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Program and abstracts book

Cover photo: Melt inclusions in olivine from Bárðarbunga volcano, Iceland (c) Alberto Caracciolo

Abstract book edited by Alberto Caracciolo, University of Iceland

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Preface and information

It gives us great joy to welcome all participants to the 27th ECROFI (European Current Research on Fluid Inclusions) conference. The conference, organized by the geochemistry-petrology group from the University of Iceland, is held from the 2nd to the 6th of July, 2023, in the building of Natural Sciences at the University of Iceland.

This is the 27th edition of the biennial international conference dedicated to the investigation of fluids and magmas through the study of fluid and melt inclusions.

The conference follows the conventional structure of the ECROFI meeting, including a pre-conference workshop on July 2nd about fluid and melt inclusions given by Prof. Robert J. Bodnar, a visit to the labs of the university, five different scientific sessions with talks and posters and a post-conference fieldtrip on the Reykjanes Peninsula.

The conference is held in Askja building in room 132, Sturlugata 7, 102, Reykjavik, Iceland.

Scientific sessions

S1 – New frontiers in fluid and melt inclusion research – theory and experiments.

S2 – Inclusions in magmatic and magmatic-hydrothermal environments.

- S3 Deep and metamorphic inclusions.
- S4 Inclusions in sedimentary environments.
- S5 Ore fluid inclusions.



Conference Map





Conference Program

Monday, July 3 rd			Tuesday, July 4 th	Wednsday, July 5 th		
Session S1 – New Frontiers		Session S2 – Inclusions in magmatic settings		Session S4 – Inclusions in sedimentary settings		
9:00 - 9:30	Keynote – Zajacz Z.	9:00 - 9:30	Keynote – Hartley M.E.	9:00 - 9:30	Keynote – Mangenot X.	
9:30 - 9:45 Bakker R. J.		9:30 - 9:45	Xu X.	9:30 - 9:45	Zhao W.	
9:45 - 10:00	Beeskow M.	9:45 - 10:00	Mororò E. A.	9:45 - 10:00	00 Fan J.	
10:00 - 10:15	Huang X.	10:00 - 10:15	Berkesi M.	10:00 - 10:15	Sosa G.	
10:15 - 10:30	Caumon M.C.	10:15 - 10:30 Bozkaya Ö.		10:15 - 10:30 Hollenbach A.		
10:30	0 - 11:00 Coffee break	10:30 - 11:00 Coffee break		10:30 - 11:00 Coffee break		
Session S2 –	Inclusions in magmatic settings	Session S1 – New Frontiers		Session S1 – New Frontiers		
11:00 - 11:15	Lima A.	11:00 - 11:15	Chen W.	11:00 - 11:15	Lange T. P.	
11:15 - 11:30	Capriolo M.	11:15 - 11:30	Liu Y.	11:15 - 11:30	Goldstein R. H.	
11:30 - 11:45	Caracciolo A.	11:30 - 11:45	Fusswinkel T.	11:30 - 11:45	Hess T.	
11:45 - 12:00	Mendoza N.	11:45 - 12:00	Myovela J. L.	11:45 - 12:00	Xu X.	
12:00 - 12:15 Lentz D. R.		-	12:00 – 13:00 Lunch		2:00 — 13:00 Lunch	
1	2:15 - 13:15 Lunch	Session S4 – Inclusions in sedimentary settings		Session S2 –	Inclusions in magmatic settings	
Session S3 – In	clusions in metamorphic settings	13.00 - 13.30	Invited – Voigt M.	13.00 - 13.30	Invited – Friðleifsson G. Ó.	
13:15 - 13:30	Ferrando S.	13:30 - 13:45	Pironon J.	13:30 - 13:45	Hüne L.	
13:30 - 13:45	González-Esvertit E.	13:45 - 14:00	Krüger Y.	13:45 - 14:00	Schmidt C.	
13:45 - 14:00	Spránitz T.	14:00 - 14:15	Liu X.	14:00 - 14:15	Beauchamps G.	
14:00 - 14:15	Fall A.	14:15 - 14:30	Arnuk W. D.	14:15 - 14:30	Koděra P.	
14:15 - 14:30 Frezzotti M. L.		14:30 - 14:45 Sahasrabudhe N. K.		14:30 - 15:00 Coffee break		
14:30 - 15:00 Coffee break		14:45 - 15:15 Coffee break		15:00 - 17:00 General Discussion		
Session	n S5 – Ore fluid inclusions	Session S1 – New Frontiers		17:00 - 18:00 Poster Session		
15:00 - 15:15	Smitha R. S.	15:15 - 15:30	Mandon C.		<u>Sunday, July 2nd</u>	
15:15 - 15:30	15:15 - 15:30 Bozkaya G.		Farsang S.	o Pre-confei	rence workshop I in room N-121	
15:30 - 15:45	Tarantola A.	15:45 - 16:00	Estrella M. P.	from 9 to	17.	
15:45 - 16:00 Gómez-Gajardo A.		16:00 - 16:15	Diamond L. W.	• Pre-conference workshop II at 16.00.		
16:00 - 16:30 Coffee break		16:15 - 16:30	Steele-Macinnis M.	\circ Ice breaker party at 18.00		
16:30 - 16:45 Raza M. Q.		16:30 - 16:45	Appold M. S.	Thursday, July 6 th		
16:45 - 17:00 Cho V.		16:45 – 18:00 Poster Session		• Post-conference fieldtrip in Reykajnes		
17:00 - 17:15 Arduin-Rode F.		19:00 Conference dinner in Askja		Peninsula. Departure at 9.00.		
17:15 - 17:30 Zachariáš J.						
17:30 – 18:30 Poster Session			e u kypa			



Session S1: New frontiers in fluid and melt inclusion research – theory and experiments

Solubility of geologically important minerals in hydrothermal fluids within the roots of volcanic geothermal systems

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Keywords: experiments, mineral solubility, supercritical fluids (poster)

Fluid-rock interaction and solubility of minerals at conditions occurring in the roots of volcanic geothermal systems are of fundamental importance controlling supercritical hydrothermal fluid (>374°C) chemical composition. Previous deep drilling projects, i.e., IDDP-1 and IDDP-2, have encountered supercritical fluids such with temperatures of ~440°C and ~500-600°C, respectively. However, modeling the chemical composition of such supercritical fluids at low pressures is difficult due to the lack of thermodynamic formulations, such knowledge being critical to understand their nature and utilization potentials.

Here we report experimental measurements on the solubility of geological and engineering relevant salts (Li, Na, K, Rb and Cs chlorides), sulfates (Na and K sulfates) and oxides (SiO₂) in supercritical water at temperatures of 400-600°C and pressures of 50-300 bar.

The experiments were conducted using a U-tube reactor system. The experimental that results demonstrate mineral solubilities increase with increasing pressure consistent with а thermodynamic model first proposed by Pitzer and Papalan (1986) assuming stepwise hydration (H₂O addition) of the neutral gas-like molecules to form molecular water clusters. The other systems of interest and geological studied relevance to be include carbonates and oxides as well as silicates and aluminum silicates.

This research serves great importance for deep drilling projects with the aim of exploiting high enthalpy and low-density field fluids for more economical utilization. Furthermore, this research gives opportunities to perform geochemical modeling of supercritical fluids and SiO₂ and carbonate scaling in boreholes.

The experiments also reveal the transport and mobility of certain elements, e.g. valuable metals, in both hydrothermal and volcanic systems as the affinity for the liquid and gas phase may change passing the supercritical point for certain elements.

The project has received funding from the European Union's Horizon 2020 under Grant Agreement #818169 (GeoPro).



Experimental quantification of the partitioning of zinc and copper between brine and dolomite under sedimentary basinal conditions

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Keywords: experiments, sedimentary basins, ore deposits

The concentrations of base metals like zinc and copper in hydrothermal fluids are among the most valuable types of information for understanding the origin of ore deposits of these metals. Fluid inclusions can be a valuable source of base metal concentration data but commonly fluid inclusions suitable for obtaining this information are not present in ore-stage minerals. In such cases, partitioning theory can be a useful alternative method for determining base metal concentrations hydrothermal fluids. If the in concentration of a major element can be measured in both an ore-stage mineral and its parent hydrothermal fluid, e.g. inclusions, and if the from fluid concentration of the base metal can also be measured in the ore-stage mineral, then the concentration of the base metal the hydrothermal fluid can be in calculated if the partition coefficient value is known.

Calcite and dolomite are common in sediment-hosted many base metal deposits and base metals can potentially substitute into their crystal lattices. Rimstidt et al. (1998) have compiled experimental partition coefficient values as a function of temperature for several base metals that can enter calcite from aqueous solutions. These values were used by Smith-Schmitz & Appold (2018) and Appold and Bauchau (2021) to determine that Zn concentrations in the hydrothermal fluids that precipitated calcite in the Illinois-Kentucky and Central Tennessee Mississippi Valley-type districts in the central U.S. were no higher than on the order of 10's of ppm, but as high as 30,000 ppm in fluids that

precipitated calcite in the Lemhi Pass Th-REE district in Idaho and Montana in the western U.S.

Ore-stage calcite is not present in every sediment-hosted base metal deposit but in some of those deposits, ore-stage dolomite is present. However, the partitioning of base metals between water and dolomite has not been as well characterized as for calcite. The present study has therefore sought to address this knowledge gap. To date, a suite of experiments has been completed the partitioning quantifying of Zn between brine and dolomite at temperatures between 125° and 200° C at 10 MPa, and another suite of experiments on the partitioning of Cu between brine and dolomite under these conditions has been started. For the reaction,

 $Zn_{(aq)}^{2+} + CaMg(CO_3)_{2(dol)} \rightleftharpoons$ $Mg_{(aq)}^{2+} + CaZn(CO_3)_{2(dol)}$

partition coefficients at 125°, 150°, 175°, and 200° C range between about 20 and 45±10.

References:

Appold M.S., Bauchau P.H. (2021) Insights from partitioning theory into the zinc content and origin of mineralizing fluids in the Lemhi Pass Th-REE district, Idaho-Montana: Geological Society of America Abstracts with Programs, Vol 53, 184-7.

Smith-Schmitz, S.E., Appold, M.S. (2018) Prediction of ore fluid metal concentrations from solid solution concentrations in orestage calcite: Application to the Illinois-Kentucky and Central Tennessee Mississippi ,Valley-type districts: Geochimica et Cosmochimica Acta, Vol 225, pp 210-227.

E C R I F

3D Raman mapping of complex fluid inclusions to shed light on fluid compositions in the deep lithosphere

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Keywords: fluid inclusion, new frontiers, metamorphism

The micron-scale resolution of Raman spectroscopy revolutionized fluid and melt inclusion research in the past decades and lead to а better understanding of fluid-related geological processes in the lithosphere. In this study we demonstrate the applicability of 3D Raman mapping, with special attention to the determination of volume proportions of each phase within the inclusions. We studied garnet-hosted multiphase fluid inclusions (MFI) in eclogites and granulites from the Cabo Ortegal Complex (NW-Spain) from where a robust petrographic and geochemical database, including 2D Raman maps is available (Spránitz et al., 2022). These MFI represent deep subduction fluid and contain optically non-distinguishable solid-fluid phases at room temperature.

3D Raman models were compared to Focused Ion Beam - Scanning Electron Microscopy (FIB-SEM) slicing of three previously 3D Raman mapped MFI, optimize allowing us to Raman spectroscopy data evaluation and provide volume proportion calculations (Fig. 1). Using model analysis with curated reference spectra, together with empirically determined Raman cross sections of the phases inside the inclusions can vastly improve the quality of Raman maps. In case of garnethosted MFI, the host garnet is always an adjustment overestimated, thus factor of 300-400% should be applied, meanwhile the Raman intensity of underrepresented CO₂/CH₄ fluids need to be adjusted to 30% of the intensity of the host. We found that a non-optimized

Fig. 1: 3D models of the studied MFI and the proportion of phases (vol%) based on Raman datasets.

The results provide more precise, valuable input data for thermodynamic modelling and draw implications for fluid/rock interactions. This research was supported by the NKFIH_FK research fund nr. 132418.

References:

Spránitz, T., Padrón-Navarta, J. A., Szabó, Cs. et al. (2022): J.Metamorph.Geol., 40:1291–131



P-T-X conditions of the Bétaré-Oya gold deposits: constraints from the fluid inclusion studies

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Keywords: Fluid inclusion, P-T-X conditions, Bétaré-Oya gold deposit

The Bétaré-Oya gold district is located in the eastern Cameroon, Central Africa. The district is underlain bv volcano-sedimentary Neoproterozoic rocks, which were metamorphosed and mineralized during the Pan-African event. Quartz grains of the ore bodies were sampling for petrography, microthermometry, and Laser Raman spectroscopy of fluid inclusions studies. The results revealed two fluid inclusion assemblages of three types of fluid inclusions. The assemblage 1 consisting of gold deposition is composed of types 1 and 2 fluid inclusions (Fig. 1), while assemblage 2, the post-gold mineralization, consists of type 3 fluid inclusions. Type 1 H_2O-CO_2- NaCl±N2±CH4 fluid inclusions occur as early fluid inclusions with a melting temperature of carbon dioxide (Tmco2) ranging from -59.8 to -56.5 °C, salinity from 0.5 to 10.8 wt% NaCl equiv, densities from 0.87 to 1.00 g.cm⁻³, and the total homogenization temperatures (Th) between 280 and 360 °C. Type 2 CO₂ $(\pm H_2O-NaCl)\pm N_2\pm CH_4$ fluid inclusions exhibit Tm_{CO2} ranging between -60.0 and -56.7 °C, Th_{co2} from 13 to 25 °C, and densities between 0.73 and 0.85 g.cm⁻³. Type 3 H₂O-NaCl fluid inclusions show salinity between 0.2 and 10.1 wt% NaCl equiv, densities between 0.82 and 0.98 g.cm⁻³, and total homogenization temperatures (Th) from 160 to 235 °C.

Therefore, calculated data revealed that the gold deposition took place at \sim 310 °C and at a depth of \sim 8 km. The ore-forming fluid was low salinity (\sim 6.2 wt% NaCl equiv) H₂O-NaCl-CO₂±N2±CH₄. The assemblage 1 fluid inclusions contained daughter minerals

consisting of nahcolite, magnesite, and arsenolamprite.



Figure Microphotographs of 1: assemblage 1 fluid inclusions from the Bétaré-Oya gold deposit. (a) Type 1 fluid inclusions displaying two phases composed of liquid carbon dioxide (Lco2) and aqueous (L_{H2O}) fluids, with some showing magnesite daughter mineral (s); (b) carbon dioxide rich fluid inclusions coexisting with type 1 fluid inclusions.

New developments of the software package *FLUIDS*: the programs *PURES* and *LonerAP*

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Keywords: thermodynamic calculations, software

Several new programs have been developed in the long series of the package *FLUIDS* (Bakker, 2003) to analyse pure fluids (PURES) and fluid H₂O-CO₂-CH₄-NaCI-KCI mixtures of (LonerAP) in pore spaces and fluid inclusions. The main objective of this work is to make highly complicated equations of state accessible to the community of fluid inclusionists, and to minimize the "black box" effect. This software is a refreshment of the programs originally designed in 2003, with additional issues and a better user interface (more flexibility), which also better control the allows а on mathematical procedures. The use of highly complicated equations of state makes the design of oversimplified approximations of these equations unnecessary, that are often offered in literature. In other words there is no need for redundant simplification. It must be noted that there is a certain relationship between complexity of systems and accuracy of calculations.

Although fluid inclusions seldomly contain pure fluids, bulk fluid properties often include separate procedures for individual observed phases at room temperature. For example, the density of the CO₂-rich vapour phase in a H₂O-NaCl-rich liquid phase can be obtained from the use of an equation of state for pure CO_2 , assuming that the extreme low concentrations of NaCl and H₂O do significantly affect pure CO₂ not properties. The program PURES contain fluid components that are occasionally observed in fluid inclusions (H₂O, CO₂, CH4, N2, C2H6, O2, NH3, CO, H2, D2O, Ar, C₃H₈, SO₂, H₂S and He) using Helmholtz Similar energy functions. fluid components are offered in the NIST website and the software GERG, but not

adapted for specific fluid inclusion work. In contrast, the program *PURES* is freeware without any commercial intentions (the open-access principle of science).

The program LonerAP calculates fluid properties in multicomponent mixtures including H₂O, gases (CO₂ and CH₄), and salts (NaCl and KCl), which is commonly observed in fluid inclusions. A complete analysis of a fluid system above 300 °C offered, including calculations of is critical points, spinodal, and binodal (dew-point curves and bubble-point curves). Isochores and $iso-T_h$ lines can be calculated in a homogenous fluid field and within an immiscibility field. A varietv of special thermodynamic properties, such the as double intersection of an isochore with the dewpoint curve, and spinodal conditions within the homogeneous fluid field can be visualized with this program. The benefits and drawbacks of the used equation of state can be carefully scrutinized comparison by to experimental data.

Programs can be downloaded at https://fluids.unileoben.ac.at or at https://rohmin.unileoben.ac.at/download s

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PySILLS, a newly developed Python-based open source tool for a modern data reduction of LA-ICP-MS experiments

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Keywords: LA-ICP-MS, mineral composition, fluid inclusion

Laser ablation – inductively coupled plasma – mass spectrometry (LA-ICP-MS) is a sensitive, efficient and costeffective method for analyzing the major, minor and trace element compositions of minerals as well as of fluid and melt inclusions.

Due to the high spatial resolution, low detection limits and multi-element capabilities of the LA-ICP-MS technique, it is ideally suited for rapid in situ chemical analysis of geological materials with minimal sample preparation requirements. Because of the wide use of LA-ICP-MS in geosciences, material sciences and life sciences, there is a considerable need for modern data reductions tools that combine an intuitive and efficient workflow, a comprehensive statistical analysis and the strengths of open source software development.

The new LA-ICP-MS data analysis tool PySILLS is completely written in Python, a popular, high-level and generalpurpose programming language. A key design concept of PySILLS is to keep the code simple, in order to make the development of plugins, for example novel quantification methods for the analysis of fluid or melt inclusions, and additional features as user-friendly as possible. Another key concept is to keep the workflow and the possible settings efficient, flexible and intuitive. PySILLS was initially developed in the context of a M.Sc. thesis project and has been brought to the level that the widely used SILLS (Guillong et al., 2008) tool offers and features already an increasing improvements. range of important Further extensions, for example the of implementation user-developed

plugins such as a fluid inclusion quantification method that combines LA-ICP-MS and microthermometric data with thermodynamic modeling, also developed at our institute, are available and provide PySILLS with modern, unique and state-of-the-art analysis methods. PySILLS is free and runs on current operation systems of Windows, Macintosh and Linux.

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Keyword list:

LA-ICP-MS, mineral composition, major elements, minor elements, trace elements, fluid inclusion, melt inclusion, data reduction, open source, Python, element compositions, experimental data, statistical method, SILLS, mineralogy, hydrothermal fluids



Microcapillaries for the calibration of heating-cooling stages and Raman microspectrometers

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Keywords: fluid-phase equilibria, experiments, new frontiers

Microthermometry and Raman spectroscopy, the most popular techniques to study fluid inclusions, require the use of external independent standard for calibration: calibration of the heating-cooling stage in temperature and of the spectrometer in wavelength. As transparent micro-samples containing gas, liquid and/or solids of various composition and pressure, microcapillaries open up a wide range of possibilities to quickly creating samples that resemble fluid inclusions: fluidphase equilibrium state and phase transitions can be observed in Fused Silica Capillary Capsules (FSCC) by any microscope equipped by standard transmitted light (Chou, 2012). The measurement of composition and density by Raman spectroscopy is also possible.



Fig. 1: preparation of an FSCC: sealing the tube containing frozen gas.

The FRAnCIs method (Fluid: Raman Analysis of the Composition of Inclusions) aims to determine the composition and density of $CO_2-CH_4-N_2$ gas mixtures by Raman spectroscopy within a large $PX\rho$ range (Le et al., 2021, 2020, 2019). It can be used by any laboratory on any Raman spectrometer,

provided that the apparatus is calibrated in wavelength with a low-pressure standard of CO_2 or CH_4 (*Fig. 1*). GeoRessources lab provides on-demand FSCC standards along with FRAnCIs software for calculations.

FSCC with well-known composition can also be used as temperature standard for calibrating heating-cooling stages for microthermometry. Melting of organic compounds (carboxylic acid, fatty acid) wide range offer а of possible temperatures as closely approaching the expected temperature of various phase transitions in fluid inclusions (Table 1). A distinct phase transition and a high reproducibility of the temperature measurements are the key parameters to select the most appropriate compounds.

Compound	Melting temperature		
octane	−56.85 °C		
decane	-29.80 °C		
heptanoic acid	-10.50 °C		
lauric acid	43.90 °C		
palmitic acid	62.51 °C		
benzoic acid	122.0 °C		
citric acid	154.0 °C		

Table 1: Melting temperature of a selection of organic compounds.

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Improvement of in situ LA-ICP-MS U-Pb Dating for Carbonate minerals and Its Application in Petroleum Geology

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Keywords: Carbonate minerals, U-Pb geochronology, LA-SF-ICP-MS.

In situ carbonate U-Pb dating is gaining popularity, and it has great potential for application in petroleum geology. However, the low U content (< 10 μ g/g) and high common Pb content of carbonate minerals, along with the uneven distribution of U and Pb and the lack of matrix-matched reference material make carbonate U-Pb dating inaccurate and less successful, limiting widespread application the in geosciences. This study evaluated the limitations of in situ carbonate U-Pb dating and proposed a method to rationally determine the laser ablation parameters of samples by improving the experimental approach based on the LA-SF-ICP-MS instrumentation. By setting a different spot size and ablation frequency for the reference material and unknown samples in the same session based on the U content of the sample, the ablation craters of the reference material and unknown samples were given the same depth/width ratio, avoiding systematic offset caused by differences in down-hole element fractionation and saving the valuable reference material. Depending on the characteristics of carbonate minerals with low U and Pb contents and heterogeneity, the grid screening method and setting ablation spots while screening were used to quickly eliminate domains with high U and low common Pb, effectively improving the efficiency of setting laser spots and the success rate of dating, as well as reducing the experimental time and economic cost. The accuracy and success rate of carbonate U-Pb dating were effectively improved by improving the experimental method, and the technique was applied to two examples that were difficult to date by traditional methods, namely the saddle dolomite with low U and high common Pb contents in the central Sichuan Basin and the calcite cement with low U and high common Pb in the sandstone reservoir of the Cretaceous Qingshuihe Formation on the southern margin of the Junggar Basin. The robust validation of ages has been obtained, which constrains the timing of the diagenetic and hydrocarbon accumulation process in the study area (*fig.1*).



Fig. 1 U-Pb dating results of hydrothermal saddle dolomite in Central Sichuan area, Sichuan Basin. (a) cathodoluminescence photo of well MX148, Z2dn2, 5606.35 m, bright red represents coarse crystalline saddle dolomite; (b) the corresponding U-Pb dating result map of the dolomite; (c) cathodoluminescence photo of well MX42, P2q, 4652.9 m, bright red represents crystalline saddle dolomite; and (d) the corresponding U-Pb dating result of the dolomite.

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Use of stratigraphic depth to estimate P and T of fluid inclusion trapping in hydrothermal environments: mean-density approach

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Keywords: hydrothermalism, geothermal energy, diagenesis

Fluid inclusions are a uniquely direct source of the density of fluids in the earth's crust, whether ancient or modern. Isochores constructed from the density of homogeneously trapped fluid inclusions have long been used to estimate the fluid pressure and temperature at which the inclusions were trapped (P_{trap} , T_{trap}). This has proven to be extremely useful in understanding а wide variety of including hydrothermal processes, alteration and ore formation, geothermal activity, hydrocarbon migration, diagenesis, etc.

For fluid-permeable geological settings such as sedimentary basins, oceanic crust and devolatilizing shallow intrusions, the true instantaneous fluid pressure at the depth of inclusion trapping (z_{trap}) is normally a function of transient or steady-state hydraulic gradients in the overlying fluid-filled porous rock column:

$$P_{trap} = g \int_0^{z_{trap}} \rho \, dz \tag{1}$$

where *P* is in Pa, z_{trap} in m, *g* is the gravitational acceleration (9.8 m s⁻²), and ρ is fluid density (kg m⁻³).

In modern, active circulation systems, hydraulic gradients can be determined only by direct borehole observations, whereas for paleo-systems only numerical simulations can provide model estimates. In the absence of such information, fluid pressures are normally assumed to be hydrostatic.

One way to estimate the hydrostatic P_{trap} is to use stratigraphic constraints to estimate z_{trap} . Traditionally, this is done by calculating a cold hydrostatic pressure-depth gradient from the earth's surface or from the seafloor:

The intersection of this P_{trap} with the fluid inclusion isochore in a P-T diagram yields the model T_{trap} .

