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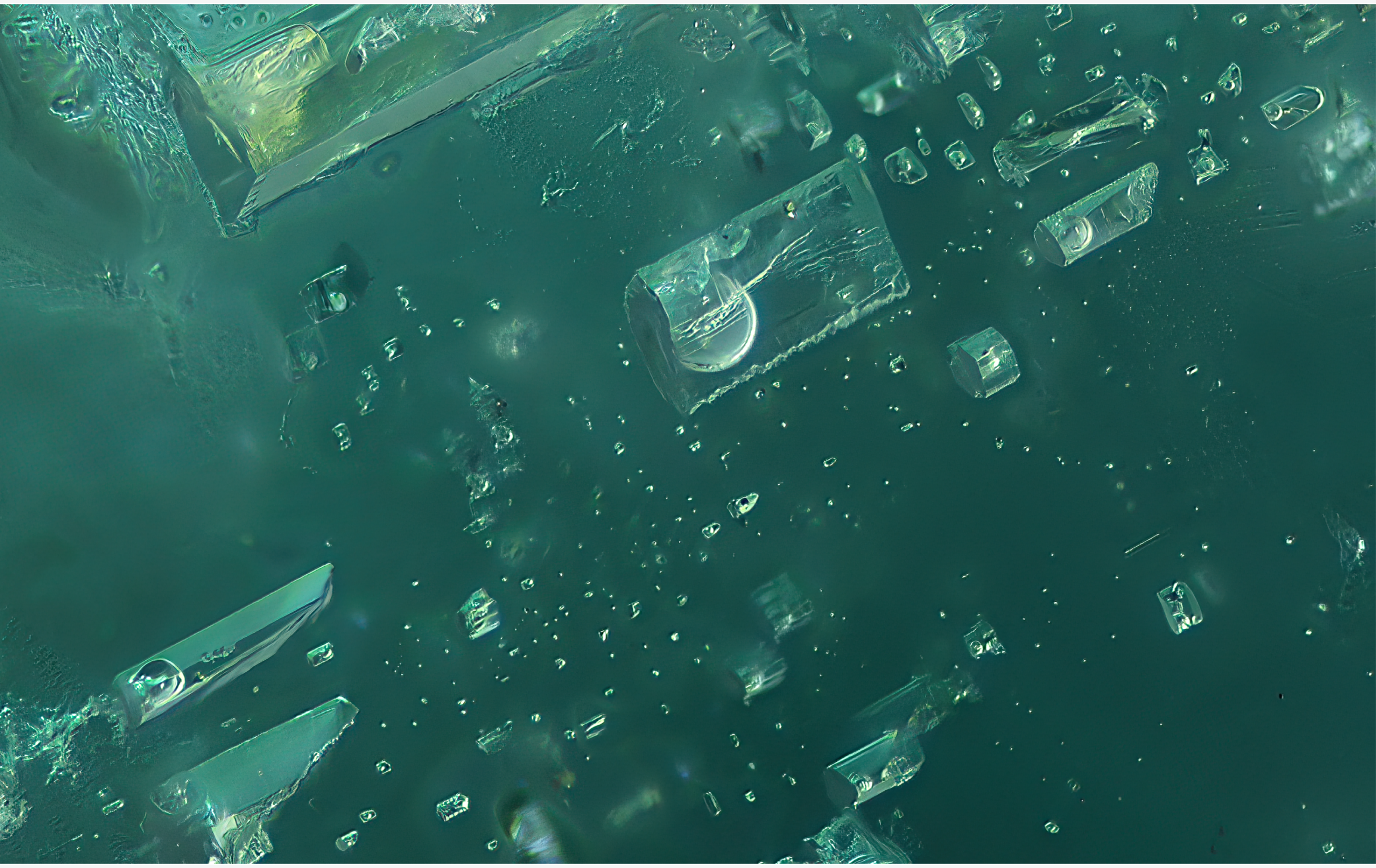
Abstract Book for

2° Italian Workshop on Fluid and Melt Inclusions (IWI)



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Abstract Book of 2° Italian Workshop on Fluid and Melt Inclusions (IWI)

The "Second Italian Workshop on Fluid and Melt Inclusions", organized by the Department of Earth and Marine Sciences (DiSTeM) at the University of Palermo, took place in the beautiful location of the Botanical Garden of Palermo, Sicily, Italy, on 12, 13, and 14 of November 2024. The workshop attracted a diverse range of participants, including researchers, PhD, master's, and bachelor's students, as well as individuals from national and international universities and research institutions, including the National Institute of Geophysics and Volcanology (INGV). The main objective of the workshop was to explore the identification, characterization, and application of fluid and melt inclusions in the field of Earth Sciences. Additionally, it aimed to facilitate communication between academic researchers, young researchers, and the national and international business community. Notably, the workshop integrated the expertise of gemologists who approached the study of fluid and melt inclusions from a commercial standpoint, bridging the gap between academia and industry.

Group Photo of the participants in the beautiful background location of the Orto Botanico of the University of Palermo.

COVER PHOTOGRAPH: Francesco Protopapas | Biphase Inclusions in Emerald

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Melt inclusions in metamorphic mafic rocks as a tool to quantify volatiles and incompatible elements transfer to the mantle

Borghini A.[1*], Ferrero S.[2], O'Brien P.[3], Laurent O.[4], Wunder B.[5], Remusat L.[6], Majka J.[1,7], Nicoli G.[8], Borghini G.[9]

[1]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland; [2]Department of Chemical and Geological Sciences, University of Cagliari, Monserrato (CA), Italy; [3]Institut of Geosciences, University of Potsdam, Potsdam, Germany; [4]CNRS, Geosciences Environment Toulouse, Observatoire Midi-Pyrenees, Toulouse, France; [5]Deutsches GeoForschungsZentrum (GFZ), Potsdam, Germany; [6]Museum National d'Histoire Naturelle, Paris, France; [7]Department of Earth Sciences, Uppsala University, Uppsala, Sweden; [8]Yorkshire Wildlife Trust, York, United Kingdom; [9]Department of Earth Sciences "Ardito Desio", University of Milano, Milano, Italy.

* *borghini@agh.edu.pl*

Primary melt inclusions in metamorphic rocks are snapshots of melt produced during anatexis in terms of major, trace elements and volatiles. These inclusions can be studied *in situ* and they provide direct information on crustal differentiation and volatiles and incompatible elements cycles.

