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POSTER PROGRAMME

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Crystal mush infiltration and reactive liquid flow: insights from the Klokken intrusion, South Greenland Joshua Hughes (Durham University, UK)
Halogen behaviour within peralkaline magmas and the implications for REE and trace metal transport and concentration Fiona Iddon (University of Cambridge, UK)
Cumulate causes for the low contents of chalcophile elements in the continental crust Frances Jenner (Open University, UK)
Investigation of the Kencana low-sulfidation Au-Ag deposit, Gosowong mining district, Halmahera, Indonesia Thomas Tindell (Kyushu University, Japan)
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Hydrothermal baddeleyite and zircon in the Tengtie Fe skarn deposit, South China: Implications for timescales and processes of skarnization Wen Zhao (The University of Hong Kong, China)

ORAL ABSTRACTS
(in programme order)

Porphyry-type ore deposits: origins, fertility indicators and exploration targeting

Wilkinson, J.J.[1,2], Loader, M.A.[1,2], Pacey, A. [1,2], Sievwright, R.H. [1,2], Hart, L.A.[1,2], Brugge, E.[1,2], and Wilkinson, C.C.[1,3]

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Porphyry ore deposits source much of the copper, molybdenum, gold and silver utilized by humankind and are also repositories of a diverse range of other elements of economic interest, including critical metals like rhenium and palladium. They typically form in magmatic arcs above subduction zones via a series of linked processes, beginning with magma generation in the mantle and ending with the precipitation of metals from hydrous fluids in the shallow crust. A number of key steps, or "gates", may be involved in the formation of fertile (i.e. those with economic potential) porphyry systems. These are: (1) the generation of hydrous, metalliferous melts in the mantle source region; (2) cyclic refertilization of magmas in the deep crust; (3) the potential for sulphide saturation, that may both enhance and destroy ore-forming potential; (4) the efficient transfer of metals into hydrothermal fluids during magma ascent and crystallization; and (5) efficient precipitation of metal sulphides from the exsolved fluids. For a significant concentration and abundance of metals to develop, these gates must be negotiated with optimum efficiency.

Although all processes are required to a greater or lesser degree, only some processes operate on the right spatial and temporal scales to account for the restriction of large deposits to specific arc segments and time periods. Understanding these controls is critical for reducing investor risk and minimising the environmental footprint of porphyry exploration. The recognition of the operation of key processes and the establishment of optimal magma conditions is possible via a number of tracers that utilise minerals, such as zircon, apatite and magnetite, crystallizing at different stages of magma evolution. Thus, these minerals may be very valuable tools for the assessment of the fertility of magmatic arcs and district scale discrimination between mineralized and barren igneous complexes. The NERC Highlight Topic project "FAMOS" (From arc magmas to ores) has recently just started to investigate these issues using a combination of data from natural rock records, experimental petrology, and physical modelling using both numerical and analogue experimental approaches.

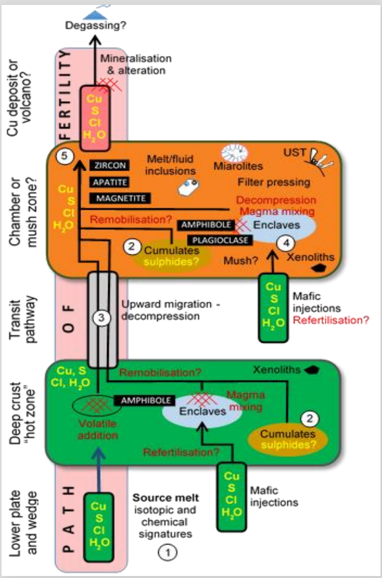

Figure 1. Schematic diagram illustrating processes being investigated in the FAMOS project

Once a fertile magmatic-hydrothermal system has been established, it will generate a broad alteration footprint on the shallow crustal host rocks into which it has been emplaced. The proximal alteration zones are relatively well understood but the key domains with respect to current exploration challenges are the advanced argillic "lithocap" that may form above (and conceal) porphyry deposits, and the distal, propylitic "green rock" environment that forms the broadest halo to mineralization. Recent advances in our understanding of the green rock domain demonstrate a much greater metasomatic magmatic fluid influence than hitherto recognised, extending for many kilometres from the ore zone. The fluid-rock interactions in this domain produce subtle gradients in alteration mineral chemistry that can be used as vectors towards the system centre, and even enable prediction of distance to a potential orebody.

In this presentation, these topics are explored using a series of examples primarily from the research being carried out in the LODE research group, partly in collaboration with researchers at CODES, University of Tasmania, Australian National University and Lakehead University.

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Timescales of porphyry copper deposits: what do they tell us?

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Porphyry copper deposits are localized anomalies of Cu and S in the upper crust of the Earth. Cu and other metals are precipitated as sulphide minerals from magma-derived fluids through physico-chemical processes of which cooling is the most effective one (Fontboté et al., 2017). Up to a few decades ago porphyry copper deposits were considered to form nearly "instantaneously" at the geological timescale. Recent technical and analytical advances in U-Pb, Re-Os and Ar/Ar radiometric dating have brought down uncertainties on absolute age determinations to <0.1% (<10000 years for a 10 Ma old event). This, coupled with field observations that ore mineral deposition is cyclical and with numerical modelling indicating potential durations of single ore cycles of few tens of ka, has brought to widespread attempts to bracket the duration of magmatic-hydrothermal events in porphyry copper deposits. The capability to accurately determine the duration of magmatic-hydrothermal activity for porphyry copper deposits may have profound implications on understanding the mechanisms of their formation. In fact such duration fixes the rate at which Cu and other metals are precipitated and therefore the rate of exsolution of the metal-bearing magmatic fluid; this, in turn, poses also constraints on the total volume of the fluid and of the magma from which such fluid has exsolved. Ultimately the volume of the magma and the rate of its emplacement are controlled by first-order large-scale geodynamic processes occurring in the subduction and post-subduction environments hosting porphyry copper deposits.

A selection of robust radiometrically determined durations of porphyry ore deposition results in an apparent broad correlation of such durations with the Cu endowments of the deposits (Fig. 1). If this correlation will stand the test of further accurate dating, this would mean that Cu is deposited at a similar average rate in different porphyry copper deposits and that their different size is mostly controlled by the duration of magmatic-related hydrothermal activity. This in turn depends on the availability of magma volumes large enough to feed the surficial magmatic-hydrothermal system connected with the porphyry mineralization. Stochastic modelling of magma generation and evolution in the crust suggests that the magma volumes necessary to feed upper crustal magmatic-hydrothermal porphyry systems associated with the largest Cu endowments can only be initially accumulated in the mid- to lower crust (Figs. 1 and 2). At these depths, such magmatic systems acquire also peculiar geochemical signatures (e.g., high Sr/Y) that are typical of those associated with the largest porphyry deposits (Fig. 2). Only after their accumulation at mid- to deep crustal levels, can these large magma volumes be transferred to shallower depths where they may form porphyry deposits.

Although recent developments in radiometric dating techniques are allowing us to better understand how these deposits form, many open questions still remain. For instance, whereas radiometric dating indicates that porphyry deposits form within widely variable timescales, ranging from few tens of ka to almost 2 Ma, it is not yet clear whether the deposits formed within the longer time intervals are the cumulative result of multiple mineralising pulses having the same Cu endowment and lifetime as the shorter duration porphyry deposits (i.e., few tens of ka) or whether they may be formed by fewer "super-pulses" during which most of the Cu is deposited. These are essential problems to be solved to understand the geodynamic and magmatic processes ruling the genesis of porphyry copper deposits and require an accurate combination of detailed fieldwork and high-precision geochronology.

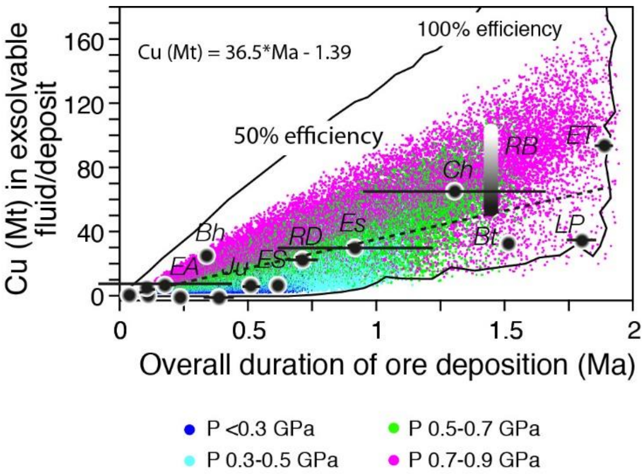

Fig. 1: Monte Carlo simulations of Cu (Mt) in the exsolvable fluid of hybrid melts after injection times of 0 to 5 Ma versus the overall duration of the ore deposition period. Color classes indicate different pressures of magma accumulation. The black dots represent radiometrically measured timescales of porphyry Cu deposits with respect to their endowment (from Chiaradia and Caricchi, 2017). Abbreviations: EA = El Abra; Bh= Bingham; Ju = Junin; ES = El Salvador; RD = Reko Diq; Es = Escondida; Ch = Chuquicamata; Bt = Butte; RB = Rio Blanco; LP = Los Pelambres; ET = El Teniente.

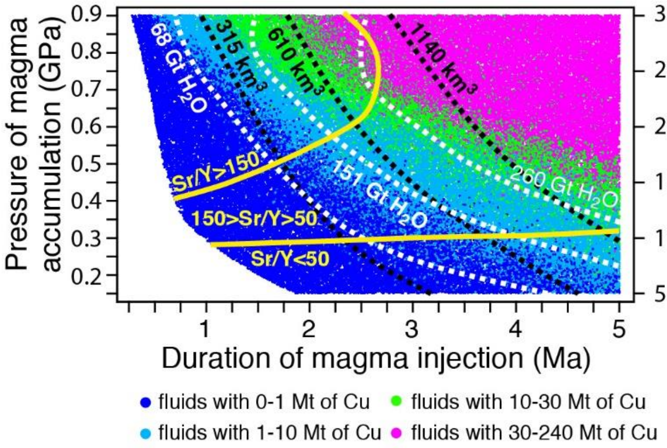

Fig. 2: Monte Carlo simulations of pressure versus time conditions for the generation of magmatic systems with different Cu potential endowments (white and black dashed lines indicate the Gt of H_2O dissolved in the hybrid melt and hybrid melt volume in km^3, respectively; yellow lines represent limits of Sr/Y values of hybrid melts resulting from Monte Carlo simulations) (from Chiaradia and Caricchi, 2017) (from Chiaradia and Caricchi, 2017).

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NOTES

A detailed history of magmatism at Spence porphyry copper deposit, northern Chile: Integration of high-precision zircon geochronology and geochemistry

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The Spence porphyry copper deposit occurs within the Paleocene-Early Eocene metallogenic belt of northern Chile, and consists of Cu-Mo mineralisation centered upon porphyritic granodioritic intrusives of late Paleocene age (Rowland & Clark, 2001). The deposit was emplaced into carbonaceous siltstones of the Jurassic Cerritos Bayos Formation and is overlain unconformably by Miocene gravels ranging from 50 to 100 m in thickness. The Spence intrusive suite exhibits a sub-parallel NNE-SSW alignment coincident with the dextral Antofagasta-Calama strike-slip fault. The intrusives are focused into four zones along the trace of the fault with varying degrees of mineralization, referred to as the South, Central South, Central North and North zones.

Previous work at Spence has identified textural similarities between igneous rocks within different zones, and on this basis ascribed them as the same units (Rowland, 2001). However, subtle textural variations within these rocks and a lack of clear cross-cutting relationships leads us to argue that this is not a robust approach. Instead, we are re-examining the igneous stratigraphy of Spence based upon a detailed petrographic and textural study of each intrusive body, combined with high-precision isotope-dilution-thermal ionization mass spectrometry (ID-TIMS) U-Pb zircon geochronology, to develop a spatio-temporal framework within which the magmatic and mineralising processes can be considered. Trace element analysis of zircon by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICPMS) was conducted upon a set of zircons prior to U-Pb dating and is combined with a broader set of zircon trace element analyses to infer chemical changes through the magmatic history of the deposit, both leading to, and following, mineralisation.