The present study provides a simple improvement to the traditional approach, which yields more accurate P_{trap} and T_{trap} estimates. Instead of using Eqn. (2), a mean gradient is calculated from the fluid density at the Earth's surface (or seafloor) and the density defined by the fluid inclusion isochore:

$$P_{\text{trap}} = g[(\rho_{\text{surface}} - \rho_{\text{isochore}})/2]z_{\text{trap}} \quad (3)$$

Elementary calculus shows that this mean density approach yields a closer approximation to the true P_{trap} in a transient or steady-state hydraulic regime. Then, as in the traditional approach, P_{trap} from Eqn. (3) can be intersected with the fluid inclusion isochore to obtain a more realistic estimate of T_{trap} .

This methodogical improvement requires no additional data beyond that collected in the traditional approach, and solution of Eqn. (3) is trivial. For inclusions trapped homogeneously at low temperature the improvement in accuracy is minimal, but as trapping temperatures increase, the aain becomes large and significant for petrologic geochemical, and hydrogeological applications of the final P_{trap} and T_{trap} estimates. Therefore, the proposed mean-density approach is recommended for *all* cases in which depth estimates in fluid-permeable settings are employed to constrain the temperature and fluid pressure during inclusion trapping.

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P_{trap} = g \cdot \rho_{surface} \cdot z_{trap} (2)
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Characterization of the mineralizing fluids and melts in alkalic porphyry systems - Mount Polley deposit, British Columbia

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Keywords: fluid inclusion, melt inclusion, ore deposits

Alkalic porphyries are Cu-Au high-grade deposits also known to host important PGE resources. In contrast to calc-alkalic porphyries, the information available on composition and the of fluids mineralizing processes responsible for alkalic porphyry systems is limited. Similarly, causative the plutons responsible for mineralization have not been identified in alkalic porphyry deposits.

In this context, the objectives of this research project are (1) to identify the likely source of the mineralizing fluids, and (2) to characterize the physicochemical properties of these fluids over the evolution of Mount Polley copper deposit, as representative of well mineralized alkalic porphyry systems.

Mount Polley is a silica-undersaturated alkalic porphyry located in the largest alkalic porphyry province known, in south central British Columbia. It is one of the shallowest deposits of this kind, such that the alkalic intrusive complex hosting the mineralization is well exposed on the surface. Mineralization in Mount Polley is Late Triassic age and occurs in a series of discrete Cu-Au (-Ag) ore zones related to hydrothermalbreccia bodies.

Unaltered intrusive and volcanic units peripheral to the system are exposed at the surface and commonly have melt inclusions in mafic phenocryst generations (Fig. 1). Melt inclusions occur mainly in secondary clusters and primary assemblages. Identified melt inclusions will be analyzed towards determining whether melts became water saturated. Fluid plus melt inclusion assemblages will be analyzed to

determine budget and partitioning of metals.

Fluid inclusions within the mineral deposit are preserved in apatite within extensively altered and mineralized zones. Fluid inclusions hosted in apatite are mostly secondary vapor-rich or liquid-rich, although polyphase (?) inclusions have also been observed. Intermediate-density and hypersaline fluid inclusions, which are common in calc-alkalic porphyry systems, have not been observed so far.

Samples through 200 meters of vertical exposure will be used to determine the changing properties of the fluid as it migrates through the rock. The final aim of this project is to contribute to the development of a representative geologic model for alkalic porphyry systems, which are important and still challenging exploration targets.



Fig. 1: Photomicrograph of a) melt inclusions in mafic phenocrysts and b) fluid inclusions in apatite from rocks of the Mount Polley district area.

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The effects of oxygen fugacity, temperature, and salinity on sulphur speciation in magmatic fluids and their implications for magma redox and ore genesis

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Keywords: fluid inclusion, experiments, ore deposits

The speciation of sulphur in magmatic fluids, exsolving from the silicate melt in ascending arc magmas, affects the climate and controls metal transport and precipitation in magmatic-hydrothermal ore-forming systems. To study the effect of oxygen fugacity (fO_2), temperature, and salinity on sulphur speciation, we first trapped sulphur-bearing aqueous fluids pre-equilibrated at controlled conditions as synthetic fluid redox inclusions (SFI, Fig. 1) in guartz. For this purpose, we used a prototype externally heated molybdenum-hafnium carbide vessel apparatus equipped with semipermeable hydrogen membrane simultaneously allowing for rapid quenching and flexible, precise, and accurate redox control [1]. The fluids contained 5 mol% S (added as H₂SO₄) and 0, 1, or 4 m NaCl or KCl and were trapped at P = 2 kbar, T = 750, 875, or 1000 °C, and up to eight different fO_2 at each temperature ranging from -1 to +2.5 log units relative to the Ni-NiO buffer. Following the synthesis, we reheated the SFI to their entrapment temperature in a microscope heating stage and analysed them by in situ Raman spectroscopy, employing two different laser excitations. During our heating experiments we observed several reactions, including sulphur comproportionation and the formation of sulphur radical species, underlining the unquenchable nature of sulphur speciation in magmatic fluids and the need for in situ measurements at elevated pressure and temperature. Our experimental design allowed for the quantification of different sulphurbearing aqueous species, including sulphide, SO₂ and sulphur radical

species, previously inaccessible at oxygen fugacity temperature and conditions. Our experiments showed that SO_2 and sulphide (H_2S and HS^-) are the dominant sulphur species in high-P-T fluids. Although sulphur radical ions are ubiquitous at high-P-T, these were only detected in minor amounts. An increase in temperature from 750 to 1000 °C shifts the H₂S to SO₂ transition to lower fO₂ by approximately 2 log units. Finally, our salinity series experiments show that the presence of alkali ions enhances the formation of sulphur radical species. Our findings have important implications for the redox evolution of magmas and the likelihood of associated ore formation.



Fig. 1: Photomicrographs of synthetic fluid inclusions trapped in quartz taken at 25 °C. L-liquid, S-solid sulphur, V-vapour. The presence of elemental sulphur as daughter mineral is due to the comproportionation of reduced and oxidized sulphur species upon quenching of the experiment.

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Triple-halogen (Cl-Br-I) LA-ICP-MS fluid inclusion microanalysis – a powerful fluid provenance tracer

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Keywords: fluid inclusion, ore deposits, hydrothermalism

The heavy halogens (Cl, Br, I) are exceptional tracers of fluid provenance due to their largely conservative behaviour during fluid-rock interaction. While bromine-chlorine ratios have long since been used as provenance tracers, mounting evidence suggests that processes such as evaporation and organic matter interaction result in similar Br/Cl signatures, significantly impacting the utility of Br/Cl ratios as a fluid source tracer in many crustal provides environments. Iodine an additional constraint that makes it possible to discern these convergent processes, but its low concentrations <10 (typically µg/g) in most hydrothermal fluids pose significant analytical challenges. Until recently, iodine analysis was restricted to bulk analytical techniques that cannot resolve sample-scale variations in fluid signatures. However, advances in LA-**ICP-MS** fluid inclusion halogen make microanalysis it possible to measure Cl-Br-I concentrations in individual fluid inclusions, providing novel opportunities for the study of hydrothermal ore systems with complex and protracted fluid histories.

We present an overview of triple-halogen systematics from а variety of hydrothermal settings (barren metamorphic, orogenic gold deposits, magmatic-hydrothermal Sn-W and rare metal deposits and unconformity-type base metal mineralization), focusing on their application in reconstructing fluid provenance and fluid-fluid interaction processes. In unconformity-type settings, mixing processes between halite dissolution brines and residual bittern brines can be resolved on the sample scale. In magmatic-hydrothermal Sn-W systems, CI-Br-I systematics provide a sensitive proxy for influx of external (e.g. meteoric, basinal or metamorphic) fluids. Halogen signatures in Phanerozoic metamorphic fluids form a continuous and narrow compositional array due to interaction with organic fluid source matter in the rocks, independent of metamorphic grade. Conversely, Archean metamorphic fluids from similarly organic matter-rich source possess unique lithologies halogen compositions, which are incompatible with more recent fluid source signatures halogen fractionation and known but rather reflect the mechanisms, fundamentally different biogenic halogen cycles of the early Earth.



Fig. 1: Overview of Br/Cl – I/Cl systematics in various crustal hydrothermal systems.



Connected Clusters of Cavities: Implications for the Reliability of Petrographically Primary Fluid Inclusions

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Keywords: fluid inclusion origin

Fluid inclusionists interpret inclusions as primary if there is petrographic evidence that vacuoles formed and fluids were entrapped because of crystal growth. However, are we sure that the fluids in such vacuoles were trapped at the same time the vacuoles formed, even after eliminating the possibility of thermal reequilibration and recrystallization? Or, is it possible that *some* petrographically primary vacuoles remain open to pore fluids, and entrap a later fluid through necking down after crystal growth? Here, we present evidence that: (1) some petrographically primary vacuoles are filled with later fluids; (2) intracrystalline micropores are common and can remain open to pore fluids; and (3) objectbased modelling results show that intracrystalline clusters of cavities have a high probability of connecting at a threshold abundance, size, and shape.

Oil-filled fluid inclusions are useful for illustrating that later fluids can fill primary vacuoles. Petrographic relationships indicate two mechanisms by which later fluids are trapped in One primary vacuoles. mechanism comprises cryptic microfractures that intersect primary vacuoles or dense arrays of connected vacuoles. Such inclusions appear primary, but their fluid postdates crystal growth (Fig. 1).

Another mechanism comprises dense arrays of connected primary vacuoles. Where they intersect surrounding pores, vacuoles are filled with pore fluid, and may neck down to trap late fluids. Evidence for such open networks of intracrystalline micropores is especially apparent in samples impregnated with blue epoxy. These show networks of intracrystalline micropores in calcite, dolomite, quartz and feldspar.

probability of a network The of intracrystalline micropores forming open clusters of connected cavities can be modelled using the object-based modelling and statistical approach of Eltom et al. (in press). A logistic rearession equation shows that abundance of cavities, shape, and size are important factors for connectivity.

Thus, fluid inclusionists may consider two new evaluations of reliability for primary inclusions: (1)Use our connectivity algorithm. Calculate the probability that vacuoles, of measured size, shape and abundance, were connected or not. This assesses if they may have been open to later fluids. (2) Measure microthermometric data from different areas of the same growth zone. The data should yield the same results if vacuoles are filled with primary fluids and yield variable results if some FIAs are filled with later fluids.



Fig. 1: Fluorescent fluid inclusions, of secondary origin in dolomite, occupying vacuoles distributed along primary growth zonation. (transmitted light and UV)

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The first geochemical and mineralogical characterisation of a prehistoric rock crystal mine in the Swiss Alps

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Keywords: fluid inclusions, new frontiers, hydrothermalism

Rock crystal (SiO₂) is among nature's most fascinating materials. In Switzerland, it is formed in alpine-type fissures by hydrothermal processes. Due to its physical properties, it has been a valuable resource throughout history.

Over the past decades, there has been increasing evidence for the use of rock crystal by prehistoric communities in mountainous environments. These include craft specialisation for the production of stone tools and longdistance exchange. Yet there are only a few known sites where the mineral was quarried in sustainable quantities.

One of them is situated near Eggishorn mountain in the Upper Valais (southwestern Switzerland) at an altitude of 2600 m above sea level. The archaeological finds and features date to the Early Mesolithic (almost 10.000 years ago) and a final stage of the Neolithic (3500-2200 BC).

The following talk presents the results of a petrographic characterisation of the material occurring at the investigated site. It provides a description of the fluid inclusions within the quartz crystals and an overview over the related mineral paragenesis.

This gives interesting new insights into the formation of the analysed fissure and allows comparing rock crystal artefacts found in other archaeological sites to this particular source. The results form the basis for further investigations concerning the circulation and distribution of the precious raw material in the past.



Fig. 1: Photomicrograph of fluid inclusions observed in a sample from the archaeological site Fiesch-Eggishorn (photograph: J. Mullis).

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Development and application of artificial intelligence in petroleum geology experiment technology: a case from fluid inclusion

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Keywords: Fluid inclusion, experiment technology, Artificial intelligence.

Fluid inclusions is useful in reflecting directly various fluid compositions and the formation conditions of temperature and pressure in the geological period. Due to the complex petrographic characteristics and small size of fluid inclusions, how to better observe and identify fluid inclusions and obtain the chemical physical and information contained in fluid inclusions has become an integral part of petroleum and gas exploration. At present, the method for measuring the homogenization temperature of gas-liquid inclusion inclusions is time-consuming and labourintensive, which sometimes generated a large error, especially when the size of gas-liquid inclusion is relatively small. Aiming at improve the accuracy and efficiency of microthememotry, an improved YOLOv5 (Jocher G. et al., 2020) neural network is applied to the gas-liquid inclusions identification and homogenization temperature measurement, and a kind of one stage real-time fluid inclusion identification system with high accuracy and fast identification speed is proposed.

In the structure of the improved YOLOv5 neural network, the primary features of the original images are used for data enhancement, combined with attention mechanism and multi-scales feature fusion, the ability of the backbone network to extract cross-channel semantic information is increased, and the high-level semantic information and low-level fine-grained information are fully integrated to improve the recognition effect of the identification efficiency of the model in small volume of gas-liquid inclusion identification. The experimental results show that the improved YOLOv5 network gas-liquid inclusion achieves high accuracy which is about 96.43% under the condition of limited samples, which is higher than the unimproved YOLOv5 network gasliquid inclusion. Therefore, the improved yolov5 neural network can meet the requirements of gas-liquid inclusion identification.

We have achieved the goal of guickly detecting the types of fluid inclusions in samples and determining the homogenization temperature, and applied it to carbonate reservoirs in Sichuan Basin, and achieved good results. The artificial intelligence and machine learning can greatly improve the efficiency and accuracy of experimental analysis in fluid inclusion analysis and machine experimental analysis and testing.



Fig. 1: Photomicrograph of fluid inclusions T_h identified by using the improved yolov5 neural network.

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Metastable phase equilibria in the ice II stability field. A Raman study of synthetic high-density water inclusions in quartz

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Keywords: water phase diagram, experiment, fluid inclusion

Microthermometric measurements of a synthetic high-density (984 kg/m^3) water inclusion in quartz revealed that only part of the super-cooled liquid water (L) transforms to solid ice Ih upon ice nucleation (L \rightarrow ice I_h + L). While ice nucleation occurs in the ice Ih stability field at -41 °C and 28 MPa the pressure increases instantaneously to 315 MPa into the ice II stability field. At this point, both phases, liquid water and ice Ih are metastable. The coexistence of these two phases was confirmed by Raman spectroscopy and could be traced down to -80 °C. The pressure along this lowtemperature metastable extension of the ice I_h melting curve was determined by means of the frequency shift of the ice Ih peak position using both the O-H stretching band around 3100 cm⁻¹ and the lattice translational band around 220 cm⁻¹. At -80 °C and 466 MPa the supercooled ice Ih melting curve encounters the homogeneous nucleation limit (T_H) liquid and the remaining water transformed either to metastable ice IV (ice I_h + $L \rightarrow$ ice I_h + ice IV) or occasionally to metastable ice III (ice Ih + L \rightarrow ice I_h + ice III). The nucleation of ice IV resulted in a pressure drop of MPa. Upon subsequent about 180 heating the pressure develops along a slightly negatively sloped ice Ih-ice IV equilibrium line terminating in a triple point at -32.7 °C and 273 MPa, where ice IV melts to liquid water (ice I_h + ice $IV \rightarrow ice I_h + L$). Hitherto existing experimental data of the ice IV melting

curve (ice IV \rightarrow L) were found to be in line with the observed ice I_h-ice IV-liquid triple point.

If, on the other hand, ice III nucleated at -80 °C (instead of ice IV) the associated pressure drop was about 260 MPa. The ice I_h-ice III-liquid triple point was determined at -22.0 °C and 207 MPa (ice I_h + ice III \rightarrow ice I_h + L), which is in agreement with previous experimental data.



Fig. 1: P-T phase diagram of water showing the stability fields of liquid water (L), and different ice polymorphs (I_h, II, III and V). Solid lines denote stable, dashed lines metastable equilibria. phase Tн denotes the homogeneous nuclation limit of ices. This study: Ice Ih melting curve (red), ice Ih-ice IV coexistence curve (orange) and the approximate trend of the I_h-ice III equilibrium line in purple.

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Hydrous nano-silicate melt inclusions revealed by transmission electron microscopy, Persani Mountains Volcanic Field

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Keywords: metasomatism, melt inclusion, mantle

A volume of the Earth's mantle is fluid-mediated affected by mantle metasomatism during which continuous and micronanoscale fluid-solid interactions occur. Although similar reactions are assumed during both type of fluid-solid interaction, it is not clear what type of fluid is present during the reaction. Therefore, we conducted transmission electron microscopy (TEM) studies on amphibole lamellae and nanosilicate melt inclusions in an amphibolebearing mantle xenolith from the Persani Mountains Volcanic Field, southeastern Transylvania (Romania).

Based on petrography, the amphibole lamellae formed as a result of postentrapment reaction between the host clinopyroxene and the trapped CO₂-rich fluid in the micron-scale fluid inclusion. After amphibole formation, fluid escape occurred along the clinopyroxeneamphibole interface leading to the formation of nano-silicate melt inclusions that were mapped by TEM. The inclusions consist of ~80 vol% silicate glass and ~ 20 vol% bubble. The silicate glass has high SiO₂ (>60 wt.%) and Al₂O₃ (>20 wt.%) and low CaO, FeO and MgO (sum <8 wt.%). We used Monte Carlo simulation to calculate the original bulk composition of the nano-silicate melt inclusions by using hydrated fluid complexes. Based on the results, the

nano-silicate melt inclusions originally had a low SiO₂ (~43.6 wt.%) and high Al₂O₃ (~15.5 wt.%), Na₂O (~11.9 wt.%) and H₂O (~30.3 wt.%) content.

The composition of the studied nanosilicate melt inclusion suggests that significant compositional change occurs during nano-scale fluid formation from the parent CO₂-rich fluid. This change is owed to the surface free bond and molecule interaction. Therefore, our results suggest the nanoscale hydrous mineral precipitation and growth takes place along mineral interfaces as a result of fluid fractionation. Furthermore, we propose that fluid metasomatism in the lithospheric mantle (e.g., H₂O, Na, Al consumption during amphibole formation) can continue at nanoscale after a metasomatic event. Eventually, our results also provide information about the interactions of H₂O globally in the lithospheric mantle where hydrous minerals are stable and along the lithosphere-asthenosphere boundary in younger oceanic and continental plates.

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Quantifying Fluid Inclusion Data: A General Framework Integrating Microthermometry, LA-ICP-MS Analysis, and Thermodynamic Modelling

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Keywords: fluid inclusion, fluid-phase equilibria, thermodynamic calculations

The development of LA-ICP-MS and other microanalytical techniques for in situ analysis of single fluid inclusions has enabled accurate quantification of fluid inclusions of varying complexity and from diverse geological environments such magmatic, sedimentary, as metamorphic and ore-forming systems. Conventional microthermometric quantification methods rely on binary or ternary systems to represent natural systems, which may be inaccurate for complex geofluids, especially when the fluids contain significant concentrations of four or more components. Another approach involves the use of a mass or charge balance approach, along with ionic ratios, which improves compatibility with complex natural geofluids. However, this approach is based on the equivalent concentration of NaCl or Cl derived from the NaCl-H₂O binary system, which can introduce systematic uncertainties in the concentrations of all elements.

A solution to overcome this issue is to calculate the thermodynamic equilibrium at the melting point of the last-melting solid phase (e.g., ice, hydrate, or salt). By incorporating constraints from both microthermometry and LA-ICP-MS, along with an accurate thermodynamic model (such as the Pitzer model) for modelling the properties of aqueous solutions, it is then possible quantify the to concentrations of different elements in fluid inclusions of high complexity. A general framework has been developed in Python for such modelling and data quantification, which does also include a procedure for calculation of the uncertainty propagation.

Comparison with experimental results, including solubility data and synthetic fluid inclusion data in the system Na-K-Li-Ca-Mg-Fe-Cl-SO₄, demonstrates that the model can effectively reproduce the composition of solutions over wide ranges of composition. Uncertainty analysis shows that the uncertainties propagated from other elements to Na, the internal standard commonly used for quantification of the LA-ICP-MS data, are not significant.



Modelling SiO₂ solubility over wide P-T conditions: advances and open problems

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Keywords: Fluid-phase equilibria, Thermodynamic calculations, New frontiers

Fluids in the Earth's crust and upper mantle constantly change chemically, physically, and catalyze different processes, such as mass transfer, with implications for large-scale geodynamics. Silica solubilization has profound implications for mass transfer wide over а range of geologic environments, from upper crustal levels down to the deepest portion of subducting slabs and at the hot base of large orogens. Here I investigate, by using electrolytic fluid thermodynamic modelling, the solubility and speciation of SiO₂ in H₂O at 100–1400 °C and 0–10 GPa, with a particular focus on the geothermal gradients typical in subduction collisional zones and orogens. I show how SiO₂ solubility strongly increases with temperature, reaching dissolved loads between 5 wt% and >70 wt%, within subducting slabs. Similarly, results indicate that fluids with dissolved SiO₂ ranging from 3 to 57 wt% along Barrovian and Buchan-type P-T gradients can be expected, questioning the long-standing assumption of the isochemical nature of regional metamorphism. Additionally, an assessment of the capability of novel thermodynamic modelling in reproducing solubility experiments allows establishing the reliability of such models in investigating solute-bearing fluids over a wide range of P-T A by-product of this conditions. investigation is the tracking of the source of mineralizing fluids responsible for widespread fluid inclusion-rich quartz veins back to the deeper and hotter roots of orogens where amphibolitic to granulitic-facies conditions are encountered.



GIS-based fluid inclusion petrography

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Fluid inclusion study is based on thorough and detailed petrography requiring mapping and classification of the single fluid inclusion, to be able to find it months or even years after it has been first observed. This is because the thick section used for fluid inclusion study is going, sooner or later analysed by some in-situ techniques (e.g., µ-Raman or LA-ICPMS) or broken into small pieces for microthermometric Traditionally, analyses. hand-made drawings and sketches have been used map fluid inclusions at to all magnifications, from 2.5x down to 100x. This is an invaluable step since it allows describing the distribution, shape and constituents of each fluid inclusion, reaching an understanding of the trapping and post-trapping processes that occurred to the analysed fluid inclusion assemblages that common photomicrograph cannot properly record. And this understanding is crucial for the correct interpretation of easily misleading fluid inclusion analyses.

Fluid inclusion petrography is particularly relevant while studying (complex) multiphase inclusions, including crystallized inclusions. melt Here, multiple solid phases might be present with fluid phases in varying proportions. These solid phases can be distinct minerals and/or multiple crystals of the same mineral. To retrieve meaningful information the nature on and composition of the originally trapped fluid, the distinction between daughter and step-daughter minerals, and their proportions, is fundamental. Such a scenario, although rare at shallower conditions, is a common occurrence in metamorphic high and ultra-high pressure and/or temperature environments, where trapped the

inclusions are, usually, small (ca. 3-15 μ m in diameter).

Carefully collected photomicrographs (at increasing magnifications) of single fluid inclusions combined with GIS software (Geographic Information Systems, i.e., a software that can manage huge amounts of spatially distributed data and large image-based information), like ArcGIS, allow building a high-resolution and high-magnification database of fluid inclusions at the thin/thick section level. This approach allows for data integration among optical, cathodoluminescence and BSE images, and X-ray elemental maps. Moreover, the use of GIS-based fluid inclusion mapping facilitates correlations between petrographical information (e.g., liquid/vapour ratio, habit and position of solid phases) and analytical data (e.g., microthermometric data, µ-Raman analyses), allowing to reconstruct the distribution of the fluid (e.g, iso-density inclusion physical curves) and chemical (volumes of daughter and/or step-daughter minerals) properties.

Such a combination provides a precise down to the single fluid inclusion correlation between microstructures and compositions of minerals and hosted fluid inclusions, accurately revealing the fluid-rock interactions that have occurred in the studied samples.



Metal transport in volcanic gases

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Keywords: volcanism, ore deposits, thermodynamic calculations

Despite our perception of gold as a shiny precious metal, a small amount of gold is actually transported by magmatic gases and emitted in the atmosphere at most volcanoes on Earth. This gaseous transport is made possible by the very volcanic nature of gases: hightemperature non-ideal water vaporgases, dominated mixture of also containing other major constituents such as sulfur, carbon dioxide and halogens. This combination allows for volatile transport of virtually all elements from the periodic table, through the formation of gaseous compounds between trace elements and major gas species.

However, the complexity of volcanic gases also makes them difficult to apprehend; little is known on the solubility and behavior of trace elements. Moreover, the gas composition varies from one volcano to another, while changes in pressure and temperature between occur gas exsolution from the magma and emission at the surface. Interactions between the gas phase and surrounding rocks and fluids can furthermore affect volcanic gases on their way to the surface.