In subduction settings, melts and fluids released by the subducted slab interact with the overlaying mantle transferring volatiles and incompatible elements that then can be partly re-emitted into the atmosphere via arc volcanism. In these settings, melt inclusions of continental crust origin trapped in mantle bodies can be targeted to investigate crust-mantle interaction and deep volatile cycles.

Here we present examples of such melt inclusions trapped in different eclogite lenses and boulders involved in subduction and continent-continent collision during the Variscan orogeny that formed the Bohemian Massif (Germany). In particular, the samples investigated are high-pressure (HP) eclogites hosted in peridotite bodies surrounded by the HP granulites of the Granulitgebirge and ultra (U)HP eclogites hosted in the diamond-bearing gneisses of Saidenbach in the Erzgebirge.

Melt inclusions are randomly distributed in the inner part of the garnet. They occur either as glass or more commonly as polycrystalline inclusions with a mineral assemblage typical of nanogranitoids (feldspars polymorphs, quartz/rare cristobalite, biotite and white mica). The melt is granitic and it displays a trace element signature akin to the continental crust. Hence it most likely originated from the partial melting of deeply subducted continental crust and it was then trapped in the mantle. This melt is responsible for the mass transfer from the crust to the mantle and represents the perfect target to quantify element mobilization.

Carbon, Cl and F were measured *in situ* in some of these examples and their content is notably high. Thus, the continental crust can carry and mobilize a significant amount of volatiles and have an impact on the past global volatile cycles.

CO_2-rich xenoliths at Mt. Vulture volcano (southern Italy): new constraints on the volcano plumbing system

Carnevale G.[1,2*], Caracausi A.[2,3], Coltorti M.[4], Faccini B.[4], Marras G.[5], Paternoster M.[2,6], Rotolo S.G.[1,2], Stagno V.[5,2], Zanon V.[7], Zummo F.[6]

[1]Department of Earth and Marine Science, University of Palermo, Palermo, Italy; [2]National Institute of Geophysics and Vulcanology, Palermo Section, Palermo, Italy; [3]Departamento de Geología, Universidad de Salamanca, Salamanca, Spain; [4]Department of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy; [5]Department of Earth Sciences, Sapienza University of Roma, Roma, Italy; [6]Department of Science, University of Basilicata, Potenza, Italy; [7]Instituto de Investigação em Vulcanologia e Avaliação de Riscos, Universidade dos Açores, Ponta Delgada, Portugal.

* *gabriele.carnevale@unipa.it*

This study provides new mineral chemistry data together with micro-thermometric measurements on fluid inclusions (FIs) hosted in ultramafic xenoliths (lherzolite, wehrlite, and dunite) brought to the surface by the last Mt. Vulture volcano activity (140 ka; southern Italy), and fed by melilitite-carbonatite magmas.

Mantle xenoliths were collected from a compact, fine-grained, carbonate-dominated matrix in an ash-tuff deposit (Carnevale et al., 2022). They are rounded, with an average diameter of 4-5 cm (wehrlite and dunite) and a maximum of 10 cm (lherzolite). The lherzolite is fine- to medium-grained (0.5-1 mm), the wehrlite and dunite are medium- to coarse-grained (2-5 mm). The texture is protogranular, except for the dunite which shows a transitional texture between porphyroclastic and tabular equigranular. Olivine usually shows undulose extinction and intracrystalline deformation structures. Olivine shows an almost constant chemical composition all across the crystal (e.g. Fo_{89-90}). Orthopyroxene is exclusively found in lherzolite and its composition shows a high proportion of enstatite (En_{86-87}) compared to wollastonite (Wo_{2-3}) and ferrosilite (Fs_{10-11}). The composition of clinopyroxene (Wo_{42-44}, En_{49-52}, Fs_{5-7}) is more variable than the coexisting olivine and orthopyroxene. It shows a wider range of Mg# (0.88-0.91) in wehrlite compared to the almost constant Mg# (0.88) of the lherzolite. Thus, petrographic evidence and mineralogical compositions of Mt. Vulture xenoliths are consistent with an origin in the upper mantle.

FIs are generally rounded (2-10 μm in diameter) with re-equilibration features, such as (i) the presence of dark halos (Bodnar, 2003), and (ii) stretched shapes (Fig. 1). No primary FIs were found, and clinopyroxene is the main host for secondary FIs (i.e. trapped after the crystal growth). In all studied xenoliths, FIs are CO_2-dominated with melting temperatures (Tm) ranging between -56.5 and -57.0°C (± 0.1°C), and with variable homogenisation temperatures from the vapour to the liquid phase (ThL). The equilibrium temperature calculated by geothermometric estimates ranges from 1039°C (± 36°C) to 1142°C (± 15°C), and entrapment pressures of FIs with post-trapping re-equilibration correspond to the local crust-mantle boundary (32 km depth), and to a shallow reservoir located at 12-14 km depth. These results contribute to constraining the origin of these xenoliths and the depth of storage of magma erupted from Mt. Vulture.

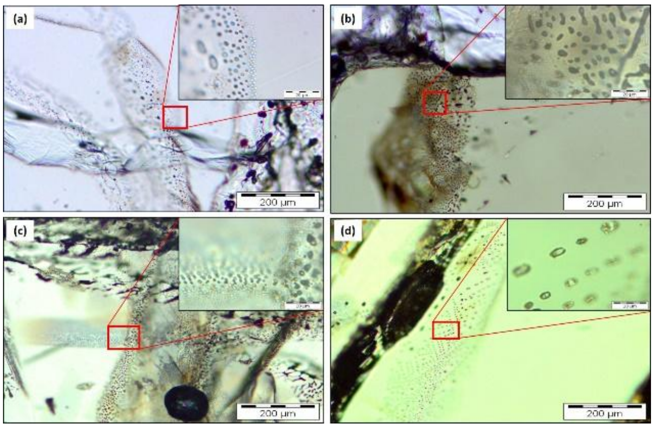

Figure 1 *Plane-polarized light (PPL) photomicrographs of textures of FIs trapped in (a) olivine, (b) orthopyroxene, and (c,d) clinopyroxene.*

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Investigating the origin of degassed CO_2, volcanic climate forcing, and the thickness of the carbonate platform associated to Mt. Somma-Vesuvius based on mafic melt inclusion

Esposito R.*

Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy.

