the melt inclusions follow the differentiation trends of all major and most trace elements, regardless of the host mineral.

In a given host mineral, uncertainties on the calculated element concentrations in the melt inclusions mainly depend on the mass ratio between the inclusion and the host mineral. Moreover, concentrations of compatible elements have larger uncertainties than incompatible elements due to the uncertainty in the analyses of the host phase. Despite this limitation, uncertainties in the element concentrations below 10% can be achieved in multi-element mode (n=25) if the melt inclusion contributes more than 20% to the mixed signal and the signal-to-noise ratio is bigger than about 10. Limits of detection obtained for spherical 10<sup>3</sup>m melt inclusions calculated for each individual ablation are of the order of a few ppm for incompatible elements and of a few tens or hundreds of ppm for major elements in the host. These limits of detection can be improved by reducing the element menu to a few elements and by special tuning of the mass spectrometer.

### MS03 : TUpo11 : PO Physicochemical Conditions of Final Stage of Klyuchevskoy Volcano Magma Evolution-Insight from Melt Inclusions in Minerals of High-Alumina Basalts

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Magmatic inclusions were studied in phenocrysts from the high-alumina basalts of Klyuchevskoy Volcano, with special emphasis on melt inclusions in olivine (Fo71-79), clinopyroxene (Mg#70-81) and plagioclase (An47-84) phenocrysts (Mironov et al., 2001; Pletchov et al., 2000). Glassy melt inclusions were analyzed for major elements by an electron microprobe and water content was estimated using calculation methods (for ex. Danyushevsky, Sobolev, 1996). The data obtained allowed us to estimate the physicochemical conditions of melt crystallization. Variation in water content was the major factor, controlling liquidus phase relationships of the melts. Increase of water content during olivine and clinopyroxene crystallization resulted in delay of plagioclase crystallization and melt enrichment in Al<sub>2</sub>O<sub>3</sub>, producing magmas chemically similar to high alumina basalt (see also Ariskin et al., 1995). The subsequent evolution of melt composition was controlled by plagioclase crystallization from the magma, which resulted in melt depletion in Al<sub>2</sub>O<sub>3</sub>. Phenocrysts of high alumina basalts: olivines (Fo 71-79), clinopyroxenes (Mg#70-81) and plagioclases (An 47-84) crystallized from compositionally diverse melts at temperatures 1145-1030 C and pressures no higher than 5 kbar (in average 1.5 kb). The earliest of these phenocrysts correspond to melts containing ~ 5-6 wt.% MgO and varying amounts of Al<sub>2</sub>O<sub>3</sub> (16-20 wt.%) and H<sub>2</sub>O (0-5 wt.%). A model of the final stage of Klyuchevskoy Volcano magma evolution is proposed. According to this model, the crystallization of minerals of high-alumina basalts occurred under conditions of rapid decompression during magma ascent toward the surface of the volcano and was accompanied by a decrease in H<sub>2</sub>O content owing to degassing of magma. It was shown that the formation of dacite melt trapped by the plagioclase and clinopyroxene phenocrysts was probably related to the processes of extensive crystal fractionation of initial basaltic magmas. The formation of more silicic melts can be explained by the specific mechanism of melt inclusion entrapment by plagioclase crystals (Nakamura, Shimakita, 1998).

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## MS03 Magmatic Inclusions in Minerals

### MS03 : TUpo12 : PO Melt Inclusion Study in the Miocene Silicic Pyroclastic Series of the Bükkalja Ignimbrite Volcanic Field, Northern Hungary

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Silicate melt inclusions form when a drop of magma is trapped on mineral surfaces during crystal growth (primary inclusions) or in minerals during healing of fractures formed during crystal growth (pseudosecondary inclusions) or in minerals during healing of later fractures (secondary inclusions). Therefore, silicate melt inclusions preserve a fluid thought to be representative of the magmatic system at the time of entrapment. Silicate melt inclusions trapped at different times during the crystallization of a magma and therefore provide powerful information about the evolution of the magma.

The Bükkalja Ignimbrite Volcanic Field (BIVF) exposes a silicic pyroclastic sequence originated roughly continuously between 20 Ma and 13.5 Ma (Márton & Pécskay, 1998). Based on extensive palaeomagnetic study, the pyroclastic sequence is divided into three horizons and named as Lower, Middle and Upper Ignimbrite Units (Márton & Pécskay, 1998). Each volcanic horizon contains phenocryst such as plagioclase, quartz, orthopyroxene, clinopyroxene, amphibole, biotite and ilmenite. The majority of these mineral clasts contain large amounts of silicate melt inclusions, which provide a unique opportunity to have an insight into the stages of the evolution of silicic magmas. We present here the first study on silicate melt inclusions in silicic magmatic system in the Carpathian-Pannonian Region.

Silicate melt inclusions in the (BIVF) are most abundant in plagioclase, quartz, orthopyroxene and very rare in ilmenite. They occur both in the core and rim of the phenocrysts and show no differences in petrographic features. Size of the silicate melt inclusions is up to 120 microns in diameters. The silicate melt inclusions particularly in orthopyroxenes are generally rounded or negative crystal. However, irregular mostly elongated forms can be also observed characteristic of plagioclase and quartz phenocrysts. Silicate melt inclusions consist mostly of colorless or brown glass, single large bubble (and/or several tiny ones) and one or more crystallized solid phases as daughter minerals. There is not much difference among the three ignimbrite horizons in terms of silicate melt inclusion petrography, except in the sizes. Silicate melt inclusions of the Middle Ignimbrite Unit are smaller than those of the Upper and Lower Units.

Our preliminary results show that major element compositions have wide variation in the silica content. Compositions of the silicate melt inclusions analyzed range from trachytic to high-silica rhyolite with an SiO<sub>2</sub> content of 66.5 to 78.8wt% on an anhydrous basis. They have strongly potassic character with a K<sub>2</sub>O/Na<sub>2</sub>O ratio of 1.4 to 3.3 (K<sub>2</sub>O=4.2-6.7wt%). Melt inclusions from ilmenite reflect the less silicic (dacitic) geochemistry, whereas those from the quartz and plagioclase are rhyolites to high-silica rhyolites. It is remarkable that the samples from the plagioclases are generally more silicic and less potassic than the melt inclusions from the quartz.