In this work, we explore the transport processes controlling the abundance of trace elements in volcanic gases. We use major and trace element composition from fumarolic gases from Vulcano, Italy sampled over a 14-year period and during both background emissions and unrest. This data is used for thermochemical calculations using the HSC Chemistry software.

We explore the factors that affect metal transport in volcanic gases, such as 1) cooling of the gas from the exsolution temperature to the emission temperature at the surface, 2) pressure decrease from the depth of exsolution to atmospheric pressure, 3) composition of the gas and therefore ligand availability, 4) transport rate and its effect on mineral deposition from the gas.

Trace element transporting species



Fig. 1: Fig. 4: Role of major ligands in forming gaseous complexes with trace elements in gas rich and poor in HCl.



Raman 3D imaging of complex inclusions in amphibole-rich upper mantle xenoliths from the Styrian basin (NW Hungary)

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Keywords: fluid inclusion, melt inclusion, mantle

The Styrian Basin, situated in the transition zone between the Pannonian Basin and the Eastern Alps, is believed to have formed in supra-subduction The Plio-Pleistocene setting. alkali basalts sampled the subcontinental lithospheric mantle beneath the basin, bringing mantle xenoliths to the surface^{1,2}. This study focuses on modally metasomatized supra-subduction xenoliths as evidenced by the presence of amphibole. One xenolith contains both melt and fluid inclusions while the other contains only fluid inclusions. Our goal is to conduct a comparative study on secondary inclusions (1-30 µm) between two xenoliths using the Raman spectroscopy, SEM-EDS, FIB-SEM and EMPA. The fluid inclusions are irregular to negative crystal-shaped, whereas melt inclusions are glass-rich with rounded to negative crystal shapes.

We used 3D Raman imaging to 1) discover complex phase assemblages in fluid inclusions and 2) test the applicability of this novel technique.

Preliminary results show that the fluid is CO_2 -(0.71 g/cm³) and liquid H₂Odominated. The fluid is also associated with solid phases (i.e., sulfide, magnesite, sulfate, quartz, and glass). EMPA has shown that the SiO₂-content of glass in melt inclusions is 56-60 wt% with a trachyandesite composition. The estimated volatile content in this glass is max. 3 wt%.

Our pilot findings suggest that CO_2 -H₂O fluid (where H₂O content is high relative to mantle fluids) and SiO₂-rich coexisting melt could have been circulating in the

mantle above a subducted slab and could have played essential role in amphibole formation as well. Furthermore, 3D Raman imaging has proven to be a powerful tool to unravel complex phase assemblages in inclusions.



Fig. 1: Photomicrograph of fluid and melt inclusions in enstatite from the Styrian Basin (NW Hungary).

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Preliminary Study of melt inclusions of the Copahue volcano of the phreatomagmatic eruptions of 2000, 2012, and 2016, Andean Southern Volcanic Zone, Argentina-Chile

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Keywords: melt inclusion, Copahue volcano, Andean Southern Volcanic Zone (ASVZ).

The Copahue volcano is currently the most active volcanic system in Argentine and borders of Chile. Volatiles are the fundamental cause of the ascent, effervescence, expansion, and fragmentation of the magma and have been used to study a wide range of topics (Rose-Koga et al. 2021). To understand the content of pre-eruptive magmatic volatiles, the pyroclastic material was studied in the eruptive events of 2000, 2012 and 2016, which identifying allowed Melt Inclusion Assemblages (MIAs). The different MIAs identified by Cannatelli et al. (2016) are found in all mineral phases, mostly recrystallized with one or more bubbles and daughter oxide minerals. This indicates a mixing of two types of magmas that evolve at different depths. The material was described in thin sections, by looking at 3 eruptive events that ejected bomb of basaltic-andesite composition with phenocrysts of plagioclase, pyroxene, and olivine. As a preliminary result, the host minerals (olivines and pyroxenes) were selected and the MIAs differentiated into 4 types (Tab. 1) were identified: MIA rich glass (MIAg), MIA rich crystal (MIAc), MIA rich bubble (MIAb), MIA rich crystal and bubble (MIAcb). The heterogeneity of these MIAs could indicate different processes in the trapping conditions of these volatiles in the magma. At least 3 MIAs were identified for each eruptive event, indicating different phases of volatile content during the magma ascent. Preliminary observations show the existence of MIAg zonation in

pyroxenes, and also more incipiently in olivines. The next step will be working toward establishing a chronological scheme for the formation of these MIAs.

	Eruption 2000		Eruption 2012		Eruption 2016	
	Olivine	Pyroxene	Olivine	Pyroxene	Olivine	Pyroxene
Type of MAI	MIAc + MIAg + MIAcb	MIAc + MIAg + MIAcb + MIAb	MIAc + MIAg + MIAb	MIAc + MIAg + MIAcb	MIAg + MIAb	MIAc + MIAg + MIAb
Size (µm)	≤20	≤40	≤10	≤45	≤30	≤150
Rate MI/G	43%	10% y 24%	9%	10%	13%	8% y 17%
MAI texture of growing or zonation	-	yes	yes	-	-	insipient

Tab. 1: MIAs classification in the 2000, 2012 and 2016 eruptive events of the Copahue volcano. Melt Inclusion rich glass (MIAg), Melt Inclusion rich crystal (MIAc), Melt Inclusion assemblages rich bubble (MIAb), Melt Inclusion rich crystal and bubble (MIcb).

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Constraint solar nebula compositions and processes from melt inclusions in ordinary chondrites.

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Keyword: melt inclusion, fluid-phase equilibria, meteorites

As a result of numerous studies over the past centuries of understanding of the formation and evolution of the solar system. For the observation of these materials and very small at far distances. Astronomy and Astrophysics different instruments used and methodologies. In order to improve the interpretation of these data, it is necessary to develop techniques in laboratory, which analogous in measurements and hypothesis can be made in materials from space, such as meteorites.

The primary target of this project is to determine, through a combination of detailed chemical petrologic classification, mineral/textural observations and characterization of melt inclusions assemblages (MIAs) found mainly in olivine crystals present chondrules, in order to better in understand the composition of solid and gas components trapped before the closure of the system, to constraint solar nebula compositions and processes.

Melt inclusions observed in olivines from chondrites, several formation theories proposed. have been One model interprets that melt inclusions are formed through the trapping of parental melt from melted chondrules. Another model interprets that melt inclusions are remnants of a melt that was present when the olivines formed through vapor condensation (Varela et al., 2002). They have also been interpreted as evidence of impact melting (Harvey & Roedder, 1994).

Melt inclusions have been observed in minerals from five meteorites belonging to the repository of the Department of Geology at the University of Chile, corresponding to finds: "Catalina 11", "Catalina 15", "Catalina 18", "Catalina 27", and "Los Vientos 357". Most of the inclusions are primary and homogeneous with crystallization on the walls, although homogeneous inclusions with the presence of bubbles and/or crystals, as well as some irregularly shaped inclusions, were also observed.

The next part of this study is to analyse the melt inclusions using Raman spectroscopy to identify the composition of the melt, daughter crystals, and bubbles observed within the inclusions, and thus detect volatiles in them.



Fig. 1: Photomicrograph of melt inclusions in Olivine.

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Some considerations on the consequences of immiscibility in systems containing water, salts and molecular gases

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Keywords: fluid inclusion, fluid phase equilibria, thermodynamic calculations

Fluid phase separation is a common phenomenon in many hydrothermal environments and has numerous consequences for fluid-rock reactions. It is well known that saline hydrothermal fluids can undergo phase separation up to very high temperatures (T); gas-rich fluids can undergo phase separation up to very high (P); and fluids that contain both salts and gases can therefore undergo immiscibility over wide ranges of both *P* and *T* (Bowers and Helgeson, 1983a, b; Heinrich, 2007). When phase separation takes place, the equilibrium between two fluid phases imposes severe constraints on activities of H₂O and other components in both fluids, and hence on mineral equilibria involving aqueous species (Bowers and Helgeson 1983a; Heinrich, 2007).

Here, we explore theoretically some additional consequences of how immiscibility proceeds during progressive cooling or decompression of fluids that contain water, salts and gases. This work was prompted in part by the general observation that watersalt-gas fluids commonly seem to differ from simpler water-salt fluids in terms of how immiscibility manifests in the fluid inclusion record. Fluids of the type those water-salt (like common to porphyry Cu deposits, for example) commonly show evidence of immiscibility in the form of bimodal assemblages of brine inclusions coexisting with vapor rich inclusions, wherein each latter type broadly consistent shows phase proportions. In contrast, in systems that contain significant concentrations of all three components, more commonly we find chaotic assemblages of inclusions

showing wide ranges of phase proportions.

Using thermodynamic calculations that expand on the work of Li et al. (2020), we show quantitatively how progressive phase separation of water-salt-gas fluids is likely to yield an array compositions and densities. We discuss how this is a natural consequence of high thermodynamic variance and mutual aversion between salts and gases. The key factor is the fact that, unlike watersalt systems where compositions of immiscible fluids are constrained by P and T alone, in the case of water-saltgas fluids the compositions of immiscible pairs also strictly depend on bulk composition. As a result, in systems undergoing phase separation, domains of even slightly different bulk compositions produce disparate immiscible pairs, leading to a cascade of compositions and densities as phase separation proceeds. We discuss how can this process explain both of inconsistent fluid observations inclusion assemblages, and local-scale variability in metamorphic and metasomatic mineral assemblages.

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Magmatic skarn formation: evidence from melt inclusions

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Keywords: melt inclusion, magmatism, metasomatism

Calc-silicate skarn deposits are virtually always interpreted to be hydrothermal in origin (Meinert et al., 2005). However, at the Chating porphyry deposit (China), we find evidence for the formation of "magmatic skarn" driven by carbonate assimilated by silicate magma in a shallow porphyry setting (Xu et al., 2023). In pods of endoskarn and associated veins from Chating, we find melt inclusions rich in sulfate and calcsilicate minerals (diopside + garnet + wollastonite + epidote, Fig. 1). These inclusions were remelted in heating experiments showing a variety of liquid immiscibility and often coexisting with chloride-rich salt melt inclusions and CO₂ vapor inclusions (Fig. 1 C). We argue that skarn at Chating was formed by fractional crystallization of an immiscible, calc-silicate-rich melt, and these melts were generated by the assimilation of limestones with interbedded gypsum evaporites, followed by coupled decarbonation and desilication. The coeval assemblages of anhydrous salt-melt inclusions found in Chating, as well as the occurrence of phases such as thenardite, celestine, apatite, and chondrodite in the calcsilicate-bearing melt inclusions (Fig.1 C, D), suggests that the skarn-forming melts were stabilized by a variety of fluxes including elevated Na⁺, Sr²⁺, Cl⁻, F^- , PO_4^{3-} and SO_4^{2-} . Meanwhile, the coeval vapor inclusions represent the products of decarbonation of the assimilated material and degassing of the CO₂ thus produced. Although some have noted that consumption of limestone by silicate magma is more likely in deeper, hotter settings in the midcrust (Gaeta et al., 2009; Chu et al., 2019), our results suggest the possibility

carbonate assimilation that and magmatic skarn present in the upper crust. We argue that at Chating-and probably other skarn deposits where part evaporites are of the host sedimentary package—assimilation of carbonate rocks and generation of calc-



silicate-rich melts was a key process of skarn formation.

Fig. 1: Petrography and phase assemblages of fluid and melt inclusions at Chating. Anhanhydrite, Qtz-quartz, Ccp-chalcopyrite, Pypyrte, Dio-diopside, Scp-scapolite, Aegaegirine, The-thenardite, Chn-chondrodite, Brt-barite, Cel-celestine.

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Keynote - Talk

Developments to increase the utility of silicate melt inclusions in understanding volatile element systematics in arc magmas

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Keywords: experiments, volcanism, ore deposits

Volatile systematics in magmas are typically reconstructed by using silicate melt inclusions (SMI) in minerals. SMI can be used to understand the degassing history of magma the during differentiation and fluid transfer between various parts of complex maama reservoirs. Current limitations are in the elements volatile choice of the concentration of which can be easily determined, as well as particularities of chemical behavior. Water their concentrations can be rapidly modified by post-entrapment diffusion through the host minerals, whereas most CO₂ is typically lost during very early stages of magma degassing. Chlorine will effectively degas at upper crustal pressures only from rhyolitic melts, whereas the interpretation of the concentration of S is complicated by its redox dependent fluid/melt partitioning and the potential saturation of magmatic sulfides and anhydrite.

We experimentally study the fluid/melt partitioning of S and rarely used volatile elements such as Br and I with the ultimate objective of the construction of models that accurately predict fluid/melt partition coefficients in pressure temperature - compositional space. In we experiments, these equilibrate silicate melts and fluids of various composition at relatively high fluid/melt mass ratios (0.3 - 1) to reduce the propagated errors on the mass balancecalculated equilibrium fluid compositions. Experiments using mafic to felsic calcalkaline and alkaline series melt compositions are conducted in rapidquench René 41 Molybdenumor Hafnium Carbide pressure vessels and a piston cylinder apparatus over the pressure range of 30 - 800 MPa. Partitioning models for S in oxidized and reduced form have already been

developed and reproduce experimental data with better than 25% absolute percentage error. The partitioning of Br and I has so far been studied in rhyolitic melts as a function of melt aluminosity, and fluid salinity. These pressure experiments used fluids with chloride being the main halogen species analogous to natural systems. The results show that Br and I partition into the fluid phase systematically about 3 times as strongly as Cl, and 5 respectively. Therefore Br/Cl and I/Cl ratios measured in SMI can be used to track magma degassing and fluid fluxing in intermediate and felsic systems. This includes the tracing of crystallizationinduced degassing, which plays a critical role in magmatic-hydrothermal ore genesis.

The determination of S, Br and I concentrations in bulk SMI is however rather challenging. We are developing Ablation Inductively Coupled Laser Plasma Mass Spectrometry (LA-ICP-MS) methodologies to analyze Cl, Br, I, S and Se at geologically relevant concentration because this technique levels, can sample the entire mass of the SMI including the shrinkage bubble. This the development involves of new standard reference materials and a specialized sample introduction system reduce gas blanks and memory to effects. Furthermore, MS/MS - reaction cell methodologies are being developed to improve S, and in particular Se analysis on our Agilent 8900 triplequadrupole ICP-MS. At present, we are already capable to analyze all the above elements in intermediate to large-sized SMI with good accuracy and useful while simultaneously precision, determining a full suite of conventional major and trace element concentration.



Session S2: Inclusions in magmatic and magmatichydrothermal environments



Poster

Study of fluid inclusions in the GLC-1 borehole of the Gale-Le-Koma geothermal field, Republic of Djibouti

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Keywords: fluid inclusion, hydrothermalism, geothermal energy

Witnessing magmatic and tectonic activities throughout its whole evolution, the Asal-Ghoubbet rift has been subject to geothermal exploration from the 1970s to today. In the present study, we will focus on one of the exploration areas: the Gale-Le-Koma geothermal field situated in the southern part of the rifting zone.

Previous studies in the area described two main geothermal reservoirs. An intermediate reservoir presents medium temperatures between 400 and 570 mMD. The targeted deep reservoir shows a maximum of 263.5°C at 1180 mMD.

The slim-hole well GLC-1 with a depth of 538 mMD was drilled in the Gale-Le-Koma field in 2016. The main purpose of the drilling was to study and evaluate the potential of the intermediate geothermal reservoir. During the exploration, a temperature of 130°C was measured from 450 to the bottom.

To constrain the characteristics of the fluids involved in the alteration processes, we used hand-picked secondary quartz from rock cuttings within 420 mMD and 508 mMD. This range was chosen due to the occurrence of loss zones and the high presence of hydrothermal quartz.

Two generations of fluid inclusions can be observed. The first one is characterized by vapour-rich inclusions, and this is the dominant inclusion type. They occur as clusters or individual inclusions sometimes following growth zones of hydrothermal quartz (Fig. 1). They are spherical or negative crystal shaped. They measure up to $30 \ \mu m$. Their presence could indicate that the quartz has formed in a vapourdominated reservoir.

Liquid-rich fluid inclusions ($\leq 20 \mu m$) are here described as the second generation. They have irregular shape and are mostly located along the healed fractures. Based on this observation, the liquid-rich inclusions formed later compared to the vapour-rich ones and may be representative of the current geothermal conditions within the studied intermediate reservoir. The difference between the primary vapour-rich inclusions and the secondary liquiddominated ones suggests a change in the physical properties of the geothermal fluid during the evolution of the geothermal field. This physicochemical change will be further explored through fluid inclusion microthermometry and Raman spectroscopy.



Fig. 1: Photomicrograph of fluid inclusions in Quartz (Qz) at 500 mMD in GLC-1. Liquidrich (L-rich) along healed fractures, Vapourrich (V-rich) around crystal growth zone

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Cooling of geothermal systems as recorded by fluid inclusions and chlorite geothermometry. The example of the Terre-de-Haut geothermal system (Les Saintes archipelago, Guadeloupe)

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Keywords: Hydrothermal alteration; fluid inclusion; chlorite thermometry; paleogeothermal system; Terre-de-Haut, Bouillante

The study of paleo-geothermal system is the key to improving our knowledge of actual geothermal systems, their evolution overtime as well as their lifetime. It is challenging because it requires to decipher the system history through numerous recorded episodes, from the thermal peak to the closure of the system.

The Terre-de-Haut island (Les Saintes archipelago, Lesser Antilles arc) presents a cross-section of an extinct geothermal reservoir which is quite accessible to allow the study of its cooling as well as the associated hydrothermal episodes.

The system functioning and cooling was associated with the development of chlorite as an alteration product and mineralized N70 trending fractures quartz crystals. containing euhedral Temperatures were estimated bv combinina chlorite geothermometry (Bourdelle et al., 2013) and a fluid inclusion study in zoned quartz crystals. Three different episodes during functioning and cooling of this system were identified: (i) in the quartz cores, primary inclusions give a temperature of 240-270°C, supposed at least to correspond of the geothermal reservoir functioning, (ii) chlorite formation at about 120°C, and (iii) in the outer growth zones of the guartz crystals, monophase inclusions indicate temperatures of ~50°C or less. These 2 last episodes are interpreted as corresponding to the end of the geothermal activity. Fluid composition is

of low salinity (about 2 wt% NaCl), and is interpreted as the result of the mixing of meteoric and sea waters. Additionally, a second fluid inclusion type in a banded quartz vein indicates another episode of a CO₂-dominated fluid, with traces of H₂S, interpreted as resulting from gaswater immiscibility at low temperature. This study shows that some alteration episodes also occur at low temperature during the cooling of the geothermal system (Beauchamps, 2019; Beauchamps *et al.*, 2021).

Hence, the paleo-geothermal of Terre de Haut shows a hydrothermal alteration zonation, temperature informations and fluid composition that are similar and consistent with those of the Bouillante active geothermal system, which is located 35 km NW of Terre-de-Haut, on Basse-Terre.

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Carbonatite formation in continental settings via high pressure – high temperature liquid immiscibility

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Keywords: melt inclusion, volcanism, magmatism

The goal of this study (Berkesi et al. 2023) is to compare compositions of high temperature silicate-carbonatite known from melt immiscible melts, inclusions and experiments, to compositions of silica-undersaturated volcanic rocks from continental settings, in order to improve understanding of the formation of calcite carbonatite rocks worldwide. Melt inclusions in this study are abundant in perovskites crystals from magnetite-perovskite cumulates sampled at the Kerimasi volcano in the Melilitite melts are low in SiO₂ (29.4-33.5 wt%), moderate in MgO (4.0-5.9 wt%) but high in CaO (16.3-24.4 wt%), FeO^T (9.0−13.5 wt%), Na₂O (6.8−12.7 (1.8 - 3.2)wt%) and K₂O wt%). Coexisting carbonatite melts also show high CaO-content (28.4-39.0 wt%), along with moderate-to-high Na₂O (8.2-20.2 wt%) + K₂O (4.1-6.6 wt%) compositions (total alkalis ranges between 13.1 and 24.3 wt%). We compared the studied silicate melts in the inclusions with a global dataset of continental melilitite 146 and 640 nephelinite compositions (GEOROC database). We argue that the studied calcite-saturated melilitite melts formed in a continental rift setting and were able to exsolve carbonatite melts that crystallized voluminous calcite carbonatite rocks during their evolution. In contrast, magnesian melilitite and nephelinite volcanic rocks from

East African Rift System. The temperature of complete dissolution of daughter minerals in the melt inclusions and the high CO₂-content of the silicate melt (5.4–9.8 wt%) support early formation of the rock and entrapment of melts at high temperatures (~1100 °C) pressures (~1 GPa). Heatedand quenched melt inclusions indicate the presence of immiscible mafic-melilitite and Ca-Na-K-carbonatite melts together with a fluid phase at entrapment.

intracontinental settings are compositionally far away from any immiscibility field at feasible pressures and were only able to unmix carbonatite melts during late-stage evolution, leaving little opportunity for calcite crystallization. CaO- and alkali-rich, but extremely SiO₂-undersaturated melilitite melts play a key role in early silicatecarbonatite immiscibility, can only be pre-served in melt inclusions and cannot be represented by volcanic rocks. The parental melts of the studied melilititecarbonatite melts probably formed via low-degree partial melting of modally metasomatized continental lithosphere.

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Fluid inclusion characteristics in hydrothermal calcite and quartz from the Kızıldere geothermal field, SW Türkiye

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Keywords: fluid inclusion, hydrothermal-geothermal

Geothermal waters are widely used in Türkiye to generate power. In this study we have investigated the paleogeothermal system of the Kızıldere geothermal field, located to the east of the Büyük Menderes Graben, southwestern Türkiye.

Fluid inclusions in calcite and quartz from cracks/veins and void fillings, are two-phase liquid + vapor, vapor- and liquid-rich inclusions. The fluids have boiled and in some samples blade-like calcite has been replaced by silica which is a recognized boiling texture.

The very negative the eutectic temperature (Te) values are indicative of the hydrothermal fluids containing CaCl₂, and NaCl. The homogenization temperatures (T_h) of primary and secondary inclusions average 199 and ٥C calcites show higher 154 in temperature in the early stages and lower temperatures in later stage. Primary and secondary inclusions have different salinities, averaging 1.65 wt.% and 6.64wt.% NaCl respectively (Fig. 1). T_h of quartz-hosted inclusions, average 198 °C, with an average salinity of 4.29 wt.% NaCl is similar to the inclusions in calcite.

The fluid inclusion data are consistent with the current reservoir temperatures. The fluids would remain in the liquid field in under high pressure in deeper parts of the system. During ascent and on reaching shallower depths, through fault or fractures, they pass into the vapor field, boil, and increase the salinity of the remaining liquid. The main elements of individual fluid inclusions, analyzed by LA-ICPMS, are Na and K, with trace amounts of As and Li. Element compositions show positive correlations between Ca/Na, Mg/Na, Fe/Na, Sr/Na, and B/Na ratios indicating they are derived from a single source (marble, schist, gneiss). That Sr/Na and B/Na ratios show significant positive correlations with Ca/Na, Mg/Na and Fe/Na indicate that these ratios, elements are probably derived from the dissolution of clastic and carbonate host rocks.

The microthermometry data indicate the paleo-geothermal fluids had an average temperature of 180 °C, a pressure of 14 bars, and a density of 0.9 g/cm³. These were trapped at shallow depth (~200 m) and low pressure (maximum 50 bar) with boiling occurring at a depth of ~ 500 m.



Fig. 1: Homogenization temperature and salinity of fluid inclusions in calcite and quartz from the Kızıldere geothermal field.

The magma plumbing system of Large Igneous Provinces: Insights from melt inclusions

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Keywords: melt inclusions, X-ray microtomography, oxygen isotopes

The Central Atlantic Magmatic Province (CAMP, at about 201 Ma; Marzoli et al., 1999) and the Deccan Traps (DT, at about 66 Ma; Sprain et al., 2019) are among the most voluminous Large Igneous Provinces (LIPs), and their activity was synchronous with endand Triassic end-Cretaceous mass extinctions, respectively. Primary bubble-bearing melt inclusions within crystal clots from both CAMP and DT basaltic lava flows were investigated via a multi-analytical approach to gain insights into the transcrustal plumbing system of LIPs.

Confocal Raman microspectroscopy was employed to characterize the volatile content of bubbles in melt inclusions and to quantify their CO_2 concentration.

Synchrotron X-ray microtomography was used to reconstruct the morphology of crystal clots and melt inclusions in 3D (Fig. 1) and to determine the precise bubble/inclusion ratios of CO₂-rich melt inclusions, which are essential for estimating the original CO₂ concentration in the entrapped melts.

Electron microprobe (EMP) major element analyses and secondary ion mass spectrometry (SIMS) oxygen isotope analyses were additionally employed on the glass of melt inclusions and their host clinopyroxene to constrain the evolution of CAMP and DT magmas and to assess their volatile budget.

Overall, microstructural observations and geochemical data revealed the presence of a crystal mush within the magma plumbing system of the studied LIPs, and put tighter constraints on the origin of carbon and its transfer from the mantle to Earth's surface.



