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EDITORIAL

Introduction to thematic issue on fluid and melt inclusions

During the past century and a half, fluid and melt inclusions in minerals have evolved from being a scientific curiosity (Sorby 1858) to perhaps the most used and dependable tool for determining temperatures, pressures, and compositions of fluid-mediated processes in the Earth's crust and upper mantle (Roedder 1984). In 2012, research related to fluid and melt inclusions was presented at three international conferences. The Pan American Current Research on Fluid Inclusions (PACROFI) meeting was organized by Iain Samson and held at the University of Windsor, Canada (Fig. 1). The Asian Current Research on Fluid Inclusions meeting was organized by Terry Mernagh and held in Brisbane, Australia. Finally, Bob Bodnar and Iain Samson organized a session entitled "Frontiers in Fluid and Melt Inclusion Research" at the Goldschmidt Conference in Montreal, Canada. This thematic issue of Geofluids contains 15 papers that were presented at one of these three venues.

The growth in the number of publications that include data from fluid and/or melt inclusions is summarized in the contribution by Kesler *et al.* These authors note that, while fluid inclusions in minerals were first recognized nearly 2000 years ago, it was not until about the 1960s that papers began to report fluid inclusion data, and today about 700 publications annually refer to fluid inclusions. Similarly, melt inclusions became more widely used in the 1980s and today about 200 publications each year include melt-inclusion data. These results indicate that the study of fluid and melt inclusions is an active field of research that continues to grow.

Melt inclusions and magmatic evolution are the subjects of the next five papers in this issue. Magmatic liquids are a topic not previously covered in contributions to *Geofluids*; however, it is increasingly being recognized that, at certain crustal and mantle conditions, fluid–magma systems may exhibit a continuum of compositions and properties. The inclusion community is among the leaders in combining the study of fluids with the study of magmas, as reflected by contributions to this issue. Indeed, as noted by Roedder (1984, p. 2),

> In much of the inclusion literature, the term fluid inclusion has been used only for those inclusions that trapped a fluid that remains in large part fluid at surface temperature, and the term 'melt inclusion' has been used for those that have become essentially solid at surface temperature. As will be seen, however, a continuum exists between these two extremes ……

Much uncertainty exists concerning the origin of granites and melting processes in the deep crust owing to the lack of samples associated with these processes. Bartoli and

Fig. 1. Group photograph of participants at the Pan American Current Research on Fluid Inclusions (PACROFI) meeting held at the University of Windsor, Canada, June 18–20, 2012.

coworkers describe a method to study nanogranite inclusions that represent anatectic melt trapped in peritectic minerals in migmatites and granulites. Using a piston-cylinder apparatus, these workers were able to homogenize and quench the inclusions to produce a homogeneous glass representing the original trapped melt. Subsequent analyses of the glass indicate that the inclusions retained their original water contents, thus providing valuable information concerning volatile budgets in the source region for these samples.

Melt inclusions provide perhaps the best source of information concerning the pre-eruptive melt composition in volcanic systems. Robertson and coworkers studied melt inclusions in olivine, plagioclase, orthopyroxene, and clinopyroxene from the Mutnovsky Volcano, Kamchatka, Russia, and found a wide range in melt compositions from basalt to rhyolite. These workers interpreted this range to reflect fractional crystallization and magma mixing. Specifically, individual melts evolved separately, perhaps in isolated magma chambers, and mixed prior to eruption.

Severs and coworkers used melt inclusions to study magmatic processes at Mount St. Helens, specifically focusing on the pre-1980 eruptive history. These workers examined compositionally zoned phenocrysts from these earlier eruptions and analyzed melt inclusions by laser ablation ICPMS to constrain major and trace element variations. The observed compositional variation was consistent with fractional crystallization, requiring no mixing or assimilation. The compositions of the melts suggest that the source of the magmas was metamorphosed underplated arc gabbro.

Zircon is a common accessory mineral in igneous and high-grade metamorphic rocks. Darling studied zircon-bearing melt inclusions in peritectic garnet from the Adirondack Mountains, New York, USA. Based on the large size of the zircons, which is incompatible with the low Zr solubility in silicate melts, Darling interprets the zircons to be trapped solids. He further suggests that melts generated by biotite melting adhered to the zircon crystals and were trapped as mixed zircon + melt inclusions as the garnet grew around them.

A question that often arises in studies of melt inclusions concerns the role of boundary layer processes and whether the trapped melt has been modified by crystal growth and does not represent the composition of the bulk or 'far-field' melt. Anderson addresses this issue related to silicate-rich inclusions in spodumene from the Tanco pegmatite. Anderson shows that crystal-rich inclusions occur in both primary and secondary spodumene. He concludes that the inclusions are temporally and spatially unrelated to a boundary layer melt and have compositions consistent with trapping of a silicate-rich aqueous carbonic fluid.

The conferences also saw a wealth of new information presented on more traditional fluid inclusions. Li and coworkers present an experimental study of the nucleation and growth of spodumene from both aqueous solution and melt using a modified hydrothermal diamond anvil cell. These workers found that crystal size was a function of the ratio of solid material ($LiAlSi_2O_6$) to H_2O loaded into the cell and that fewer nuclei form when crystals nucleate in the aqueous phase rather than in the melt. They concluded that the giant crystals often observed in granititic pegmatites likely grew from an aqueous solution rather than from a melt phase.