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### MS03 : TUpo13 : PO Role of Deep Clinopyroxene Fractionation in Producing the Alkaline Magmas, La Palma, Canary Islands: A Magmatic Inclusion Study

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The Canary Islands sit above a low buoyancy flux plume impinging on thick, Jurassic-age oceanic lithosphere. La Palma is currently the most active of all Canary Islands, as befits its position at the head of the Canarian plume track. Products of La Palma magmatism are characterized by highly alkaline, 'basanitoid' compositions during its 4 My history. In order to understand better processes responsible for this alkaline end-member of the compositional spectrum of OIB, we have studied melt and fluid inclusion in olivine and clinopyroxene phenocrysts from La Palma lavas of two ~700 ka continuous stratigraphic sections (from the Fagundo and Izcagua barrancos) from the main shield, Taburiente. There are some differences between whole rock compositions of the lavas of these sections - Izcagua lavas are highly alkaline, "basanitoid", lavas typical of La Palma in general, whilst the Fagundo lavas are characterised by more silica-rich, "transitional", non typical for La Palma compositions. Experimental and analytical study of magmatic inclusions have shown that the typical basanites are rather differentiated melts (MgO 5-6% wt.; 1080-1150°C) in equilibrium with relatively evolved liquidus assemblages (<Fo84-85). These basanitoid melts result from a deep (5-7 kbar), clinopyroxene dominated fractionation of a less Si-undersaturated "transitional" melt which is represented by the Fagundo samples. Such "transitional" melts under La Palma themselves evolved by cotectic olivine-clinopyroxene crystallisation under high-pressure (>7 kbar) at temperatures of 1300-1250°C, MgO 11-10% wt., and are in equilibrium with olivine Fo 86-87. Magmatic inclusion data, in conjunction with mineralogical and whole rock data, thus provide strong evidence for explaining the generation of the highly alkaline, silica under-saturated (basanitoid) lavas of La Palma as the result of extensive clinopyroxene fractionation at depth 22-15 km, beneath La Palma Moho. The basanitoid lavas that largely comprise the shield building phase of La Palma have previously been interpreted to result from low degrees of melting as the result of the thick (Jurassic) lithospheric lid lying above the Canary mantle plume. Our study instead suggests that it is the promotion of deep fractionation which is more likely the control of the lithosphere in shaping the highly alkaline nature of the lavas in La Palma and possibly many other ocean islands.

### MS03 : TUpo14 : PO Tracking Magma Degassing at Stromboli Volcano (Italy) from Melt Inclusions and Volatile Fluxes

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Stromboli volcano, in the Aeolian island arc, has displayed almost continuous degassing and mild-explosive eruptive activity since 1800 years, producing more gas than lava on a time-averaged basis [1]. Such a sustained activity raises generic questions about the magmatic processes operating at this and other steadily erupting volcanoes. Here, we discuss the implications of new geochemical results we have obtained on present-day volatile fluxes and crystal melt inclusions in ancient (Vancori) pyroclastics dated between 25 and 13 ky [2]. The K-basaltic melt inclusions (MI) hosted in olivine grains Fo68-90 display a wide range in major elements (CaO/Al<sub>2</sub>O<sub>3</sub> = 1.06 to 0.39) and a high total volatile (CO<sub>2</sub>, H<sub>2</sub>O, S, Cl, F) content varying from 4 to 0.7 wt.%. However, they form a dominant cluster in olivines Fo<sub>83-84</sub>, with a composition (CaO/Al<sub>2</sub>O<sub>3</sub> = 0.62; 3.2-2.5 wt.% H<sub>2</sub>O; 1240-490 ppm CO<sub>2</sub>; 1700 ppm S and Cl, 660 ppm F) similar to the crystal-poor K-basaltic liquid expelled during present-day most energetic explosions. The similarity in crystallisation sequence and degassing trends for Vancori liquids and for present-day magmas [3] demonstrates a steady feeding system at Stromboli over time together with ascent of primary, H<sub>2</sub>O and CO<sub>2</sub>-rich mantle derived-melts preserved as MI in Fo<sub>90</sub>, but not identified among the erupted K-basaltic products. The H<sub>2</sub>O exsolution

at low pressure (≤100 MPa) determines the crystallization and should produce a gas phase with rather constant S/H<sub>2</sub>O ratio but decreasing S/Cl (2.6 to 0.4) and H<sub>2</sub>O/Cl (60 to 12) ratios along with gradual decompression. S/Cl ratios of 2.5-2.9 and 1.3-1.8 measured in 1993 and 1997 in Stromboli volcanic plume [4] probably tracked changes in the dynamics or/and the depth of magma degassing. The background CO<sub>2</sub>/S weight ratio of 7-8 during passive crater degassing (which increases during explosions) implies that 90% of the emitted CO<sub>2</sub> is derived from magma degassing and bubble rise deeper than 100 MPa, and suggests an original content of 1.2-1.4 wt.% CO<sub>2</sub> in the melt.

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### MS03 : TUpo15 : PO Platinum-Group Elements (PGE) in Podiform and Stratiform Chromitites from the Eastern Alpine Ophiolite, Austria: Mineralogical Constraints

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Podiform and stratiform chromitites are generally well defined based on distinct geological, geochemical and mineralogical features. Podiform chromitites usually represent discordant relatively small bodies in residual harzburgites and dunites from the mantle section of ophiolites, whereas stratiform chromitite are concordant in respect to the foliation of the host ultramafics in the upper crustal section of an ophiolite suite. It is generally assumed that podiform chromitites are dominated by platinum-group minerals (PGM) of the IPGE-group (Os, Ir, Ru) while stratiform chromitites show pronounced secondary PGM enrichment of less refractory PPGE (Rh, Pt, Pd). However, in many examples a clear mismatch can be demonstrated between total PGE concentrations in chromitites and the PGE mineralogy as observed in polished sections. This, together with frequent incomplete mineralogical data, makes a division between chromitite from the mantle section, transition zone, or crustal section difficult.

In this study we present detailed PGE geochemical and mineralogical data obtained from unaltered podiform and stratiform chromitites from Krauthaus, which is the largest dunite-harzburgite massif within the Eastern Alps, Austria. In particular, the podiform chromitite displays a negatively sloped chondrite-normalised PGE pattern similar to typical ophiolitic-podiform chromitite. PPGE are much more enriched in the stratiform chromitite like those typical for the crustal section of ophiolites.