* *rosario.esposito@unimib.it*

Monte-Somma Vesuvius volcano (SV) has been quiescent since the last eruption in 1944. During SV's volcanic history, this system was able to generate several high explosive eruptions such as the infamous Pompeii 79 AD which occurs after 295 years of dormancy. At this time, the crater shows minor fumarolic activity. Currently, CO_2 gas fluxing at SV from soil and groundwater is 301 t/d. But in its past activity, ashes and peaks of SO_4^{2-} in Greenland ice cores have been ascribed to the Pompeii eruption, implying the capability of climate forcing caused by SV volcano eruptions. Another characteristic of SV consists of its development above a carbonate platform. For SV, the base of this platform is still debated, and, thus, the effect and intensity of magma/carbonates interaction and its role in triggering high explosive eruptions.

In this contribution, I present the state of the art about the volatile evolution of SV based on melt inclusion (MI). Firstly, the depth of formation of MI is reported. In particular, several MI show depths which are greater than 12 km (Marianelli et al., 2005; Esposito et al., 2023) which is the maximum possible depth at which the base of the carbonate platform can be located. This implies that CO_2-rich melts exist(ed) deep below SV at a depth not associated with the carbonate platform. Based on the deepest MIs the CO_2 flux of past eruptions at SV shows a similar magnitude relative to the possible CO_2 fluxing generated by relatively shallow assimilation and decarbonation of the carbonate platform.

The gap in pressure of formation based on MI hosted in olivine corresponds to 7-8 km Esposito et al. (2023). Estimating the depth of formation based on MI gives the opportunity to indirectly calculate the thickness of the platform as this has been never resolved based on geophysical data.

Lastly, the halogen contents of this magma indicate, firstly, that the amount of S degassed from the Plinian eruption at SV is capable of influencing the global climate in the short term. For Instance, an estimate of S budget (27 Tg) based on MI of the Pompeii 79 AD eruption is comparable to those of Tambora 1815, which triggered a three-year extreme climate globally. Secondly, the amounts of Cl of these magmas are anomalously high for mafic composition (2739-6220 ppm) and suggest a strong connection between the generation of magmas below SV and subducted slab fluids.

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Linking volcanic gases to mantle fluids: clues from mineral-hosted fluid inclusions in ultramafic xenoliths from Mayotte Island (Comoros archipelago, Indian Ocean)

Faccincani L.[1], Casetta F.[2*], Rizzo A.L.[3], Faccini B.[1], Liuzzo M.[4], Nardini N.[1], Di Muro A.[5], Coltorti M.[1,4]

[1]Department of Prevention and Environmental Science, University of Ferrara, Ferrara, Italy; [2]Department of Lithospheric Research, University of Vienna, Vienna, Austria; [3]Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy; [4]National Institute of Geophysics and Vulcanology, Palermo Section, Palermo, Italy; [5]Laboratoire de Géologie de Lyon: Terre, Planétes, Environment (LGL-TPE), Université Claude Bernard Lyon, Lyon, France.

* *federico.casetta@univie.ac.at*

Combining the geochemistry of gases emitted in active volcano-tectonic regions with the signature of fluids preserved in mantle-derived rocks represents the next exploratory frontier in geodynamics and volcano monitoring. In recent years, the integration of chemical/textural data from mantle-derived xenoliths with the determination of volatile concentrations and isotopic signature of mineral-hosted fluid inclusions provided important clues on: i) the nature and evolution of the lithospheric mantle; ii) the storage and mobility of fluids through the lithosphere; and iii) the origin of fluids migrating within the mantle underneath active volcanoes and their plumbing systems. In this study, we present new mineral and fluid inclusion chemistry (noble gases and CO_2) data on a unique suite of mantle-derived xenoliths hosted in phonolite pyroclastic deposits in Mayotte island (Comoros archipelago, Indian Ocean), which was the scene of one of the largest submarine eruptions ever documented from 2018 to 2021. The studied samples are spinel-bearing harzburgites and lherzolites, and are composed of Cr-spinel (Cr# = 0.4-0.55), Mg-rich olivine (Fo_{90-92}, NiO = 0.3-0.5 wt%), orthopyroxene (Mg# = 91-92; Al_2O_3 = 1.5-3.0 wt%), and clinopyroxene (Mg# = 91-94; Al_2O_3 = 2.0-3.5 wt%). The mineral major and trace element distribution indicates that the xenoliths represent fragments of a residual lithospheric mantle which experienced 20 to 25% partial melting. Olivine-, orthopyroxene-, and clinopyroxene-hosted fluid inclusions are CO_2-dominated and have air-corrected $^3He/^4He$ isotopic ratios of 5.6-6.8 Ra that are intermediate between the typical signature of Mid-Ocean Ridge Basalt (MORB = 8±1 Ra) and Sub-Continental Lithospheric Mantle (SCLM = 6±2 Ra). Such He isotopic signature is similar to that of subaerial and submarine gaseous emissions in the Mayotte area (Liuzzo et al., 2021). With respect to the mantle xenoliths from the neighbouring Grande Comore Island (Coltorti et al., 1999), the peridotites from Mayotte lie within a narrower compositional range, being moderately depleted and not showing significant sign of metasomatic enrichment. Despite comparable $^3He/^4He$ ratios, fluid inclusions in the Mayotte samples have higher $^4He/^{40}Ar^*$ values than expected for a refractory mantle (Rizzo et al., 2021), likely indicating a shallow overprinting by magmatic fluids from the present magmatism. Altogether, mantle xenoliths and hosted fluid inclusion data are used to speculate about the melt-fluid/rock reactions in the lithospheric mantle, the genesis and ponding of magmas linked to the recent volcanic activity at Mayotte and the intricate geodynamic setting of the Comores archipelago.

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Petrology and geochemistry of the slab-released fluids: what fluid inclusions tell us

Ferrando S.*

Department of Earth Sciences, University of Torino, Torino, Italy.

* *simona.ferrando@unito.it*

Fluids released by the slab during subduction at sub-arc depths have strong petrological and geochemical effects on the metamorphic evolution of the subducting rocks and on the metasomatism of the overlying mantle wedge. The study of natural fluid inclusions trapped in ultra-high pressure (UHP) minerals is the direct way to characterize these fluids.

An increasing number of studies on UHP fluid inclusions reveals: i) the presence of three distinct populations of UHP fluid inclusions (l.s.), i.e. chlorite-bearing aqueous ± non-polar gaseous inclusions, multiphase-solid inclusions and melt inclusions; ii) the local preservation of the fluid chemical composition.