Our U-Pb zircon results indicate a shift in magmatic activity from south to north, occurring over a total duration of 717 ± 69 Kyr. Igneous rocks which were previously correlated between zones are separated by significant time gaps, which range up to nd are thus considered to be separate units. The zircon U-Pb dates from single hand specimens indicate a protracted and episodic zircon crystallisation history spanning a few hundred thousand years, where periods of growth can be correlated between samples from the same zone. We thus suggest that the Spence intrusives were derived from a common source region, from which magma was periodically tapped when the storage environment was perturbed leading to the emplacement of porphyritic intrusions. Further work integrating U-Pb zircon geochronology with zircon trace element geochemistry, will enable inferences to be made regarding phase fractionation and late stage geochemical trends within the storage zone, and as magma intrudes to shallower levels.

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NOTES

Linking fluid flux, fluid chemistry and degassing timescales of incrementally grown plutons: Implications for mineralization and volcanic degassing

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Typical silicic arc magmas are fluid-saturated and degas large quantities of volatiles and metals upon cooling and crystallization within the upper crust. Magma degassing is the main process driving the formation of porphyry copper deposits (PCDs) (Sillitoe 2010; Hedenquist and Lowenstern 1994) and plays an important role in controlling the dynamics of volcanic eruptions (Parmigiani et al. 2016; Sparks 2003)

Modern views of arc magmatism involve the incremental assembly of magmatic systems within the crust at typical rates of 0.0001–0.1 km^3/yr (de Saint Blanquat et al. 2011). Using thermal modelling and statistical simulations, we have modelled the flux and chemistry of outgassed fluids during pluton growth in the upper crust for various magma injection rates and final volumes (Chelle-Michou et al. 2017). Our results show that during magma injection, the volatile flux remains nearly constant and proportional to the magma injection rate. At magma fluxes >0.001 km^3/yr, low flux fluid outgassing persists long after magma injection has ceased. Interestingly, within the range of typical intermediate to felsic arc magma composition, the composition of the computed fluid is similar to that of high-temperature single-phase intermediate-density fluid inclusions measured at PCDs.

Our model suggests that (i) porphyry copper deposits can form from normal arc magmas (no enrichment required), and (ii) the size of PCDs correlates with the volume of the pluton at depth and the timescales of magmatic and hydrothermal activity. We conclude that high-precision geochronology (CA-ID-TIMS U–Pb zircon or N-TIMS Re–Os molybdenite) may be use as a tool to provide a rough assessment of the size of the deposit.

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NOTES

Porphyry copper deposit formation in the context of transcrustal magma systems

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The world's largest porphyry copper deposits (PCD) are associated with oxidised, hydrous, subduction zone magmas. It is increasingly recognized that chemical differentiation in such settings occurs within crystal-dominated mushy systems that span the entire crust, rather than, discrete melt-dominated magma chambers in the traditional sense. Mushy systems involve the independent movement of buoyant melts and fluids through a deformable crystalline matrix, consistent with observations at active arc volcanoes. Percolating fluids and melts react with their solid matrix, undergoing chemical modification en route, as melts and fluids from deeper parts of the system encounter materials (solids, melts, fluids) in the shallower part of the systems. This, volcanoes are the final expression of processes that operate over a considerable time and depth range.

Trans-crustal mush systems have considerable implications for PCD formation, notably because they provide an effective means to focus the flow of melts and fluids sourced from a large magmatic system through a narrow volcanic conduit. Modeling of polybaric magmatic differentiation, using experimental phase equilibria coupled with fluid-melt partitioning data, shows that most subduction-related transcrustal mush systems produce potential ore-forming supercritical fluids, despite the prevalence of sulfide saturation in the mid-crust. Sulfide saturation depletes residual melts in Cu, such that felsic magmas associated with PCDs have less than 50 ppm Cu. The ability of such melts to liberate Cu-rich fluids is attributable to the strong complexation of Cu with chloride ligands in the fluid. Consequently, Cu partitioning between fluids and melts is strongly dependent on fluid salinity. In turn, fluid salinity is controlled by Cl partitioning between fluids and melts, which is greatest for rhyolitic systems. Cl enrichment in fluids is further enhanced by the salinity of the fluids themselves, conferring a strong positive feedback on fluid salinity and Cu extraction. Highly saline brines that separate from supercritical ore-forming fluids at low pressure, further concentrate Cu. Copper partitioning between coexisting brines and vapours depends linearly on their salinity ratio.

Numerical modeling of fluid release from a sub-volcanic magma reservoir shows that ore-forming fluids are preferentially discharged through high permeability conduit systems, such as those associated with breccia pipes or dyke-related damage zones. As fluids ascend, they undergo phase separation to form discrete, annular lenses of magmatic brines at depths of 1-2 km. Brine lenses are capped by a layer of halite precipitated from the ascending fluids, protecting them against erosion by convecting shallow groundwaters. Thus, brine lenses are stable and long-lived. They match closely the shape, depth and electrical resistivity of shallow conductors identified by magnetotelluric surveys at many arc volcanoes. The tendency of Cu to follow salinity during phase separation concentrates Cu in the brine lenses. Subsequent addition of SO_2- and CO_2-rich fluids from the deeper magmatic system to these brines triggers sulfide mineralization and hydrothermal alteration. The resulting ore-body has a form that resembles the salinity distribution in sub-volcanic brine lenses.

NOTES

The Fate of Cl During Differentiation of Arc Magmas: Implications for Ore Formation

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Numerous studies have shown that Cl is the dominant ligand controlling the extraction and transport of Cu, Mo, Pb, Zn, and W in hydrothermal fluids, with at least a strong influence on Au, Ag, and many other ore metals[1,2]. As a result, understanding how metals are concentrated during differentiation and transferred to hydrothermal fluids requires that we understand the timing and controls on Cl-degasing. Yet numerous aspects of Cl-degassing have remained poorly constrained, especially for deeper, more primitive periods of magma differentiation. In order to provide a framework to understand the fate of Cl throughout magma differentiation we will examine results from both new experiments and existing data. Our approach addresses three major factors for Cl degassing; How do the composition of the magma, pressure of degassing, and the total chlorine available affect Cl partitioning out of magmas and into magmatic volatile phases (MVPs). We have developed an experimental design that allows for examining each of these controls independently while integrating much of the existing data into a more cohesive view of Cl behaviour throughout differentiation.

Our melt-MVP experiments examine the Cl fluid-melt partition coefficient for genetically related rhyolites, dacites and andesites from the Laguna del Maule volcano in Chile. We will present results from experiments using Inconel, TZM/MHC, and piston cylinder experiments ranging from 50 MPa to 600 MPa and covering salinities from 2 – 16 wt% $NaCl_{eq}$ salinity in the MVPs. Most of the experiments make use of an in-situ fracturing technique for trapping synthetic fluid inclusions, ensuring quantitative characterization of equilibrated fluid compositions. The combination of TZM/MHC, cold-seal, and Piston-Cylinder experiments have been used to cover relevant a pressure, temperature and compositional range that allows for examination of complete differentiation of magmas from andesite through to rhyolite along any P-T path through the crust. We will also examine Na, K, Fe, Ca and trace elements to further constrain MVP compositions during degassing.

The results from the experiments show that for more evolved melts (rhyolites and dacites) Cl partitioning does become stronger going from 50 MPa towards 300 MPa, but then begins to plateau going to higher pressures. In all cases we also observe the expected increase in chlorine partitioning into MVPs with increasing total chlorine[3]. As a result of this non-Henrian behavior, multi-phase (vapor-brine) MVPs, where *a*Cl becomes fixed in all phases, requires characterizing both fluids directly to address thermodynamic and mass balance effects of melt-vapor-brine equilibrium on chlorine partitioning. We will also present the details of Cl partitioning in andesitic systems at a range of pressures. Combining all these datasets shows how deeper less evolved magmas differentiate towards a maximum Cl extraction efficiency as they reach dacitic to rhyolitic compositions from 300 down to 100 MPa. As we better parameterize these results, and incorporate Cl-dependant functions for ore metal partitioning (e.g. Cu-Mo)[2], we will be able to model fully the potential for enrichment and extraction of ore metals into Cl-rich MVPs for a variety of differentiation paths.

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NOTES

Very Hydrous Magmas, Cryptic Water and Metal Transport Efficiency

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Porphyry copper deposits have long been recognised as an expression of hydrous calc-alkaline magmatism (Burnham 1979; Sillitoe 1973). Some of the indicators of magmatic fertility, e.g. anomalous Sr/Y (Loucks 2014) can be directly linked to porphyry-associated magmas being particularly wet (Richards 2011). 4 wt% H_2O is a common mass fraction of water reported from arc magmas, including their mafic parental melts (Plank et al. 2013). If the parental systems are 4 wt% H_2O, then simple mass balance suggests that the intermediate melts derived from lower crustal fractionation of hydrous arc basalts will be much higher in water, perhaps in excess of 10 wt%, and thus with sufficient water to saturate prior to significant crystallisation in the upper crust (Annen et al. 2006).

Simple models of fractionation that incorporate both crystalline phases and a hydrous fluid can be used to assess whether very hydrous magmas would have distinctive geochemical fingerprints as a result of water extraction and fractionation, and whether they would be effective at contributing to copper porphyry mineralisation.

Preliminary modelling of a very hydrous magma using recent partition coefficients for fluid-mobile elements (e.g. Cl, Cu, Rb) suggests that very high water contents and subsequent water extraction would be poorly recorded in whole rock chemistry – in general, the partitioning of elements into a hydrous phase is too low, even at very high water contents, for a whole rock or melt inclusion record of significant water loss. Thus, very hydrous magmas may be responsible for petrologically “cryptic water” in the crust.

It is logical that if melts and their solidified products are apparently undepleted in e.g. Cu, then the net transfer of Cu into the aqueous fluid phase is relatively inefficient. Very hydrous magmas can however, move larger masses of hydrophile elements, even if apparent concentration changes are subtle. As recognised by Cline & Bodnar (1991), copper porphyry systems need a large volume of magma to supply the Cu; large volumes of water within such magmas may be another important factor in ore-forming potential.

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NOTES

Metal volatility and environmental impacts: lessons from volcanic plume measurements

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Understanding the composition and fluxes of metals in volcanic plumes is important in terms of their impacts on the environment and human health and their use as markers of volcanic activity in environmental archives. However, such measurements also give us crucial insights us into metal volatility and behaviour in magmas. These lessons are relevant for understanding some potential ore forming processes, the use of metals as tracers of igneous/magmatic processes and wider processes associated with the composition, evolution and differentiation of silicate planets. We will present an overview of how recent plume measurements can be used to further our understanding of subsurface processes and the impacts and fate of volcanic metals in the Earth's environment following emission. Themes will include metal volatility, the role of sulphides, ash leaching and measurements of environmental availability. We will highlight the key outstanding questions ripe for future research in order to build a systematic understanding of metal behaviour in volcanic systems.

NOTES

Hydrothermal Alteration and Gold Mineralization in Talang Santo Deposit, Lampung Province, Indonesia

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Talang Santo low-sulfidation epithermal gold deposit is located in southern Sumatra, Indonesia. Sumatra Island is an attractive target with huge gold resources (770.8 t) due to a propensity of epithermal gold deposits (Maryono 2014). These deposits are controlled by active subduction between the Australian Plate and the Eurasian Plate. Talang Santo deposit began exploitation from 2011 with 1.7 Mt resources and an average of 5.39 ppm Au as of 2014. However, the relationship between gold mineralization and hydrothermal alteration zoning in this deposit has not been clarified yet. Thus, this research aims to estimate this relationship based on a three-dimensional distribution of ore mineral and clay mineral assemblages. Sampling was conducted from surface samples (700-720 masl), underground samples (from the production tunnel at 675, 650 and 620 masl) and drill-core samples (from 11 drill holes; 350-680 masl) from veins currently under exploitation.