On the basis of 235 PGM grains, 65 of which represent different polyphase PGM associations, obtained from podiform (type 1) and stratiform (type 2) chromitites, we documented about 30 different PGM and one Au-rich mineral. Type 1 chromitite is dominated by laurite (45% of all PGM) which occurs in complex polyphase assemblages with alloys (Ir-Os, Os-Ir, Pt-Fe), sulphides (kashinite-bowieite, PGE-rich thiospinel, braggite, unnamed (Ni,Fe,Cu)-(Ir,Rh)-S) and Pd telluride (keithconite). It contains a variety of PGE-sulpharsenides (30%). Sperrylite and stibiopalladinite are found in minor amounts (2%). In contrast, type 2 chromitite is dominated by sperrylite (50% of all PGM) which occurs in polyphase assemblages with tetraferroplatinum and Pd-rich minerals such as stibiopalladinite, mayakite, unnamed Pd-Rh-As and several Pd(Pt)-(As,Sb) minerals. Type 2 contains PGE-sulphides and sulpharsenides (about 7% each) that are represented by laurite, erlichmanite and irarsite, respectively. Native platinum, osmium, Pt-Pd alloy, unnamed Pt-Pd-Bi-Cu and tetrauricupride are found subordinately.

All six PGE are recorded in mineral phases in both chromitite types and are interpreted as primary, occurring as euhedral polyphase inclusions in chromite. Therefore, we tentatively propose that the stratiform chromitite from

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Kraubath might be considered as indicative rather for the transition zone of an ophiolite, closely above the mantle section, than as a representative of the crustal cumulate pile. As such, it probably represents a first description of primary PGM assemblage in ophiolite environments with pronounced enrichment of PPGE.

We gratefully acknowledge the Austrian Science Fund for financial support through grant M601-CHE to K.N.M.

### MS03 : TUpo16 : PO Platinum Group Mineral Inclusions in Podiform Chromitites as Indicators of the Sulfur Fugacity in the Ophiolitic Upper Mantle: Examples from the Mediterranean Area and from the Urals

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Most of the Platinum Group Minerals (PGM) associated with chromitites are considered as magmatic minerals formed at high temperature, and trapped in growing chromite crystals. Objective of this work is to compare the PGM included in chromitites from Mesozoic ophiolites of the Mediterranean (Vourinos, Othrys, Troodos) and Paleozoic ophiolites of the Urals (Kempirsai, Kluchevskoy, Ray-Iz) in order to estimate the conditions of  $fS_2$  and T during chromite precipitation in ophiolitic upper mantle. Laurite is the ubiquitous PGM at all the investigated localities, but important differences occur concerning presence and relative abundance of Os-Ir alloys, erlichmanite ( $Os_2S_3$ ), and Ir-Rh sulfides. Although, this might be related with the initial concentrations of Os, Ir, Ru and Rh in the chromite forming systems, more likely it is due to different T- $fS_2$  conditions during PGM precipitation. The  $fS_2$  is expected to increase with decreasing T in magmatic systems. The rather constant association Os-Ir alloys + Ru-rich laurite observed in the Vourinos chromitites is indicative of very low  $fS_2$  in the upper mantle, spanning a maximum range of about 2 log units between the Ru-RuS<sub>2</sub> and Ir-Ir<sub>2</sub>S<sub>3</sub> buffers. The (Ru,Os)<sub>2</sub>S<sub>3</sub> + Os<sub>2</sub>S<sub>3</sub> assemblage reported from Othrys suggests that  $fS_2$  was initially as high as to cause Os-rich laurite to be stable and increased up to reach the Os-Os<sub>2</sub>S<sub>3</sub> buffer, although probably did not exceed this limit much. The presence of mono-mineralic laurite assemblages (Troodos) is consistent with T and  $fS_2$  intermediate between the two previous cases, but at the same time, even more restricted ranges of variation. The PGM assemblages of Kempirsai, Ray-Iz and Kluchevskoy suggest that  $fS_2$  was initially as low as to enable precipitation of Ru-rich laurite as the only sulfide phase coexisting with Os-Ir alloys, but it increased of at least 4 log units, reaching the stability field of erlichmanite and Ir-Rh bearing sulfides in the final stages. Such a wide range of  $fS_2$  indicates that PGM crystallization proceeded down to much lower temperatures compared with the Mesozoic ophiolite complexes, thereby implying that chromite crystallization started at relatively low temperatures, probably incompatible with an anhydrous magmatic system. This feature may be related with the different geodynamic setting in which the Mesozoic chromitites of the Mediterranean and the Paleozoic chromitites of the Urals formed

### MS03 : TUpo17 : PO Na-Fe-Green-Core Pyroxenes and Mantle Metasomatism: New Evidence from LA-ICPMS Data

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The Cantal massif in the French Massif Central is the largest volcano of the Tertiary Mid-European Volcanic Province. Green-core clinopyroxenes (GCPX) of Na-Fe augite composition are frequent in the Supra-Cantal basalt (5-3 Ma) and rare in Infra-Cantal (13-9 Ma) ones. An electron microprobe study of the GCPX in the Cantal basalts (Pilet et al., 1999) demonstrated their crystallization in silicic liquids at intermediate to mantle pressures. Contrasted geochemistry between the two basalt groups seems related to a metasomatic event involving, in

particular, an enrichment in Ta and Nb of their sources. According to Bodinier et al. (1997) this enrichment is probably related to the crystallization of Ta, Nb-rich oxides in the mantle and seems to occur between the two main periods of basalt emission. The main hypothesis put forward to explain the deposition of these Ta, Nb oxides is the percolation of Si and K-rich metasomatic melts through the mantle. Recently, Wulff-Pederson et al. (1999) described amphibolitic veins within spinel peridotite xenoliths from La Palma (Canary Islands) containing kaersutite associated with Nb-rich oxides and augite, whose composition is identical to the Cantalian GCPX. They considered them as evidence for the presence in the mantle of siliceous metasomatic liquids. Pilet et al. (1999) suggested a relationship between such siliceous melts, the timing of percolation and the crystallization of GCPX observed in the Cantal basalts. LA-ICPMS analyses were carried out on GCPX. Preliminary results show higher Ta/Th contents and higher Ta/Th ratios in the GCPX (Ta/Th >4) than in the pyroxene in equilibrium with the basaltic liquids (Ta/Th ~1.5-2.5). Conversely, pyroxenes of phonolites show Ta/Th ratio <1. As the Ta and Th distribution coefficients in pyroxene remain constant with magma differentiation (Villemant, 1985), the Ta/Th ratio in the pyroxene is representative of the Ta/Th bulk-rock ratio. Therefore, we can exclude a xenocrystic origin from low pressure differentiated phonolitic liquids for the GCPX. On the other hand, their high Ta/Th ratio is in agreement with their derivation from a modal (as opposed to cryptic) metasomatized mantle source, and with the observed Ta-Nb enrichment of the Supracantal basalt source. Following the concept of "percolative fractional crystallization" of Harte et al., (1993), we suggest that Na-Fe-GCPX crystallized into mantle-trapped differentiated melts, which is supported by geochemical modeling of the basalt evolutionary trends. GCPX in basic rocks of alkaline provinces could thus be regarded as relict phases evidencing modal metasomatism of their mantle source.