These data indicate that, at increasing the geothermal gradients, a deep subducted slab can release: a) water-dominated solutions containing moderate concentrations of chlorides, Si, Al, and alkalis, ± non-polar gases; b) alkali-aluminosilicate-rich aqueous fluids at P-T conditions near or just above the second critical end-point of H_2O–silicate systems; c) hydrous-silicate melts enriched in incompatible trace elements. Data from the overlying mantle wedge reveals that it is metasomatized by subduction-related solute-rich COH fluids or subduction-related melts, both enriched in incompatible trace elements.

Growing interest of the scientific community in alkali-aluminosilicate-rich aqueous fluids is due to their chemical and physical properties. In fact, the major- and trace-element content in alkali-aluminosilicate-rich aqueous fluids is due to a progressive-to-complete dissolution (not melting) of UHP minerals such as phengite, carbonate and epidote *s.l.*. This process allows the fluid: i) to incorporate similar or even higher amounts of trace elements with respect to a hydrous-silicate melt released at the same P-T conditions; ii) to fractionate trace-element distinctly from hydrous-silicate melts, regardless of the source lithology. Finally, because they are polymerized fluids, their metasomatic efficiency is much more similar to that of hydrous-silicate melts than that of typical crustal fluids dominated by halite ligands. These properties make the UHP aqueous fluids released above the second critical end-point of the H_2O-rock system the most effective metasomatizing agents of the mantle wedge, and their chemical fingerprint can be preserved in orogenic magmas.

The relevant data obtained so far suggest that, although hampered by some analytical difficulties, the research on UHP natural fluid inclusions continues to be relevant for its implications on metamorphic and magmatic petrology.

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Nanogranitoids and fluid inclusions unravel crustal evolution, one drop at a time

Ferrero S.*

Department of Chemical and Geological Sciences, University of Cagliari, Monserrato, Italy.

* *silvio.ferrero@unica.it*

Nanogranitoids are crystallized droplets of anatectic melt found in metamorphic minerals mostly from rocks of crustal affinity (Fig. 1). These inclusions can survive the long journey of the host rock to the surface and remain unchanged because sheltered in refractory minerals, mainly garnet.

In recent years, the increasing availability of high-resolution techniques, in combination with classic petrology and phase equilibrium modelling, made feasible the detailed investigation of these minute objects as well as of the primary fluid inclusions often coexisting with anatectic melt inclusions. This allowed us to make massive advancements in the understanding of crustal differentiation, one of the chief processes shaping the Earth´s crust through endless cycles of crustal reworking, re-melting and melt migration for the last 4 billion years.

For instance, by finding and studying these inclusions we are now able to directly measure natural melts and COH fluids generated from melting of virtually any protolith, throughout the entire geological timescale and over a wide P-T range.

The trace elements signature of the preserved melt clarifies which melting reactions took place, and this helps to correlate melt presence with P-T-t evolution of the rocks.

The volatile content (CO_2, H_2O, Cl, F) of the melt shows instead which fluid (aqueous, carbon-rich or saline) and how much of it was present at depth during melting. With these novel data, we can calculate more precisely the melt viscosity at depth, as well as refine the estimates of the continental crust contribution to the global volatile cycle over geological times.

This is also a fertile ground for unexpected discoveries such as new mineral phases and crustal carbonatites - just two examples of the new research avenues opening up as we target more and more case studies of melt inclusions in metamorphic rocks.

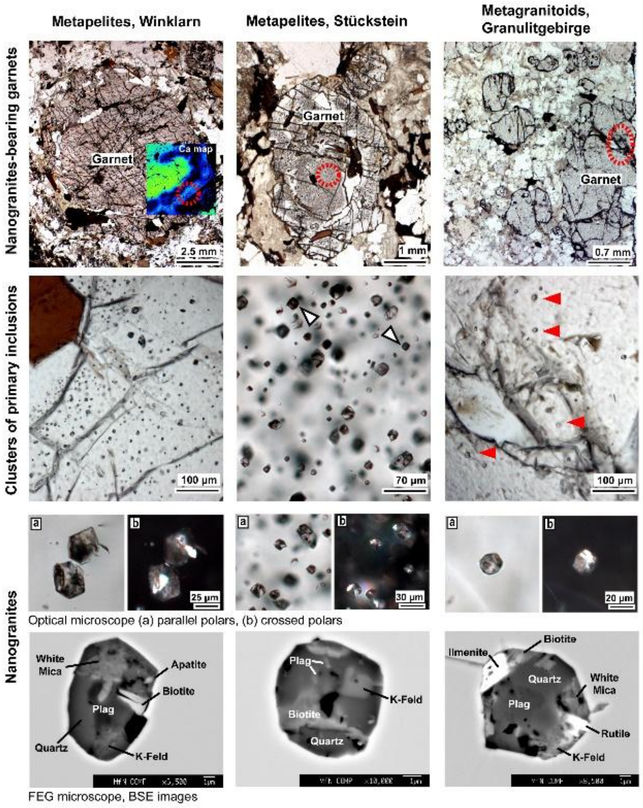

Figure 1 *Primary anatectic melt inclusions in partially melted crustal rocks from the Bohemian Massif (Ferrero et al., 2019). Red dashed circles= nanogranitoid clusters; white arrows= fluid inclusions; red arrows= nanogranitoids.*

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X-ray computed microtomography techniques for the study of melt and fluid inclusions

Lanzafame G.*

Department of Biological, Geological, and Environmental Sciences, University of Catania, Catania, Italy.

* *gabriele.lanzafame@unict.it*

X-ray computed microtomography (X-CT) is one of the most advanced tools for three-dimensional (3D) visualisation and analysis of the inner structure of different types of materials at micron scale. This technique has been mainly applied in clinical settings and biomedical research for decades, but in recent years its use has become routinely adopted for advanced geologic and particularly petrologic research. Indeed, the possibility to visualize and measure the morphologic features of the rock components in 3D overcomes the limits of conventional two-dimensional (2D) imaging on thin sections, which may not be capable to fully represent the true inner structure of materials leaving a large degree of uncertainty in the characterization of the samples. An additional benefit of the application of XCT includes its non-destructive procedure, an essential prerequisite for performing sample screening in search of features of interest before the analysis.