Based on the distribution and assemblages of the clay minerals, this deposit was divided into three as follows; Illite-Chlorite Zone (IC), Argillic Zone (AG) and Kaolinite-Illite Zone (KI).
In the deep level (approximately 350 masl), wall rock alteration is intense and defined as IC. IC is characterized by presence of chlorite and illite which are formed under near-neutral and high temperature (< 230 ºC) conditions. Surrounding IC, at shallower depth and further from the main fluid conduits, AG is formed, recognized by smectite, suggesting that a temperature less than around 150 ºC and at near-neutral pH. Above IC, KI is marked with kaolinite which formed under acidic-pH and relatively low temperature (100-200 ºC) conditions.

According to microscopic observation and SEM-EDX analysis, the major identified metal minerals are pyrite, chalcopyrite, argentite, stephanite (Ag_5SbS_4) and electrum (Ag content; 46.34- 69.15 at%). Almost all electrum are observed in the IC zone and accompanied by pyrite, chalcopyrite and argentite. By contract, assemblages of pyrite and chalcopyrite, which are not present in gold-silver mineralization, are concentrated in AG.

According to the above results, the formation of hydrothermal alteration with gold mineralization can be estimated as follows;

1. From the deep level (<350 masl at present), high temperature (>230 ºC) and near neutral pH hypogene ore-forming fluid ascended. Due to this, IC was formed and gold-silver mineralization ensued with electrum and argentite precipitation and associated gangue minerals.
2. In the shallower, or further form main conduit of ore-forming fluid, AG was formed with pyrite due to relatively low temperature (about 150 ºC) and near neutral-pH fluid.
3. Above IC (> 650 masl at present), KI was formed under low temperature (100-200 ºC) and acidic-pH condition which was formed due to H_2S gas oxidation by groundwater.

NOTES

Mass wasting events and their impact on the formation and preservation of submarine magmatic–hydrothermal ore deposits

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In the terrestrial environment landscape processes can significantly affect mineral deposit evolution. For example, sector collapse at the Luise volcano had a profound impact on the formation of the giant Ladolam epithermal gold deposit, and progressive paleosurface degradation plays a key role in telescoping porphyry hydrothermal ore deposits. However, most conceptual models of mineral deposit formation in the submarine environment envisage that mineralization takes place in a relatively static landscape. The volcanic lithofacies of submarine and emergent volcanoes show that dome degradation, passive and explosive eruptions, and syn- and post-eruptive mass-wasting events dramatically alter the submarine landscape, which in turn have the potential to significantly modify associated magmatic-hydrothermal and geothermal systems.

Milos island, Greece, has on-land exposures of well-preserved, young (<3 Ma) submarine and mineralized volcanic edifices. Using the historically exploited Pb-Zn-(Ag) mineralization of Triades as analogues for seafloor mineralization, here we show mass wasting events in the shallow (<500 m) marine environment influence deposit style and metal inventories, and negatively impact on the resource prospectivity of the seafloor. In the Triades area, coherent lava domes have brecciated margins and debris aprons of hyaloclastite and reworked autobreccia. Intact lava domes are still present as steep-sided topographic highs and the seafloor palaeotopography was presumably dominated by the steep sided lava domes, much as it is now (Figure 1). Mineralization is associated with intensely silicified (quartz) and baritized breccias (Figure 1), which often occur as steep sided, <10 m high, edifices usually associated with NE- and E-trending faults.

Figure 1 View of lava domes and breccia bodies at Triades. Solid lines show the limits of coherent dome facies, which is unaltered or only has incipient hydrothermal alteration. Dashes lines show the locations of quartz breccia bodies.

Late stage crystalline quartz and barite envelopes breccia body surfaces and dilated fractures, and commonly exhibits euhedral, void filling textures. Sulfide ore minerals are found in the matrix of the barite-quartz breccias, or as pod-like veins and lenses at the base of the breccia domes. In addition, clasts of reworked barite (with and without sulfide ore) in barite-cemented breccias are evidence of periodic or continual reworking of the partially exhalative hydrothermal mineralization, and variably altered volcaniclastic material in the breccias suggest input from lava domes. The geological evidence points towards the repeated growth of over-steepened domes comprising both lava and hydrothermal minerals, with partial and complete collapses and re-cementation of the brecciated material. The mineral paragenetic sequence is consistent with a Pb-Zn-(Ag) massive sulfide system, and analogous to the early stages of a Kuroko-type deposit, but Triades lacks massive sulfide bodies. We, therefore, suggest that mass wasting events literally truncated the developing mineral deposit as it formed on the seafloor, destroying massive sulfide bodies and limiting the development of the ore mineral assemblages. Mass wasting processes in volcanogenic massive sulfide systems are ore-destructive, with little opportunity for “telescoping”, unlike terrestrial equivalents. Shallow marine systems in terrains subject to mass wasting may have low preservation potential, or may be classified as epithermal-like vein systems rather than stockwork portions of massive sulfide deposits.

NOTES

Gold Mineralisation in the Southern Uplands – Longford Down Complex in Scotland and Ireland: Review and synthesis of the role of late-Caledonian magmatism

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Alluvial gold is widespread in southern Scotland, but the fundamental causes of mineralisation remain elusive. The gold is hosted by the Southern Uplands–Down-Longford Terrane (SUDLT), a Lower Palaeozoic accretionary prism and foreland fold and thrust belt dominated by turbidites and black shales. Structurally hosted lode-gold associated with As and Sb mineralisation is known from a small number of localities and the region has been classified as an orogenic gold province [1]. However, late Caledonian calc-alkaline plutons of the Trans-Suture Suite (TSS) [2] together with minor intrusions of lamprophyre, granodiorite and appinite support a possible magmatic role in mineralisation. Alteration mineral assemblages are compatible with epithermal and intrusion related systems. Gold is associated with magmatic PGE-rich Ni-Cu sulphide within a diorite sill at Talnotry [7]. Fluid inclusion data indicate that remote from known intrusions gold was deposited from a mixed magmatic-metamorphic fluid [3,4]. The As-Sb-Au deposits exhibit a spatial association with minor dioritic, monzonitic and granodioritic intrusions [5] but not clearly with the major plutons [3, 6]. Porphyry Cu, associated with late Caledonian granodiorites at Black Stockarton Moor also supports a magmatic source of sulphide and metals.

Isotopic characteristics of the TSS plutons indicate a source in Avalonian crust that was underthrust beneath the Iapetus Suture, including a component derived from pelites of the Skiddaw Group [8]. The lamprophyres and appinites were probably sourced in sub-continental mantle metasomatised by subduction. The granitoid magmas were probably hydrous due to a hydrated mantle source [8]. At least some of the more primitive (appinitic) magmas have transported gold, PGE's, Cu and Ni from the lower crust or mantle and have become sulphide-saturated at higher crustal levels.

Recent U-Pb zircon ages show that TSS magmatism occurred between 425-380 Ma, coeval with that in the Grampian Highlands. Magmatism in both regions can be explained by slab break-off and partial delamination of the Avalonian lithosphere following the collision of Avalonia with Laurentia [6,9]. Extrusion of asthenosphere through the slab window caused melting of metasomatised lower lithospheric mantle, generating voluminous lamprophyric magmas that underplated the crust, triggering partial melting and generation of the intermediate and granitoid magmas that formed the major TSS plutons and minor intrusions. We extend this scenario and suggest, following [10,11], that sulphides in the metasomatised mantle or underplated lower crust were enriched in PGE's, As, Cu and Au and that these elements could have been remobilised during partial melting and carried to higher crustal levels. Sulphur saturation, perhaps due to interaction with Skiddaw slate and/or Moffat Shale, could have triggered exsolution of an auriferous sulphide melt which, during crystalisation at shallow crustal levels (~5 km) would have released gold into aqueous fluids that could have migrated along active faults to form Au-As, Sb and Cu lode deposits of an epithermal and intrusion-related character. In addition, metamorphic reactions due to the heat flow associated with the magmatism could have generated sufficient metamorphic aqueous fluids capable of mobilising and concentrating dispersed gold from the metasedimentary country rocks of the SUDLT. The well-constrained geology of the SULDT provides excellent opportunities to investigate further the relationships between magmatism, tectonism, metamorphism and gold mineralisation during the transition from subduction to collision.

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NOTES

Precambriam magmatic ore systems of the northern São Francisco Craton-Bahia-Brazil

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The northern part of the São Francisco Craton in the State of Bahia in Brazil displays important metalogenetic corridors associated to magmatic ore systems nested along paleosutures that bound the Archean blocks of the São Francisco Province. According to geochronologic data they are related to magmatic events which have occurred both in the Neoarchaen and immediately after the Eburnian-Tranzamazonic collision between the Congo Craton and the Archaen Blocks that came to form the Sao Francisco Craton [1].

The metalogenetic corridors consist of two main ore systems: 1- Caraiba (2.5Ga.) mafic-ultramafic-related Cu- deposit and b) the Fe-Ti-V mafic-ultramafic-associated (2.64Ga.) Maracás deposit, and 2-Palaeoproterozoic Layered intrusions-associated Ni-Cu-PGE, Cr and Fe-Ti-V deposits a) Ni-Cu-PGE (2.06) magmatic sulfide deposits, b) Stratiform and (2.08Ga) Komatitic/Picritic sills-related chromite deposits. It is observed that the chromium belts are located hundreds of kilometres far in the northern part of the Salvador-Curaçá Block, whilst the Ni-Cu and Fe-Ti-V belt are located in the southern part of the Itabuna-Salvador Block. We propose this situation can be modelled by inferring a northward-drifting Sao Francisco Plate (Atlantica Continent) over a fixed hot spot or plume head.

According to the literature [2] plume-related magmatism is responsible for the production of very large volume of magmas usually credited for the formation of LIP – Large Igneous Province, such as Continental Flood Basalts, (eg. Paraná, karoo, Cape Smith, Siberia and Large Layered Intrusions e.g. Bushveld Complex). In this contribution we believe the Neoarchean and Paleoproterozoic magmatic provinces have been fed by a melting zone over a plume head that may have affect an area larger than thousands of square kilometres of the Archaen and Paleoproterozoic terrains of the Northern São Francisco Craton. Magmas from the melting zone may have travelled thousand kilometers away from the plume head or hot spot which, may have left a trail of contemporaneous mafic-ultramafic bodies. The trails are coincident with major crustal discontinuities, faults, rifts boundaries and axial zone of ancient continental rifts as predicted in the literature [3], that have been constituting long lived magma conduits within province scale magma freeways [4].

By applying this plume model we propose the chromium and nickel-copper magmatic ore systems of the Itabuna-Salvador-Curaçá Block have been fed by different parts of the Orosirian plume. In this scenario komatitic magmas from the plume centre could have been the source of the chromium magmatic ore systems, whilst picritic magmas adjacent to the plume centre, might have supplied the Ni-Cu magmatic ore systems. On the other hand, ferro-picritic magmas could be the source of the Fe-Ti-V Neoarchean magmatic ore systems.

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NOTES

The Factors Influencing Sc Concentration in Nickel Laterite Deposit, Carrascal, Eastern Mindanao Island, Philippines

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Scandium (Sc) is used in many fields, which utilize aluminum alloys, such as the aircraft and manufacturing industries. Recently, it is more economically effective to recover Sc as by-product from operating mines, rather than opening new Sc mines. Nickel laterite deposits produce more than 60% nickel in the world and concentrate many other elements during the weathering process. There is potential for Sc production from nickel laterite deposits due to the significant eluviation of mobile elements which concentrate REE (especially Sc) as it weathers. Additionally, the market for Sc is expected to rise new Sc leaching processes going online. However, the concentration mechanism of Sc has not been fully understood. Therefore, this study aims to reveal the geochemical behavior of Sc during weathering, and factors influencing Sc concentration on the nickel laterite deposits.