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## Wednesday AM Session

### MS03 : WEam01 : G8 Interaction between Ocean Island Basalt-Type and Island Arc Basalt-Type Mantle Sources in Convergent Margin Settings: Evidence from the Southern Tyrrhenian-Sicilian Region

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The geodynamic setting of the Southern Tyrrhenian-Sicilian region has drawn the attention of many investigators since its evolution is accompanied by two radically different types of volcanism, an essentially calc-alkaline magmatism found in the Aeolian Islands and a magmatism of basaltic affinity expressed in the nearby Eastern Sicily volcanoes (Mount Etna and Iblean Mountains). There is, however, no clear evidence that Eastern Sicily volcanisms are directly connected with active subduction beneath the Aeolian arc; seismic investigations indicate the active Benioff zone is not located directly beneath Sicily but slightly outside. Eastern Sicily volcanisms are generally associated with: a) shallow-level distensive tectonics related to crustal spreading induced by the active Aeolian subduction or some rifting process; b) a developing hot spot in a destructive margin marking the collision zone between two continental plates; and c) the sideway suction of asthenospheric material from under the African plate, associated with rollback motion of the Ionian slab. Here, we characterise the source chemistry of Vulcano Island, Mount Etna and Iblean Mountains volcanisms by examining the trace-element composition of primitive magmas preserved as primary melt inclusions in magnesian olivine phenocrysts. The results point to a variety of primitive melts that define a one-dimensional array in composition space. The variations observed among these primitive magmas can thus be explained by a two-mantle source component mixing relationship, where one end-member is a mantle component (referred as the Vulcano-type mantle component) characterized by high Rb/La (~2.5), Ce/Nb (~11) and B/Ba (~0.55) ratios and the other is a mantle component (referred as the Iblean-type mantle component) with low Rb/La (~0.3), Ce/Nb (~1.5) and B/Ba (~0.002) ratios. The Vulcano-type mantle component shows the trace-element characteristics of island arc basalt-like sources (i.e., high concentrations of LILE and LREE/HREE ratios, and relatively low concentrations of HFSE), whereas the Iblean-type mantle component shows a continuous decrease in the abundances of Ba, K and Rb and characteristic enrichments of Nb relative to similarly incompatible elements, which are similar to the mantle plume sources inferred from the chemistry of oceanic island basalts showing HIMU-type isotopic signatures. Various extents of mixing between melts of the two sources can account for both the global chemical evolution of the Etnean primary magmas through time and the characteristics features (strong enrichments in alkalis, with accompanying increases of <sup>87</sup>Sr/<sup>86</sup>Sr ratios) of the present-day and recent (post-1970) lavas. The final aim of the study is to attempt to reconcile the presence of these distinct mantle sources with the global geodynamic framework of the region and to discuss plausible mechanisms that can account for their interaction.

## MS03 Magmatic Inclusions in Minerals

### MS03 : WEam02 : G8 Assimilation of Lower Crust Cumulates Recorded by Melt Inclusions in Olivine Phenocrysts from the Siqueiros FZ MORB

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The Siqueiros fracture zone is a ~20 km wide terrain that offsets the EPR by 140 km at ~8.3°N. Unusually mafic, recent, olivine-rich picritic basalts have been collected between intra-transform spreading centers (Perfit et al., 1996; Lundstrom et al., 1999). These basalts represent liquids that have accumulated olivine on ascent or during very limited, initial stages of fractionation prior to eruption in the fault axis.

A glassy melt inclusion (~70 microns in diameter) containing euhedral transparent high-Al spinel (~20 microns) has been found in an olivine phenocryst (Fo 90.0) from sample ALV-2384-3. The compositions of glass and spinel are shown in Table 1 (Nos. 1, 2). This is the only inclusion in that phenocryst. The composition of the host olivine (including minor elements) is similar to other phenocrysts in this sample (Fo range 89.4-91.1; average 90.4). The trapped melt composition was not in equilibrium with the host olivine as indicated by diffusion profiles of Ca and Cr in olivine around the inclusion. The glass composition is strongly depleted in all incompatible elements (La = 0.052 ppm; Yb = 0.34; La/Sm(n) ~0.27) and has large positive Sr and Eu anomalies (Sr/Sr\* ~30; Eu/Eu\* ~3). It also has low S (0.015 wt%) and relatively high Cl (180 ppm). Spinel has high ZnO content of 1.5 wt%. We interpret the trapped melt as a result of melting of olivine-plagioclase rich lithologies in the lower crust, with high-Al spinel being the residual phase. Eruption of Siqueiros MORB magmas in the transform setting facilitates their interaction with the lower crust material.

An example of 'normal' melt inclusions in olivine phenocrysts (ie, similar in composition to pillow-rim glasses) is shown in Table 1, No. 3 (host Fo 90.6). Such inclusions have ~0.11 wt% S; ~50 ppm Cl; La/Sm(n) and La/Yb(n) ~0.35; and weak positive Sr anomalies (Sr/Sr\* ~1.6). The composition of spinel associated with this inclusion is typical for MORB spinel, and has lower Al and higher Ti than the high-Al spinel (Table 1, 4). ZnO is ~0.05 wt%.

Composition 5 (Table 1) shows an inclusion in Fo 90.5. The trapped melt represents a mixture between the 'normal' Siqueiros MORB and the assimilated. This composition has lower TiO<sub>2</sub>, Na<sub>2</sub>O, K<sub>2</sub>O and Cr<sub>2</sub>O<sub>3</sub>, and slightly higher Al<sub>2</sub>O<sub>3</sub> and CaO contents than 'normal' inclusions. It also has lower S (0.025 wt%); more depleted in incompatible elements (La/Sm(n) ~0.29); has larger Sr anomaly (Sr/Sr\* ~12) and weak Eu anomaly (Eu/Eu\* ~1.3). Spinel associated with this inclusion (Table 1, 6) is also intermediate in composition between the 'normal' spinel and the high-Al spinel.