Fig. 1: 3D reconstruction by Synchrotron Xray microtomography of a single-bubble melt inclusion, consisting of glass (dark blue phase) and a bubble (light blue phase), in a CAMP rock sample from the Newark Basin (North America).

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CO₂ concentrations of fluid bubbles in melt inclusions from the 2021 and 2022 Fagradalsfjall eruptions, Iceland

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Keywords: melt inclusion, magmatism, volcanism

~6000 After years of magmatic quiescence, two fissure-fed volcanic eruptions occurred in 2021 and 2022 in the Fagradalsfjall volcanic system on Reykjanes Peninsula in southwest Iceland. Geochemical evidence indicates that these eruptions were sourced from Moho depths (Halldórsson et al. 2022), providing a window into the deep parts of the Fagradalsfjall plumbing system. Here we target bubble-bearing melt inclusions (MIs) hosted in 65 olivine and plagioclase macrocrysts, issued throughout the entire period of activity. We present preliminary data of MI and bubble volumes, reconstructed with 2D images, along with CO₂ concentrations contained in fluid bubbles. Between one and 12 bubbles are found within individual MIs erupted during the firefountaining phase of the eruption (April - May 2021), whereas MIs erupted during later stages contain between one and four bubbles. Among 178 fluid bubbles analysed in 78 MIs, 43% (n=77) do not show any peaks related to volatiles in their Raman spectra, thus these can be interpreted as true shrinkage bubbles. 57% of analysed bubbles contain pure CO₂ fluid, as their Raman spectra show Fermi diads at ~1285 cm⁻¹ and ~1388 cm⁻¹. When individual bubble volumes in multibubble MIs are added together, 94% of MIs are occupied by <10 vol% of bubbles (Fig. 1). Large bubbles (>10 vol% of MI volume) are exclusively found in samples from the firefountaining phase (Fig. 1). CO₂ densities, calculated using the universal densimeter for pure CO2 fluid inclusions (Le et al. 2021), range from 0.01 to 0.26 g/cm³, with no correlation with eruption dates. These densities correspond to total CO₂ in bubbles between 5 ppm and

3150 ppm. Saturation pressures based on fluid bubble CO₂ contents, calculated with VESIcal (Iacovino et al., 2020) using the MagmaSat model (Ghiorso and Gualda, 2015) and assuming a H₂O content of 0.2 wt% (Halldórsson et al., 2022), range between 0-4.6 kbar, with highest saturation pressures the indicating sub-Moho depths. This is ongoing work and CO₂ concentrations, and saturation pressures are minimum estimates, which will be integrated with volatile (H₂O, CO₂) analyses in the glass phase of MIs via SIMS.



Fig. 1: Plot showing vol% of bubble in MIs as a function of CO_2 in bubbles. Samples are coloured according to eruption month.

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Poster

Traces of metasomatism recorded by pervasive alteration of vein filling apatite from the Jolotca ore field of the Ditrău Alkaline Massif, Romania.

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Keywords: fluid inclusion, metasomatism, ore deposits

The Jolotca ore field of the Ditrău Massif in Alkaline the Eastern Carpathians hosts REE-containing ore mineralization which is a result of a complex post magmatic-hydrothermal including activity metasomatic overprinting (Hirtopanu 2019). Apatite is one of the most common phosphate minerals in Jolotca, and its detailed analysis can reveal the physical-chemical conditions of each metasomatic stages (Harlov and Förster 2003).

Cathodoluminescence (CL) and BSE images reveal four apatite crystallization phases. The oldest, tawn CL coloured phase can be found in cores of the grains, followed by a pale tawn CL coloured one. A yellow CL coloured phase appears along hairline cracks or as irregular patches, whilst the youngest phase with greenish yellow CL colour appears as an overgrowth. The two older apatite phases are more REE- and Narich, while the younger phases are nearly Na-free with very low REE content, but contain more Ca than the older ones.

Two fluid types are observed in all apatite phases, an $H_2O-NaCl\pm(CO_2)$ (1) and an $H_2O-NaCl-CaCl_2\pm(CO_2)$ (2). In the volatile containing type 1 fluid, a CO₂-poor (2-4 mol%) (Fig. 1/a) and a CO₂-rich type (10-20 mol%) (Fig. 1/b) are observable, while only a CO₂-poor in the case of fluid 2. The salinity gradually increases ($\sim < 10$ to > 22 mass% NaCl_{eq}.) from the older to the younger phases. The Ca content of the fluid increases abruptly in the younger phases; moreover, fluid type 2 is present as primary FIs in the younger apatites and only as secondary in the older ones. $T_{\rm h}$ tot (LV \rightarrow L) values are in the ~200-260 °C range in volatile free and CO₂-poor, while ~320-380 °C in CO₂-rich FIs in all FIA.



Fig. 1: a) volatile-free aqueous fluid inclusion and b) CO_2 -rich aqueous fluid inclusion in apatite of the Jolotca REE-rich ore veins.

The vein-filling bulk apatite preserves traces of at least 4 consecutive metasomatic stages. The salinity and Ca/Na ratio of the fluids increased steadily, while the CO₂ content changed pulse-like during each metasomatic infiltration. T_h -X(fluid) data suggest metasomatic fluid mixing in a rockdominated vein network, where excess CO₂ is occasionally added to the system.

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Invited Talk

The Iceland Deep Drilling Project – overview 2000-2023

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Keywords: New frontiers, Supercritical hydrothermal, IDDP

An overview of the Iceland Deep Drilling Project (IDDP), from onset to date, is presented. The IDDP was first announced at the WGC-2000 in Japan⁽¹⁾, as an opportunity for international collaboration in joining in drilling and research into supercritical geothermal systems for their economic potential. The project has been funded by the Icelandic Geothermal Industry, supported by Statoil (Equinor), ICDP, US-NSF and EU-Horizon 2020 grant to DEEPEGS. An IDDP Feasibility Report was completed in 2003⁽²⁾, selecting in a priority order, several drill sites within three different drill fields, targeted for 4-5 km deep drillholes for supercritical targets. These three high-T fields are within the Reykjanes-, the Hengill- and the Krafla volcanic systems (see Fig.1).

The 1st deep well was attempted at Reykjanes in 2005, but lost during an intermediate flow test at 3 km depth. The 1st proper deep well (IDDP-1) was then drilled in Krafla during 2008-2009. Unexpectedly, this well hit molten rock, 900°C hot magma, at only 2.1 km depth⁽³⁾. The well was flow tested with a rewarding success, for 2 years during 2010-2012, creating a magma driven EGS system, potentially enabling a new era in power production at Krafla.



Fig. 1: Map of Iceland with location of Reykjanes, Hengill and Krafla geothermal sites

The 2nd deep well, IDDP-2, was then drilled to 4.659 m slant depth in the Reykjanes high-T field in $2016-2017^{(4,5)}$, an on-land analogue to the world ocean floor black smokers. The deep reservoir is permeable, and at supercritical condition, close to 600°C hot at pressures ~340 bar^(6,7), meeting the set IDDP target.

The 3d IDDP well is expected to be drilled within the Hengill volcanic system during this decade. Estimated total cost for the entire IDDP project is about 100 MUSD.

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S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Poster

Composition of olivine, plagioclase and clinopyroxene hosted melt inclusions from the Fagradalsfjall 2021-2022 eruption, Iceland

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Keywords: melt inclusion, mantle

Petrological and geochemical data from the 2021 Fagradalsfjall eruption in the Reykjanes Peninsula reveal that these lavas were sourced from deep (near-MOHO) regions (Halldórsson et al. 2022).

То better understand the source characteristics and mixing parameters of this compositionally rapidly changing single eruption, we present here major element data from glassy melt inclusions hosted in olivine (MIs) (n=376),plagioclase (n=425) and clinopyroxene (n=97) from lava and tephra samples throughout the duration of the 2021-2022 Fagradalsfjall eruption and Laser Ablation ICP-MS data from the early dates of the 2021 eruption.

The K₂O/TiO₂ ratios vary between 0 and 0.83 and this large variation is present regardless of collection date. This variation suggests that melts derived from compositionally different sources were present before the onset of crystallisation. Olivine hosted MIs show the largest variation in K_2O/TiO_2 at 88.2-86.4 olivine forsterite content. The K_2O/TiO_2 variation decreases with evolvina host mineral composition, possibly indicating concurrent mixing and crystallisation.

Trace element analysis from March-April 2021 show La/Sm=0.16-3.20, Sm/Yb=0.53-1.98 and La/Yb=0.32-3.50 (Fig. 1). These ratios vary in groundmass glass 2.03-3.10, 1.02-1.37 and 2.10-4.22, respectively (Halldórsson et al. 2022). The MIs entrap a depleted source composition not seen in the carrier melts but include the enriched component similar to the groundmass, as well as different trends in Sm/Yb vs. La/Sm values that lie outside the groundmass/whole rock values (Fig.1). All in all, these incompatible element ratios demonstrate that the Fagradalsfjall eruption was compiled from compositionally varying sources.



Fig. 1: Melt inclusion Sm/Yb vs. La/Sm. Groundmass and whole rock composition (Halldórsson et al. 2022) for comparison.

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Keynote - Talk

Halogens in silicate melt inclusions: Opportunities and challenges

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Keywords: melt inclusion, magmatism, mantle

Halogens are incompatible and fluidmobile elements, and are concentrated in serpentinized altered oceanic lithosphere. Deeply subducted residues return F, Cl, Br and I to the mantle, although the sizes of these fluxes are at present poorly constrained (Barnes et al., 2010). Nevertheless, halogens are therefore potentially excellent tracers of recycled subducted lithologies in the Earth's mantle.

To explore the utility of halogens as geochemical tracers of recycled subducted mantle lithologies, we have measured halogens and trace elements in olivine-hosted melt inclusions from Iceland and the Canary Islands. Melt inclusions from Iceland's neovolcanic zones typically contain up to 600 μ g/g F and 300 μ g/g Cl, with average F/Cl ratios of ~2.7-3.0. In contrast, melt inclusions from Iceland's off-axis flank zones contain up to 1100 μ g/g F and 700 μ g/g Cl, and those from the Canary Islands contain up to 1800 μ g/g F and 1200 μ g/g Cl; both these locations have low average F/Cl of \sim 1.4-2.0. These data suggest that high F and Cl contents coupled with low F/Cl may be a characteristic fingerprint of melts derived from recycled subducted mantle lithologies. Chlorine contents, and ratios of CI to similarly incompatible trace elements (e.g., Cl/K, Cl/Nb) coupled with lithophile trace element signatures may also help distinguish between seawateraltered versus carbonated oceanic crust recycled components in the mantle (Hanyu et al., 2019).

Determining Br and I contents in basaltic melt inclusions is analytically

challenging. Ion microprobe analyses indicate that Icelandic melt inclusions contain <2 μ g/g Br, but accurate measurement of lower concentrations is hampered by mass interferences on the ⁷⁹Br and ⁸¹Br peaks. Neutron-irradiated noble gas mass spectrometry (NI-NGMS) promising offers а alternative to measuring measuring ng/g-level Br and I contents in low-mass samples such as silicate melt inclusions. Based on published Br/Cl and I/Cl ratios for ocean islands (Kendrick et al., 2012), we can predict Br contents of ~150-1500 ng/g and I contents of ~3-30 ng/g in Icelandic melt inclusions. Accurate Br and I measurements in melt inclusions will present new opportunities to characterise the halogen inventories and signatures of diverse recycled mantle sources; to constrain lengthscales of halogen heterogeneity in the mantle; and to better constrain how and where halogens are fractionated from one another during subduction. Advances in micro-analytical techniques may also provide impetus for the development of multi-component C-H-O-S-halogen volatile solubility models, which are currently lacking.

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Temperature and salinity of the deep geothermal fluid in the Reykjanes geothermal field, Iceland based on fluid inclusions

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Keywords: fluid inclusion, hydrothermalism

Fluid inclusions are a strong geochemical tool, providing the ability to constrain the composition of fluids and thermobarometric conditions within geological systems. As direct sampling of fluid at depth and flow testing was limited due to partial collapse of the casing of the RN-15/IDDP-2 well, fluid inclusions represent one of the only insights into the temperature regime and fluid composition at depth.

Secondary fluid inclusions along healed fractures found in hydrothermal and magmatic quartz grains from ~3.1, 3.6 and 4.3 km depth in the RN-15/IDDP-2 well were studied using petrographic microscopy, Raman spectrometry and microthermometry.

At all depths, FIAs show signs of boiling/phase separation, they contain both vapour and brine/liquid-rich inclusions and display variable homogenization temperatures and salinities. FIAs at 4.3 km depth contain vapour-rich inclusions and brine inclusions with up to four different solid phases (halite, multiple hydrous Fe-K-Mn containing salts, opaque) and vapour bubbles. These brine inclusions homogenize at 430-460 °C, mostly by dissolution of halite. This suggests that (Liquid+Vapor+Halite) three phases coexist in the fluid at 4.3 km depth.

The secondary FIAs represent the most recent event recorded within the quartz grains. The recorded homogenization temperatures are, with the exception of those of a second fluid generation found in core 3 samples, very consistent, which confirms relatively stable conditions in the geothermal system over time. Furthermore, the derived temperatures fit well with pre-drill estimates and Horner estimates, confirming that the fluid inclusion

trapping temperatures represent the actual fluid temperature at depths (Figure 1, Friðleifsson et al., 2020). We find that the bottom of the convective cell of the Reykjanes geothermal system is located at between 3.1 and 3.5 km depth. Below this depth, temperature increases steeply towards the bottom of the well (Bali et al., 2020), suggesting lower permeability, conductive heat transfer and proximity to a heat source, i.e. an intrusion.



Fig. 1: Temperature observations vs depth in the RN-15/IDDP-2 well. The upper part of the Reykjanes geothermal system is dominated by convection, the bottom part (> 4000 mbs) part by conduction. Note that the shallow data is true depth, fluid inclusion data is borehole depth and that there are two generations of FIAs at 3600 mbs. The temperatures derived from fluid inclusion analysis are comparable with other temperature and models, estimates especially with the FT inversion and FT Horner estimates (Friðleifsson et al., 2020).

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S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Talk

Hibbingite [γ-Fe₂(OH)₃Cl] daughter mineral as a geochemical indicator of magmatic-hydrothermal processes

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Keywords: fluid inclusion, salt melt inclusion, oxygen fugacity

Ferrous hydroxychlorides occur in nature two polymorphs: orthorhombic in hibbingite, and recently described trigonal parahibbingite (Koděra et al., 2022). These minerals are difficult to identify due to their extreme sensitivity to oxidation and hydration in contact with air. However, we have provided their Raman spectra as a quick and reliable tool for their identification, particularly applicable in fluid inclusions. The Raman spectrum of hibbingite has a sharp strong peak at 3450 cm⁻¹ (affiliated to OH group in structure) and two moderate peaks at 199 and 385 cm⁻ 1

Applying the Raman spectroscopy, hibbingite was found to occur as a common daughter mineral hosted by brine fluid inclusions and by salt-melt inclusions associated mostly with granitic systems, especially related to Au-, Cu-Au- and Sn-porphyry and Fe-skarn deposits. Typically, this mineral has a green-yellow colour, high relief, and tabular habit (in salt-melt inclusions only). Based on microthermometry data, it crystallizes upon cooling from ~460 to <150°C.

In detail, we have studied hibbingite in salt-melt inclusions from the Auporphyry deposit Biely Vrch (Slovakia). Hibbingite was recognized here as the only phase that carries "water" (as a hydroxyl group) in otherwise H₂O-free salt-melt inclusions, which enables to exactly calculate the amount of H₂O that was originally dissolved in salt melts (1.6 to 3.0 wt%). The H₂O content is an important variable for the understanding of the accompanying magmatic-

hydrothermal processes, as these fluids with extremely high salinity are able to transport gold and some other metals very efficiently (Koděra *et al.*, 2014).

The presence of hibbingite in inclusions can be also used as a geochemical indicator of oxygen fugacity in a mineralforming fluid. According to Zubkova et al. (2019), crystallization of hibbingite is only possible under reducing conditions. This is confirmed by the assemblages of accompanying daughter minerals, where the absence of anhydrite or Fe(III) oxides indicates the reducing conditions in fluids. In brine inclusions, hibbingite is mostly attended by halite, sylvite, various K-Fe²⁺-Cl and Fe²⁺-Cl hydrates, and pyrosmalite-(Fe), while in salt-melt inclusions it is mostly accompanied by javorieite, chlorocalcite halite, and rinneite (Koděra et al., 2022).

In contrast, in the other studied Auporphyry deposit Lindero (Argentina), anhydrite is a common daughter mineral in salt-melt inclusions, but hibbingite is absent, which indicates the oxidized conditions of the parental fluid.

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Crystallized Melt Inclusions: an underutilized treasure trove

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Keywords: crystallized melt inclusion, µXRF, LA-ICPMS

Crystallized melt inclusions (CMIs) are very commonly preserved in minerals in intrusive to volcanic environments. In fact, melt inclusions (MI) preserved as glass or even devitrified glass are quite rare relatively. In fact, Bodnar and Student (2006) reminded us that Sorby noted these stone-cavities in his work, which others refer to as cMIs. Baker (2008) and others before him have noted the many syn- to post-formation processes that affect these inclusions, including the integrity of host phenocryst and the nature on the reactions causing crystallization of these trapped melt to quenched glass, including cooling and (or) depressurization of the phenocrysts. Optical and ChromaSEM-CL imaging of quartz and plagioclase phenocrysts helps evaluate the integrity of cMIs as well. There are obvious limitations with what we can do with cMIs, but still can yield fundamental information about the complex systems being studied that may not preserve other "ideal" melt inclusion features (e.g. Sirbescu and Nabelek, 2003). The differential quenching of these systems (P-T) cause variable degrees of MacLellan crystallization (see and Trembath, 1991), especially in the subvolcanic plutonic and even environment, although there seems to be features preserved in the phenocryst and even the crystalline inclusion that show their basic integrity is maintained, volatile except components. hydration Devitrification related to reactions have the potential to alter mobile components, but robust analysis can help discern the good, bad, and the ugly. SEM-EDS and µXRF-EDS analyses are quite robust (Spray and Rae, 1995; Flude et al., 2017), so can be used to evaluate the bulk composition and even do grainsize analysis а that is informative on the subsolidus crystallization features. Although there

are limitations with µXRF-EDS imaging based on the standard 20 µm spot size used for EDS mapping, there are huge advantages for integration time that enhances detection limits, precision, and accuracy of EDS analyses. Although polished thin sections can be used, polished thick sections (120µm) are ideal due to the excitation volume from a 20µm beam using the µXRF. For plagioclase- and guartz-hosted cMIs, 120µm is better as well for Laser Ablation ICP-MS (LA-ICPMS) to help maintain the integrity during spot ablation or mapping ablation. The normalization of LA-ICPMS data to SiO₂ and Al₂O₃ from integrated SEM-EDS or µXRF-EDS analysis is quite robust, so that the trace element suite of data can be integrated with the bulk majorelements.

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S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Talk

New views on Somma-Vesuvius shallow magma chamber system by fluid and melt inclusion studies.

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Keywords: Silicate-liquids immiscibility, hydrosaline melt, magma differentiation

The geochemical gradients observed in pyroclastic deposits of Plinian eruptions of Somma-Vesuvius volcanic system have been interpreted to reflect the progressive withdrawal of a chemically (and density) stratified magma chamber located at shallow depth beneath the volcano. To explain SV pre-eruptive chamber geochemical magma stratifications several processes have been hypothesized such as crystal-liquid fractionation by simple chemical differentiation of unique parental magma, by the arrival of diverse magma batches from deeper reservoirs or by magma withdrawal dynamics. New views are proposed to explain the Somma-Vesuvius pre-eruptive magma chamber stratification and geochemical the increase in explosivity during Plinian eruptions. It is based on fluid and melt inclusion studies, on compositional variations of eruptive products and on literature data (Gilg et al., 2001). Composite melt inclusions have been found for the first time in skarn bearing minerals that show two types of immiscibility between liquid phases at about 100 MPa: a new undocumented one presumably between two silicate liquids at about 1060°C and the second, already known, between silicate and hydrosaline melts at about 700°C. During long repose times, very differentiation by silicate liquid immiscibility led to the arrangement of magma in two layers, the bottom one formed grey pumices, the top one the white pumices. Explosiveness increases during ongoing Plinian eruptions would be caused by syn-eruptive formation of droplets of immiscible hydrosaline fluids

instantaneously occurring at about 700°C. Even if the proposed model needs to be corroborated by further and more current data, it has the merit of introducing a new vision and new ideas to improve both the knowledge of magmatic dynamics and eruption explosivity.



Fig. 1: A) Different type of inclusions in the same wollastonite crystal from skarn sample, at room temperature. CO2 fluid inclusion vapor rich; SMI = saline melt inclusion, CMI = composite melt inclusion. B) CMI cooling experiment. a) inclusion is not completely homogenized to avoid decrepitation and the bubble is still visible; b) two melt pockets start to grow separately; c and d) melt pockets increase in volume; e) at about 700 °C in a flash there is the formation of immiscible fluids; f) droplets converge in the different formed pockets/bubbles

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The role of volatiles in magma chamber dynamics: a case study from the 1932 eruption of Quizapu Volcano (Chile)

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belongs Quizapu volcano to the Descabezados Volcanic Group, which is part of the northern segment of the Andean Southern Volcanic Zone in Chile. The volcanic complex is characterized by "twin" eruptions of similar chemical composition (dacites and basaltic andesites) and erupted volumes of 5 km³.

We determined the pre-eruptive conditions and the triggering mechanism of the 1932 eruption by using Melt Inclusions (MIs) hosted in phenocrysts from tephra deposits. We collected tephra samples from the entire eruptive column, which included the initial (Initial Scoria - andesite), middle (Lower and Upper Dacite) and final stages (Final Scoria - andesite) of the eruption. Dacitic samples contain plagioclase, biotite, hornblende and pyroxene, with plagioclase compositions ranging from labradorite to oligoclase. Andesitic samples contain olivine (Fo₇₁₋₈₁), pyroxene and plagioclase with compositions ranging from labradorite to andesine. We selected homogeneous (± bubbles) olivine- and plagioclase-hosted MIs (Fig. 1) that were in equilibrium with the host crystal, providing certainty about the composition of the parental magma.

The average pre-eruptive temperature and pressure determined for the dacitic reservoir is $873 \pm 39^{\circ}$ C and 1.35 - 1.9kbar, respectively. These conditions were calculated considering equilibrium with the host mineral and CO₂ - H₂O vapor pressure curves. These values confirm the existence of a shallow dacitic reservoir as the source of the 1932 eruption.





We provide the direct first measurements of H₂O and CO₂ in the Quizapu products from the 1932 eruption by SIMS. H₂O concentrations range from 4.6 wt% for the dacite, 0.58 wt% for the Final Scoria, and up to 1 wt % for Initial Scoria. The average CO₂ concentrations range from 136 ppm for the dacite, 92 ppm for the Final Scoria, and up to 295 ppm for the Initial Scoria. CO₂ contents in bubble-bearing MIs could not be quantified by Raman Spectroscopy due to fluorescence of the samples, therefore our CO₂ contents should be considered to be minimum values.

One of the studied crystals had a H₂O content of up to 7.75 wt.%, which suggests there was either а heterogeneous distribution of volatiles in the magma chamber or mixing of a volatile-rich magma batch. Our results that the dacitic suaaest magma degassed as a closed system with little to no exsolved volatile phases.



S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Poster

Pilot Data from Fluids in Faults from above the Chilean Triple Junction show shallow flashing

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Keywords: flashing, neotectonic, Patagonia Chile

The Liquiñe-Ofqui fault zone (LOFZ) is located in Chilean Northern Patagonia and runs a length of ~1200 km from north to south and is coincident with the major Southern Volcanic Zone (SVC). Assessment of the geologic and geodynamic setting including the structural analysis focused primarily on geothermal targets in this investigation. Hydrothermal fluids in faults and fractures provide important insight into how the LOFZ operates because fluid pathways are critical for the productivity of geothermal reservoirs which are commonly controlled by structures. The LOFZ has many geological implications including geohazards (as a seismic source) to being a source for geothermal energy. Here we present the first time ever results of fluids that were a trapped in fluid inclusions in the LOFZ near the Chilean Triple Junction (CTJ).

Here we present a detailed petrographic study of fluid inclusion from within the fault core of the LOFZ Secondary vaporrich Fluid Inclusion Assemblages (FIAs) hosted in calcite indicating flashing of the fluid. Primary liquid-rich FIAs hosted in bladed calcite with homogenization temperatures (T_h) ranges from 190 to 200 °C. These observations suggest liquid fluids were from near lithostatic pressure and decompress passing to the vapor phase immediately "flashing". Gradually decrease in temperature to touch the liquid vapor curve producing bladed calcite. The Th indicates a minimum pressure of 12-15 bar (126-165 m depth), which perhaps formed during fault rupture. What this means is that the flashing occurred a shallow

depth which suggests a) there is perhaps a high geothermal gradient here as suggested from some geophysical studies, and b) that during fault ruptures that fluids rich in calcium migrate through and precipitate in the fault zone.