Laterite and bedrock samples were collected from drilling holes and mining benches of nickel laterite deposits located in Eastern Mindanao island, Philippines. Laterite samples were classified into three rock units by their FeO contents: limonite (i.e., FeO>60%), earthy saprolite (i.e., 30%<FeO<60%) and rocky saprolite (i.e., FeO<30%). Limonite zone exhibits a deep reddish brown color due to the presence of Fe minerals such as goethite and hematite. Saprolite zone (i.e., earthy saprolite and rocky saprolite zones) consists mainly of serpentine and exhibits light yellowish brown color. Microscopic observation shows that the bedrock is harzburgite containing olivine, orthopyroxene and serpentine.

Bulk X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analyses reveals that Sc concentrates in the shallower zones (i.e. limonite and earthy saprolite zones) because of its immobility. Positive correlation with Fe and Al are also observed, since mobile elements are dissolved and percolated downward during the weathering process. On the other hand, Sc was immobile against the weathering because Sc showed similar geochemical behavior of Fe3+ as Sc replaces Fe3+. Scandium distribution in the bedrock was determined by elemental mapping using LA-ICP-MS (NWR193UC Laser Ablation System + Agilent 7900 ICP-MS). Olivine contains higher Sc value (45ppm) than orthopyroxene (26ppm). However, Sc is more easily distributed into pyroxene rather than olivine according to the partition coefficient of ultramafic minerals from the previous study. The factors on why Sc content in olivine is higher than in pyroxene are: (1) clinopyroxene, which has higher partition coefficient than orthopyroxene, is not observed in the Carrascal samples; (2) higher Ca content limits the Sc distribution in pyroxene during the magmatic crystallization.

NOTES

The fate of sulfur in Arcs

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Volcanic arcs, where continental crust is built, and earthquakes and volcanoes are sourced are the breading grounds for the biggest ore deposits. Despite their immense metal budgets, arcs stand out mostly as sulfur anomalies. More sulfur is erupted from arcs than is thought possible (Oppenheimer et al., 2011) yet magatons remain in the crust. How could arcs be so sulfur rich? To make matters even more confusing, arc magmas carry sulfur as dissolved sulfide and/or sulfate in the melts and excess S as sulfide melt or anhydrite crystals. This mixed valence is both a key complication and a key clue to unraveling sulfur's pathways through arcs. Once exsolved, S travels as gas, vapor, liquid (brine) or melt, all of which are found in sub-volcanic ores. Veins of quenched sulfosalt melt are present in structural feeder zones to "high-sulfidation" epithermal deposits (Tanner et al., 2015), while chalcopyrite-anhydrite veins are ubiquitous in the deeper porphyry environment. Thus, at least two sulfur valences (S^{2-} and S^{6+}) are found in these environments. For many years we have known that copper chloride is extremely soluble in solution (e.g. Hack and Mavrogenes, 2006). However, recent experiments (Louvel et al., 2017) suggest that copper is insoluble if reduced sulfur is present. Thus, copper chloride in solutions containing oxidized sulfur may be major transport process active in arcs. Furthermore, local reduction of sulfur at or near the depositional site provides anhydrite plus sulfides in porphyry vein systems (Mavrogenes and Blundy, 2017). Thus, both copper and sulfur can be transported until wall-rock reactions trigger sulfide/sulfate deposition in veins. These veins often contain the bulk of the copper extracted from a porphyry mine. There are, of course, other pathways for fluids/gases to traverse the lower crust and form ores at shallow levels. Epithermal feeder zones provide a view of one such pathway. Another pathway is only glimpsed in metamorphosed sulfide deposits exposed from deep in the crust. These melts may link from deep crustal melting to shallow ore formation (Tomkins and Mavrogenes, 2003).

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NOTES

Sulfide saturation and breakdown during the 2014–2015 Holuhraun eruption, Iceland

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The 2014–2015 Holuhraun basaltic fissure eruption (Bárðarbunga volcanic system, Iceland) lasted for six months (from 29 August 2014 to 27 February 2015) and was remarkably sulfur-rich, emitting large quantities of SO_2. The gas flux varied through the eruption, with maximum emission rates measured in early September 2014 [1]. Sulfide globules, representing quenched droplets of an immiscible sulfide melt, are preserved within erupted tephra. In this study, we investigate the extent to which shallow breakdown of co-existing sulfide phases may have modulated the efficiency of sulfur and trace metal outgassing.

Sulfide globules in rapidly quenched tephra are preserved within both matrix glass and as inclusions in crystals. The size distribution of sulfide globules ranges from <1 µm to 30 µm, with a modal diameter of ~10 µm. Sulfides are not uniformly distributed, and are instead most commonly observed in association with sub-millimetre-scale plagioclase-clinopyroxene-olivine glomerocrysts, which exhibit sub-ophitic growth textures. Maximum dissolved sulfur concentrations of 1750 ppm in melt inclusions and matrix glass next to sulfides are consistent with empirical determinations of the sulfur content at sulfide saturation (SCSS) for MORB, expressed as a function of melt FeO at low pressures (Fig. 1; [2]). The Holuhraun magma appears to have been sulfide-saturated, and therefore co-existing with an immiscible sulfide liquid, throughout much of ol-cpx-plag crystallisation. Individual globules are associated with locally elevated dissolved sulfur concentrations, with concentration gradients away from sulfides preserved over distances of 10–40 µm from the melt-sulfide interfaces (Fig. 1). Compositional gradients are most apparent for sulfides in confined positions, such as within crystal embayments. Kinetically limited disequilibrium sulfur degassing likely maintained localised sulfide saturation during shallow ascent and eruption.

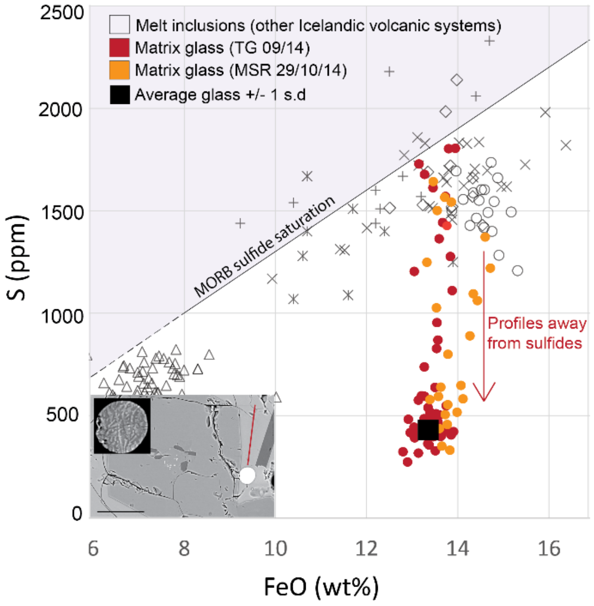

Fig. 1: Elevated sulfur concentrations in glass surrounding sulfide globules, compared to degassed melt. Dashed line indicates SCSS for MORB as a function of melt FeO at low P [2]. Analysis points were spaced at 10 µm intervals along profiles away from sulfides [e.g., red line in inset image]. Sulfur concentration gradients away from sulfide globules were preserved over distances of 10-40 µm from the melt-sulfide interfaces.

Sulfide microtextures indicate segregation of Ni/Fe-rich (monosulfide solid solution) and Cu-rich (intermediate solid solution) domains during cooling and crystallisation (Fig. 2). Five distinct textural classes are identified: [1] Homogeneous; [2] Finely intergrown; [3] Coarsely intergrown; [4] Discrete domains; and [5] Partial dissolution. The proportion of sulfides within each class varies through the eruption, with a temporal increase in the number of globules exhibiting partial dissolution from 18% in a sample from 4 September 2014 to >50% in samples erupted after 29 October 2014. The reconstructed bulk sulfide liquid composition – (S) 33 ± 1 wt.%, (Fe) 47 ± 4 wt.%, (Ni) 2.3 ± 0.5 wt.% and (Cu) 17 ± 5 wt.% – remains constant throughout the eruption.

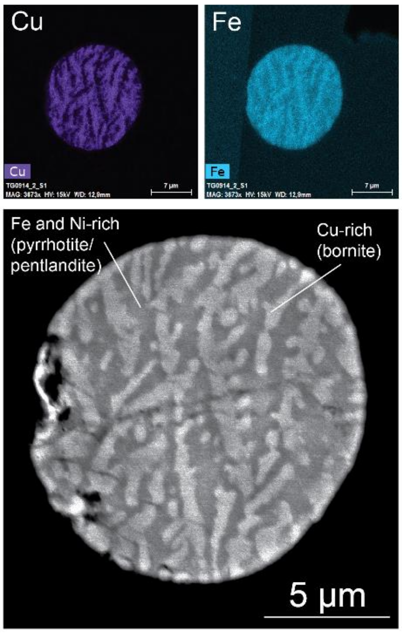

Fig. 2: Sulfide globules exhibit micro-scale exsolution textures, indicating crystallisation of a sulfide liquid into Fe/Ni-rich and Cu-rich domains. Trace metals partition differently between monosulfide- and intermediate-

Chalcophile metal abundances are identical in glass next to and away from sulfides, suggesting sulfide-silicate melt equilibrium. However, sulfide globules observed in close proximity to vesicles show clear breakdown textures and are markedly sulfur- and metal-poor (yet Fe-rich). We propose that sulfur and metals were released directly into a vapour phase during syn-eruptive sulfide dissolution. Further research aims to reconstruct chalcophile element budgets from analysis of trace metal abundances in co-erupted silicate glass, Fe-Cu-Ni sulfide, and volcanic plume aerosol.

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NOTES

Chalcogen Variations in Oceanic Plateau Basalts and the S Budget of their Associated Eruptions

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Voluminous eruptions of oceanic plateau basalts, which form some of the largest flood basalt provinces on Earth, have the potential to release significant volumes of volatiles to the atmosphere. Sulphur (S) plays a key role in climatic regulation (as SO_2) as well as controlling the distribution of chalcophile (sulphide-loving) elements between the mantle and crust. However, low pressure degassing of volatile-rich melts makes it difficult to constrain pre-eruptive S budgets and therefore the atmospheric flux of S associated with large volcanic eruptions. Unlike S, Se shows minimal evidence for degassing during volcanic eruptions. Well-constrained S/Se ratios, together with other chalcophile element ratios, may therefore be used to constrain the pre-eruptive behaviour of S in magmatic systems.

We have determined the major, volatile (H_2O, CO_2, F, P, S and Cl) and trace element content of 63 igneous glass samples from the plume-related Ontong Java (OJP; n=37), Shatsky Rise (n=14) and Kerguelen (n=12) plateaus by EPMA, LA-ICP-MS/MS and SIMS. All plateau samples are sulphide-undersaturated in contrast to the behaviour shown by the mid-ocean ridge basalt (MORB) array. Cu and Ag increase significantly with differentiation (decreasing MgO). In addition, both S/Se and Cu/Se are constant for any given plateau (OJP, Shatsky and Kerguelen). This contrasts with the MORB array where sulfide-saturation leads to increasing S/Se and significantly decreasing Cu/Se with differentiation.

CO_2 is degassed during differentiation and/or eruption in all the plateau samples studied. However, only those from the Tamu Massif, a sub-marine shield volcano of the Shatsky Rise show evidence for S degassing. S/Se and S contents are comparably lower at a given MgO than the MORB-OPB array. At a median MgO content of 6 wt.% for Tamu Massif glasses, a S/Se of 3244 is estimated from the associated undegassed Shatsky – Ori Massif. This value corresponds to a pre-eruptive S content of 1459 ppm. At a median measured S content of 471 ppm, Tamu Massif samples are therefore calculated to have lost approximately 68% of their pre-eruptive S content (988 ppm).