Table 1. Compositions of inclusions in olivine phenocrysts (wt%). Compositions of residual glasses are affected by olivine crystallisation on the walls of inclusions.

	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO*	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Cr <sub>2</sub> O <sub>3</sub>
1	48.20	0.04	20.20	7.77	0.10	7.47	14.61	1.06	0.003	0.02
2	0.13	0.01	62.90	9.18	0.07	22.23	0.06	2.80		
3	48.72	1.04	17.28	8.36	0.19	9.41	13.27	1.41	0.024	0.07
4	0.10	0.31	37.16	13.04	0.09	18.39	0.05	29.23		
5	49.02	0.29	19.77	7.68	0.15	5.64	15.92	1.47	0.013	0.03
6	0.14	0.05	48.10	11.32	0.07	20.22	0.04	18.15		

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### MS03 : WEam03 : G8 Melt Inclusions as a Tool for Investigating and Circumventing the Effects of Crustal Contamination in CFB Provinces: An Example from the Oligocene Flood Basalts of Yemen

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One common limitation to investigating the mantle sources of continental flood basalt (CFB) provinces is that the interaction between basaltic magmas and overlying continental crust strongly alters the chemical and isotopic composition of many mantle-derived melts. Relative to basaltic magma, the continental crust is enriched in incompatible trace elements and may have highly radiogenic isotopic signatures. Thus the addition of even small amounts of crustal material to basaltic magma will mask the relatively subtle trace element and isotopic variations that are related to mantle processes and sources.

One novel and potentially powerful method by which the processes of crustal contamination of basaltic magma may be investigated is by examining melt inclusions in phenocryst phases from contaminated basalts. Melt inclusions will sample melt compositions present during crystal growth, and the compositions of the crystal hosts will record the degree of differentiation at the time of trapping. This provides the means to track compositional changes during progressive assimilation and fractionation. In addition, melt inclusions trapped in primitive phenocrysts may preserve melt that contains little or no assimilated crustal material, and thus can be used as a guide to the pre-assimilation composition of lavas where whole-rock compositions have been altered by crustal contamination.

In order to examine melt inclusions from crustally-contaminated basalts we have studied melt inclusions from Oligocene flood basalts in Yemen. The studied samples are lavas that are relatively primitive (Mg# 59-68) and have whole rock isotopic and chemical compositions that reflect differences in both the degree of contamination and in the composition of the contaminant (e.g. <sup>206</sup>Pb/<sup>204</sup>Pb ~18.2-19.1, K/Nb ~136-488, Ba/Th ~53-168). All lavas examined contain abundant olivine and clinopyroxene phenocrysts. Olivines range in composition from those in equilibrium with mantle-derived melts to those that crystallised after ~25% crystal fractionation, and thus sample melts present during an extended range of differentiation. Initial results show that melt inclusions record a variety of melt compositions and appear to reflect liquids that range in both their primary compositions and the degree of assimilation of crustal material. A reassuring observation is that for each sample studied the average melt inclusion composition (corrected for crystal fractionation) is similar to the bulk lava composition, suggesting that the melt batches sampled by melt inclusions combined to form the erupted lavas (in roughly the proportions analysed). This implies that the processes that dictate melt inclusion compositions also control bulk lava compositions and demonstrates that we can use the compositions of melt inclusions to study the origin of their host lavas.

### MS03 : WEam04 : G8 Origin of Chlorine-Rich Melt Inclusions from Raivavae, Austral Islands: Evidence for Altered-Lithosphere Assimilation by Ascending Magmas

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The extent to which melts assimilate lithospheric material during magma ascent can be influenced by the presence of pre-existing features such as fracture zones. Fracture zones allow deep penetration of hydrothermal fluids into the lower crust and shallow lithospheric mantle. The resultant hydrated crust and mantle is more easily melted and assimilated than anhydrous lithosphere. We have measured major and trace element and volatile concentrations in a suite of olivine-hosted melt inclusions from Raivavae to evaluate the influence of melt/lithosphere interaction on melt composition. The island of Raivavae is part of the Austral Island chain and sits on top of the Austral Fracture Zone (AFZ). Preferred dike orientations on the island generally parallel the fracture zone, suggesting that melts ascended through the shallow lithosphere and crust along pre-existing fractures.

Most melt inclusions have major and trace element compositions similar to the host lavas. Chlorine concentrations in these inclusions range from below detection to 0.2 wt.%, and broadly correlate with potassium and other incompatible elements. These correlations reflect the incompatible behavior of Cl during partial melting and suggest that the inclusions were trapped prior to extensive degassing. A small subset of inclusions contains much higher Cl concentrations, ranging from 1 to 2.5 wt.%. The Cl-rich inclusions have similar major-element compositions as other inclusions, but have lower Si, K and P concentrations. The Cl-rich inclusions are much more depleted in most incompatible trace elements than other inclusions. The depletions are most pronounced in high-field-strength elements (HFSEs) such as Th, Nb and Zr. In contrast, fluid-soluble elements such as Li and Rb are typically less depleted than HFSEs. Assimilation of Cl-rich brines cannot account for the distinctive trace-element depletions in these inclusions. Instead, partial melting of hydrothermally altered lithospheric mantle or crust could produce trace-element depleted, Cl-rich melts. Migration of magmas through pre-existing fractures associated with the AFZ triggered partial melting of the hydrothermally altered wall-rock.

Isotopic variability is greater at Raivavae than at other Austral Islands. Although the Cl-rich inclusions provide strong evidence for assimilation of lithosphere-derived melts, it is unlikely that this assimilation is the source of isotopic variability at Raivavae. Because the lithosphere-derived melts represented by the Cl-rich inclusions have much lower Sr and Nd concentrations than the host lavas, assimilation of such melts will have only a minor effect on Sr- and Nd-isotopes. However, other elements of geochemical interest, such as Li and B, may be dominated in some lavas by the lithospheric assimilate. Assimilation of hydrothermally altered lithosphere may be an important process in tectonic settings such as at MOR transform faults where melts migrate through previously faulted areas.