Fluid-mediated Rare Earth transport and mineralization in carbonatite systems

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Keywords: fluid inclusion, carbonatite, ore deposits

The rising demand for REEs (Rare Earth Elements) has sparked renewed interest in carbonatite systems, one of the main sources of REEs on Earth. In this study, we present data from REE-bearing fluids in carbonatite systems and a model for fluid mediated REE-transport and deposition leading to REE mineralization.

The studied secondary quartz-hosted fluid inclusions are from a metamorphic xenolith collected at the Oldoinyo Lengai volcano. Petrographic and geochemical data indicate an interaction of the preexisting metamorphic rock with both fluids and melts originated from Oldoinyo Lengai magmatism. At room temperature, multiple daughter phases (halite, sylvite, nahcolite, and REEbearing natritess) coexist with liquid and vapor CO₂ within the fluid inclusions. Raman-combined microthermometry showed that nahcolite dissociation occurs bellow 200 °C; natritess melts at approximately 400 °C. Homogenization of fluid inclusions happened above 600 °C, indicating minimum entrapment temperatures compatible with Oldoinyo Lengai magmatism. FIB-SEM-EDS serial sectioning technique and Raman imaging were used to created fluid inclusion 3D models (Fig. 1) and to calculate bulk fluid composition, showing an alkalicarbonate CO₂-rich H₂O-poor fluid composition.

Bulk compositions of fluid inclusions studied here are remarkably similar to fluids that coexist with carbonatite melts (Guzmics et al., 2019). In contrast, NaCl-H₂O fluids, commonly interpreted as early fluids in carbonatite systems (Walter et al., 2021), were never observed to coexist with melts in immiscible carbonate-silicate melt systems. Our results demonstrate that natrite_{ss} contains significant amounts of Sr, Ba and REE.

In this study we explore compositions analogous to fluids coexisting with immiscible carbonatite melts and present a model for fluid-mediated REE transport and mineralization.

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Fig. 1: Representative 3D model. pink – halite, red – sylvite, yellow – REE-rich natrite_{ss}, green – nahcolite; light blue - CO₂-vapor.

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Poster

Fluid inclusion analyses in granite intrusion cuttings from boreholes at Hoffell/Miðfell area in Geitafell Central volcano, Iceland

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Keywords: Fluid inclusion, fluid composition, felsic intrusion.

Geitafell is a fossil central volcano in the SE of Iceland, formed within a rift zone in central Iceland, active from 5 to 6 million years ago and considered now as low-temperature geothermal system. The low-temperature geothermal field has been explored in recent years in Hofell/Miðfell area within Geitafell. Five deep explorations/production wells have been drilled in Hoffell in 2012 and several gradient wells. Drill cuttings evidence the presence of a thick granite intrusion from 1000 to about 1590 m depth hosted by series of basaltic lavas and mafic intrusions. Litholoav characterization and reservoir evaluation has been held in this system; however, fluid processes related to this felsic intrusive have not been developed.

Granite cutting samples contain plagioclase, K-feldspars, and quartz (\approx 1 mm in length) with disseminated magnetite. Polished thick sections (200 μm and 300 µm) of subhedraltranslucent quartz grains were made from different depths (1290, 1500, 1718, 1730 m) in the well HF-5. The quartz grains contain different clusters and isolated fluid inclusions and fluid inclusion assemblages. Based on petrographic observations, the following main inclusion types were identified: a) Spherical to elongated vapor-rich inclusions (< 20 µm diameter), arranged as linear clusters parallel to the crystal margin and in crystal cracks; b) Spherical to elongated shaped liquid-rich inclusions (20 µm diameter). These inclusions may be found isolated or in clusters of a few inclusions; c) Subspherical to highly irregular shaped

liquid rich inclusions containing a small gas of bubble (< 20 μ m elongated axis) along healed crystal fractures (Figure) and d) Negative crystal shaped three-phase (liquid-vapor-solid) inclusions (10 μ m elongated axis). These inclusions are isolated and less common to be found.

Microthermometric and Raman analyses will be presented to define the homogenization temperature and composition of these fluid inclusions. As a result, we will better understand fluid processes in the in the vicinity of the felsic intrusions in Iceland, which is highly important to constraint the design of future boreholes (i.e., IDDP-3 borehole in Hengill area) and minimize drilling problems (i.e., molten rock intercepted during IDDP-1 in Krafla).



Fig. 1: Photomicrograph of a cluster of liquidrich fluid inclusions containing a bubble in Quartz from cutting samples of the well HF-5 at 1290 m depth in Hoffell-Geitafell area.



Fluid Inclusion Studies of Paramanahalli Gold Prospect, Chitradurga Greenstone Belt, Dharwar Craton, Peninsular India

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Gold mineralization at Paramanhalli in the Chitradurga Greenstone Belt of Dharwar Craton, Peninsular India is associated with altered metabasalt BIF. and quartz veins in Fluid inclusion studies involving inclusion petrography, micro thermometry, and Raman spectroscopy were carried out on four different types of veins such as quartz vein, quartzcarbonate vein, quartz tourmaline vein, and mineralized quartz vein in primary BIF. Three types of inclusions are prominent: type Iaaqueous inclusions (Fig.1a & 1b), Ib-carbonic monophase type inclusions (Fig.1c), and type Icaqueous carbonic inclusions (Fig.1d). Type Ia and Ib are more abundant and are commonly found to coexist in all types of veins. Inclusions of type Ic were observed only in guartz The veins. micro-thermometric of analyses different types of inclusions indicate homogenization temperature (Th) range from 116°C to 392°C (quartz vein), 138°C to 252°C (quartz-carbonate vein), 206°C to 340°C (quartz tourmaline 220°C to 362°C vein), and (mineralized quartz vein). The calculated salinity values (in terms of wt% NaCl eq.) vary from 2.05 to 23.05 (quartz veins), 1.41 to 11.93 (quartz-carbonate vein), 3.55 to

22.82 (quartz tourmaline vein) and 1.07 to 18.10 (mineralized quartz vein) respectively. The abundance of CO₂ and CO₂-H₂O inclusions indicates the metamorphic derivation of mineralizing fluids (Goldfarb and Groves, 2015). The fluid has lowmoderate salinity, a medium-high temperature of Th, and low density that are similar to other orogenic lodes gold deposits reported elsewhere in the world. This is confirmed by the Th-salinity plot of inclusions during this study.



Fig.1: a-d. Representative photomicrographs of (a) liquid-rich aqueous biphase, isolated (Type-1a), (b) liquid-rich aqueous biphase, clustered (Type-1a), (c) monophase inclusion (Type-1b), (d) CO₂-rich aqueous biphase inclusion, clustered (Type-1c).

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Peralkaline fluids and the formation of magmatic and hydrothermal Zr, Nb, and REE deposits

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Keywords: peralkaline fluids, ore deposits

magmatic Peralkaline rocks and carbonatites host the largest of the accumulations critical raw materials Nb and rare earth elements (REE) and the largest primary Zr deposits on Earth. The most common fluids include peralkaline silicate melts±H₂O and carbonate±hydrogen carbonate±H₂O melts and solutions (e.g., Nikolenko et al. 2022, Schmidt et al. 2023). Peralkaline silicate melts can transport high concentrations of Zr, Nb, and REE, which mainly depend on temperature, peralkalinity, H₂O content, and which early crystallized Zr, Nb, and/or REE mineral(s) are equilibrium with these melts (e.g., Schmidt et al., Alkali carbonate fluids 2023). can contain high concentrations of REE (Nikolenko et al. 2022), but their transport capacity for Nb and Zr is poorly constrained.

In a current study, we investigate the capacity of carbonate and hydrogen carbonate fluids for remobilization, transport, and further concentration of REE, Nb and Zr. In the first step, we determine the compositions of carbonate carbonate-bearing and hydrogen inclusions from carbonatites and alkaline ianeous rocks. As expected from literature reports, we observed nahcolite- and REE-carbonate-bearing aqueous inclusions in a metasomatised carbonatite (Fig. 1A). In addition, we found abundant hydrous Na₂CO₃ melt inclusions (Fig. 1B). In comparison, carbonates and hydrogen carbonates appear to be less abundant but not rare in inclusions from alkaline igneous rocks (Fig. 1C). Alkali-rich hydrous fluids are very mobile and reactive and can cause extensive high-temperature metasomatic alteration of country rocks, i.e. fenitisation, and may also be responsible for the remobilization of rare metals. Thus, we plan experiments to study phase equilibria in the system Na2O-NaCl-CO₂-H₂O±REE₂O₃ and of the solubility of key ore-forming minerals in carbonate-chloride-sulphate brines.



Fig. 1: A, B) Inclusions in quartz from Barra do Itapirapua, Brazil. A) Crossed polars, aqueous fluid inclusion (max. diameter 60 μ m) with CO₂-bearing vapour bubble and a nahcolite crystal. B) Hydrous Na₂CO₃-melt inclusions to about 60 μ m in size. C) Inclusion (max. diameter 42 μ m) in eudialyte from the Narssârssuk pegmatite, Igaliku, Greenland, 1 – vapour (CH₄, H₂, C₂H₆, other hydrocarbons, 2 – silicate glass? (no Raman signal detected), 3 – REE-rich apatite, 4 – unidentified carbonates, sulfates, and/or silicates. Based on Raman spectra, ancylite and gaylussite were tentatively identified in an inclusion in quartz in contact with the eudialyte crystal.

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Poster

Fluid phase separation and the dynamics of heat transfer in the deep-roots of magma-driven hydrothermal systems

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Keywords: geothermal energy, volcanism, hydrothermalism

Numerical simulation tools provide insight into fluid phase state distribution, boiling and condensation processes, and the dynamics of heat transfer in hydrothermal systems. This contribution highlights several recent studies (Scott et al., 2017; Scott and Driesner, 2018; Scott, 2020) investigating the thermohydraulic structure of hydrothermal systems driven by transiently cooling magmatic intrusions in the shallow crust.

dilute Hvdrothermal convection of meteoric fluids may lead to the development of zones of single-phase intermediate density ('supercritical') fluid near the intrusion, which are hotter and more extensive if the host rock has a intermediate permeability (10⁻¹⁵ m²) and high (>400 C) brittle-ductile transition temperature. The dynamics of fluid flow and heat transfer near intrusions are significantly altered in saline systems. The formation of hypersaline brines to nucleation and ascent of vapor bubbles out of liquid-like fluid near the intrusion reduces the effectiveness of advective heat transfer and leads to the potential for the clogging of pore space by halite precipitation. However, heat transport by advection of high-enthalpy vapor is maximized in saline systems driven by an intrusion deeper than ~4 km due to phase separation via condensation of a saline brine phase out of an intermediate-density vapor near the intrusion (Fig. 1).

As a result of the progressive cooling of the magmatic heat source, the thermal structure of the system changes throughout its lifetime. These numerical simulations inform conceptual models of hydrothermal systems and provide a virtual test bed to explore scenarios for supercritical resource exploitation.



Fig. 1: Phase diagram of the system H_2O -NaCl (Driesner and Heinrich, 2007) illustrating the effect of intrusion depth on the style of phase separation of an initial seawater-salinity fluid. The blue arrows represent a boiling upflow near a shallow intrusion following heating of liquid at ~20 MPa (~2 km depth). The red arrows represent condensation of a saline brine out of an intermediate-density vapor if fluid is heated at a higher pressure (~40 MPa, 4 km depth). Modified from Scott et al. (2017).

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Poster

Melt inclusion constraints on monogenetic eruptions: CO₂ density for Paricutin and El Astillero, Michoacán-Guanajuato Volcanic Field, Mexico

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Keywords: melt inclusion, volcanism, olivine.

Paricutin (1943-1952) and El Astillero (AD ~500-700) are two of the youngest monogenetic volcanoes in the Michoacán Guanajuato Volcanic Field in Mexico. Both eruptions started with an explosive phase producing Strombolian tephra deposits followed by an effusive phase emplacing lava flows. The eruptive sequence and the geochemistry of the products emitted from both volcanoes has been studied previously, but the preeruptive conditions are not fully constrained.

Tephra representing initial products (first days/weeks) from both volcanoes was collected and olivine crystals (300 µm -2 mm) were hand-picked for melt inclusion (MI) analysis to determine the pre-eruptive conditions. Under the Raman spectrometer, 8 olivine crystals with MIs were analyzed and, according to previous textural description and EMPA, to capture distinct MI assemblages (MIAs). Most samples displayed two distinguishable phases: glass and bubble.

A JY Horiba Labram 800 with a 520 nm laser wavelength and 1800 g/mm spectral resolution was used to obtain volatile content in bubbles from MIs. Spectra were collected from 100 to 2000 cm⁻¹ to study the CO_2 in the melt and the bubble.

According to identified MIs with vapor bubbles, the Raman spectra show, in general, two peaks at ~1285 and ~1388 cm⁻¹. These peaks are related to the distance between two Raman lines (collectively referred to as the Fermi diad), a value useful to obtain the CO₂ density. To calculate the CO₂ density preserved in bubble-MIs from El Astillero and Paricutin (0.225 \pm 0.015 and 0.221 \pm 0.015 g/cm³, respectively), the Fermi diad (Δ) splitting method and the equation proposed by Fall et al. (2011) representing the characteristics of the instrument were used.

Such values are consistent with the MI typologies observed in both volcanic centers (both primary zoned MIs with ~5 vol.% vapor bubble), confirming CO₂ presence and melt saturation.

The volatile contents (CO_2, H_2O, S) , together with major elements will be used to determine thermobarometric conditions (e.g., MI entrapment depth) in both eruptive centers.



Fig. 1: Photomicrograph of MIs (blue) in olivine from TANC-1830A, El Astillero.

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S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Poster

Unraveling Magma Compositional Zoning at Novarupta Volcano (Alaska, USA): A Silicate Melt Inclusion Study

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The 1912 Novaruta eruption was the largest eruption of the 20th century, ejecting 17 km³ of fallout and 13 km³ dense rock equivalent of magma. The eruption consisted of 5 main stages. The first stage consists of eruptive material of rhyolitic composition, followed by stage 2 and 3 with a mixture of dacitic and andesitic tephra. The final stages, 4 and 5 saw a succession of andesitic and rhyolitic domes.

Silicate Melt Inclusions (SMI) were studied in phenocrysts in thin sections and grain mounts belonging to the different stages of the eruption. Samples were examined using a petrographic microscope to inventory melt inclusion and textures present. Samples contain mostly glass, and to a lesser extent phenocrysts, comprising feldspars, quartz, pyroxenes, and olivine. Plagioclase exhibited sieve texture potentially resultant from magma mixing or volatile loss during magma ascent. SMIs were selected based on several criteria, such as size (diameter >30um due to minimum beam aperture for later microprobe analyses), glassy texture (for a high degree of compositional homogeneity within the inclusion), fractures (free of fracture that would cause leakage of volatiles). Abundant glassy inclusions were found, including several melt inclusion assemblages (Fig. 1) that run from core to rim of suitable for phenocrysts tracing magmatic evolution.

Recrystallized SMIs were rehomogenized by using the Linkam TXY1400 stage. success partial was achieved. Rehomogenized and glassy SMIs were examined using a SEM to look for recrystallization and microlites within the inclusion. Both groups of inclusions were selected for further study in order to compare if compositional differences exist indicating post entrapment modification. Samples were then examined at the Advanced Instrumentation Laboratory at University of Alaska Fairbanks using an electron microprobe to determine major element compositions for each inclusion. Further analysis will be conducted by Raman Spectroscopy and Ion Probe to quantify volatile contents and trace elements respectively.



Fig. 1: Photomicrograph of a melt inclusion assemblage hosted in a quartz crystal from the rhyolitic Novarupta dome. (Vlahovich, 2022)



Poster

Fluid inclusion features of a hematite-dominated, copper-gold mineralization at Qibaoshan, Shandong Province, China

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Keywords: fluid inclusion, ore deposits

The Qibaoshan polymetallic ore deposit hosts economically high-grade copper and gold, and contains a range of ironoxide and sulfide-bearing mineralization. The ore occurs mainly as cementations within the breccias, exhibiting vug-filling, vein-like stockworks and disseminated structures in the brecciated porphyritic quartz diorite and granodiorite. The mineralized veins are composed almost invariably of chlorite, coarse specular hematite, quartz and carbonates with subordinate pyrite and chalcopyrite. Passing inwards from the deep and peripheral parts towards the central ore zones, the intermediate- to felsic-host rocks mainly follow a sequence of hydrothermal alteration consisting of pervasive potassic and later acid alteration (chloritic and sericitic) events. The acid alteration is coeval with the first pulse of copper deposition and marked by the typical gangue mineral chlorite and quartz (Qz1); which is followed by the iron oxide stage with the deposition of specular hematite and euhedral quartz (Qz2); then the sulfide stage (2nd) with the formation of chalcopyrite and pyrite; and the last carbonate stage (i.e., calcite and siderite) in the vein center. Thus, based on these mineral assemblages, hydrothermal alteration, paragenesis of mineralization, we suggest that the deposit is akin to the iron oxide-coppergold family of deposits (e.g., Barton, 2014).

Within the Qz1, two types of coeval fluid inclusions were identified in one fluid assemblage (FIA). One is aqueous inclusions with inconsistent proportions of the vapor phase, mainly two-phase vapor-rich to monophase all-vapor inclusions. The other type is brine inclusions with an aqueous liquid phase, an assemblage of solid (daughter) phases and a vapor bubble (Fig. 1A). Under the IR light, the hematite-hosted FIAs are most commonly composed of opaque inclusions and two-phase (vapor +liquid) aqueous inclusions, and in some cases a solid phase could also be identified in some inclusions (Fig. 1B). Based on microthermometry, Qibaoshan shows evidence of at least two fluid and the earliest, pulses, highest temperature portion of each pulse contributed to the copper endowment. Mixing between the early magmaticderived, fluid metal bearing and meteoric water seems to have controlled progressive trend of cooling and а dilution, and are responsible for the ore deposition. Another metal-bearing fluid pulse is recorded by the abundant copper deposition stage, which seems to record a return of higher salinities and high temperatures during the third stage. This pulse too shows evidence of waning towards а lower salinity, moderate temperature fluid during the precipitation of late carbonates.



Fig. 1: Fluid inclusions in quartz (Qz1) and specular hematite from Qibaoshan ore deposit. L-liquid, V-vapor, H-halite.

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S2 – Inclusions in magmatic and magmatic-hydrothermal environments

Poster

Carbon Enrichment in the Lithospheric Mantle: Evidence from the Melt Inclusions from the Hainan Island Basalts, China

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Key words: Melt inclusions, Lithospheric mantle, Metasomatism

The Earth's mantle is the largest carbon reservoir, which contains approximately five orders of magnitude more carbon than the atmosphere-ocean system (Sleep and Zahnle, 2001; Coltice et al., 2004). However, the location of carbon storage in the Earth's interior and the mechanisms for carbon enrichment are unclear. In this work, we report CO₂-rich olivine-hosted melt inclusions in the mantle xenoliths of late Cenozoic basalts from the Penglai area, Hainan Island, China, which may shed some light on the carbon enrichment process in the lithospheric mantle. We also present a detailed petrological and geochemical investigation of the late Cenozoic basalts and mantle xenoliths from northern Hainan Island, China.

Melt inclusions in the olivine of mantle xenoliths include 1) CO₂ bubble-rich melt inclusions; 2) multiphase melt inclusions (glass+CO₂ bubble+ daughter minerals); 3) pure glass melt inclusions (Fig.1). Magnesite is as daughter minerals in the olivine-hosted melt inclusions, which could be interpreted as secondary mineral formed bv а interactions of CO₂-rich fluids with olivine host due to post-entrapment effects. Clinopyroxene (La/Yb)_N-Ti/Eu and clinopyroxene Ca/Al-Mg[#] diagrams indicate that the mantle peridotite experienced the metasomatism of both silicate and carbonate melts. The glasses in olivine-hosted melt inclusions have high SiO₂ contents (60.21–77.72wt%).

Our results suggest that a considerable amount of CO_2 -rich melt inclusions are captured in the lithospheric mantle during metasomatism. The lithospheric mantle can therefore act as is a 'carbon trap', with much CO_2 being absorbed by the lithospheric mantle in this way.



Fig. 1: Photomicrographs of melt inclusions in this study

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Melt inclusions record magmatic processes in the formation of iron oxide-apatite deposits

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Keywords: melt inclusion, magmatism, ore deposits

The genesis of iron oxide-apatite (IOA) deposits has long been controversial, with some arguing for hydrothermal origins and others arguing for magmatic origins (Hofstra, et al., 2016; Hou et al., 2018). We report the ubiquitous occurrence of high-temperature, polycrystalline melt inclusions in IOA deposits from around the world, revealing the previously underestimated role of magmatic processes in IOA mineralization. We studied thousands of inclusions from different IOA deposits based their petrographic on characteristics at room temperature, phase compositions identified by Raman spectroscopy and EDS-TEM, and phase changes during micro thermometry experiments. These polycrystalline inclusions show complex compositions of chlorides, sulfates, carbonates, silicates, calc-silicates, and metal sulfides and oxides. We summarized four main types of polycrystalline inclusions with endmember components (Fig. 1): (i) chloride (including melt inclusions svlvite, halite, hibbingite, etc.); (ii) sulfate melt inclusions (including anhydrite, cesanite, and barite, qypsum); (iii) calc-silicate melt inclusions (including diopside, wollastonite, garnet, and tremolite/ actinolite); and (iv) carbonate melt inclusions (including calcite, dolomite, natrite, and trona). Although we reported some examples of end-member type inclusions, most studied inclusions are transitional between different types, underscoring that all four types are represent intimately related and different flavors of a broader category of salt melts. Polycrystalline inclusions

across all studied deposits re-melt between 585 °C and 1200 °C, and thus represent high-temperature ionic liquids. These melt inclusions are widespread in all deposits studied, and seem to be a fundamental feature of IOA systems. Although the detailed characteristics, types, and distribution of inclusions vary different deposits, between taken together they suggest a key role of magma contamination and immiscibility. that Therefore, we argue these processes are central to the formation of



IOA deposits.

Fig. 1: Polycrystalline inclusions with endmember components from IOA deposits. Achloride melt inclusions; B- sulfate melt inclusions; C- calc-silicate melt inclusions; Dcarbonate melt inclusions; HI-halite, Hibhibbingite; Hem-hematite, Anh-anhydrite, Brt-barite, Ces-cesanite; Wo-wollastonite, Mag-magnetite, Cal-calcite.

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Session S3: Deep and metamorphic inclusions

Poster

Fate of fluid inclusions after ultrahigh-temperature metamorphism: case study from the Napier Complex, Antarctica

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Keywords: fluid inclusion, metamorphism

CO₂-rich fluid inclusions in granulites have been considered the strongest evidence for the crucial role of fluids high-grade metamorphism. durina However, their textural interpretation may be ambiguous (Lamb et al., 1987), consequently the reliability of those inclusions and their relationship to peak metamorphism are questionable. Recent studies indicate that fluid inclusions trapped at peak conditions re-equilibrate with their host during the retrograde path and therefore inclusions that have not undergone re-equilibration may contain fluids that are late-stage in origin (Carvalho et al., 2020). This is especially a problem in rocks with an isobaric-cooling (IBC) path, where highdensity CO2 inclusions can be easily trapped at post-peak metamorphic conditions.

The Napier Complex (Enderby Land, East Antarctica) is the type locality of ultrahigh temperature (UHT) granulites where peak conditions were 8-11 kbar and >1000 °C, and cooling occurred through an IBC path. Previous works have reported the presence only of monophase "very high-density pure CO2" fluid inclusions in this locality (Tsunogae et al., 2008). We revisited UHT rocks from the McIntire and Tonagh Islands, where the fluid inclusions have been reported. The investigated rocks are felsic and mafic granulites and gneisses. Irrespectively to their bulk compositions, contain all rock types numerous multiphase fluid inclusions (MFI) in various textural positions (Fig. 1). These negative crystal shaped inclusions, hosted in garnet, orthopyroxene, and sillimanite, sapphirine alwavs contain high-density CO₂ (up to 0.8-1.05

g/cm³), one or two carbonates (magnesite, ankerite or siderite) depending on the composition of the host and pyrophyllite.



Fig. 1: MFI clusters in garnet (A) and trail of elongated MFI in enstatite in a mafic UHT granulite from Tonagh Island.

Our observations show that, after entrapment, the fluid and host reacted causing both volumetric and chemical re-equilibration. Preliminary results indicate that these MFI could represent near-peak fluids, which contain higher amounts of H₂O (up to 10 mol.%) than the previously reported CO₂ inclusions from the Napier Complex. This work indicates that fluids trapped near UHT conditions may have more hydrous compositions than previously believed. This research was funded by PNRA 2018 (HOT ANTACTICA project, grant number PNRA18 00103 – A to Bruna В. Carvalho).