This talk will provide an overview of the working principles of conventional and synchrotron radiation X-Ray microtomography, exploring the most used image analysis techniques to extract quantitative data such as amount, number, volume and morphological descriptors of the phase of interest. The entire process for acquiring and analysing 3D images, from the submission of proposals to research facilities to the image processing will be described, emphasizing the steps of the image analysis using both commercial and freeware software.

Finally, results of recent XCT application for the 3D visualization, mapping and quantitative data extraction of melt and fluid inclusions in samples of mantle xenoliths will be presented.

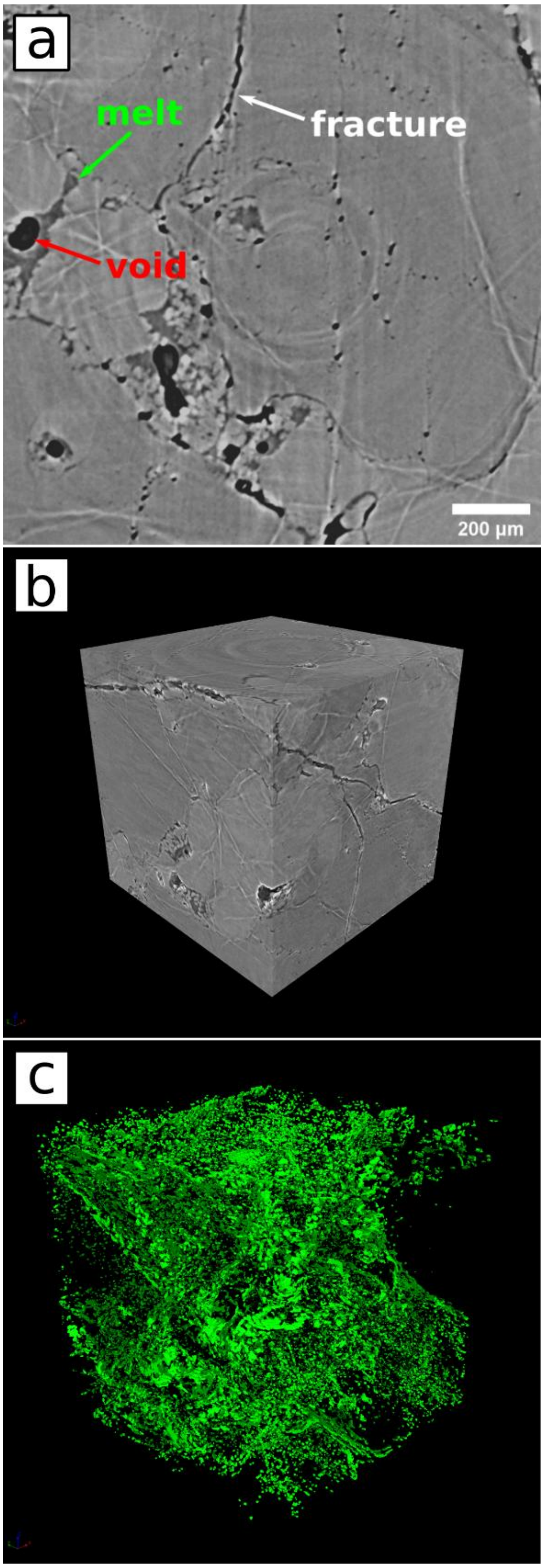

Figure 1 *(on the right →) Results of Synchrotron radiation X-CT analysis of a mantle xenolith from Antarctica:* ***a)*** *single 2D reconstructed slice;* ***b)*** *3D volume rendering of the sample; c) extracted melt phase for morphologic analysis.*

The plumbing system of Fogo volcano (Cape Verde archipelago), inferred from fluid and melt inclusions

Lo Forte F.M.[1*], Aiuppa A.[1], Rotolo S.G.[1,2], Zanon V.[3], Rizzo A.L.[4]

[1]Department of Earth and Marine Science, University of Palermo, Palermo, Italy; [2]National Institute of Geophysics and Vulcanology, Palermo Section, Palermo, Italy; [3]Instituto de Investigação em Vulcanologia e Avaliação de Riscos, Universidade dos Açores, Rua Mãe de Deus, Ponta Delgada PT-9500-321, Portugal; [4]Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy.

* *francescomaria.loforte@unipa.it*

This study investigates the magma plumbing system of Fogo Volcano in the Cape Verde Archipelago using fluid (FI) and melt (MI) inclusions. The research aims to expand the limited knowledge about the volcano from the mantle to the surface and provide new constraints for assessing volcanic risk, given the catastrophic nature of recent eruptions (1951, 1995, and 2014/15). The microthermometric analyses of FI hosted in olivine and clinopyroxene were conducted on lava and tephra products spanning the last 120,000 years of volcanic activity. We reconstructed the architecture of the magma storage system, identifying two main magma storage zones (at ~25 km and 13–21 km) and a magma stagnation zone at ~9–12 km depth, where magma ponded for a short time and where inclusions re-equilibrated before their final ascent to the surface.

The MI analyses were conducted on olivine-hosted melt inclusions from recent (<10 ky) basanitic tephra erupted by Fogo. Our results (i) confirm the previous barometric findings and (ii) constrain a deeper magma reservoir (27–36 km), where the carbon-rich parental melt of Fogo (2.1 wt.% CO_2) is stored in the lithospheric mantle before being injected into a vertically stacked magma ponding system. Overall, we develop a degassing model for volatiles (H_2O, CO_2, S, Cl, and F) and corroborate previous indications of a CO_2-rich nature in alkaline ocean island volcanism. Our findings show that the mantle beneath Fogo is highly carbon-enriched, with concentrations of up to 400 ppm.

Figure 1 *Pico do Fogo volcano, the currently active volcanic structure on Fogo Island.*

Additionally, noble gas (He, Ne, Ar) and carbon (C) isotope results from olivine- and clinopyroxene-hosted FI in enclaves, lavas, tephra, and volcanic gas samples were used to constrain the crustal-like signature for carbon in primary melts, which is stored at ~77 km depth. Moreover, we developed a $\delta^{13}C$-CO_2 degassing model for volatile degassing in the mantle-to-crustal magma plumbing system.