### MS03 : WEam05 : G8 Oxygen Isotopic Variations in the Source of Icelandic Tholeiites: Evidence from Ol-Hosted Glass Inclusions

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Compositional variations of MORB and OIB reflect those of their source but can also result from shallow crustal contamination. Iceland represents a hotspot underlying the mid-oceanic ridge and also a region, where interaction between mantle-derived magmas and a crust is widespread (e.g., Muehlenbachs et al., 1974). We report <sup>18</sup>O/<sup>16</sup>O ratios measured *in situ* in glass inclusions, host Ol phenocrysts [Fo<sub>67-90</sub>] and quenched matrix glasses from primitive picritic lavas erupted in the neovolcanic rift zone that allows us to constrain O isotopic composition of the mantle beneath Iceland.

The <sup>18</sup>O/<sup>16</sup>O ratios were measured with the Nancy IMS 1270 ion microprobe. Samples were sputtered with a 10 kV Cs<sup>+</sup> primary beam and secondary <sup>18</sup>O and <sup>16</sup>O ions were analyzed at a mass resolution of ca. 5000 using multicollection. An instrumental mass fractionation of ca. 4‰ was observed and corrected using a set of olivine and basaltic glass standards. Counting statistics and reproducibility are ±0.2-0.4‰ and ±0.5‰.

The inclusions studied fall into two populations, enriched [EM, (La/Sm)<sub>n</sub> = 1.4-2.1] and depleted [DM, (La/Sm)<sub>n</sub> = 0.08-0.35], both present within a single specimen, and exhibit significant variation of Ba and Sr concentrations [(Ba/La)<sub>n</sub> = 0.9-4.4, (Sr/Ce)<sub>n</sub> = 0.8-10] and B isotopic composition [δ<sup>11</sup>B = -8.2 to -12.3‰] (Gurenko and Chaussidon, 1995, 1997). The inclusions and their host Ol vary significantly in δ<sup>18</sup>O, from +5.4 to +7.5‰ in glass inclusions and from +3.0 to +7.3‰ in Ol, with no difference between EM and DM types. Their matrix glasses show similar high δ<sup>18</sup>O of +6.2 to +6.8‰. Almost all glass inclusions are in oxygen isotopic equilibrium with adjacent olivine, while the variations within a single olivine grain can reach 1.1‰. Based on δ<sup>18</sup>O-δ<sup>11</sup>B relationships, the variations of δ<sup>18</sup>O between +5.4 to +6.5‰ found in glass inclusions are interpreted to reflect those of primary magmas and, consequently, of their mantle source. The elevated δ<sup>18</sup>O values were ascribed to assimilation of basaltic crust altered by seawater.

## MS03 Magmatic Inclusions in Minerals

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### MS03 : WEam06 : G8 Tracking Carbon in Olivine-Hosted Melt Inclusions by Nuclear Reaction Analysis

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Carbon is one of the most important volatile constituents in magmas, Earth mantle or Solar Nebula. Here, we present new data on carbon concentrations and heterogeneities in olivine-hosted melt inclusions (MI) from different origin as determined by nuclear reaction microanalysis (NRA). On the basis of <sup>12</sup>C(d, p)<sup>13</sup>C spectra, the carbon distribution is profiled on about 8-9 µm at depth in MI either exposed at the surface or not. Heterogeneous C distribution within one and different MI hosted in olivine from CV3 chondritic meteorites (e.g. Kaba, Allende, Vigarano [1]) is confirmed on the basis of new results from Ningqian CV3 carbonaceous chondrite. The C concentrations range from 658-678 ppm to less than 140 ppm C in MI trapped in one isolated olivine grain (13.2 wt.% FeO). It brings new evidence of heterogeneous C distribution within one inclusion and between different inclusions in one single crystal, which is regarded as the result of the trapping process. Carbon has also been mapped in primary mantle-derived melt inclusions from cumulative olivine pyroxenite xenolith (DW-905) occurring in the ash-tuffs of West Eifel in Germany [2]. MI heated under high pressures (10-12 kb piston cylinder apparatus) were studied for carbon after quenching. Different images illustrate the highly heterogeneous C concentration between 9 and about 1.5 µm depth, with C concentrations varying from 0.2 wt.% to more than 5 wt.%, on the micrometer scale. It appears that C is mainly distributed around the bubble. Because MI are still enclosed within the host mineral, external carbon contamination is ruled out. Similar results obtained for different inclusions indicate rapid C diffusion during quench. They undoubtedly confirm the existence of highly C-rich silicate melts trapped as MI. Carbon was also determined by <sup>12</sup>C(d,p) <sup>13</sup>C NRA in basaltic glass samples together with K-basaltic MI hosted in olivine from ancient pyroclastic deposits of Stromboli volcano (Italy). Repetitive analyses of one particular basaltic glass fragment after different sessions indicate a good reproducibility 296 ± 35 ppm C by NRA and 300 ± 28 ppm C by FTIR. The most primary MI hosted in Fo<sub>80-81</sub> from Stromboli deposits have recorded high C concentrations (up to 1650 ppm CO<sub>2</sub>) indicative of rather high pressure crystallization and possibly rapid transfer of magma towards the surface as discussed in [3].

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### MS03 : WEam09 : G8 Parental Melts and Mantle Sources of Hawaiian Shield Tholeiites: The Constraints from Studies of Melt Inclusions in Olivines

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We present the results of systematic study of melt inclusions and host olivines from shield tholeiitic picrites of Mauna Kea and Mauna Loa volcanoes, Hawaii. The samples represent more than 100 ka of entire history of each volcano. Naturally and experimentally quenched melt inclusions were analysed for major, trace elements and volatiles by electron, ion and nuclear probes. These data are also compared with results from Koolau volcano (Sobolev VA et al., 2001)

The composition of melt inclusions in olivine phenocrysts from Mauna Loa, Mauna Kea and Koolau shows a great variability of compositions of parental melts either within a single volcano plumbing system or between volcanoes. The common features of all studied volcanoes are: (1) Strong garnet buffering effect in the parental melts recorded by both low and very uniform concentrations of HREE and Y at given MgO. (2) Variable and generally high Si contents of primary melt, commonly negatively correlated with Ca and Ti. (3) Presence of exotic primitive melts, either ultra depleted or extremely enriched, in most incompatible elements. (4) Strong preference of exotic melt inclusions to be trapped in the most Mg-rich olivines.

Each volcano shows also some specific features. They are: (5) Sr-rich inclusions with ghost plagioclase signature (Sobolev et al, 2000) have been found only in olivines from relatively recent (last 50 ka) lavas of Mauna Loa volcano. (6) The highest content of Si is indicated in Koolau melt inclusions. (7) Strong positive Nb anomalies (relative to La) are common for Mauna Kea parental magmas.