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Faden quartz textures and fluid inclusions as guides for understanding fracturing processes in geothermal settings

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Keywords: fluid inclusions, metamorphism, geothermal

Fracture-filling minerals formed during fracture opening may partially to fully occlude fractures and faults, enhancing or degrading the capability of fractures and faults to conduct fluids and heat. In many cases, mineral textures combined with fluid inclusions can be used to reconstruct the history of deformation and fluid geochemistry (Fall, 2021), both of which control the development and production of geothermal, hydrocarbon and water reservoirs, as well as the underground storage of CO₂, energy, (e.g., hydrogen), and waste (e.g., nuclear).

Quartz in low-grade metamorphic environments, such as Alpine-type quartz precipitated during active fracture growth (Mullis, 1975), may form rims or isolated deposits that locally bridge the fractures. Faden guartz (Richards, 1990) from the Zhob District in Balochistan, Pakistan (Fig. 1), is characterized by a milky, string-like core that is comprised of numerous, closely spaced subparallel microfractures -as revealed by SEM-CL imagingthat trapped textbook examples of aqueous fluid inclusion assemblages (FIAs) parallel to the fracture walls (Fig. 1).

Microthermometry indicates a narrow T and salinity range within FIAs in the central thread of 140-146°C and 3.5-5 wt% NaCl equiv. throughout the crystals. Inclusions trapped in late clear quartz overgrowths show similar results. Crush fast-scan mass spectrometry indicates the presence of up to $\sim 7 \text{ mol}\% \text{ CO}_2$ in the inclusions. The central thread comprising closely packed FIAs, the narrow T and salinity range, and quartz cement growth rate calculations indicate that Faden quartz growth was a rapid, porosity occluding process. Such rapid cement accumulations at ≥200°C are

potentially detrimental to subsurface fluid flow along active fractures that could be relevant for geothermal systems.



Fig. 1: Photomicrograph and SEM-CL image of Faden quartz, parallel FIAs and microfractures in Faden quartz from Zhob, Pakistan.

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Fluid inclusion study in anatectic metapelite xenoliths from the Tibetan Plateau (northern Karakorum, China)

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Keywords: metamorphism, fluid inclusion

The study of fluid and melt inclusions in peritectic minerals of deep crustal graphite-bearing metapelites that experienced partial melting (i.e., migmatites and granulites) allows to characterize the role of water and carbon durina crustal anatexis at the amphibolite-to-granulite facies transition. These hosting lithologies can reach the surface as large bodies, through slow tectonic processes, or as smaller xenoliths, through fast ascent in lava.

Here, we investigate the metamorphic evolution and the fluid-melt production, occurred in the upper part of the lower crust of the Tibetan plateau, through the characterization of anatectic graphitebearing metapelite xenoliths hosted in lamprophyric dykes of the Shaksgam valley, northern Karakorum (Xinjiang, China).

The anatectic graphite-bearing metapelites contain quartz, plagioclase, K-feldspar, and chemically homogeneous garnet. Rutile and graphite are common accessory minerals. Very rare biotite and kyanite relics occur in the garnet core, primary multiphase inclusions occur at the core-rim transition, and sillimanite needles occur at the garnet rim.

Fluid inclusion petrography, coupled with imaging, EDS analysis BSE and micro-Raman spectroscopy, indicates the presence of primary multiphase inclusions randomly distributed in garnet, at the core-rim transition. They are dark to light-coloured inclusions and are 5-50 µm in diameter. They show ellipsoidal-to-negative crystal shape and local evidence of decrepitation. The inclusions contain variable proportions of CO_2 , N_2 , Fe-carbonate, graphite, apatite, pyrophyllite, chlorite, biotite, quartz, and feldspars.

Microstructures, mineral assemblages and fluid inclusion study suggest metamorphic re-equilibration of the graphite-bearing metapelites at HP-HT conditions and subsequent partial melting and COHN fluid production through mica dehydration and graphite oxidation.



Carbon fluxes in the lithospheric mantle recorded by fluid and melt inclusions

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fluid inclusion, melt inclusion, geodynamics

The lithospheric mantle represents the mechanical barrier between convecting mantle and crust and, for this reason, records mass transfer and convective heat processes (i.e. metasomatism). Its ability to store and release carbon over variable timescales makes it essential for modelling the deep-Earth to surface carbon fluxes. In the lithosphere, including the cratonic lithosphere, carbon is present mainly as metasomatic carbonate and diamond. Geothermal gradients related to active tectonics control residence times in the lithosphere. Fluid and melt inclusions in peridotites and pyroxenites testify for carbon release, generating fluids and melt fluxes.

Data show that in the off-craton lithospheric mantle, both in oceanic and continental settings, the dominant fluid phases are CO2-rich \pm brines at depths below 70-80 km. Carbonic fluids might contain N2, SO2, and/or CO. Major solutes in aqueous fluids are chlorides, sulfates, silica phosphates (saline melts; > 50 wt.% NaCl eq.). At greater depths, alkali-carbonate-rich (silicate) melts are observed in peridotites.

These results indicate that carbon-rich fluids and melts play a substantial role in the global geochemical and petrological evolution of the lithospheric mantle. Saltbearing C-O-H fluids in peridotites equilibrated at depths < 80 km in intraplate and extensional geodynamic settings show broad compositional similarities with deeper carbonate-bearing melts/fluids generated at greater depths in the lithosphere. CO2 fluxes are generated from reacting metasomatic carbonate-rich melts rising from greater depths. Mantle-derived CO2 (±brines) may eventually reach crustal levels, including the atmosphere, resulting in massive carbon degassing independent from and in addition to magma degassing.

This contribution intends to celebrate the career of Csaba Szabò



Basement- and cover-hosted Giant Quartz Veins: a comparative fluid inclusion appraisal in the Eastern Pyrenees

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Keywords: fluid inclusion, hydrothermalism, giant quartz vein

Giant Quartz Veins (GQVs) are large structures, tens to hundreds of meters wide and up to several kilometres long, that are present worldwide in different tectonic settings. They form in zones of localized deformation in both lowerductile crustal and upper-crustal seismogenic domains, and are sometimes related to economically important ore deposits, such as orogenic gold. Moreover, GQVs are multi-scale fingerprints of the structural and geochemical evolution of their host rocks. However, the tectonic and geochemical controls leading to their formation, as well as their fluid sources and fluid flow mechanisms, are not well understood yet.

In the Pyrenees, hundreds of GQVs are hosted by Mesozoic sedimentary and (more often) pre-Mesozoic basement rocks. They commonly record cataclastic to ultramylonitic deformation, which have led to post-entrapment migration and dismemberment of those fluid inclusions associated with massive milky quartz masses. However, a late quartz growth stage, by which euhedral crystals fill open space, is often recorded in GQVs and shows well-preserved FIAs (Fig. 1).

Here we present a comparative fluid inclusion characterization of this last vein-forming stage from GQVs hosted by metamorphic and igneous basement rocks of the Canigó and Cap de Creus Massifs, and by sedimentary cover rocks of the Roc de Frausa Massif. Petrography, microthermometry, Raman spectroscopy, and LA-ICPMS microanalysis of single fluid inclusions а were carried out using novel Geographical Information System (GIS)based approach, by which a dynamic thin section map is generated.

Fluid inclusions from the three study areas are petrographically similar and mostly two-phase aqueous (80-90L and 20-10V). However, FIAs from different areas show significant variations regarding fluid systems, homogenization temperatures (Th), salinity, and chemical compositions. In the basement-hosted GQVs, H₂O-NaCl-CaCl₂ FIAs show Th and salinities respectively ranging from 190-250°C and 11-15% eq. NaCl in the Canigó Massif, and from 160-210°C and 16-20 % eq. NaCl in the Cap de Creus Massif. Contrary to this, Th of 220-240°C and salinities of 4-7% eq. NaCl were obtained for H₂O-NaCl FIAs in the coverhosted veins of the Roc de Frausa Massif. Elemental compositions, including those of the halogens, further show differences regarding the host rocks. These results indicate different sources and GQV formation fluid conditions for each of the study areas, which were probably influenced by the type and chemical composition of the host rocks involved in fluid-rock interactions leading to GQV formation.



Fig. 1: Focus-stacked photomicrograph of representative primary (P) and secondary (S) fluid inclusions from a Giant Quartz Vein in the Cap de Creus massif. Scale bar is 250 μ m.


Fluid evolution history during metamorphic P-T path of the Cabo Ortegal Complex, Spain: detailed fluid and mineral inclusion study

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Keywords: subduction fluid, metamorphism, elastic thermobarometry

Inclusions trapped in metamorphic rocks, originating from а fossil subduction zone, such as the Cabo Ortegal Complex (NW-Spain), serve as direct tools to characterize chemical composition, entrapment conditions and preservation of subduction fluids. Our study was carried out on fluid, multiphase fluid (MFI) and mineral inclusions trapped in garnet of various metamorphic rocks by means of complex analyses, including Raman spectroscopy, FIB-SEM, elastic and trace element thermobarometry and thermodynamic modelling (Spránitz et al., 2022, 2023). Primary MFI in eclogite and granulites represent C-O-H-N fluids originally dominated by H₂O and CO₂, during prograde-to-peak metamorphism. Elastic thermobarometry on quartz and zircon inclusions, coexisting with MFI, allowed us to estimate their entrapment P-T conditions during host garnet growth without any evidence of resetting. Intersection of the entrapment isomekes and Ti-in-quartz isoplets is at a pressure and temperature of 1.8 ± 0.2 GPa and 870 ± 70 °C, respectively. The result of the applied two independent approaches thermobarometry of showed qood agreement with each other. During postentrapment evolution of the MFI, the trapped fluid, has interacted with the host garnet, resulting in 1) the formation of carbonates and phyllosilicates; 2) the passive enrichment of nitrogen in the residual fluid observed in the studied MFI (N_2 content: 13–68 mol% in the observed MFI) and 3) enrichment of methane in MFI in eclogite (varying from 21 to 87 mol%). A specific horizon in shallow subduction-zone around 300-400 °C, within the stability field of pyrophyllite, can be marked as a nitrogen-enriched fluid regime. The release of these fluids likely contributes to the understanding of N₂-rich fluid composition during devolatilization in forearc regions of convergent margins. The results on secondary fluid inclusions record that the studied rocks have been involved in multistage fluid migration events with different chemistry during the retrograde path of its metamorphic evolution in a Variscan subduction channel. This contribution provides new constraints to understand the nature and evolution of subduction fluids with implications for nitrogen enrichment during retrograde processes in а subduction channel.

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Session S4: Inclusions in sedimentary environments



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Early Eocene Paleotemperature Record from Fluid Inclusions in Green River Basin Halites from Western North America

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Keywords: climate change, sedimentary basins, fluid-phase equilibria

The Green River Formation of Wyoming, Colorado, and Utah (USA) comprises an extensive deposit of sodium-carbonatebearing saline lacustrine evaporite facies, coincident with the Early Eocene Climatic Optimum (EECO) (52.6-50.3 Ma) (Zachos et al., 2001, 2008). This deposit offers a unique opportunity to study the pacing and magnitude of climate change in the EECO, a significant period of global warming in the Cenozoic. The evaporite facies of the Green River Formation contains a wealth of information about lake chemistry and local/regional climate at the time of including deposition, bottom-water paleotemperatures obtainable through fluid inclusion liquid-vapor homogenization (T_h) .

Primary bottom-grown halites act as a host to monophase liquid fluid-inclusions that, when undeformed, provide us with information about lake bottom-water temperatures at the time of entrapment. Bottom-water temperatures are strongly associated with mean annual air temperature in modern saline lake basins, and, when lake depths are greater than approximately 12 meters, bottom-water temperatures are stable year-round and approximately equal to mean annual air temperatures (Olson et al., 2023). Therefore, temperatures obtained from primary bottom-grown halites may be used as a proxy for mean annual air temperatures during the EECO.

Here we present preliminary T_h data from halite fluid inclusions of the Green River Formation. In order to measure liquid-vapor homogenization in these monophase liquid inclusions we employed single ultra-short laser pulses to stimulate vapour bubble nucleation, thus transferring the inclusions from a metastable liquid into a stable liquidvapour equilibrium state. The technique, also referred to as nucleation-assisted microthermometry (NAM), enables vapor bubble nucleation only few degrees thus, avoiding below Th, plastic deformation of the inclusion walls due to large tensile stress that occasionally spontaneous at triggers sub-zero temperatures. Additionally, replicable and selective measurements obtained by this method yield precise results with relatively low uncertainties.

Preliminary paleotemperatures from Green River Formation halites of the Piceance Creek Basin (Colorado, USA) indicate temperatures ranging from ~20 to 27°C.



Fig. 1: Photomicrograph of a two-phase fluid inclusion in halite after laser-induced bubble nucleation (Piceance Creek Basin, CO, USA).

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Characteristics and Significance of Fluid Inclusions in Deep Carbonate Reservoirs: A Case Study of Dengying Fm. in Penglai Area, Central Sichuan, China

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Keywords: Sichuan Basin; Ediacaran; Fluid inclusions

Deeply buried reservoir (DBR) has become the important target for oil and gas exploration at present in China. However, geofluids in depth have the characteristics of high temperature and high pressure, strong fluid interaction complex reservoir-forming and mechanism which restricts the further hydrocarbon exploration and development. Great gas field has been discovered in Ediacaran dolomite of Penglai area in Sichuan basin recently. In order to get better understanding of the hydrocarbon accumulation and formation mechanism, systematic observations of cores and thin sections in Pengtan area were carried out in this study.

The fluid inclusions of 28 samples of dolomite in Dengying 2 Formation of Sinian system from four wells in Penglai central Sichuan basin area, were analyzed in details by means of multifunctional optical microscope, cathodoluminescence microscope, and fluid inclusion microthermometry and Raman spectropic analysis.

The photomicrographs (Fig.1) and T_h frequency histogram show that part of fluid inclusions experienced in-situ reequilibration in deep carbonate reservoirs , which may be resulted from high temperature and high pressure in depth. Therefore, it is necessary to exclude such inclusions when we take into account the microthermometrical measurements. Multi-types fluid inclusions i.e. gas-liquid-solid inclusions, liquid-solid inclusions and single phase fluid inclusions have been discovered in Dengying2 Fm. The Raman spectrum analysis of gas+liquid fluid inclusions show that the main component is CH₄, with a small amount of CO₂ and H₂S. The gas-liquid-solid inclusions contain solid sulfur, bitumen and calcite minerals. The results of fluid inclusion analysis show that the temperature and pressure conditions of TSR reaction are ranged from 180°C to 230°C and the pressure range is over 120MPa.



Fig. 1: Photomicrographs showing the reequilibration phenomenon of fluid inclusions in Fluorite (Fl) from Penglai area, Sichuan basin China. N.S.: needle-shape pattern; Necking down phenomenon; D.H.: decrepitation haloes pattern.

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Stable isotope study on Middle Miocene evaporites from the eastern Transylvanian Basin, Romania

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Keywords: fluid inclusions, stable isotopes, evaporites

Detailed petrographic and geochemical study was carried out on Middle Miocene (Badenian) evaporite from the Praid (Transylvanian Basin) salt mine. The evaporite rock is tectonically reworked after it formed during the so-called Badenian Salinity Crisis. However, some primary textural features, such as chevron halite remnants, are still preserved. The stable O and H isotope composition of fluid inclusions (FI), hosted in the halite, can reveal the origin of the H₂O in the fluid (e.g., seawater or meteoric) (Rigaudier et al., 2011).

Precedina the stable isotopic measurements, petrographic careful observations were made on thin sections and non-soluble residue (anhydrite grains) of the Praid rock samples. microthermometry Furthermore, and cryogenic Raman spectroscopy were performed on primary FI (pFI) of halite grains to test their seawater origin.

The homogenization temperature of the pFI ranges between 10 and 34 °C. As a result of Raman spectroscopy, Na-, Caand Mg-hydrates have been identified within the pFI, in agreement with the observed low eutectic temperatures ($T_e = -52 - -43$ °C).

The stable isotopic composition of sulphate extracted from anhydrite grains exhibits a narrow range both in δ^{34} S (from +20.4 ‰ to +22.4 ‰) and in δ^{18} O (from +12.9 ‰ to +14.5 ‰). The inclusion-filling H₂O extracted from halite, gives a range from -17.9 ‰ to -

7.8 ‰ and from -91.5 ‰ to -74.2 ‰ for δ^{18} O and δ^{2} H, respectively. The isotopic characteristics of the anhydrite proved its seawater origin and fits to the "sulphate age curve" of Claypool et al. (1980). Regarding the highly negative δ^{18} O and δ^{2} H values of the halite FIs, several processes could be invoked to interplay during the evaporite rock formation, such as crystallization of other O and H-containing minerals prior to halite formation, bioactivity, and mixing of seawater with meteoric water (Fig. 1).



Fig. 1: Schematic map of presumed water input paths and isotopic mixing in the Middle Miocene Transylvanian Basin.

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Combining microthermometry and U-Pb dating to distinguish hydrothermal conditions from ambient burial temperature

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Keywords: new frontiers, hydrothermalism

It is necessary to recognize evidence of hydrothermal fluid flow in the sedimentary realm because it impacts every facet of the petroleum system from source rock reservoir. to Notwithstanding the economic import, hydrothermal fluid recognizing flow hinges on one's ability to show that the temperature of the fluid was significantly than the ambient higher burial temperature of the host rock (Machel and Lonnee, 2002).

The homogenization temperatures (Ths) in primary fluid inclusion assemblages within diagenetic minerals provide a temperature record at certain intervals of a rock's history. However, there is no straightforward way to know if those values record ambient burial temperature or hydrothermal conditions. That is because ambient temperature changes over time depending on the depth, geothermal gradient, and surface temperature. With these unknowns, the best that researchers can do to identify hydrothermal fluid flow is show that Ths are higher than the highest ambient burial temperature possible for the entire history of the rock (Smith, 2006).

A more broadly applicable approach is to (1) measure Ths of primary fluid inclusion assemblages, (2) constrain the of mineral precipitation timing by obtaining a U-Pb date with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), (3) constrain the depth of the host rock by selecting the depth range (from burial history) that is contemporaneous to the U-Pb date within uncertainty, (4) select a surface temperature, (5) select а geothermal gradient, (6) calculate the highest possible ambient burial temperature for the date, and (7) compare the geothermometric record to the calculated ambient burial temperature.

We illustrate the methodology with samples in the midcontinent USA's Anadarko Basin. The Ths of four primary fluid inclusion assemblages in a vugreducing calcite range from 113 to 115°C. The LA-ICP-MS U-Pb date of this calcite is 318 ± 18 Ma. The burial history before 300 Ma (318 minus 18 Ma) constrains the depth of the rock to no more than 1.45 km. The ambient burial temperature corresponding to this depth 56°C, calculated via a surface is temperature of 20°C and a geothermal gradient of 25°C/Km. The Th values are distinguished from ambient burial temperature by being at least 57°C higher, indicating hydrothermal fluid flow occurred at 318 \pm 18 Ma, relatively early in the rock's burial history (Figure 1).



Fig. 1: The host rock's burial and ambient temperature history with tie lines corresponding to the calcite's U-Pb date (318 \pm 18 Ma).

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Tropical land temperature record across Terminations V and IV derived from stalagmite fluid inclusions using nucleation-assisted microthermometry

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Keywords: stalagmite, paleoclimate, monophase fluid inclusions

Stalagmites are cave deposits that form by precipitation of calcite from drip They grow over long time water. periods, and their age can be accurately determined by U-Th chronology. Cave temperatures are commonly nearly constant throughout the year and closely reflect mean annual outside temperatures. All these aspects and the simple arowth aeometrv make stalagmites a valuable archive of past climate changes.

In the present study we used a 190 mm long stalagmite (WR5_B) from Northern Borneo that covers two glacial terminations (T-V and T-IV) to reconstruct a cave temperature record based on fluid inclusion homogenisation temperatures T_h .

Fluid inclusions in stalagmites are primary and contain relics of the former calcite-supplying drip water. The inclusions are typically monophase liquid and spontaneous nucleation of the vapour bubble fails to occur upon cooling due to long-lived metastability of the liquid state. In order to measure liquidvapour homogenisation temperatures in these inclusions, we used nucleationassisted microthermometry (Krüger et al., 2007), a technique that employs single ultra-short laser pulses to stimulate vapour bubble nucleation in metastable liquid inclusions, and thus, enabling sub-sequent measurements of T_h . The measured T_h values were then

corrected for surface tension effects (Marti *et al.*, 2012).

The cave temperature record we present is based on more than 2000 analysed fluid inclusions from 49 growth bands. T_h distributions within the individual growth bands typically have standard deviations (1SD) between 0.7 and 1.3 °C. The mean values of the T_h distributions are considered as the best approximation of the cave temperatures. Standard errors of the mean (2SE) range between 0.2 and 0.5 °C.

Our record from the tropical Western Pacific provides a detailed picture of glacial-interglacial land temperature variation and shows a tight correlation changes in atmospheric CO_2 with concentrations. The onset of deglacial warming was found to coincide with the beginning of pronounced drying events, a concurrence that has also been observed for the last glacial termination (Løland et al., 2022). Our data indicate a magnitude of glacial-interglacial temperature changes in Northern Borneo of 4.2 ± 0.5 °C from MIS 12 to MIS 11 and of 4.1 ± 0.5 °C across T-IV, after for correcting temperature effects related to sea level changes.

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Middle Eocene Paleoclimate recorded in halite deposits in Jianghan Basin, Central China

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Keywords: fluid inclusion; surface; climate change

The Eocene epoch (56–34 Ma) has been the warmest in the past 66 million years and is characterized by the abundance of salt-mudstone rhythms in the basins of eastern China. If these rhythms are studied properly, current climate global warming can be understood as well.

A salt core retrieved from a well (~39 Ma) in the Qianjiang Depression, Jianghan Basin, was crushed by a small hammer and further separated by an art knife. liquid-phase fluid inclusions (FI) were identified and photographed in chevron and cumulate halite crystals. Bubble nucleation process and other details were analyzed following Robert and Spencer (1995).

A total of 74 homogenization temperatures (T_h) in 20 fluid inclusion assemblages (FIA) were obtained. The distributing range of T_h within all FIAs falls below 15 °C and below 10 °C for 85%, and below 5°C for 30% of the entire dataset. In a second run, T_h values were 0.1–1.9 °C lower than what was measured in the first attempt.

The histogram of T_h (Fig. 1) exhibited two separate ranges: 12.1-29.9 °C and 36.2-47.2 °C, representing winter and summer temperature fluctuations, respectively. The results are significantly higher than what was obtained from plant assemblages reconstruction in the Jianghan Basin but were similar to the coeval sea surface temperatures in the northern Peri-Tethys and T_h results of the most previous halite studies from ancient deposits. Moreover, our

from temperatures halite were comparable to modern evaporative settings of Badwater Basin in Death Valley and temperatures calculated from $^{18}\delta O$ in mudstones and dolomites that are spatially related to our halite sample. The calculated temperatures when combined with carbon and oxygen isotopes suggested that water influx and evaporation capacity rather than elevated temperature controlled the slat deposition rate in the middle Eocene of Jianghan Basin, indicating the а monsoon climate was likely dominant in the middle Eocene epoch in the Jianghan Basin during halite and mudstone deposition.



Fig. 1: Histogram of homogenization temperatures obtained from originally liquid-phase inclusions in chevron and cumulate halite crystals.

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Keynote - Talk

Coupling FI analysis with isotopic analysis of fluids and minerals (e.g., U-Pb, Δ^{47}) to enhance P-T-t-x properties of petroleum reservoirs.

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Keywords: new frontiers, sedimentary basins, oil&gas.

The *P*-*T*-*t*-x properties of diagenetic fluids play a crucial role in developing accurate reservoir quality models across time and space. They also help to better assess paleothermicity, paleobarometry, and fluid circulation regimes within sedimentary basins, especially for the O&G temperature window. To achieve this, it becomes essential to couple petroleum and aqueous fluid inclusions analysis (PIT/AIT) with recent advancements in stable isotope geochemistry such as LA-ICPMS U-Pb dating of carbonate, carbonate clumped isotope geothermometry (Δ_{47}), methane clumped isotope analysis ($\Delta^{12}CH_2D_2$ and Δ^{13} CH₃D - IRMS), and δ^{18} O/ δ D analysis of aqueous inclusions. This approach comprehensive mav offers а understanding of the petroleum system's *P*-*T*-*t*-x evolution through time, and each tools's limits and advantages.