Survival of melt inclusions in minerals under variable, pre- and syn-eruptive conditions: an experimental petrology study

Lupica Spagnolo F.[1*], Cioni R.[1], Scaillet B.[2]

[1]*Department of Earth Sciences, University of Firenze, Firenze, Italy;* [2]*Laboratoire ISTO-CNRS, Orleans, France.*

** faustolupica@gmail.com*

Melt inclusions are small droplets of silicate melt (typically <100 μm in the longest dimension) that are trapped in mineral structures during their growth from the magma. Melt inclusions play a fundamental role in understanding the processes that occur in a magmatic system during a variety of petrological processes (eg. Magma mixing or crystallization) and represent a snapshot of the magma at the time of their entrapment in host crystals. They can also reveal an important key to understanding the complexities of pre-eruptive magma evolution and the eruptive dynamics. The aim of this work is to understand how melt inclusions are modified and how long they survive when mafic magma intrudes into a system characterized by a more evolved composition. Based on the existing literature, this condition has often occurred at Vesuvius (Italy), where magma mixing processes between mafic and evolved magmas are observed in the products of many large eruptions. In order to reproduce these conditions 42 melt inclusions – hosting pyroxenes were selected from mafic scoria produced during a violent strombolian eruption at Vesuvius. To simulate the natural process to investigate, selected pyroxenes were experimentally heated in capsules containing phonolitic powder. Experiments were conducted using an internally heated pressure vessel (IHPV) at the ISTO-CNRS laboratories in Orlèans (France), and different conditions of interest were experienced. The experiments were performed at a pressure of 2 kb under controlled fO_2, water saturation and variable range of temperatures and durations. Parallel to these experiments, natural samples of the same pyroxenes and of pyroxenes from the Plinian 79 CE Pompeii eruption were prepared for comparison. All the samples were subsequently analysed using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS). Textural data extracted from image analyses of the melt inclusions, together with data obtained from compositional analyses, allowed us to define the general behaviour of MI under different pre-eruptive conditions. Furthermore, the comparison of experimental results with natural samples allowed us to provide robust constraints to the natural conditions under which magma mixing processes have occurred.

The role of metasomatised lithosphere in carbon cycling at ocean intraplate settings

Maffeis A.[1*], Frezzotti M.L.[1], Esposito R.[1], Malusà M.[1], Ferrando S.[2], Aiuppa A.[3] and Rizzo A.L.[1]

[1] Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy; [2] Department of Earth Science, University of Torino, Torino, Italy; [3] Department of Earth and Marine Science, University of Palermo, Palermo, Italy.

** andrea.maffeis@unimib.it*

Through a comprehensive petrological, fluid and melt inclusion, and thermodynamic analysis of spinel harzburgite and lherzolite xenoliths from Cape Verde, a Cl-P-S-F-volatile-rich alkaline silicate-carbonate metasomatic agent is shown to be present beneath ocean islands. Geobarometry indicates equilibration pressures from 21 kbar up to 35 ± 4 kbar (107 ± 13 km depth) within the aragonite stability field, confirmed by finding aragonite in harzburgite xenoliths. Thermometry yields temperatures of ~950–1060 °C for harzburgites and ~1140–1200 °C for metasomatic reaction coronas. Thermodynamic modelling shows that orthopyroxene–silicate–carbonate melt interaction in thick, depleted lithosphere can produce deep-seated CO_2, explaining elevated CO_2 emissions in ocean islands. Multiphase fluid inclusions in orthopyroxene and olivine contain $CO_2 + CO$ (XCO from 0.19 to 0.01) and locally disordered graphite. The $CO_2 + CO$ mixture is strongly carbon-supersaturated and metastable due to graphite not precipitating before fluid entrapment, allowing calculation of fluid fO_2 in equilibrium with mantle fO_2. Fluid-derived fO_2 at 35 kbar and 1200 °C is low matching olivine-spinel fO_2 estimates in harzburgites. Furthermore, the metasomatic melt composition resembles experimental silicate–carbonate melts from carbonated sediments and oceanic crust, and similar melts in mantle xenoliths from other ocean islands, suggesting a common mechanism for mantle metasomatism and carbon cycling. Metastable fluid inclusion and Spl-Ol fO_2 data reflect the mantle's initial reduced state beneath Cape Verde. Comparison with equilibrium conditions reveals the elevated oxidising capacity of sediment-derived silicate-carbonate metasomatic melt while allowing us to gain a mechanistic understanding of such a process.

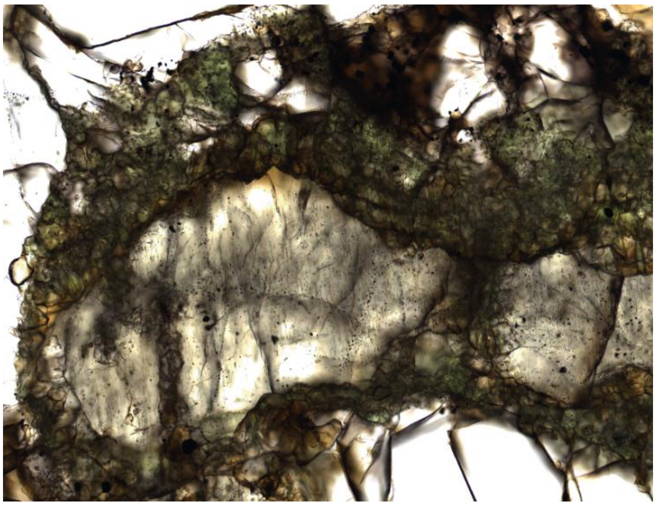

***Figure 1** Photomicrograph of peculiar metasomatic reaction corona around relict-fluid inclusion cluttered-orthopyroxene in an aragonite-bearing harzburgitic xenolith.*

Fluid Inclusions in gemstones: are they always naturality proof?

Musa M.*

Department of Environmental and Earth Sciences, University of Pavia, Pavia, Italy.

* *maya.musa@unipv.it*

In the gemological laboratories, where the gemstones are identified and graded, the inclusion study represents one of the main pillars of the analytical protocols. Contrary to what happens in other diagnostic fields, it is always important to remember that the samples studied in gemology can never undergo any preparation, and all analyses must be non-invasive.

Sometimes, just observing the inclusion by the gemological microscope, its morphology and aspect, could be a valuable information source about gemstone identification, especially in terms of natural origin vs synthetic possibility; treatments eventually applied to enhance the gemstone's aspect or a precious help to hypothesise the geographic origin of the gem material. On the other hand, inclusions can sometimes act as a false friend for gemologists.