Assuming all S degasses as SO_2, an eruptive volume of 2.5×10^6 km^3 and an average magma density of 2.5 g cm^{-3}, we calculate a total atmospheric SO_2 flux of 1.2×10^{13} tonnes associated with the formation of the Tamu shield at ~140 Ma. This corresponds to a total eruptive SO_2 volume of 4.7×10^6 km^3. Such values suggest a catastrophic flux of volatiles to the atmosphere associated with the formation of sections of the Shatsky Rise.

NOTES

The effect of titanite crystallisation on Eu and Ce anomalies in zircon and its implications for the assessment of porphyry Cu deposit fertility

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Zircon ($ZrSiO_4$) has proved to be one of the most useful minerals in the study of igneous and metamorphic petrogenesis because of its robustness as a geochronometer, the sensitivity of certain trace element substitutions to intensive parameters, and its resistance to high-temperature diffusive re-equilibration. Experimental studies[1,2] have demonstrated that the magnitude of Ce and Eu anomalies (commonly observed in zircon) vary as a function of melt oxidation state. This makes zircon a potentially useful mineral indicator in exploration for porphyry Cu deposits[3] which are thought to be derived from oxidised magmas[4]. However, Eu anomalies in particular are also strongly affected by the co-crystallisation of phases such as titanite ($CaTiSiO_5$), which strongly partitions REEs and imparts positive Eu anomalies on residual melts.

We report the trace element chemistry of zircons from titanite-bearing intrusions associated with mineralisation at the world class Oyu Tolgoi porphyry Cu-Au deposit (Mongolia). Zircons frequently display rims which contain small (<10µm) inclusions of titanite, and cores which lack titanite inclusions. There is a systematic difference between the chemistry of cores and titanite-bearing rims, the latter of which have extremely high Eu/Eu*, Ce^{4+}/Ce^{3+}, and Yb/Gd, and lower Ta, Nb, and Ta/Nb than the cores (Fig. 1).

Using fractionation models, we demonstrate that the unusual chemistry of the rims may be accounted for by the late-stage *in situ* crystallization of vanishingly small amounts of titanite (~0.2 vol.%). Consequently, we suggest that neither Eu/Eu*, nor Ce^{4+}/Ce^{3+} are robust proxies for melt redox conditions, because they are both too strongly dependent on melt REE concentrations, which are usually poorly constrained and which may be controlled by the crystallisation of titanite and other REE-bearing phases. Ce/Ce* is not affected by this process, and may provide a more robust measure of melt redox conditions, although this parameter is difficult to calculate. Eu/Eu* may still be a useful indicator of porphyry magma fertility, as it is able to broadly distinguish between fertile and barren systems.

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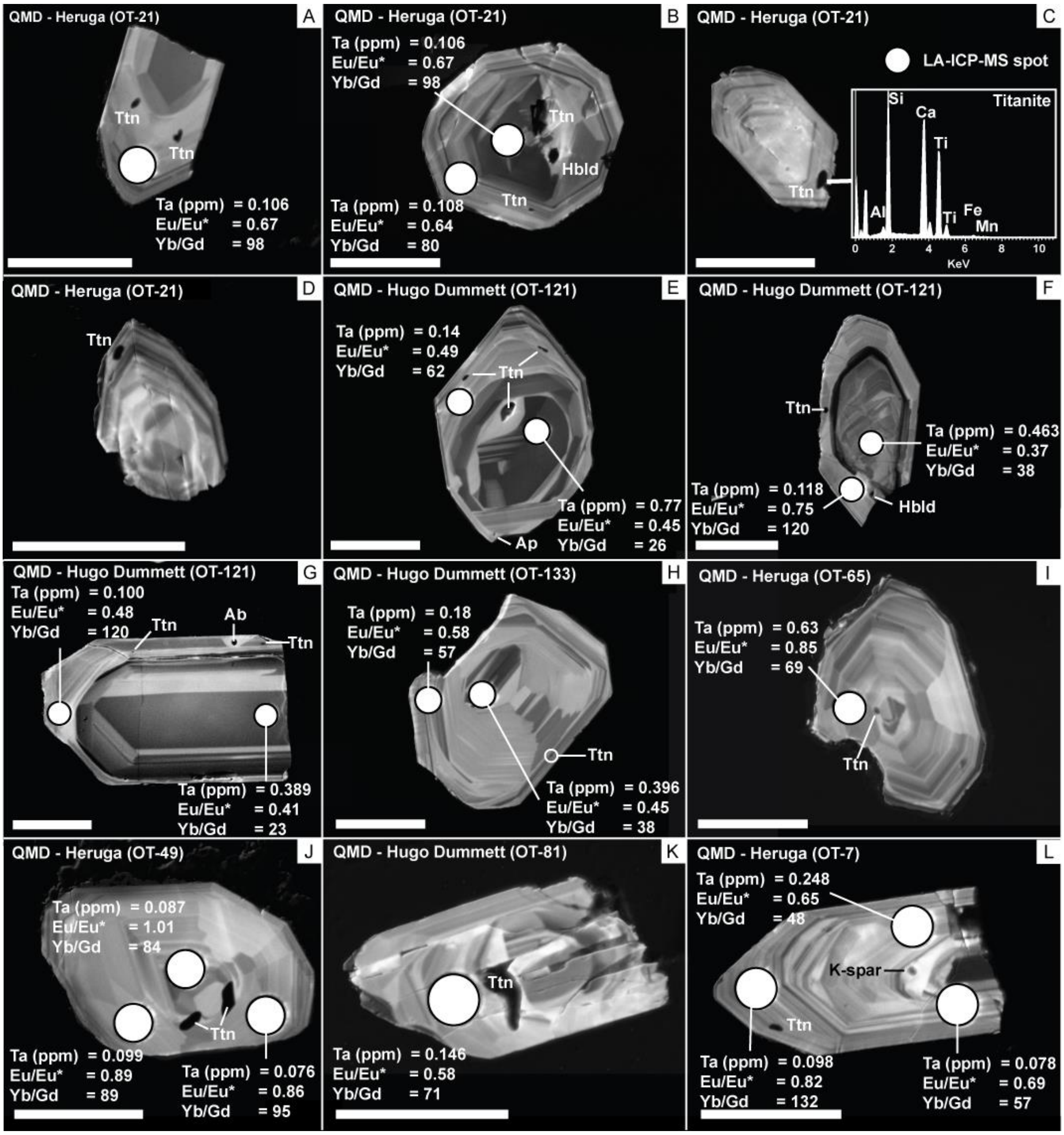

Figure 1. SEM-cathodoluminescence images of zircon grains from quartz monzodiorite intrusions of Oyu Tolgoi. Several grains contain distinct rims and cores, which are separated by a dissolution boundary (e.g. A, E–H, and L), and rims contain inclusions of titanite (Ttn), which was identified by EDS analysis (inset). Zones which contain titanite have higher Eu/Eu*, Yb/Gd, and lower Ta than zones without titanite. Other mineral inclusions are albite (Ab), K-feldspar (K-spar), hornblende (Hbld), and apatite (Ap). Scale bar in all figures is 100µm.

NOTES

Applying the plagioclase discriminator to the GEOROC database of Japan

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Plagioclase discriminator

The diminishing discovery rate of near-surface porphyry copper deposits necessitates new methods for identifying targets situated deeper in the crust. Techniques that enable this vectoring towards prospective arc segments and identifying magmatic suites with high ore-forming potential may provide additional exploration tools. Mineral chemistry is one such technique where we might identify magmatic processes that increase the probability of ore formation.

The study of Williamson et al. (2016) indicated that plagioclase composition can potentially be used as an indicator of porphyry-forming potential in calc-alkaline arc magmatic rocks. The method is based on identifying the presence of excess Al (Al*), higher than the theoretical maximum in the plagioclase structure, which is calculated using the formula $Al^* = (Al/(Ca+Na+K))-(0.01*An)$. Values >1 identify as a greater potential for ore formation, whereas those <1 are determined to have lower potential. In a case study of a nested porphyry system, Williamson et al. (2016) showed that plagioclase from the La Paloma and Los Sulfatos deposits in Chile plotted mainly in the fertile field.

Geology of Japan

The basement of Japan consists predominantly of accretionary complexes and gneiss, which were then then intruded by Cretaceous granitoids (Sasaki and Ishihara 1979). The basement was originally part of the Eurasian continent but was separated during Mid-Miocene rifting. Tertiary magmatism consists mainly of reduced ilmenite-series plutons with the presence of some magnetite-series intrusions in northwest Honshu, and northern Kyushu. No porphyry copper deposits have been discovered to date in Japan, despite the supposed favourable tectonic setting and the occurrence of related hydrothermal deposits. Several hypotheses have been proposed for the absence of deposits, including, a history of extensional regimes more suited to the formation of VMS-style mineralisation, the presence of extensive caldera collapse features indicating loss of volatiles, and a dominantly reducing basement that restricts the emplacement of oxidised granitic melts in the shallow crust (Sillitoe, 1980; Qin and Ishihara, 1998).

Japan fieldwork

GEOROC is an online database of worldwide published geochemical data consisting of >1,000,000 analysis of whole rock data and mineral analysis. This provided a valuable and testable data set for a desk study to identify possible areas of sampling interest. Fieldwork conducted in northern Honshu in June 2017 was a sampling regime aiming to collect a range of Cretaceous, Miocene and Quaternary igneous rocks. The objectives of this are to test the plagioclase discriminator in relation to the associated mineralisation. These will be compared to samples collected from worldwide porphyry deposits, which were selected from the ore collection at The Natural History Museum.

Abstract submitted for a poster presentation – (however, the presenting author will unfortunately be absent on the final day)

NOTES

Fenite as an exploration indicator for rare earth and niobium mineralisation, and their importance within the magmatic story

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Carbonatites and alkaline rocks are the most important source of rare earth elements (REE) and niobium (Nb), metals imperative to technological advancement and associated with large supply risks (Wall, 2014; Goodenough et al., 2016). Intrusions of these alkaline magmas are typically associated with metasomatically altered aureoles of country rock, termed fenite. Multiple pulses of alkali-rich fluids are expelled from cooling melts, altering the surrounding country rock in a process called fenitisation (Morogan, 1994).

The vast majority of research regarding these carbonatite and alkaline complexes focus on the igneous intrusions, with literature comparatively neglecting descriptions and interpretations of the associated fenite aureoles. Fenitizing fluids contain high quantities of alkalis (up to 30 % Na_2O + K_2O, Bühn, 2002) and volatiles that were originally components of the magma. Therefore descriptions of these systems are incomplete without a description of their associated fenite.

Complexing anions such as Cl^-, F^- and CO_3^{2-} are also contained within these fenitizing fluids, greatly enhancing the solubility of REE and Nb (Williams-Jones et al., 2012), causing them to mobilised out of an enriched magma and in to the surrounding country rock. Micro-mineral assemblages enriched in these elements are precipitated within the surrounding fenite (see Fig. 1) (Dowman et al., 2017). REE are typically concentrated in later, more evolved magmatic intrusions due to their incompatibility (Wall, 2014) and Nb within intermediate stage intrusions (Mariano, 1989). Therefore the complexity of a fenite and brecciation, associated with the release of fluid and volatiles from a crystallising melt, could reflect the stage of magma evolution and therefore enrichment in REE and Nb within the source intrusion. Alteration patterns have been used with great success as a tool to finding ore deposits associated with igneous intrusions, such as porphyry copper. The presence of REE and Nb micro-mineral assemblages in addition to spatial mineralogical and textural fenite zonation (Le Bas, 1981; Doroshkevich et al., 2009), indicates a great potential for these fenites to be used as exploration indicators.