To demonstrate the power of this we've selected different approach, illustrative case studies where this coupling has been applied. First, we'll discuss a study from the Aquitaine basin (France - Lacq reservoirs) that employed clumped isotope geothermometry (Δ_{47}) and PIT/AIT analysis on the same set of samples to reconstruct the true paleopressures and paleotemperature of multiple conditions cementation events. Next, we'll discuss how U-Pb

dating, FI PIT/AIT, and clumped isotope analyse (on carbonate and methane) helped reveal both the diagenetic history of natural calcite fractures ("beefs") (Argentina) and their relationship to petroleum generation/migration history. We'll also introduce a proof-of-concept study on measuring CH₄ clumped isotope $(\Delta^{12}CH_2D_2 \text{ and } \Delta^{13}CH_3D)$ from methane inclusions in quartz and discuss how this geothermometer new can improve ultimate sources of petroleum migration in reservoirs. Finally, we'll present a few additional examples to illustrate how U-Pb dating of carbonate can assist inclusionist in better evaluating the timing of FI trapping in carbonate and better decipher the primary VS. secondary nature of FI assemblages in such "soft" host minerals.

Overall, the case studies presented in this abstract demonstrate the benefits of using these complementary techniques to provide valuable insights into the properties of diagenetic fluids and their evolution, contributing to a better understanding of the processes that control reservoir quality in sedimentary basins. It is an essential approach for the oil and gas industry and has the potential to lead to more efficient exploration practices in the future.

Microthermometry on fluid inclusions in stalagmites: what does the retrograde homogenisation tell us?

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Keywords: speleothems, thermodynamic calculations, fluid inclusion

Stalagmites contain fluid inclusions filled with remains of former calcite-supplying drip water entrapped during stalagmite growth. Assuming that these inclusions have not been affected by physical or chemical changes, they record the cave environment at the moment of their encapsulation. This allows investigating past climate changes in continental environments by fluid inclusion microthermometry in stalagmites.

Fluid inclusions in stalagmites generally are monophase liquid and spontaneous vapour bubble nucleation does not occur due to the long-lived metastability of the liquid state of water. However, it is possible to measure liquid-vapour homogenisation temperatures T_h by nucleation-assisted means of microthermometry (Krüger et al., 2007). This technique employs ultra-short laser pulses to induce bubble nucleation in the metastable liquid and, thus, enables for subsequent measurements on the homogenisation. The measured T_h values are then corrected for surface tension effects (Marti et al., 2012) to obtain the stalagmite formation temperature.

In addition to the prograde T_h upon heating, we also observe а corresponding retrograde homogenisation T_{hr} upon cooling owing to the density maximum of water. In an isochoric pure water system, the T_h - T_{hr} curve ends at 4.0 °C, where T_h equals *T_{hr}*. In pure water fluid inclusions, however, this endpoint is shifted to higher temperatures due to the thermal expansion of the host mineral (Marti et al., 2009).

Here we present preliminary data on the T_{h} - T_{hr} relationship derived from fluid inclusions in a stalagmite. The

stalagmite fabric is characterized by up to cm wide composite crystals that consist of numerous nearly iso-oriented columnar crystal units. The fluid inclusions are mostly inter-crystalline, tiahtlv sealed between adiacent columnar crystal units. *T*_h-*T*_{hr} data from these inclusions revealed significant scatter around the modelled *T*_h-*T*_{hr} curve that clearly exceeds analytical precision. Our current hypothesis is that tiny cracks related to the calcite cleavage system and/or the crystal boundaries between the columnar units may affect the resulting thermal volume change of the inclusions.

To test our hypothesis, we stretched some inclusions by inducing small cracks in the inclusion walls. This was done by means of pressure waves produced by small-scale laser ablation next to the inclusions using the femtosecond laser at higher pulse energies. Subsequent microthermometric measurements showed a systematic change of the T_h - T_{hr} relationship both with respect to the initial state of the inclusions and the model curve.

The background of this investigation is an attempt to identify potential processes that may explain the significant scatter of

T_h values observed in coeval stalagmite fluid inclusions.

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History of the fluids of the Lorraine Carboniferous sedimentary basin (France) from the past to the present

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Keywords: new frontiers, diagenesis, fluid inclusions

The Lorraine Carboniferous Basin is an ultra-deep sedimentary basin located on the border between France and Germany. Of Westphalian to Stephanian age, it is covered by the Mesozoic Paris basin. Work combining petrographic observations with analyses and modelling of fluid inclusions was confronted with hydro-geochemical data in boreholes. For this, an innovative probe (®SYSMOG) system for measuring dissolved gases, in-situ and continuously, was designed by the Solexperts company and the CNRS/University of Lorraine and deployed in the Folschviller stratigraphic borehole (Moselle-France) drilled in 2006 by FDE, and completed by a casing of 6 cm in internal diameter. At the same time, rock samples were taken from neighboring core drillings. The siliciclastic sediments show pores and fractures that are cemented by diagenetic minerals whose typical paragenetic sequence is marked by the temporal succession: siderite, ankerite, quartz, dickite, sphalerite and barite.

Microthermometric data on aqueous fluid inclusions from fracture systems show very saline fluids (20 wt% eq. NaCl) with homogenization temperatures around 100 to 140°C for ankerite, around 170°C for quartz and 105°C for sphalerite.

These fluids, in thermal imbalance with the surrounding rock, formed during the Albo-Cenomanian period marked by the opening of the North Atlantic Ocean. This hydrothermal circulation impacted the two superposed basins. The rising fluid is loaded with salt at the top of a hydrothermal loop and is responsible for the maturation of organic sediments and the genesis of liquid hydrocarbons. The fluid (a mixture of water and oil) dehydrates by precipitation of dickite. The asymmetrical histogram in Figure 1 can be understood as a marker of water content decrease with time.

Nowadays, the liquid hydrocarbons have disappeared from the fracture system, and CH₄ dominates the gases of current fluids, resulting from the thermal maturation of coal over time. Siderite and ankerite are two common minerals found in the coal-bearing sequence. These minerals may undergo oxidationreduction reactions to generate hydrogen at deeper compartments of the Carboniferous. Hydrogen represents approximately 17% of the gases dissolved in formation waters at 1100 m depth. The H₂ concentration increases with depth giving hope for a new future for the Lorraine coal basin.



Fig. 1: Petroleum fluid inclusions in ankerite from the Lorraine Carboniferous Basin with associated asymmetric T_h histogram.



Identifying the composition of hydrocarbon inclusions in rock salt

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Keywords: fluid inclusions, diagenesis, radioactive waste

Rock salt is one of the three potential host rocks for the final repository for high-level radioactive waste in Germany. Further, the first German repository for low- and mid-level radioactive waste is hosted by rock salt. For the site selection procedure and for safety assessments, the content and composition of fluids trapped within rock salt can be crucial to evaluate the potential of gas formation.

Certain salt formations in northern Germany are known to contain gases and hydrocarbons as fluid inclusions (Siemann and Ellendorff, 2000; Pusch et al., 2014).

Fluid inclusion studies can provide information on the fluid composition or temperature- and pressure conditions of fluid migration. Investigating individual fluid inclusion assemblages has certain advantages compared to bulk analyses: (1) the possibility to differentiate between different fluid sources and/or (2) the reconstruction of a complex fluid history.

Among the suitable methods for the analyses of individual fluid inclusion composition is Raman spectroscopy, despite the known challenges in the application for hydrocarbon inclusions (Orange et al., 1996).

The here investigated rock salt samples originate from the Hauptsalz (z2HS) of Zechstein the upper Permian 2 formation. Hydrocarbons occur mostly along the grain boundaries of halite, where dark gas phases (H₂S?) are rimmed yellowish-brown liquid by phases (hydrocarbons) which in turn are surrounded by transparent liquids (Fig. 1). UV microscopy indicate the presence of hydrocarbons in the yellowish-brown liquid phase.

For determination of the hydrocarbon composition we used a Renishaw inVia QONTOR Raman spectrometer attached to a Leica microscope (DM3000) equipped with a 100x objective and a 532 nm laser. Raman spectra were obtained with a 2400 grating, at ~5 mW, 180–240 s acquisition time and 2 accumulations in the spectral range of 300–4000 cm⁻¹. In addition, we collected Raman spectra of the host crystal and the epoxy resin.

The analyses of the hydrocarbon phase show peaks at ~940, in the range of 2500-2700 and 2900-3100 cm⁻¹ indicating C-H stretching modes, potentially of alkanes their and derivatives (Dollish et al., 1974; Orange et al. 1996).



Fig. 1: The presence of different fluid phases along a grain boundary of halite.

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Fluid Inclusion Studies in Halites from Punjab Evaporite Basin, Marwar Supergroup, Southwestern Punjab, India

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Keywords: Halite, fluid inclusions, evaporites

Evaporite sequences are good archives of paleodepositional environment. The Punjab Evaporite Basin (PEB) is northern Nagaur-Ganganagar extension of Evaporite Basin (NGEB) of Rajasthan. In this basin, marine sediments of Marwar Supergroup were deposited on the basement rocks of Malani igneous suite and/or Delhi metamorphites. This basin considered the southernmost is continuation of this large Eocambrian basin of which Salt Range of Pakistan that forms the northern part. The NGEB of Rajasthan extending in Punjab covers over 100,000 sq. km in Rajasthan, parts of erstwhile Bhatinda, Faridkot districts in southern Punjab and parts of Sirsa district of Haryana. The area comprises geological formations from the Neo-Proterozoic through Early Cambrian and continues through Permo-Carboniferous, Jurassic, Tertiary to Quaternary sequences with little deformation. The Hanseran Evaporite Group (HEG) comprises cyclic deposits of halite (most dominant constituent) containing potash minerals, alternating and separated by a sequence with anhydrite, clay and dolomite. Exploratory drilling by the Geological Survey of India (GSI) has helped in establishing the stratigraphic succession of the NGEB.

Two core samples were used for fluid inclusion study from the evaporite sequence at the depth of 619.5 and 636 m respectively. At least four sections reprsentative wafer were prepared for the detailed fluid inclusion studies. The fluid inclusion petrography revelals that the inclusions are dominantly primary and appeared as negative crystal shaped and are

occurring as isolated (type-1) or forming fluid inclusion assemblages (type-2) (Fig. 1). Trail bound secondary inclusions (type-3) are rarely available. All inclusions are biphase with high degree of fill and showed wide variation in size (<10µm to >100µm). The obtained homogenisation temperature showed wide range (152°-263°C) and are comparatively much higher than already temperatures. reported The Raman spectroscopy on these inclusions reveals the aqueous fluid with moderately brine and presence of dissolved sulphate ions. The higher temperature from halite is possibly due to brecciation at the greater depth, related to deep seated faults located in the basin that trends NNE to SSW. Because of thrusting, there is rise in temperature, which results in dissolution of halite and in omission of many halite cycles. The halite was recrystallised and precipitated. As no evidence of igneous intrusion such as basic dykes etc or any submarine volcanic activity was recorded in the basin, the thrusting and/or faulting is considered as possible cause for the increase in formation temperature of halite,



Fig. 1: Photomicrograph showing biphase aqueous brine fluid inclusion assemblage in halite. L-liquid, V-vapour.

Fluid inclusions in petrified wood, Kyffhäuser, Germany

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Keywords: Fluid inclusions, sedimentary basins, diagenesis

Agathoxylon petrified trunks embedded in upper Carboniferous red sandstone of the Siebigerode Formation (Gzhelian, ca. 300-302 Ma), Kyffhäuser, have been studied to elucidate the physicochemical conditions of wood silicification.

Cathodoluminescence (CL), fluid microthermometry, inclusion Raman spectroscopy on carbonaceous material (CM) and trace element analysis (EPMA) were applied to wood remnants and clear quartz crystals on sections parallel and perpendicular to the trunk length. In parallel sections, quartz crystals grew inwards, perpendicular to the contacts of "rod-like" openings. In perpendicular sections, quartz crystals grew around "wood islands".

Areas with preserved wood cell structures show stronger reddish CL, whereas euhedral quartz crystals show brownish red or no CL (Fig. 1).

Primary fluid inclusions occur along quartz growth zones in the youngest quartz, typically marked by an initial stage of dark, non-CL quartz (Fig. 1). The latter quartz contains up to ca. 2000 ppm Al.

Fluid inclusions are regular to irregular and mainly 2-phase (L+V) at room temperature. Few inclusions contain daughter crystals, identified as by muscovite Raman. The fluid inclusions contain brines with H₂O-CaCl₂-NaCl composition, varying between 71-82% H₂O, 12-25% CaCl₂ and 3-12% NaCl, typical for basin brines. Total homogenization temperatures range between 77 and 267°C with frequency peaks at 120/130°C and 150/160°C. Isochore calculations indicate that the primary inclusions were trapped at 3.0-5.5 km depth and 160-240°C.

Raman CM thermometry point at temperatures between 170 and 290°C, indicating an early stage of coalification. This process probably generated a volume reduction of the original wood and produced open spaces where the diagenetic quartz could grow.



Fig. 1: CL image of preserved wood and euhedral quartz crystals. Arrows indicate fluid inclusions in dark CL quartz.



Fig. 2: Primary fluid inclusions along the growth zone of a euhedral quartz crystal.



Invited Talk

Carbfix

Turning CO₂ to stone: CO₂ storage through carbon mineralization

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Keywords: CCS, CO₂ mineral storage, climate, water-rock interaction

By imitating and accelerating natural waterrock interactions, Carbfix' mission is to mineralize climate-relevant amounts of CO₂ in the subsurface for permanent storage. To this end, CO₂-charged water is injected into suitable subsurface reservoirs such as mafic ultramafic formations where rapid and mineralization takes place. Importantly, injecting water-dissolved CO₂ and careful design of injection parameters ensures that the CO_2 does not rise back to the surface, a key difference to traditional carbon capture and storage (CCS) methods. Furthermore, suitable reservoir rocks such as basalts and ultramafic rocks enable rapid mineralization of the CO_2 in the subsurface, storing the CO_2 over geological timescales. These water-rock reactions occur in several steps: Reactions of the low-pH CO₂-charged water with the mafic reservoir rocks leads to the release of suitable divalent cations (Ca, Mg, Fe) as well as a rise in pH and alkalinity. This creates suitable conditions for carbonate mineral precipitation, binding the CO_2 in the reservoir.

subsurface This technology and the processes have been confirmed to occur rapidly under suitable conditions. For example, 95% of injected CO₂ was confirmed to be mineralized within 2 years in the first Carbfix pilot injections¹ into a low-T (20-50 °C) basaltic reservoir. Similarly, the majority of CO₂ was confirmed to have mineralized within few months in a high-T (260 °C) basalt reservoir^{2,3}.

Having more than 10 years of operational experience with this method, Carbfix is leading the efforts to bring this method to climate-relevant scale. Here, an overview is given over the latest efforts and research directions. This includes research into the use of seawater to dissolve and inject the CO_2 for

mineralization. Based on positive results from modelling and laboratory studies^{4,5}, a fieldscale pilot using seawater is in preparation that will yield important results regarding the applicability of this method.

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Fluid inclusion characteristics and hydrocarbon accumulation process of Shanxi Formation, Ordos Basin, China

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Keywords: Fluid inclusions; Tight gas accumulation stage; Homogeneous temperature; Ordos Basin

The development of tight sandstone gas has skyrocketed in China in recent years. However, the exploration and development of tight sandstone gas in China are restricted by an insufficient understanding of the accumulation mechanism and difficulty in predicting sweet spots. Investigating the tight sandstone gas accumulation process by fluid inclusions is of vital importance.

Using Axioskop 40A POL polarizing microscope produced by Zeiss and MDSG600 electric heating and cooling stage of Linkam, we carried out detailed test and analysis of reservoir fluid inclusion samples of Shanxi Formation in Sulige Gas Field, Ordos Basin, China. We analyse the characteristics, composition and homogenization temperature (T_h) of reservoir fluid inclusions. The gas charging and accumulation period is determined, which provides the basis for the analysis of gas accumulation process in the gas field.

We investigated 52 samples of 19 wells from the Shanxi Formation in Sulige Gas Field, Ordos Basin. Samples are distributed throughout almost the entire Sulige Gas Field. The results show that: (1) According to the fluid composition and observation, the fluid inclusions can be divided into three types: Liquid hydrocarbon inclusions, Gas-liquid twophase inclusions, and Gaseous hydrocarbon inclusions; (2)The homogenization temperature of brine inclusions adjacent to gaseous different hydrocarbon inclusions in occurrence ranges from 95°C to

 170° C. They are continuous and show unimodal distribution, indicating that the gas charging recorded by the inclusions presents the characteristics of one stage accumulation and is a long and continuous process (Fig. 1); (3) Based on the analysis of homogenization temperature and salinity of inclusions, combined with the burial history, thermal history and hydrocarbon generation history of the study area, it is considered that the natural gas of Shanxi Formation in the western part of Sulige Gas field experienced one stage accumulation, and the accumulation divided into initial period can be charging period and peak charging period according to the homogenization temperature distribution characteristics of associated brine inclusions. It belongs a typical continues tight gas reservoir.



Fig.1: Homogenization temperature distribution of sandstone fluid inclusions in the Upper Paleozoic reservoirs of Sulige Gas Field, Ordos Basin, China.



Session S5: Ore fluid inclusions



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Amethyst - agate geodes from Uruguay: insights from fluid inclusions and stable isotopes

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Keywords: fluid inclusion; ore deposits

Amethyst-agate geodes from the Los Catalanes gemological district (Uruguay) are hosted in basalt of the Paraná-Etendeka Igneous Province intercalated with aeolian sandstone.

The crystallization sequence in the geodes includes stage (I) celadonite, zeolite, chalcedony (agate), calcite, microcrystalline quartz, pyrite and chalcopyrite, stage (II) macro-crystalline colourless quartz and amethyst, and stage (III) calcite, fluorite and pyrite.

Primary and pseudo-secondary fluid inclusions in amethyst, colourless guartz and calcite contain predominantly singlephase liquid at room temperature (Fig. 1). Vapour nucleation was therefore induced by means of a femtosecond-Total homogenization laser pulse. temperatures (Th) of primary fluid inclusions in calcite (stage I and III) record 30-87°C (frequency maximum at 52°C), while in amethyst and quartz (stage II) Th record 15-80°C, with a few temperatures up to 117°C.

Triple oxygen isotopes obtained for agate, quartz, amethyst and calcite agree with water-quartz and watercalcite equilibria, taking the isotopic composition of water collected from closed geodes as a starting reference. In this way, crystallization temperatures of 30-60°C could be calculated for agate as well as for early calcite (stage I). Colourless quartz and amethyst (stage II) yielded 60-90°C and 45-60°C, respectively. Estimated crystallization temperatures for late calcite (stage III) are ca. 30-40°C. These temperatures concur with microthermometry.

Ice melting temperatures of the fluid inclusions measured at saturation pressure, i.e., in presence of a vapour bubble, revealed low salt concentrations ranging from 0 to 3.8 wt% NaCl. Low salinity could be confirmed by the combination of prograde and retrograde homogenisation temperatures.

The present data indicate that the geodes were mineralized at low temperatures, after the emplacement of the entire basaltic sequence. The mineralizing fluids probably originated from aquifer(s) that developed in the sediments underlying the basaltic sequence.



Fig. 1: Primary one-phase fluid inclusions in growth zone of amethyst, stage II.

Ore-forming fluids in the Tepeoba porphyry Cu-Mo deposit, NW Türkiye

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Keywords: fluid inclusion, ore deposits

The Tepeoba Cu-Mo deposit is the first and only operating deposit in Türkiye producing molybdenite. It has a total ore reserve of 26 million tons with 0.33wt% of Cu, 0.041wt% Mo, and ~10 ppm Au average grades. The mineralization is hosted within the local Permo-Triassic metamorphic/sedimentary rocks and Oligocene-Early Miocene granitoids. Orebearing veins and stockworks are developed within brecciated host rocks, consisting of guartz, chalcopyrite, pyrite, molybdenite, sphalerite, pyrrhotite and gold, with the later development of supergene goethite/limonite, malachite and azurite. Cathodoluminescence of quartz veins show multi-stage vein filling associated with the mineralization.

Fluid inclusion assemblages hosted in quartz can be classified as liquid-rich (c.70 vol%), vapor rich (>70 vol%) and with multiphase inclusions. Halite and sylvite are common daughter phases together with several other solids, i.e., ferro-pyrosmalite, hematite, magnetite, pyrite, chalcopyrite and calcite, identified by Raman spectroscopy (Fig. 1). All the solid bearing inclusions have the same crystals in them. Phase transitions during microthermometry indicates an NaCl+ KCl+CaCl₂ brine composition. T_h of vapor-rich inclusions ($\pm CO_2$ and H_2S) are ~370°C with a salinity of ~1 wt.% NaClequiv. salinity. Th for the V-phase disappearance ~300°C with salinity of ~9 wt. % NaCl-equiv. Halite dissolution temperature up to ~500°C and for hematite-bearing inclusions >600°C, with salinities of ~35 wt.% NaCl-equiv.

LA-ICP-MS and EBSD analyses of solids in open inclusions, indicate the major components in the fluid are Na, K, Ca, and Fe, with significant, but lower concentrations of Cu, Au, Ag.

The δ^{34} S values of sulfides ranges from 2.3 to 2.7‰, consistent with a magmatic source of sulfur. Also δ D, from -69 to -61‰ and δ^{18} O from 8.2 to 8.6‰ of fluid inclusions and quartz indicate a magmatic fluid source.

Re-Os ages of molybdenite are 25.03-25.11 \pm 0.14 Ma for the veins and 25.62 \pm 0.09 Ma for the breccia, consistent with the age of the granite.

The combined data suggests that Tepeoba represents an extended porphyry-copper mineralization event. The magmatic fluids produced both prograde and retrograde alteration of the host calcareous rocks and the development of a skarn-type deposit.



Fig. 1: Multiphase fluid inclusion containing L+V, *Fe-pyrosmalite (Fpsm), chalcopyrite (Cpy), calcite (Cc) and halite (H).*

The role of disequilibrium in gold precipitation in orogenic gold deposits, Discovery-Ormsby, Northwest Territories, Canada

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Keywords: fluid inclusion, thermodynamic calculations, ore deposits

The Yellowknife Greenstone Belt (YGB), located within Canada's Slave Province in the Northwest Territories (NWT), hosts several orogenic gold deposits including the world class Giant and Con mines. The composition of the mineralizing fluids, mechanisms of gold transport, and some of the controlling factors related to precipitation remain actively debated. Precipitation mechanisms proposed for gold in the YGB include fluid mixing and fluid-rock reactions associated with redox changes and sulfidation. Although mineralization style within the YGB is highly variable, there is a spatial correlation between gold mineralization and fluid inclusions containing high-pressure volatiles (i.e. $CO_2 \pm CH_4 \pm N_2$). This correlation suggests a link between mineralization and highpressure volatile-rich fluids.

The Discovery-Ormsby Property is located approximately 90 kilometers north of Yellowknife, NWT. Mineralization on the property is associated with waterabsent monophase carbonic fluid inclusions $(CO_2 \pm CH_4 \pm N_2)$ as well as graphite-bearing inclusions $(C\pm CO_2\pm CH_4\pm H_2O).$ Thermodynamic modeling of the mineralizing fluids and the host rock indicate the system was in a state of redox disequilibrium. Redox disequilibrium processes have long been recognized as a mechanism for gold precipitation and may be responsible for triggering precipitation at Discovery-Ormsby. Furthermore, the presence of high H₂S concentrations within fluid inclusions may hold further implications for gold solubility and transport within the region.



A fluid inclusion study of the mineralising fluid of the Pb-Zn-Cu ore deposit of Saint-Nicolas mine, Silberthal (southern Vosges Massif, France)

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Keywords: Southern Vosges, lead-zinc deposit, hydrothermalism

The southern part of the hercynian Vosges Massif (France), as well as the eastern part of the Schwarzwald massif (Germany) (Walter *et al.*, 2019) includes numerous Pb-Zn deposits related to the Vosges Fault and the formation of the Rhine Graben during Tertiary. The Saint Nicolas mine (Steinbach district) was exploited mainly at the beginning of the XVIIth century with sporadic activity in the XVIIIth and at the end of XIXth century-early 1900s for its silver-bearing galena (Lougnon, 1985).

The mineralisation is located in 4 main NE-SW to ENE-WSW pending veins crosscutting Visean volcanosedimentary rocks of the Molkenrain volcanic complex. Ores include galena, sphalerite, chalcopyrite in a gangue composed of quartz, baryte, siderite and sometimes fluorite. A paragenesis of secondary minerals has formed during supergene alteration and includes cerussite, anglesite and copper sulphides and carbonates.

The paragenetic sequence includes 3 quartz generations, 1/ a first episode of microcrystalline quartz growing from the wall rock or on fragments of the surrounding rocks inside the veins, 2/ large palisadic deformed quartz lamellae, 3/ a second generation of large quartz crystals. The mineralisation is composed of galena, sphalerite, chalcopyrite and pyrite. Fluid inclusions have been studied in quartz crystals. They are mainly twophase. Microthermometry has revealed that they are aqueous solutions. Eutectic temperatures are low, consistent with a high calcium chloride concentration (Gutierrez Lanz, 1985). Ice melting temperatures (-5 to -0,9°C) indicate a low salinity (mean 3,9 wt% eq. NaCl). Bulk homogenisation temperatures are distributed between 200° and 270°C but the most abundant data lie around 220°C.