Here, we will point out a specific type of gemstone inclusions, the fluid inclusions, and mainly, we will focus our attention on when they represent naturality proof and when they do not. In this scenario, some examples will be briefly discussed, considering one of the most recent gemological challenges: the declaration of low-temperature treatments. Indeed, pushed by the trade requests, the laboratories are hardly working on developing diagnostic protocols to identify gemstone colour enhancement, i.e. tourmalines with a particular focus on the Paraìba variety or the Aquamarine. Thanks to their specific temperature sensibility, the fluid inclusions may help in low-temperature conditions treatment identification, but several limits still remain.

Finally, special attention will be dedicated to the studies of a particular type of gem: the amber. Indeed, gemological materials are not limited to inorganic, but they also include the organic world. Speaking about the role of fluid inclusions in gemology, forgetting the crucial role of fluid amber inclusions could be a big gap. Due to its nature and genetic processes, amber is able to preserve precious unaltered information about, for example, the cretaceous environment; therefore, the scientific studies on ambers' inclusions can open a window into the life on our earth of 40, 80, or 100 million years ago. On the other hand, gemstone-quality amber represents a highly requested material in the trade, with a consequent breakout of falsifications. Again, if properly recognised, the fluid inclusions can be helpful for gemologists in the diagnosis of new amber-related materials in today's markets.

Figure 1 *Optical Microscopy image of a pressed amber drilled bead.*

Lead glass-filled rubies and their identification through inclusions

Protopapas F.*

Professionist

* *francproto@yahoo.it*

Rubies with fractures healed by glassy substances have been known since the 1980s, but it was only in 2004 that a new type of lead glass-treated corundum appeared on the market. This treatment uses lead-rich glass mixtures and other elements to achieve a refractive index very similar to that of corundum, making otherwise unusable specimens appear more appealing. The starting material is usually a red or pink corundum that is opaque or barely translucent, characterized by numerous fractures. It is first heated and treated with acids to improve its colour and simultaneously remove any matrix residues or impurities that could affect the treatment. The stone is then heated at low temperatures to melt the glassy substance and allow it to deeply infiltrate the fractures. The final result is a material with acceptable colour and transparency, although it presents significant durability issues compared to other types of treatments. Fortunately, these stones, which are characterized by minimal cost per carat, can be easily identified through a simple microscopic analysis of the inclusions.

Figure 1 *Typical Flash effect and gas bubbles in lead glass-filled ruby. Photo by F. Protopapas*

The journey of light noble gases in the Earth's interior

Rizzo A.L.*

Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy.

* *andrealuca.rizzo@unimib.it*

Light noble gases are key tracers for understanding the composition and dynamics of the Earth's mantle. In particular, helium isotopes (^{3}He and ^{4}He), are of special interest due to their distinct origins—^{3}He being primordial, while ^{4}He is continuously generated through the radioactive decay of U-Th, resulting in different ratios in Earth's reservoirs. Instead, neon and argon isotopes are more susceptible to contamination from atmosphere-derived fluids, as Ne and Ar concentrations in the atmosphere are several orders of magnitude higher than in magmatic or mantle fluids. Therefore, the ^{3}He/^{4}He ratio is more frequently used than other noble gas ratios to infer the presence of a lower mantle (plume) component, the recycling of crustal material into the mantle, diffusive fractionation, melt evolution during ascent, and magma dynamics over time or within a single eruptive event. When combined with other noble gases, helium isotopes are also valuable for understanding mantle metasomatism and the recycling of atmosphere-derived material into the mantle.

Noble gases are typically measured using mass spectrometry in: (i) volcanic or spring gases, and (ii) gas trapped in fluid inclusions (FI) within mafic minerals or ultramafic rocks (Fig. 1). However, recent research has shown that studying noble gases in fluid inclusions is more effective for investigating magmatic and mantle processes than analyzing volcanic or spring gases, whose composition can be altered by shallow intra-crustal processes.

Here, I will present several case studies that highlight the most common applications of light noble gases, particularly helium isotopes, in the investigation of mantle and magmatic processes. Specifically, I will focus on the following topics:

1. What drives helium isotope variability in subduction-related settings, distinguishing between metasomatic processes in the mantle wedge and contamination at crustal levels;
2. The degree of mantle melting, its composition and evolution during metasomatic processes;
3. Mantle heterogeneity and its relation to Earth's geodynamics.

Figure 1 *Photo of a mantle xenolith hosted in a basanite rock.*

Dynamic of magmatic processes during the 79 CE eruption of Mt. Vesuvius: inferences from clinopyroxene compositional zoning pattern, thermodynamic modelling and fluid inclusions

Romano P.[1*], Pelullo C.[2], Arienzo I.[2], Chakraborty S.[3], Doronzo D.[2], Sparice D.[2], Rizzo A.L.[4], Di Vito M.A.[2]

[1]*National Institute of Geophysics and Vulcanology, Palermo Section, Palermo, Italy;* [2] *National Institute of Geophysics and Vulcanology, Naples Section, Napoli, Italy;* [3]*Institut für Geologie, Mineralogie und Geophysik, Ruhr Universität, Bochum, Germany;* [4]*Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy.*

* *pierangelo.romano@ingv.it*

The AD 79 eruption of Pompeii represents one of the earliest and most extensively documented Plinian eruptions of the past two millennia. Numerous studies have explored the eruptive history of Somma-Vesuvius and its impact on both ancient and contemporary societies. Despite recurrent eruptions of varying magnitudes and eruptive styles, the densely populated areas surrounding the volcano have been continuously inhabited for millennia. In order to gather new insights into (i) the architecture of the magmatic feeding system and (ii) the magmatic processes preceding such a Plinian event, a detailed study of the mineral compositions and mineral zoning patterns was combined with isotopic analyses of minerals, bulk rocks (^{86}Sr/^{87}Sr isotope ratio) and fluid inclusions (noble gases and carbon isotope ratios). The present study focused on selected eruptive units of the 79 CE eruption and representative samples of the "white" and "grey" pumices and mafic cumulates. The mineral compositions that characterise mafic cumulates (i.e. Fo-rich olivine and high Mg# clinopyroxene) are recurrent in the white and grey pumices, which serves to highlight the occurrence of mafic recharges and mixing processes within the magmatic reservoir(s). The clinopyroxenes in the pumice samples are diopsidic and Fe-diopsidic in composition, with Mg# (molar Mg/(Mg+Fetot)*100) values ranging between 91 and 39. The compositional profiles demonstrate the presence of normal, reverse and multiple zoning patterns. The considerable diversity in clinopyroxene chemical composition can be attributed to five distinct compositional populations (ME0 to ME4), which are indicative of different crystallisation conditions (P-T-X-H_2O melt-fO_2). Each of these populations is associated with a particular magmatic environment. The crystallisation temperature and storage pressure of Vesuvius magmas can be described by clinopyroxene-liquid geothermometer and MELTS modelling, while noble gases and carbon isotopes contribute to an understanding of the magmatic processes within the reservoir(s).