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NOTES

Perspectives on the evolution of magma bodies from numerical modelling

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Constraining the duration and evolution of crustal magma reservoirs and their volatile loss is crucial to our understanding of volcanic and ore processes. Although recent studies have revealed the presence, location, and melt fraction of multi-level (polybaric) storage zones in the crust, an evaluation of the mass and heat budget of the entire crustal column has been lacking. We use a numerical model to determine the thermal conditions under which both lower and upper crustal magma bodies form. We find that large lower crustal crystal-rich magma bodies (“mush zones”) supply heat to the upper crust and reduce the amount of thermal energy necessary to form subvolcanic reservoirs. This indicates that the crust is thermally viable to sustain partially molten magma reservoirs over long timescales ($>10^5$-10^6 yr) for a range of magma intrusion rates (10^{-4} to 10^{-2} km^3/yr). Our results reconcile physical models of crustal magma evolution and field-based estimates of intrusion rates in numerous magmatic provinces (including both volcanic and plutonic lithologies). We also show that young magmatic provinces ($< 10^5$ yr old) are unlikely to support large upper crustal reservoirs, whereas longer-lived systems ($>10^6$ yr) can accumulate magma and build reservoirs capable of triggering supereruptions, even with intrusion rates lower than 10^{-2} km^3/yr. Hence, the total duration of magmatism is critical in determining the size of the magma reservoirs, and should be combined with the magma intrusion rates to assess the capability of magmatic systems to form large eruptions, as well as ore deposits.

Additional to the formation of magma bodies, volatile loss from these bodies is another important stage in the creation of ore deposits. The large amount of volatiles expelled into the atmosphere during volcanic eruptions (i.e. volcanic outgassing) is the most obvious display of magmatic volatile release. However, owing to the large intrusive:extrusive ratio (up to 30:1, in continental settings), and considering the paucity of volatiles left in intrusive rocks after final solidification (typically < 1 wt.%), volcanic outgassing likely constitutes only a small fraction of the overall mass of magmatic volatiles released to the Earth’s surface. Therefore, as most magmas stall on their way to the surface, outgassing of uneruptible, crystal-rich magma storage regions will play a dominant role in closing the balance of volatile element cycling between the mantle and the surface. We use a multi-scale numerical approach to study the migration of a magmatic volatile phase in mush zones to quantify outgassing efficiency. We find that outgassing in a crystal-poor state (< 0.4 crystal volume fraction) is likely to be inefficient. Buoyancy-driven outgassing allows for a maximum of 40-50 % volatiles to leave the reservoir for crystal volume fractions between 0.4 and 0.7, implying that a significant amount of outgassing must occur at high crystal content (>0.7) through veining and/or capillary fracturing.

NOTES

Insights into the Petrogenetic Evolution of Porphyry Systems using Integrated Zircon Trace Element and Melt Inclusion Analyses: A Case Study from the Maronia Magmatic Corridor, NE Greece

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Models of porphyry copper deposit (PCD) formation are centred on fundamental observations common across mineralised systems and have several ideas in common: 1) regional calc-alkaline magmatism produces highly fractionated, hydrous magmas; 2) oxidised conditions allow for the transport of S, Cl and metals within the magma; 3) a shallow, exsolved magmatic-hydrothermal fluid is responsible for concentrating metals from the magma; 4) a mechanism of fixing the metals into the observed reduced, sulphide-hosted hypogene mineralisation is required [e.g. 1]. However, quantification of these conditions is generally poor due to the pervasive nature of the hydrothermal alteration associated with mineralisation. Zircon, which is ubiquitous in mineralised and un-mineralised intrusions, offers a solution to this problem, providing the opportunity to study the chemistry of the original, unaltered ore metal-bearing magmas.

Our study area is the Maronia Magmatic Corridor (MMC) of Northeastern Greece. It is a NE – SW trending belt of Oligocene high-K to shoshonitic, calc-alkaline plutons hosting porphyry – epithermal style mineralisation with significant by-product metal mineralisation including Re and Au-Ag tellurides [2]. Whole-rock geochemical analyses of the unaltered host plutons indicate a metasomatised lithospheric mantle source of the magmas, with varying degrees of crustal contamination. Late, metal-bearing porphyritic intrusions closely follow the emplacement of the host plutons; however, intense argillic to advanced argillic alteration has completely destroyed the original mineralogy and igneous texture of the porphyries leaving few clues as to their petrogenesis. We use zircon, a common accessory mineral in igneous lithologies including throughout the MMC, to study the melt chemistry and fertility of these mineralisation-related porphyry intrusions.

Geologically robust, with negligible diffusion of ions through the crystal lattice even during intense hydrothermal events [3], zircon incorporates trace elements during crystallisation, reflecting the geochemistry of the parental magmatic system [e.g. 4]. Melt inclusions, aliquots of parental magmas trapped during crystallisation, are armoured by the zircon during hydrothermal alteration, thus offering the opportunity to directly study the parent magmas. By integrating geochemical analyses of the zircon with high-precision U-Pb ID-TIMS zircon geochronology, we use zircons chronicle the evolving geochemistry, both in time and space, of intrusions of intermediate to felsic magmas from a single magmatic centre.

Our results show pulsed magma accumulation of the host plutons over 100,000s year timescales in the early Oligocene, with evidence of subsequent rapid exhumation, crystallisation and cooling of these systems. By contrast, late Cretaceous cores and early Oligocene rims of the porphyry zircons suggest a more protracted magmatic history of the metal-bearing intrusions. Strong evidence of inheritance, with an S-type crustal signature, suggests mixing of a significant crustal component during porphyry petrogenesis and offers a line of further enquiry regarding the exotic metal enrichment observed in these systems.

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NOTES

The role of semi-metals (Se, Te, Bi) in precious metal transport within high temperature magmatic-hydrothermal systems.

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As well as the major source of copper, porphyry deposits represent a potential alternative high tonnage resource for platinum group elements (PGEs) and other critical metals such as Te, Se and Bi that may be recovered as by-products. The Skouries deposit is a PGE-enriched Au-Cu porphyry system in the Chalkidiki peninsula, Greece, with associated Ag, Bi, Te and Se credits. The deposit is hosted by multiple porphyritic monzonite and syenite intrusions, which are similar petrologically, close temporally, and are interpreted to originate from a large magma chamber at depth. The Cu-Au mineralisation is present as bornite, chalcopyrite and electrum in three 'main stage' vein sets.

Fluid inclusion analysis of the mineralised veins shows an evolution from an early, CO_2-rich fluid to later highly saline brines. Brine inclusions contain diverse daughter minerals including hematite, anhydrite and barite, showing the fluids to be highly oxidised. Micro-thermometry performed on a high temperature stage shows the brine inclusions homogenise by halite dissolution at temperatures of between 400°C and 870°C (n=60), with total salinities of between 60 wt. % and 95 wt. % combined salts. LA-ICP-MS of brine inclusions yielded an average Cu content of 0.34 wt.% and an average Au content of 0.7 ppm (n=44). The fluid inclusions also contain relatively high concentrations of Bi (average 405 ppm) and Ag (average 28 ppm). The Cu/Au of the first generation of brine inclusions in the mineralised veins (0.0005) most closely matches that of the whole rock assay data (0.0002). These are therefore interpreted to represent the main mineralising fluid, with the CO_2 inclusions representing magmatic gas input that waned over time.

In situ LA-ICP-MS analysis of sulphides from the main stage vein sets has shown that the majority of Se is hosted within sulphides, with bornite and galena containing average Se concentrations of 549 ppm and 3.9 wt.% (from EPMA analysis) respectively. Bi and Te are also concentrated within bornite, with average concentrations of 2451 ppm and 31 ppm respectively, as opposed to averages of 5 ppm in chalcopyrite and 7 ppm and 9 ppm respectively in pyrite. Ag is present in bornite (average 242 ppm) and chalcopyrite (average 9 ppm) but is below detection in most pyrites, except those in the first mineralised vein set (average 3.1 ppm, n=11). Au and Pd are only present in a limited number of sulphides. Au has an average concentration of 0.4 ppm in pyrites (n=15), 0.8 ppm in chalcopyrite (n=7) and 0.9 ppm in bornites (n=4) while Pd has average concentrations of 1.8 ppm in pyrites (n=22), 1.1 ppm in chalcopyrites (n=12) and 0.2 ppm in bornites (n=4). Time resolved LA-ICP-MS data shows both Pd and Au are present as micro-phases or mineral inclusions.

The extremely high temperatures of the ore forming fluids allows for the presence of co-melts, potentially including relict sulphide melt droplets. SEM-EDS and EPMA analysis of vein samples from Skouries has identified the platinum group minerals (PGM) sopcheite ($Ag_4Pd_3Te_4$), sobolevskite (PdBi), kotulskite (Pd(Te,Bi)) and merenskyite ($(Pd, Pt)(Te, Bi)_2$), as well as hessite (Ag_2Te), sylvanite ($(Au,Ag)_2Te_4$), empressite (AgTe), volynskite ($AgBiTe_2$) and electrum (Au_8Ag_2). These PGM and Au minerals have spherical morphologies and are found within euhedral hydrothermal quartz crystals. This, combined with their low concentrations in sulphides, suggests they were transported as a melt and precipitated due to a drop in temperature rather than being transported solely as ligands within the fluid. As the Pd-Bi-Te system is molten above 489^{o}C, an immiscible Bi-Te melt could potentially exsolve and act as a collector for PGEs and other precious metals in high temperature hydrothermal fluids, which ultimately precipitate as Pd tellurides and bismuthides. This would allow the formation of PGE-enriched porphyries without Pt and Pd sulphide saturation.

NOTES

Cu-Au Mineralisation at the Grasberg Porphyry Deposit: Evidence of Mafic Signatures from Sulphidesv

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The Ertsberg District of Papua, Indonesia, hosts numerous porphyry and skarn-type Cu-Au deposits, including the Grasberg Deposit, which is one of the largest porphyry Cu-Au deposits in the world. The porphyry Cu-Au mineralisation in the Grasberg Deposit is hosted by Pliocene intrusive rocks, which intrude the Mesozoic siliciclastic dominated Kembelangan Group and the Tertiary-Miocene carbonate dominated New Guinea Limestone Group. Newly identified minerals suggest the presence of mafic magma during the Cu-Au mineralisation, implying contribution of mafic magma for formation of the deposit.

The central ore zone consists of chalcopyrite, bornite and native gold, present as veinlets and disseminations. Ore mineral bearing veinlets (ccp-veinlets) are dominantly composed of chalcopyrite and bornite, with few gangue minerals in the veinlets encountered. Merenskyite ($(Pd, Pt)(Te, Bi)_2$) and Co-Ni-Cu sulphide ($(Co, Ni, Cu)_3S_4$) were newly identified as small inclusions in chalcopyrite and bornite associated with native gold in the ccp-veinlets. The chemical composition of merenskyite analyzed in this study has a composition of $Pd_{1.0}Te_{2.0}$, while Pt and Bi were not detected. The chemical composition of Co-Ni-Cu sulphides ranges from that of carrollite to cuprian siegenite ($(Co_{1.9}Cu_{1.1})_{\Sigma 3.0}S_{4.0}$ - $(Co_{1.6}Ni_{1.0}Cu_{0.4})_{\Sigma 3.0}S_{4.0}$). Pd, Co and Ni mineralisation is synonymous with mafic magmas, such as associated with Ni-Cu-PGE deposits, therefore these mineral occurrences suggest the presence of components derived from mafic magma in the ore-forming fluid.