One of the earliest and most common applications of fluid inclusions is to constrain the physical and chemical environment associated with ore formation in mineral deposits. In this volume, there are six contributions characterizing the role of fluids in the origin and evolution of mineral deposits. The Couer d'Alene mining district hosts world-class Ag, Pb, and Zn mineralization. Hofstra and coworkers studied fluid inclusions from a quartz–stibnite vein at the US Antimony deposit in Montana and found that the measured Sb concentrations in fluid inclusions were consistent with microthermometric and modeling studies of Sb solubility. The compositions of fluid inclusions in the antimony veins also suggest that these veins are part of a continuum and are part of the same large hydrothermal system that formed the giant Ag veins in the district. The spatial relationship of the Sb and Ag mineralization has important implications for exploration in the district.

One of the most important geochemical parameters associated with the formation of many types of metal deposits is the sulfur speciation and concentration in the mineralizing fluid. Mernagh and Bastrakov used Raman spectroscopy to analyze the gas phase of vapor-rich fluid inclusions from the Missouri gold deposit (Western Australia) and found that the inclusions contain highly variable CO_2/CH_4 ratios and mole fractions of H_2S up to 0.0018. These workers further examined errors associated with visual estimations of the volume fraction of vapor in fluid inclusions and showed that up to two orders of magnitude error may result from errors in visual estimation of the vapor volume.

Zhao and coworkers describe fluid inclusions from the Jinshan orogenic gold deposit that is located in the Neoproterozoic Jiangnan orogen between the Yangtze and Cathaysia blocks, China. The ore fluids are represented by the system H_2O-CO_2-NaCl, and immiscibility was observed only during the gold mineralization stage. Stable and radiogenic isotope data suggest a crustal source for the sulfur, water and, presumably, the metals in the deposit.

Hu and coworkers conducted a fluid inclusion study of the Sanshandao gold deposit, located at the northwestern edge of the Jiaodong Peninsula, eastern North China Craton, representing one of the largest gold deposits in the Jiaodong gold province. The ore fluids are characterized by

H_2O-CO_2-NaCl±CH_4. Importantly, the fluid inclusions show no variation in temperature and salinity over the entire 2,000 m depth over which mineralization occurs. This observation has important implications concerning the depositional mechanism for gold in this environment.

Fluid inclusions have been used successfully to distinguish between natural and synthetic gemstones, to determine the provenance of stones, and to determine conditions of formation of valuable gemstones. In this volume, Loughrey and coworkers have used fluid inclusions to infer the physical and chemical characteristics of hydrothermal fluids associated with the Byrud emerald deposit in Norway. The deposit is characterized by a color zonation between emerald and beryl, and Loughrey *et al.* found that emerald was precipitated from the liquid portion of a boiling (immiscible) fluid, whereas beryl was precipitated from the vapor phase.

The last three papers in this issue focus on fluids in sedimentary environments. Mathieu and coworkers used data from fluid inclusions to assess the economic potential of two carbonate units on Victoria Island in the Canadian Arctic. Salinities could not be determined in most of the FI using microthermometry owing to metastability problems, and homogenization temperatures of inclusions in calcite could not be determined because the inclusions were too small and/or had necked. SEM–EDS analyses of decrepitate mounds showed that the fluids evolved from early K-rich, to later K+Na-rich to latest Na-rich compositions. The presence of pyrite points to reduced, metal-bearing fluids and suggests that the area may have potential to host economic Zn-Cu-Pb (Mississippi Valley-type) mineralization.

In recent years, many researchers have focused on characterizing the chemistry of extreme environments to better understand conditions that may have accompanied early life on Earth as well as Mars. Benison describes fluid inclusions in modern saline lakes and in Permian halite and gypsum and shows that micro-organisms that lived in the Permian lakes are preserved within fluid inclusions. This comparative study allows researchers to identify Permian lakes that showed extremes in acidity, salinity, compositional complexity, and temperature. Importantly, Benison reports that freezing-point depression, Raman spectra, and leachate compositions of fluid inclusions are all pH dependent.

During the last quarter century, hydrocarbon fluid inclusions have provided valuable information concerning the evolution of petroleum in sedimentary basins. In this issue, Shariatinia and coworkers describe analyses of oil inclusions in calcite and dolomite from the Kuh-e-Mond field in Iran. Oil was released from inclusions by crushing and analyzed by GC-MS. A variety of biomarkers were detected and quantified, including n-alkanes, hopanes, and steranes. The biomarker data are interpreted to indicate that the reservoir oil was generated and expelled predominantly from carbonate-marly sources deposited in anoxic environments.

This thematic issue on fluid and melt inclusions highlights some of the frontiers in fluid and melt-inclusion research. Taken together, the papers also illustrate the great utility of this line of research in providing a wealth of information about the evolution of magmas and fluids in a wide range of geologic systems.

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