Most of listed features of parental (primary) melts could not have originated by the melting process itself and require significant variations of source compositions. Moreover, the common coexistence of garnet signature with high Si excess in primary melt compositions argues for involvement of olivine free lithologies in the melt production in the Hawaiian plume.

The most likely explanation of our observations is the significant heterogeneity of Hawaiian plume in three dimensions produced by mixing and reaction of mantle with recycled fragments of subducted oceanic lithosphere.

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### MS03 : WEam10 : G8 Crystallised Melt Inclusions in Greenland Basalts: Evidence for Mixing in Primitive Plume Melts

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Major and trace element compositions of crystallised melt inclusions in olivine-rich lavas (Turkov et al., 1998; Ryabchikov et al., 1998) at the Volcanic rifted margin of

East Greenland divide into three tholeiitic suites originating from: (1) LILE and TiO<sub>2</sub> rich picritic melts, (2) moderately LILE and TiO<sub>2</sub> rich picritic melts and (3) low TiO<sub>2</sub> basaltic melts. All three suites are present in olivines in samples from through out the lower 3 km of the volcanic succession, but the melts appear to contribute in variable proportions to the bulk composition of the magmas that reach upper crustal levels. Suite (1) inclusions are best compared to and dominate in early TiO<sub>2</sub> rich picrites (PAS 1, Hansen and Nielsen, 1999), suite (2) to and in moderately TiO<sub>2</sub> rich PAS 2 lavas and suite (3) to and in the younger basalts.

The three suites may suggest either 3 sources or 3 PT domains of melt generation or combination of both. Suite (2) melts are similar to melt inclusion compositions in olivines of West Greenland picrite lavas, whereas suites (1) and (3) do not seem to occur in West Greenland picrite lavas. A complex melt generation scenario is suggested for the East Greenland lavas. Although lithospheric (crustal) contamination is common, bulk compositions of East Greenland lavas similar to all three suites all have isotopic compositions (Sr, Nd, Pb, Os) within or adjacent to the Icelandic field and no significant lithospheric mantle contribution is indicated.

The complexity of crystallised melt compositions in East Greenland olivine rich lavas is suggested related to plume impact and development of active seafloor spreading. Type (1) representing melts from the stem/core of the early North Atlantic plume, suite (2) melts generated by upwelling of upper mantle around the plume head and suite (3) depleted melts generated in the low pressure regime of the developing rift.

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### MS03 : WEam11 : G8 Early Alkaline Volcanics from Mt. Etna: Indications of Different Degrees of Partial Melting from the Study of Melt Inclusions

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The earliest alkali magmas at Mt. Etna (Sicily) show diverse compositions: two main types of lavas were distinguished as related to "high P" and "low P" magmas respectively. The former type is characterised by relatively higher P (P<sub>2</sub>O<sub>5</sub> > 0.8 wt%), Ti, K and Rb contents than the latter (Busà et al., 1999). Melt inclusions in the most ferrotic olivine were studied for the less differentiated varieties of either group. For "high P" and "low P" groups, the ranges Fo<sub>81-77</sub> and Fo<sub>87-84</sub> were chosen respectively. In "high P" melt inclusions mg# ranges from 42 to 60, too low for melts to be considered as primary: only those with the highest Mg# were considered to be next to primary compositions. "Low P" melt inclusions are characterised by higher Mg#, from 62 to 69, representing then almost primary magma compositions. In "low P" group melt inclusions, trapped in Fo<sub>87</sub> olivine, were surprisingly found with a very large scatter in their compositions, even in the same crystal. Almost all of them plot within the alkali basalt field, slightly extending into the basanite and hawaiite fields; only one of the inclusions shows a distinct subalkaline composition. Alkaline inclusions show wide K<sub>2</sub>O (0.35 - 1.03 wt%), P<sub>2</sub>O<sub>5</sub> (0.61 - 1.67 wt%), Rb (8 - 27 ppm), Zr (77 - 109 ppm) and Ce<sub>n</sub>/Yb<sub>n</sub> (3.7 - 12.7) ranges, whereas variations of MgO (8.2 - 6.1 wt%), SiO<sub>2</sub> (47.6 - 45.31 wt%), and compatible elements (V, 266 - 348 ppm; Sc, 44.5 - 28.9 ppm) are quite smaller. The observed variations are similar to those already observed for melt inclusions in olivine from Aci Castello tholeiites (Clocchiatti et al., 1998). In more evolved melt inclusions (Mg# 64 - 62), found in Fo<sub>86-84</sub> olivine, the incompatible elements concen-

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trations are lower and less scattered. "Low P" melt inclusions, with the highest incompatible element contents, are very similar to the most primitive "high P" melt inclusions. The coexistence of melt inclusions in olivine from lavas of the "low P" group, with a continuous change in compositions from "high P" to "low P" magmas, suggest a cogenetic origin for the two groups. Plots of two incompatible element ratios versus the most incompatible of them (Treuil & Joron, 1975) show a good linear correlation not consistent with processes related to fractional crystallisation. Alternatively an increasing degree of partial melting, from "high P" to "low P" melt inclusions compositions, may be suggested.

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### MS03 : WEam12 : G8 Magmatic Inclusions in Olivines from the Noril'sk Intrusions (Russia) as a Source of Information on the Composition of their Parental Melts and Volatiles

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One of the vital geological problems is the origin of metal's super concentrations in the lithosphere. To understand genesis of large magmatic deposits like Noril'sk one has to answer to the question: was Noril'sk formed from the specific magma or not? Here we address this question by study of magmatic inclusions in olivine phenocrysts, which potentially can preserve information on the parental melt compositions.

The Noril'sk district is the unique object for solving such a problems, because intrusions there differ in their composition and ore potential: from ore-free to comprising super giant Pt-Cu-Ni sulfide deposits, having no analogues on the Earth. All these intrusions belong to the huge Siberian trap province.

The main goal of this study is to determine and to compare the compositions of parental melts of different intrusions (ore-bearing - Talnakh and ore-free - Low Talnakh) in order to understand specific features of ore-bearing magmas. The main method that we have used is the investigation of magmatic inclusions in earliest liquidus mineral -olivine - from toxic and picritic gabbrodolerites. In both intrusions olivine contains the following types of inclusions: crystallized or partially crystallized melt inclusions, included crystals of plagioclase, orthopyroxene, apatite, magnetite, fluid inclusions and combined inclusions from all mentioned phases. Melt inclusions were studied either after homogenization in high temperature optical stage or naturally quenched. The compositions of inclusions (about one hundred inclusions) were studied by electron probe and representative ones by ion probe. Compositions of melt inclusions were further corrected up to equilibrium with host olivines.