Trace element mapping and line analysis on Cu-Au ore using LA-ICP-MS shows that Co and Ni are concentrated in magnetite and siderite (probably replacing Fe). As barren veinlets composed of quartz, magnetite and minor siderite are cut by the ccp-veinlets, precipitation of these minerals predates the Cu-Au mineralisation. Therefore, even if hydrothermal fluid during the early stage of the magmatic-hydrothermal activity contained Co and Ni, Co-Ni-Cu sulphide is unlikely to precipitate from the fluid in the later Cu-Au mineralisation stage as Co and Ni are likely to be removed from the fluid when magnetite and siderite precipitated. This suggests additional mafic magma to the system between quartz-magnetite-siderite precipitation and later Cu-Au mineralisation stage. As mafic magma can transport a significant amount of sulfur and metals compared with felsic magma, injection and mixing of the mafic magma with more felsic magma in the late stage seems to have contributed to the world-class Cu-Au reserve of the deposit. The close temporal relationship between addition of the mafic magma and the Cu-Au mineralisation (quartz-magnetite-siderite precipitation, addition of mafic magma, followed by Cu-Au mineralisation) suggests the possibility that addition of mafic magma played an important role in triggering the magmatic activity, which resulted in the Cu-Au mineralisation, by destabilising the felsic magma.

NOTES

Elvan (Rhyolite/ Quartz-Porphyry) Dykes of SW England: New Data On Their Relation to Sn-W Mineralisation and Interaction with Lamprophyres

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The elvan dykes of SW England have long been known to have an intimate relation with Sn mineralisation and are similar to dykes in other rare metal provinces worldwide. They, in general, have similar orientation to main phase vein mineralisation and appear, in part, synchronous with later biotite-tourmaline granite intrusions. The elvans are similar in major element chemistry to granites, although more K-rich. This is likely the result of interaction of source melts for the elvans with a K-rich fluid, which was probably also the source of some metals for mineralisation. The dykes are however generally not enriched in Sn although a few have been mined, possibly as a result of forming rheological traps. Intense alteration has discouraged detailed study of geochemistry and petrography of the dykes. This study discusses new semi-regional rock geochemistry, as well as airborne magnetics and radiometrics.

The geochemistry used multi-element XRF, ICP-ES/MS analysis and shows elvans can be grouped based on the Nb/Zr ratios of Manning et al (1996) used to differentiate the granite plutons. Most dykes correlate with Nb/Zr ratios of biotite-tourmaline granites but a smaller number with the later, lithium-topaz granites. These latter dykes have much higher Li, Cs and Sn but lower in Ti. Thus both biotite and lithium-topaz granite intrusives form elvan dykes. It is suggested that the earlier dykes related to the biotite granites are Sn poor as Sn has been incorporated into biotite or rutile and is then scavenged by hydrothermal fluids into veins, whereas in the topaz granite related elvans, Sn is likely present as disseminated cassiterite.

Elvans in the Chacewater area associated with the major Wheal Jane Sn deposit appear to be of biotite granite origin although enriched in Li and Cs.

Recently flown high resolution airborne geophysics, as well as mapping the composite nature of the granites, has allowed delineation of larger elvan (and lamprophyre) dykes. One 11 km strike length dyke, previously mapped as elvan and outside the granite shadow, has anomalously high eTh. Ground follow up showed that the western part of the dyke has inclusions of lamprophyric material and geochemistry confirms that this dyke is the result of mixing of lamprophyric and granitic sources; the first time this has been observed in SW England. Thus some elvan hosting structures have seen input of mantle-derived melts, although it is not known how common this is. This observation would also explain why there is no known cross cutting relation between lamprophyres and elvans or granites.

Acknowledgement: Ben Thompson collected some samples and assisted with petrography during an M.Sc project.

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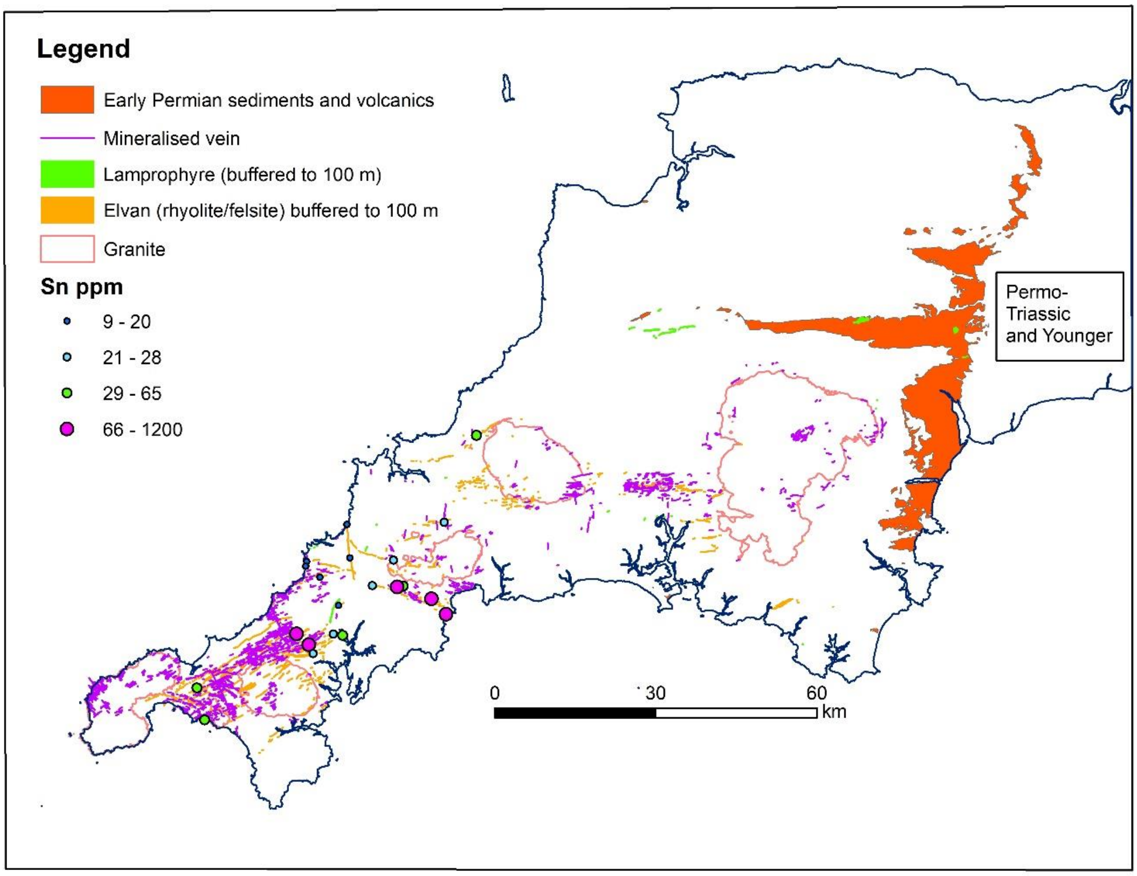
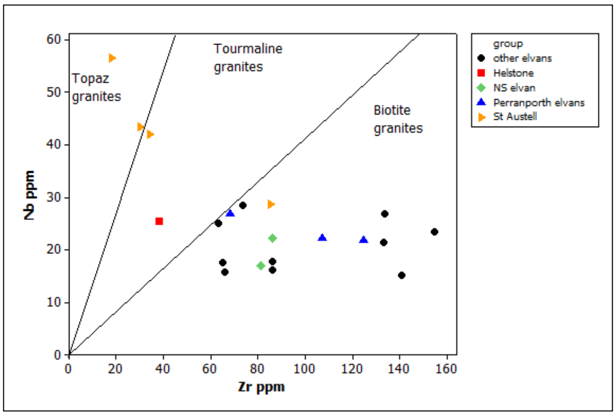
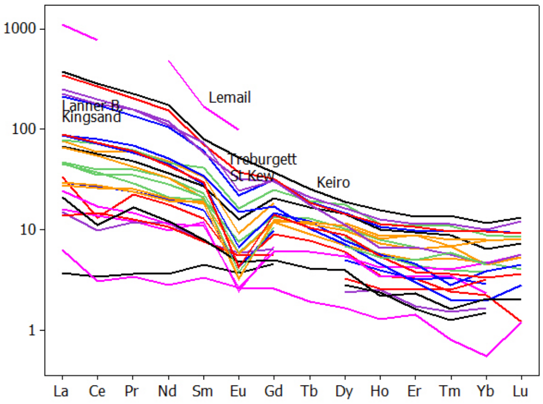


Spatial Distribution of elvans and Sn analyses of elvans





Nb/Zr plot of elvans

REE normalised plots: Elvans, Lemail (lamprophyre) Keiro, Trebugett, Lanner (mixed) and Kingsand (acid lava)

NOTES

POSTER ABSTRACTS
(in alphabetical order)

Tracking metal pathways in magmas using volcanic gas fingerprints

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As well as gases that regulate climate over geological time, volcanoes outgas prodigious quantities of metals into our surface environment. These metals and semi-metals partition into a magmatic vapor phase from silicate melt at crustal pressures. Their abundance in magmatic vapor is influenced strongly by sulfide saturation and by the composition of the magmatic vapor phase, particularly with respect to chloride. These factors are highly dependent on tectonic setting. The geochemistry of the magmatic vapor phase is reflected in the composition of quenched, high temperature volcanic gas and aerosol at the surface. Here we show, using a global dataset, that basaltic volcanoes in subduction zone settings emit high fluxes of metals in gases and aerosols, rich in copper, zinc, thallium and lead. Ocean island volcanoes, in contrast, outgas lower metal fluxes, enriched in highly chalcophile metals. Basaltic arc volcano metal fluxes into the atmosphere may be similar to those into crustal ore deposits. Metal outgassing is controlled by magma water content and redox: deep saturation in vapor and minimal sulfide in arc basalts yields metal-rich vapor; shallow degassing and resorption of sulfides feeds volcanic gas in ocean islands. Basaltic recharge of arc magma reservoirs may be important for supplying sulfur and metals to sites of copper porphyries, transported as vapor.

Crystal mush infiltration and reactive liquid flow: insights from the Klokken intrusion, South Greenland

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The grain-scale microstructure of a cumulate crystal mush (e.g. porosity, permeability and size distribution of crystal phases) and the density and viscosity of the residual melt control processes such as compaction, fractionation, and melt migration. Melt infiltration through, and interaction with, a crystal mush is a poorly understood part of the magmatic system, yet has a fundamental bearing on volcanic, magmatic and ore-forming processes occurring at a range of scales. When the infiltrating melt is out of thermal and/or compositional equilibrium with the crystal mush, the two will react (so-called '*reactive liquid flow*', '*reactive porous flow'* or '*infiltration metasomatism*'), resulting in local dissolution and precipitation of new mineral phases thus modifying the texture, geochemistry and mineralogy of the mush. The melt (and its volatile cargo) can act a transport agent for the mobilisation of trace elements through the crystal mush. Therefore improved characterisation of reactive liquid flow has wider implications for our understanding of ore forming processes in magmatic environments for a range of commodities.

The Klokken gabbro-syenite intrusion (1166 ±3 Ma), located in the Gardar Igneous Province of South Greenland, provides a remarkable natural laboratory in which to study multi-scale melt-mush interaction processes, for which we present new field, petrological and geochemical constraints. The core of the intrusion comprises a laminated syenite (LS) series, interleaved with laterally continuous, detached sheets of the roof cumulate sequence (granular-textured syenite, GS). *Inversely* graded macrorhythmic modal layering within the LS make Klokken unique among layered intrusions. Evolved volatile-rich, yet ultramafic, residual melts derived from the LS form a suite of filaments or 'wisps', comprising Na-rich hedenbergite + fayalite + titanomagnetite + F-rich biotite + Fe-rich alkali feldspar + amphibole + apatite, that appear to be infiltrating the GS. The wisps are extremely Fe-rich and enriched in LILE and HFSE (whole rock ICP-MS, ICP-AES) and halogens (EPMA).