The thermodynamic treatment of the data gives a formation temperature of about 250°C. Data obtained seem to indicate a mixing process between surface waters and hot fluids originating at depth.

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Keyword list:

Keywords: Hercynian Vosges Massif, hydrothermalism, Vosges fault, Rhine Graben, mixing



Mineralized structures from the Alhué mining district, Chile: using fluid inclusions and mineral textures

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Keywords: fluid-phase equilibria, hydrothermalism, ore deposits.

The Alhué mining district of the Coastal Range in Central Chile is approximately 70 km southwest of the city of Santiago and 24 kilometers east of Villa Alhué where stratified Jurassic and Lower Cretaceous sequences form a northtrending belt which is found along most of central Chile. More than 76 structures were recognized in the Alhué mining district hosted in andesites and tuffs with clear structural control. The structures hosting mineralization extend along a strike length of 160 to 1000 meters with grades average of 5 ppm gold (Au) and 23 ppm of silver (Ag). In this study, a University of Chile -YAMANA GOLD alliance was created to better understand this particular deposit and explore the origin of gold anomalies found in the district using both drill core samples, mine samples, and surface samples. There are wide internal variations Th and electrolytes in observed at all scales: distrital, mineralized structures and hand samples. This may reflect the diversity of ore-forming conditions in the mining district and the variability of processes and geochemical components acting in the studied zones (Figure 1). Textural and fluid inclusions assemblages (FIA) with evidence of boiling and flashing mechanisms were found in the three localities studied: Magui, Lorena and Chilco. Raman spectroscopy and LA-ICP-MS techniaues allowed better а characterization of the fluids composition and mineral paragenesis. The presence of gold (~ 3.8 ppm) and silver (~ 1424 ppm) in both vapor-rich only FIAs hosted in quartz and liquid-rich FIA hosted in

sphalerite implies that gold is being transported as sulfide and chloride complexes depending on the type of vein system. The importance of rapid coseismic dilation as revealed by flashing at specific sites such as dilational fault jogs and bends is critical for the precipitation of metals in at Alhué. New results here reveal that gold, silver and base metal veins found at Alhué mining are district Chile unusual in hydrothermal ore deposits that are structurally controlled and related to a transition between mesothermal to polymetallic environments. Evidence of boiling is also observed in the deepest levels in the Chilco vein and the proportion of samples showing boiling increases with depth, indicating that additional precious metal resources may be present beneath the deepest levels that have been explored.



Fig. 1: Spatial distribution of fluids in a general model of fluid`s migration in the Alhué Mining district.

Keyword list: fluid inclusion, fluidphase equilibria, hydrothermalism, ore deposits.



Compositional variations of the geothermal fluid of the Reykjanes geothermal system, Iceland

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Keywords: fluid inclusion, hydrothermalism, ore deposits

In this ongoing study, we have determined major and trace element variations of geothermal fluid with depth within the active Reykjanes geothermal system in southwestern Iceland. The Reykjanes geothermal field is located where the Mid-Atlantic Ridge meets Iceland. It is a sea-water dominated system that has been suggested to be comparable to basalt-hosted seafloor hydrothermal systems forming black smokers and massive sulphide deposits (SMS) (Friðleifsson et al., 2020, Zierenberg et al., 2021).

Secondary fluid inclusions along healed fractures found in hydrothermal and magmatic quartz grains from ~3.1, 3.6 and 4.3 km depth in the RN-15/IDDP-2 borehole with constrained salinities were studied by LA-ICP-MS (Hüne., 2023). Further fluid inclusion data are available from 4.6 km depth (Bali et al., 2020).

Most fluid inclusions from ~3.1 km depth have similar Fe-Na-K molar ratios as seawater (Yuan-Hui, 1991) and the geothermal fluid sampled at the well head and at shallow depth (~1.5 km downhole) (Harðardóttir et al., 2009). The Fe-Na-K ratios at the bottom of the borehole (4.5 km depth) are approximately 1:1:1and all fluid inclusions fall in a well-defined, narrow range (Figure 1, Bali et al., 2020). Inclusions from 3.6 and 4.3 km depth show large variations in Fe-Na-K ratios. Large variations are also found for concentrations of other elements at these depths. At 4.3 km depth this can be explained by halite saturation in the fluid. At 3.6 km depth, the variation is similar as at 4.3 km depth, just with lower concentrations likely due to mixing with shallower fluid and/or secondary mineral precipitation.

Fluid inclusions at 3.6 km and 4.3 km depth also contain elevated amounts of trace metals (e.g., median concentrations of Cu, Zn and Ag of 638, 2864 and 1.4 ppm, respectively, at 4.3 km depth) compared to those in the main feed zone samples at ~3.1 km depth (median concentrations of Cu, Zn and Ag of 4.7, 34.1 and <0.2 ppm, respectively).



Fig. 1: Variation of Fe, K and Na molar proportions in fluid inclusions from the RN15/IDDP-2 borehole. Shown for comparison are seawater composition (Yuan-Hui, 1991), Reykjanes fluid sampled at shallow depth and at well heads (Hardardóttir et al., 2009) and fluid inclusion data from 4.3 km depth (Bali et al., 2020). Note that there are outlier concentrations outside the shaded areas.

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Different fluids related to evolution of Guadalcazar Granite, San Luis Potosi, Mexico.

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Keywords: silver, fluid inclusion, ore deposits

The human race has been developing different techniques to acquire natural resources from different environments in the Earth since the stone age. Modern society demand more resources as the population is growing and expanding. This research describes the Guadalcázar A-type intrusive that shows extraordinary concentration of silver in in the fluid (Chryssoulis and Wilkinson, 1983).

The Guadalcazar granite is located 96 km northeast of San Luis Potosi, Mexico. In the central zone of the metallogenetic province of Sierra Madre Oriental (Carrillo-Bravo, 1971). This outcrop is roughly circular with a diameter of 3 to 4 km.

We collected 5 different types of veins in outcrops:

Sulfide Vein-Breccias: the main structure shows thickness of 2 meters and with a general strike 308° and a dip of 73° to the NE. The main ore observed in hand sample is jamesonite, stibnite, tetrahedrite, chrysocolla.

Red Garnet Skarn: this type of bodies outcrop in the southeastern portion of the granitic body near the sulfide veins and breccias and in the central portion of the granite near the quartz-muscoviteberyl veins.

Green Garnet Skarn: it is described as a skarn of green garnet (grossularia) in smaller proportion red garnet, tremoliteactinolite, plagioclase, pyroxenes, fluorite and as sulfides, pyrite and chalcopyrite.

Quartz-Fluorite Veins: the vein has a general strike of 320° with an inclination

of 78° to the NE, observed pyrite and possible silver sulfosalts (proustite).

Finally, Quartz-Muscovite Vein: this set of veins conform a stockwork type, the host rock is granite that is strongly argillized, albitized and with evidence of formalization.

Preliminary results show the Quartz-Fluorite Veins sample contain vapor-rich inclusions assemblages in feathery quartz textures with proustite minerals (Figure. 1).



Fig. 1: Photomicrograph of fluid inclusions in Quartz (Qz) from Quartz-Fluorite Veins.

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Fluid inclusion and geochemical studies of Dongargaon fluorite (±barite) deposit, India: Implications on fluorite mineralisation

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Keywords: fluid inclusion, hydrothermal, fluorite

Criticality of fluorite utilisation in the aerospace engineering, chemical metallurgy engineering and has attracted the attention of researchers in the recent past. Fluorite mineralisation is different genetically associated with geological environments such as magmatic-hydrothermal, hydrothermal and sedimentary. It also varies in terms of P-T-X condition and mechanism of mineralisation. The fluid characteristics of the reported hydrothermal fluorite mineralisation are typically low to moderate in temperature (<300°C), varying salinity (low to high, wt.% NaCl equivalent), aqueous±carbonic in nature with varying dissolved salt types (NaCl, CaCl₂ etc.). The source of dissolved solutes such as Ca, F, REEs etc. are also reported from diverse geological Similarly, reservoirs. source of fluid hydrothermal also varied extensively. Therefore, a detailed fluid inclusion and geochemical studies can play a vital role to constrain the genesis of hydrothermal fluorite mineralisation.

Dongargaon fluorite (±barite) deposit is situated in the Chandrapur district of Maharashtra, India. Regionally, the area is comprised of Bengpal gneissic complex forming basement for all overlving sedimentarv rocks. The sedimentary sequences belong to Pakhal Supergroup, Penganga Group, Sulluvai Group, Vindhyan Supergroup and Gondawana Supergroup. These sedimentary sequences are overlain by Deccan Basalts of Sahyadri Group. The recent field work carried out in the Dongargaon area reveals that the fluorite (±barite) mineralisation is hosted within the extensively brecciated

limestone and chert. The mineralisation is botryoidal, banded, coarsely cubic crystalline and open-cavity filling. Till today, a detailed and systematic study is not carried out on the deposit and a concept-based genetic model is still lacking. Therefore, in the present study, a systematic sampling of fluorite and host rocks were performed and detailed fluid inclusion and geochemical studies are carried out.

Petrography reveals that along with fluorite, quartz and barytes are also present as minor hydrothermal phases. Fluid inclusions were observed only in coarsely cubic crystalline fluorite and were highly varying in shape and size. The degree of fill is dominantly high and less varying. It is biphase, genetically primary (type 1) and secondary (type 2) compositionally aqueous and with dominantly NaCl as dissolved salt (H₂O-NaCl). Both type 1 and 2 inclusions are NaCl low in salinity (<1.5 wt.% equivalent) and also low in temperature (<180°C) representing epithermal condition of mineralisation and meteoric source of fluid.

Pure phases of fluorites and associated rocks were separated and analysed for trace and REE contents employing ICPMS. Total REE content of individual fluorite samples are low to moderate and highly varying (1-195 ppm). However, EPMA study of hydrothermal phases reveals that the associated barytes are highly enriched in REE content (Ce₂O₃: 14.6 - 17.6wt.%). Similar PAAS normalised REE+Y patterns and range of Y/Ho ratio of fluorite and sedimentary rocks of the study area suggest derivation of dissolved solutes locally.

Fluid inclusions in late-stage Oroya gold veins from the giant Golden Mile Au-Te deposit, Kalgoorlie, Western Australia

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Keywords: fluid inclusions, ore deposits, hydrothermalism

The Golden Mile deposit at Kalgoorlie ranks as one of the largest hydrothermal gold deposits in the world (Goldfarb et al., 2005). The ore bodies are bound to a vast array of shear zones, including the Oroya system. Despite a long history of research, certain aspects of the deposit, e.g. the source of the ore fluid remain controversial.

Oroya-style extensional veins contain euhedral guartz that host primary fluid inclusion assemblages consisting of cotrapped (1) inclusions rich in CO₂ liquid $(+ \text{ traces of } CH_4 \text{ and } N_2)$ surrounded by a thin film of aqueous liquid, (2) aqueous two-phase inclusions with traces of CO₂ and (3) mechanical mixtures of both. Upon cooling, the inclusions form ice aqueous (no clathrate) that melts from -2.5 to -2.3 °C revealing 3.7–4.2 wt.% NaClea neglecting the presence of minor gases. Upon heating, H₂O-rich inclusions homogenize via shrinkage of the vapour phase from 205-215 °C. The CO₂-rich inclusions show melting of solid CO₂ from -60.2 to -59.3 °C and T_m (Cla) from 9.5 to 11.8 °C. Homogenization of the CO_2 phases $(T_h(L_{CO2}V_{CO2}L_{aq}\rightarrow L_{CO2}L_{aq}))$ 15 to 24.3 °C. occurs at Total homogenization $(T_h(L_{CO2}L_{aq}\rightarrow L_{CO2}))$ was rarely observed at ~200 °C. Fluid inclusion salinities and densities were calculated using "Clathrates" (Bakker, 1997) revealing <1 wt.% NaCleg and high densities $\sim 0.8 \text{ g/cm}^3$.

Laser-ablation-ICP-MS analyses of individual H₂O-rich and CO₂-rich inclusions yield ratios for 23 elements. Normalized element concentrations reveal that certain elements, such as S, Cu, Sb and Pb, are relatively enriched in the carbonic inclusions. Comparing the normalized fluid compositions with other fluid inclusion compositions, it becomes evident that the Oroya extensional vein fluid resemble neither an orogenic gold fluid, nor a magmatic-hydrothermal fluid (see Fig. 1 for references). Especially certain trace element ratios, such as B/Na or Rb/Sr, are contrary to those of the magmatic-hydrothermal fluid.



Fig. 1: Multi-element plot of the Oroya fluids in comparison to a magmatic-hydrothermal fluid (intermediate-density fluid average, Bingham porphyry, Landtwing et al., 2010) and the extensional vein fluid (average) from the Pampola orogenic gold deposit (Fusswinkel et al., 2017).

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Genesis of Antimony mineralisation in Chitradurga central shear zone, Dharwar craton, India: Evidences from fluid inclusions and sulfur isotopes

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Keywords: Antimony, fluid inclusion, epithermal

Chitradurga Schist Belt (CSB) in the eastern part of the Western Dharwar Craton (WDC) comprised of thick volcano-sedimentary sequence, metamorphosed to greenschist facies. The major shear zone running NNW-SSE at the east of the WDC, the Gadag Mandya Shear Zone (GMSZ) along with associated second and third order shears are considered as important locii of various types of mineralisation. One such Riedel shear at an acute angle to GMSZ is the Central Chitradurga Shear Zone (CCSZ) which is present in the central part of CSB. A number of mineral occurrences are reported all along the CCSZ are G. R. Halli (Au), C. Κ. Halli (Sb), Jagalur (Au) and Honnamaradi (Au).

The Sb mineralization at Chikkonahalli (C K Halli), is hosted by guartz veins present within the metabasalt which is carbonatized at places. These quartz veins have a yellowish to limonitic coloured appearance due to stibnite alteration. The two N-S to N10E trending and N70E trending quartz veins appear to be associated with the mineralization. Five major quartz veins were characterised with either occurrence of stibnite or its oxides. Petrographic, XRD, SEM and EPMA studies clearly showed alteration of stibnite (Sb₂S₃) to different oxide phases which are mainly senarmontite (Sb₂O₃) and further to

(Sb³⁺Sb⁵⁺O₄). cervantite Jamesonite ($Pb_4FeSb_6S_{14}$), tungstibite ($Sb_2^{3+}WO_6$) and Berthierite (FeSb₂S₄) are also present as inclusions within stibnite. Detailed fluid inclusion studies shows that stibnite is precipitated from a low saline aqueous fluid with a temperature range of 208 °C to 265 °C and no evidence of metamorphic carbonic fluids. Temperature of homogenization (Th total) vs salinity plot shows epithermal ore forming environment. The $\delta^{34}S$ values of pyrites and galena from the study area show a range that varies from -0.7 ‰ to +2.2 ‰. Sulphur isotopic data of antimony with $\delta^{34}S$ values ranging from +1.80 ‰ to +4.0 ‰. Sulphur isotopic signature are similar to the reported gold mineralization of Dharwar craton. More data is necessary to characterize the nature of its source. The present study suggests that antimony is deposited in an epithermal ore forming environment, brittle regime, more lithologically controlled.



to Fig. 1: Photomicrographs of fluid inclusions in quartz veins hosting antimony (a,b); Alterations in **ECROPIN** (c,d); Sulphur isotope data (d)

Oxidation states of carbon and sulfur species in sphalerite-hosted fluid inclusions of the Lavrion Pb-Zn-Ag deposit (Greece)

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Keywords: fluid inclusion, metamorphism, ore deposits

Reduction of sulfate bv carbon compounds is a common process in nature that results in release of H₂S and CO₂ (Machel et al., 1995; Worden and Smalley, 2001). Thermochemical sulfate reduction (TSR) leads to the metals deposition in various geological environments. Interaction of marine derived sulfates with organic compounds generally leads to incomplete reactions resulting in sulfur isotopic disequilibrium and a large range of oxidation states of sulfur and carbon species.

The Lavrion Pb-Zn-Ag deposit (Attica, Greece) belongs to the Attico-Cycladic system of the Hellenides orogenic belt that formed and partially collapsed along the Africa-Eurasia convergent plate boundary active for the last 80 m.y. The district consists of low-grade porphyry Mo style, Cu-Fe skarn, high-temperature carbonate replacement Pb-Zn-Ag, and vein and breccia Pb-Zn-Ag mineralization (Voudouris et al. 2021), located in both the footwall and hanging wall of the deposited detachment and during exhumation. The analysis of sphalerite of the two last mineralization stages permits to decipher the role of the different fluid systems during ore deposition. Sphalerite was analysed by cathodoluminescence, SEM, LA-ICPMS and SIMS. The analyses of primary fluid sphalerite inclusions in bv microthermometry, Raman spectroscopy and TD/MDGC show that they contain, besides a H₂O-NaCl-CaCl₂ solution, CO₂, a large variety of organic compounds ranging from C_1 to C_6 alkanes, benzene and toluene, SO_4^{2-} , native sulfur and S_3^{-} . Furthermore, $\delta^{34}\text{S}$ punctual analyses of sphalerite show a bimodal distribution with values ranging between +4.7 to +6.6 and -1.9 and +2.6 at Esperanza and Ari respectively. These values do not support a magmatic or a marine source, and are interpreted as marking the degree of advancement of TSR processes.

These observations demonstrate for the first time the importance of the TSR processes in metal deposition history of the Lavrion district. They also support the hypothesis of the progressive exhumation of the marbles and schists through the ductile-brittle transition that allowed the evolution from a magmatic fluid reservoir into a hydrothermal system dominated by sulfate-rich evaporated seawater and meteoric fluids (Scheffer et al. 2019).



Fig. 1: Photomicrograph of liquid-vapour fluid inclusions in Sphalerite (Qz) from the Lavrion area, Greece.

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Exploration of precious-metal mineralization are associated at Joya de Cortes rhyolitic dome, south part of the Guanajuato Mining District, Mexico

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Keywords: flashing, K/Ar dating, new resources

Exploration geologists have been developing systematic approaches to search for mineral deposits for centuries, starting with he works of Georg Bauer (Georgius Agricola), who published De Re Metallica in 1556. Applying modern a competitive technology provides advantage in the search for mineral deposits because an explorationist can quickly evaluate potential targets and eliminate areas without good potential mineralization The for Guanajuato Mining District (DMG), has been worked for more than four centuries (1548) since its discovery.

The area of study is located on the Guanajuato mining district is one of the largest silver producing districts in the world and still in exploration. Working in collaboration with the industry and some educational entities in Guanajuato, samples representing all the different mineralization styles were collected from southern part, mainly on the volcanic units of rhyolitic character.

The Sierra de Guanajuato, structurally conforms a long fold, of anticlinal form faulted in block, in which the main mineral structures of this District are found, they present a NW-SE orientation through the central part of the Guanajuato State, the vetiform structures show the same orientation of the rhyolitic flows and domes.

Total rock K/Ar dating suggests ages of the rhyolitic volcanic formations between 28 to 33 Ma, such chronological records approximate an Oligocene-Miocene of the central zone in the metallogenetic province of Sierra Madre Oriental.

of the veins The textures are predominantly breccia, the cementing agent is milky white quartz, colloform quartz, chalcedony, and a smaller proportion of calcite. Bladed calcite and bladed calcite replaced by quartz are sometimes observed. Silicification and oxidation are observed in the area. The veins show between 1-5 gr/T Au and 0.02-0.003 gr/T Ag. Preliminary work shows evidence of secondary liquid-rich fluid inclusions within assemblages of coexisting liquid-rich and vapor-rich fluid inclusions in guartz.



Fluid inclusions in contact-metamorphosed hydrothermal quartz veins: resetting of fluid chemistry and density

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Keywords: metamorphism, ore deposits, fluid inclusions

Vein-type gold deposits in the central part of the Bohemian Massif (Czech are spatially related Republic) to intrusive rocks of the Variscan Central Bohemian Plutonic Complex (ca 355-335 Ma) or their immediate proximity. Individual deposits can be classified either as intrusion-related gold or orogenic-gold deposits. Their quartz gangue, irrespective of the deposit type, precipitated from low-salinity H₂O-CO₂ fluids with a minor admixture of CH4 (usually <5 mol.% CH₄ in the gaseous phase). The Mokrsko (Boiron et al., 2001) or Jílové (Zachariáš et al., 2013) deposits represent examples of unmetamorphosed deposits with original fluid inclusion (FI) assemblages.

Contact-metamorphic overprint of Aubearing quartz veins was documented at two deposits (Libčice and Voltýřov). The veins are hosted in granitic bodies' exocontact (Libčice) and endocontact (Voltýřov) zones. In addition to crosscutting relationships at the outcrop scale, the following phenomena were identified at the microscopic scale: 1) partial to total recrystallization of quartz gangue (and ore-assemblages); 2) grain reduction size and overall "homogenization" of quartz-grain-size variability; and 3) apparent expulsion of original FI from recrystallized quartz grains. The latter process results in marked transparency contrast between recrystallized (i.e. clear, wellthe transparent quartz with sparse FI) and "dusty", original quartz (i.e. the semitransparent due to large quantities of FI).

Relic grains of "dusty" quartz at the Libčice deposit show systematic variations in the CO_2/CH_4 ratio of the gaseous phase of aqueous-carbonic FI, evolving gradually from CO2-rich FI at grain cores towards CH₄-rich FI at grain rims (up to 60 mol.% CH₄). This trend was documented by Raman and microthermometric data and explained by diffusion of H₂ into FI and reduction of CO₂ to CH₄ (Hrstka et al., 2011).

Quartz veins at the Voltýřov deposit are dominated by homogeneous polygonal texture. The recrystallized quartz contains randomly 3D-distributed FI (up to 30 µm in size) that would be classified "primary" if present in as not metamorphosed gangue. In this case, however, they formed during the thermally driven steady-state recrystallization of the original quartz gangue. Both microthermometric and indicate Raman data significant variations in the CO₂/CH₄ ratio of the gaseous phase of FI, and CH₄ admixture (10-75 mol.%) much higher than in "unmetamorphosed" Au-bearing quartz veins (i.e. Mokrsko or Jílové deposits; typically <5 mol.% CH₄).

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Fluid inclusion evidence for metamorphic mobilization of chalcopyrite at the Tisová VMS deposit, Czech Republic

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Keywords: metamorphism, ore deposits

The Tisová-Klingenthal deposit, located in the southwestern part of the (Czech Republic), Erzgebirge Mts. represents a metamorphosed Besshitype VMS deposit (Pertold et al., 1994). It hosted by lower Paleozoic is metasedimentary complex (phyllites, quartzites, graphitic phyllites) intruded by metadiabase sills (accompanied by minor basaltic metatuffs). Both the deposit and its host-rocks were regionally metamorphosed at about 480-550 °C and 10-13 kbar (e.g. Faryad and Kachlík, 2013) during early Variscan subduction of the Saxothuringian Unit below the Teplá-Barrandian Unit. The Cu-(Co) mineralization (average grade 0.8 wt.% Cu) is present in the form of impregnations, veinlets and massive ores.

Fluid inclusions were studied in quartz grains enclosed in the massive sulfidic ore. Two main types of fluid inclusions were identified: carbonic (C-type) and aqueous-carbonic (AC-type). The C-type inclusions usually form short intra-grain trails in grains of clear transparent quartz (i.e. fully recrystallized quartz). The AC-type was identified in sparse grains of "dusty" quartz only. This quartz, full of tiny fluid inclusions, probably represents relic of progrademetamorphic or hydrothermal quartz grains enclosed within the recrystallized ore.

Microthermometric data of the C-type inclusions indicate almost pure CO_2 (TmCO₂ = -56.6 to -56.9 °C), and wide range of homogenization temperatures of CO_2 (from -8.5 °C to +30.9 °C; to liquid). The lower-density (0.63 g/ccm) C-type inclusions are by far more

abundant than the higher density ones (0.97 g/ccm). Trapping pressures of these fluids depend severely on the assumption of the amount of H₂O (estimated at ca 20 vol. %; invisible under the optical microscope). The AC-type inclusions show low salinity (3.0-1.4 wt.% eq. NaCl; TmClath = +8.5 to +9.3 °C) and similar Tm-CO₂ and Th-CO₂ data as the C-type inclusions. Unfortunately, they usually decrepitate before their final homogenization.

C-type inclusions were also found interspersed with tiny inclusions of chalcopyrite (5-50 µm in size), both hosted by the same microfracture plane"). ("secondary inclusion Metamorphic mobilization of chalcopyrite therefore continued from peakmetamorphic conditions (~10-13 kbar and ~500 °C), down to about 4-5 kbar. Most of the C-type inclusions record even lower pressures (~2 kbar). All the studied fluid inclusions were therefore trapped (or reequilibrated) during the retrograde metamorphic path of the complex.

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