The common features of melt inclusions compositions from both Talnakh intrusions are exceptionally high Si and low Ca contents. In these elements tapped melts drastically differ from bulk rocks of the same MgO. Most inclusions also demonstrate high concentrations of K<sub>2</sub>O and Na<sub>2</sub>O - significantly higher than in the rocks of the same MgO. Volatile contents of melt inclusions show huge variability. Chlorine varies between 0.01-0.68 wt% and correlates positively with K<sub>2</sub>O. Water content in quenched glass inclusions varies from 0.10 to 1.62 wt%. Sulfur shows positive correlation with FeO and is close to saturation level of silicate melt with sulfide melt.

Specific feature of melt inclusions from Low Talnakh intrusion (ore free) compare to those from ore bearing Talnakh intrusions is higher MgO and lower Na<sub>2</sub>O contents.

The obtained data suggest that olivine phenocrysts from both studied intrusions have not crystallized from transported melts. They have likely originated in deeply evolved crustal intrusions and have been incorporated in the picritic lavas as a xenogenic phases. Although preliminary our data suggest that olivines from ore-free rocks indicate less evolved parental melts compare to those from ore-bearing lithologies. This study was supported by RFFI (grant 00-05-64507).

### MS03 : WEam13 : G8 Olivine Hosted Melt Inclusions in Kamchatka Lavas: Implications for the Origin of High-Ca Low-Si Melt Inclusions in Island-Arc Settings

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We have studied melt inclusions hosted by high magnesian olivine (Fo 80-91) from basaltic rocks of Avacha and Kluchevskoy active volcanoes in the Kamchatka arc. Partially crystallised inclusions were reheated up to melting of the last daughter crystal and rapidly quenched. Despite some compositional variations, all analysed inclusions demonstrate a general tendency of having lower SiO<sub>2</sub>, FeO and higher CaO contents compared to the host rocks at a given MgO. In this respect, melt inclusions from the Kamchatka rocks are very similar to the melt inclusions documented world-wide in island-arc settings, summarised recently by Schiano et al. (2000). In an attempt to interpret the data we need to answer a key question, whether the melt inclusions are representative of melts existed in nature. Schiano and co-workers suggested that the melts did exist and favoured a model of their origin by assimilation of crustal rocks by mantle-derived magmas. We suggest an alternative idea. It is possible that such melts have never existed in nature. The observed compositional features can be formed during experimental re-homogenisation of the inclusions, which experienced complex post entrapment modifications such as (1) crystallisation of the daughter phases and (2) a partial loss of the residual melt due to decrepitation.

We suggest the following scenario for the origin of the 'exotic' melt inclusions. At the initial stage of their evolution, the melt inclusions have partially crystallised at a significant depth (>3 kbar). In response to the decompression of host magmas before eruption, the inclusions were variably decrepitated as indicated by aureoles of secondary inclusions around primary inclusions found in all studied samples. Predominant leakage of the residual melt from the inclusions disturbed proportions between existing daughter phases, and resulted in the enrichment of the bulk inclusion compositions by components of daughter clinopyroxene. It is crucial that the composition of the daughter pyroxene in the inclusions is very specific. Compared to phenocrysts, it has similar CaO (20-23 wt.%) but extremely low SiO<sub>2</sub> (40-45 wt.%), high Al<sub>2</sub>O<sub>3</sub> (7-15 wt.%) and TiO<sub>2</sub> (1-2 wt.%). Excess of such pyroxene in the homogenised melt inclusions may readily explain observed compositional discrepancy between the inclusions and host rocks. In summary, we suggest that the processes in the system inclusion - host mineral are able to modify strongly initially trapped melts and could be responsible for the origin of high-Ca low-Si melt inclusions common in island-arc settings.

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### MS03 : WEam14 : G8 Magmatic Inclusions in Olivine, Orthopyroxene and Augite in Ureilite Meteorites: Insights into the Mantle and Early Differentiation of an Achondritic Parent Body

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Magmatic inclusions in mafic minerals in primitive achondritic meteorites provide insight into the mantles of parent bodies other than Earth and processes of early differentiation in our solar system. Because of the rarity of these rocks, as well as (in most cases) the low abundance of inclusions, techniques commonly used in studying terrestrial melt inclusions (e.g. concentration of inclusions by separation of host minerals, experimental rehomogenization) generally cannot be applied. Primary trapped liquid (PTL) compositions must be reconstructed from the crystallization and reequilibration history of the inclusions as determined by detailed petrographic examination and EMPA in thin-section.

Ureilites are a group of highly-equilibrated ultramafic (largely olivine-pigeonite) meteorites from an unknown parent body. Their status as residues or cumulates, and the degree to which their parent body has been processed, have long been uncertain (Goodrich, 1992; Mittlefehldt et al.,

1998). Related feldspathic rocks which might provide clues are not known in meteorite collections. Melt inclusions recently discovered in a small subclass of ureilites (olivine-augite-orthopyroxene rocks) demonstrate that these are cumulates and indicate complex processes in their history (Goodrich et al., 2000; Fioretti and Goodrich, 2000). For example, the reconstructed PTL for inclusions in olivine (Fo 87) in ureilite Hughes 009, has a crystallization sequence (olivine -> augite -> plagioclase -> pigeonite) which is not consistent with formation of an olivine-augite-orthopyroxene cumulate (as predicted by models based on parameterized experimental data from terrestrial mafic rocks [Longhi, 1991]). New results will be presented for FRO 90054, an olivine-augite-orthopyroxene ureilite which is similar to Hughes 009, but has inclusions in all three primary phases (Fioretti and Goodrich, 2000; Goodrich and Fioretti, 2000). The PTL in olivine in FRO 90054 is similar to that in Hughes 009. The PTL in orthopyroxene cannot, however, be derived from that in olivine by closed-system magmatic evolution but requires addition of a silica-rich component, possibly by admixture of an orthopyroxene-saturated magma. This will be tested further using inclusions in orthopyroxene in a third ureilite (EET 96262), in which the orthopyroxene is oikocrystic and shows a reaction relationship with olivine. Implications for the differentiation history of the ureilite parent body will be discussed.

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