Understanding the deep carbon cycle through the study of fluid inclusions hosted in ultramafic xenoliths and mafic volcanic rocks

Sandoval-Velasquez A.[1*], Rizzo A.L.[2], Aiuppa A.[1], Frezzotti M.L.[2], Casetta F.[3], Ntaflos T.[3], Coltorti M.[4], Lo Forte F.M.[1], Jackson M.[5]

[1]Department of Earth and Marine Science, University of Palermo, Palermo, Italy; [2]Department of Environmental and Earth Science, University of Milano-Bicocca, Milano, Italy; [3] Department of Lithospheric Research, University of Vienna, Vienna, Austria; [4] Department of Physics and Earth Science, University of Ferrara, Ferrara, Italy; [5]Department of Earth Science, University of California, Santa Barbara, California, United States of America.

* *andreslibardo.sandovalvelasquez@community.unipa.it*

Fluid inclusions in mantle xenoliths and mafic volcanic rocks are generally dominated by CO_2 and other carbon species such as CH_4, CO and carbonates. This characteristic makes them excellent targets to study the carbon isotopic signature of the mantle and the nature of metasomatic fluids that have modified its original composition. When performing isotopic studies, values of $\delta^{13}C$ in mantle xenoliths show a wide range of variability (from -30‰ to +1‰). This variability is usually explained by the contribution of three different endmembers: mantle carbon ($\delta^{13}C$~-5‰), organic carbon (-30‰ < $\delta^{13}C$< -10‰), and carbonate carbon (-1‰ < $\delta^{13}C$ +1‰). Carbon ingassing to the Earth's mantle (Fig. 1) is governed by the subduction of carbonate and organic materials present in sediments, altered oceanic crust (AOC) and mantle layers attached to the oceanic slab. Some studies have proposed that a little part of the subducted carbon is returned to the exosphere (after dehydration of the oceanic slab) through volcanic arcs and that most of the crustal carbon is transferred into the deep mantle. Thus, the chemical reactions and the new carbon phases produced in the mantle will influence the formation of different chemical and isotopic reservoirs, which have huge implications for our understanding of crustal recycling and the major geological processes that govern deep carbon cycling.

Our studies of fluid inclusions in mantle xenoliths and volcanic rocks (from OIB and continental rift localities) have combined the analysis of carbon and noble gas isotopes. These studies suggest that the isotopic characteristics of the upper mantle are variable and strongly linked with the geodynamic history of the study area and the nature of the metasomatic/refertilization events. Some localities here studied included: Canary Islands, Mexico, French Polynesia, Cape Verde and central Europe. The aim of this work is to give new insights on the characteristics and the evolution of the lithospheric mantle in distinct geodynamic environments, as well as the occurrence of partial melting, mantle metasomatism and/or refertilization events. Another important aspect of this study regards the involvement of mantle plumes in explaining the recent magmatism in OIB localities, and the recycling into the mantle of noble gases and carbon related to recent or fossil subduction systems.

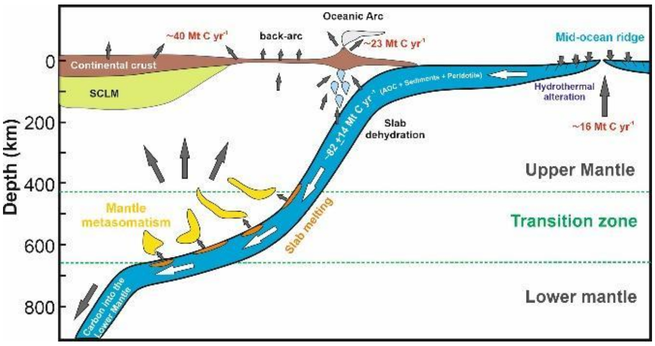

Figure 1 *Model for the deep mantle carbon cycle. Red (inputs) and white (outputs) numbers are global carbon (C) fluxes in megatons per year (Mt yr^{-1}).*

Exploring the potential of melts inclusion in chondrules

Vitrano A.[1*], Almeev R.[2], Viti C.[1], Holtz F.[2], Rotolo S.G.[3,4], Vetere F.[1]

[1]*Department of Physical Sciences, Earth and Environment, University of Siena, Siena, Italy;* [2]*Institute of Earth System Sciences (IESW), Leibniz Universität Hannover, Hannover, Germany;* [3]*Department of Earth and Marine Science, University of Palermo, Palermo, Italy;* [4]*National Institute of Geophysics and Vulcanology, Palermo Section, Palermo, Italy.*

* *a.vitrano@student.unisi.it*

Melt inclusions, commonly studied in volcanic rocks, have long been a key tool for investigating magmatic processes. However, their role in understanding chondrules—small, spherical components of meteorites—remains poorly explored and presents significant challenges. Chondrules formed in a unique physicochemical environment compared to Earth's magmatic systems. They crystallized at temperatures above 1400°C as free-floating droplets in microgravity, under a pressure of approximately 10^{-3} bar, cooling at rates of hundreds to thousands of °C/h, interacting with nebular vapour. This study aims to highlight the importance of melt inclusions in chondrules, as they can provide valuable insights into the conditions of the early solar system. Using the electron probe microanalyzer (EPMA), we examined an isolated olivine grain containing melt inclusions that vary in shape and composition. Our analysis reveals that these melt inclusions exhibit diverse chemical compositions, including Al-rich, Al-poor, and Na-rich glasses. According to the literature, the presence of such varied compositions in the same crystal can be attributed to two main processes. Na-poor melt inclusions are considered primary, having formed from the original melt from which the olivine crystallized. Meanwhile, the Na-rich melt inclusions are classified as pseudosecondary. As suggested by studies, these formed from residual melt trapped between olivine crystals, which subsequently interacted with the solar nebula, enriching the melt with sodium. The scenario we propose for the formation of this chondrule, based on the information from the melt inclusions and the enstatite rim surrounding the isolated olivine grain, involves a splashing impact while the chondrule was still partially molten, and experienced gas–melt interaction reacting with nebular gas.