The morphology of the infiltration textures varies systematically with stratigraphic position relative to the inferred paleo-roof zone. Close to the roof the GS contains continuous, planar-sided fractures that have been exploited by both LS and residual melts. Stratigraphically lower GS sheets are infiltrated by an interconnected network of irregular wisps up to 5 cm width. The spacing and the number of wisps appears to be influenced by grain size and crystal orientation of the GS crystal mush, the width of the individual GS sheet and the nature of the GS-LS contact. The lowermost sheets of GS are hybridised; here wholesale disaggregation of the mush by the infiltrating melt has occurred. We interpret this progressive variation in rock fabrics as a manifestation of changes in rheology of the GS crystal mush, from brittle to ductile, with changing temperature and crystallinity.

We hypothesise that reactive liquid flow may have been an important factor in the petrogenesis of syenite-hosted REE-Nb-Ta-Zr ± U deposits in the Gardar Province (e.g. Motzfeldt, Kvanefjeld and Kringlerne). Thus linking the geochemistry and volatile composition of late interstitial melts to the fabrics and textures of the host rocks allows us to illuminate the conditions under which trace element enrichment, transport and mineralisation might occur.

Halogen behaviour within peralkaline magmas and the implications for REE and trace metal transport and concentration

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Economic deposits of rare earth elements (REE) and trace metals are not common, with global production and supply confined to a limited number of sources. China produced approximately 85% of the world's total supply in 2015 and has strict policies controlling their export. There is a great need to identify the mechanisms under which deposits are formed in order to identify affordable and sustainable supplies for the future due to their importance in an expanding array of technology products.

Carbonatite and peralkaline igneous complexes are the primary sources of REEs and key trace metals. Peralkaline systems, defined as having an excess of alkalis with respect to aluminium, occur commonly in areas undergoing intercontinental rifting, such as the active East African Rift System (EARS). Crustal thinning associated with rifting enables partial melts, with volatiles and trace elements sourced from the meatasomatised mantle, to ascend high into the upper crust, with minimal contamination en route, prior to protracted fractional crystallisation. The low viscosity of peralkaline melts further allows for the efficient segregation of these volatile and trace element enriched residual liquids from an overall mush-dominated system.

Alkali-related volatile retention during fractionation leads to enrichment of F and Cl in peralkaline residual fluids. It has been shown that REEs and trace metals partition strongly into these halogen-rich fluids under magmatic conditions. Alkalis and F further delay crystallisation of phases, such as zircon, that preferentially allow HREE into their structures. CO_2 can also act as an agent for, and place important controls on element complexing and transport. However, beyond a very limited number or experimental studies mainly published in the 1990s, there has been little attempt to reconstruct F, Cl and trace element partitioning into these fluids. Peralkaline magma reservoirs are believed to be open systems with repeated mafic inputs. Exsolution of C and S rich gases from these mafic melts may also be key in the element remobilisation.

This study uses mineral-hosted melt inclusions from both highly evolved peralkaline rhyolites and their parental basaltic components, sourced from Kone and Aluto volcanoes, located on the Main Ethiopian Rift. We reconstruct volatile behaviour and degassing, trace element partitioning and the role of mafic inputs in remobilising and concentrating REEs and trace metals, and the halogens they complex with. The limiting factor to ore mineralisation is expected to be the timing of vapour saturation in relation to halogen/trace element bearing phase concentration, as well as the flux of fresh mafic magma into the system and fO_2 conditions. This information will be vital for producing deposit models for REE and trace metal bearing peralkaline systems and pursuing future exploration efficiently.

Cumulate causes for the low contents of chalcophile elements in the continental crust

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In addition to the formation of economically important ore deposits, chalcophile and siderophile element (CSE) systematics of magmatic rocks can be used to place constraints on a range of processes such as the evolution of the Earth's mantle and crust, delamination and subduction. Many of these constraints rely on knowledge of the minerals partitioning the CSE and comparisons between the compositions of subduction-zone magmas and mid-ocean ridge basalts (MORB). However, because the contents of many CSE are hard to analyse accurately in rocks and minerals, compositions and ratios used for comparative geochemistry are often based on scant datasets and/or relatively untested proxies. Consequently, there remains a lack of consensus regarding which minerals partition the CSE and, for example, which processes cause the subduction-related magmas and the continental crust to become enriched in some CSE (e.g., As, W, Tl) and depleted in others (e.g., Cu, Ag and Au) compared to the oceanic crust.

Using a broad range of CSE, I show that average-MORB values and certain ratios (e.g., Cu/Sc) used for comparative geochemistry can be misleading, because they do not sufficiently separate between mantle and crustal processes. Mantle-derived melts contributing to oceanic and continental crust formation rarely avoid sulfide-saturation and, on average, subduction-zone magmas fractionate sulfide at the base of the continental crust prior to ascent. Furthermore, I show that silicate not sulfide minerals dominate the bulk partitioning of many (e.g., Ga, Ge, Zn, Sn, In) of the CSE during magmatic processes.

Differentiation of mantle-derived melts causes sulfide- and silicate-bearing cumulates constituting the lower oceanic and continental crust to become enriched in some CSE (e.g., Cu, Ag and Au) compared to the upper crust. This 'storage' predisposes the cumulate-hosted CSE to be recycled back into the mantle during subduction and delamination, resulting in their low contents in the bulk continental crust. By contrast, differentiation causes the upper oceanic and continental crust to become enriched in 'incompatible' CSE (e.g., As, Tl, Sb, W) compared to the lower oceanic and continental crust. Consequently, incompatible CSE are predisposed to become enriched in subduction-zone magmas that contribute to continental crust formation and are less susceptible to removal from the continental crust via delamination.

Investigation of the Kencana low-sulfidation Au-Ag deposit, Gosowong mining district, Halmahera, Indonesia

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The Gosowong goldfield encompasses one of the most extraordinarily rich gold provinces in Indonesia, or indeed the western Pacific region. The depositional area lies on Halmahera Island, straddling a zone roughly equidistant to Sulawesi Island to the west and Papua Island to the east. Volcano-magmatic activity is related to the closure of the Molucca Sea, with an arc-arc subduction forming the Sangihe Thrust and the parallel Halmahera Thrust. The subsequent Halmahera Arc lies along the north-western arm of Halmahera Island and the north-south aligned volcanic islands chain to the south. The geology of Halmahera may be separated into two major domains; the eastern domain composed of Mesozoic ophiolite complexes and overlying Oligocene clastic sediments, with the western domain composed of Neogene to recent volcanic and pyroclastic rocks. Discovered through the major finding of the Gosowong low-sulfidation deposit in 1994, two further extremely rich epithermal deposits (Togarachi and Kencana) were subsequently discovered amongst numerous prospects. The Kencana deposit is located in the southeastern area of the Gosowong goldfield, and lies within the Gosowong Formation, principally composed of a large-scale andesite package with numerous interlayered sandstone mudstone volcaniclastic deposits.

There are three principle veins at Kencana; K1, K2 and K-LINK. The K1 vein system is exposed on the surface, but the main ore zone is located from 90m below the surface and the main focus of this study. The upper portion is composed of quartz-calcite, and high-grade ores present in the crustiform-colloform banding at 100-150m depth, with Au grades in excess of 1000g/t. Moderate to high-grades are encountered in the quartz-hematitic mudstone/volcanoclastics breccia at 150-200m depth. The K2 vein system is composed of quartz-calcite veins, breccia and stockworks. The K-Link system is largely brecciated with gingoro banding recognised as dismembered vein material in the breccia. Au grades of the deposit are extremely high, ranging from 5 to >1000g/t in the highest grade zones. Mineral resources of the deposit are more than 2.2 Moz Au and 2.2 Moz Ag. The K1 breccia system contains an early stage micro-cyrstalline quartz with chalcopyrite and electrum dissemination, with minor tellurides (hessite), this is followed by a later stage brecciation and resultant banded crustiform ore, composed of; chalcopyrite, hessite, sylvanite, galena and sphalerite in order of abundance. Analysis shows that there is a high Cd-composition in sphalerite and the extremely Cd- rich Zn sulphides recognised as zincian-greenockite.

Experimental insights into degassing of open-vent basaltic volcanoes

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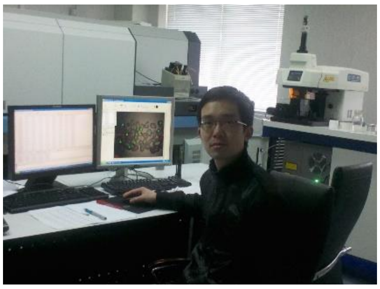
Open vent basaltic volcanism is characterised by the continuous release of gas, which may manifest itself through the intermittent release of gas slugs or more quiescent high frequency degassing of small bubbles. Prior efforts to understand the controls on the phenomena have focussed on two-phase (liquid-gas) flows, in which the stability of a foam in a magma chamber has a key role on the form of gas venting at the surface. However, it has become clear that in many cases the magma may be highly crystalline, leading to important differences in the rheology of the melt-crystal mixture, and in turn this may also influence the style of degassing.

Here we report a series of novel three-phase (liquid-solid-gas) analogue experiments aimed at probing how the dynamics of gas flow through a particle suspension varies with the particle load as an analogue for the effect of different crystal content on open vent degassing. The small-scale experimental setup consists of a long vertical Perspex tube filled with mixtures of glycerol and water of varying viscosity together with cellulose acetate particles to represent crystals. Gas is introduced via a pump at the base of the cylinder and the nature of the flow has been investigated for various gas flow rates, particle loading and liquid viscosity. Measurements of the volume, rise speed, and number density of bubbles, show systematic trends in the frequency and size of the bubbles as the particle loading is increased.

For the same gas flux and liquid viscosity with the high frequency release of small bubbles being reminiscent of quiescent degassing at Halemaʻumaʻu (Kilauea, Hawaii) while the lower frequency release of large gas bubbles may represent episodic bursting of gas bubbles as seen in Strombolian style systems. Using scaling arguments, we compare our findings with observations of open vent degassing from a series of natural systems.

Hydrothermal baddeleyite and zircon in the Tengtie Fe skarn deposit, South China: Implications for timescales and processes of skarnization



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Both prograde and retrograde skarns from the Tengtie Fe deposit, South China, contain rounded, euhedral, and anhedral zircon grains. Rounded grains were originally derived from detritus in carbonate rocks and were incorporated into the skarns. Euhedral and anhedral crystals are intergrown with various skarn minerals and are clearly hydrothermal in origin. These hydrothermal grains have low $(Sm/La)_N$ ratios and high La contents relative to typical magmatic ones and display flat LREE and subdued flattening of HREE chondrite-normalized patterns, similar to those of zircon crystallized from Zr-saturated fluids. Prograde skarns also contain baddeleyite rimed by zircon, which record a period of low Si activity during prograde skarnization relative to original magmatic-hydrothermal fluids. Hydrothermal zircon grains from Tengtie have variable Eu anomalies and slightly positive Ce anomalies, indicating that they may have crystallized from highly heterogeneous, but generally reducing fluids. They have low $\delta^{18}O$ values (–5.1 to –2.7 ‰), suggesting the involvement of meteoric fluids. Fluorine-rich fluids played an important role in remobilizing and transporting some high field strength elements (HFSE), including Zr, from the host granites into the skarn system. Reaction between HFSE-bearing fluids and carbonate rocks at the prograde stage decomposed F complexes to deposit HFSE-rich skarn minerals and baddeleyite. At the retrograde stage, alteration of the HFSE-rich skarn minerals released HFSE, including Zr and Sn, consequently producing a mineral assemblage of zircon, cassiterite, and retrograde skarn minerals. Dating results of zircons from the Tengtie skarn system by SIMS indicates roughly less than several million years duration for skarnization. Our study indicates that Zr was not only mobile locally under favorable conditions, but was also readily transported and deposited in different stages of skarnization.

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