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Granite-related ore deposits: an introduction

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Abstract: A symposium on Mineralization Associated with Granitic Magmatism was held within the framework of the 33rd IGC in Oslo, Norway, in August 2008. While our initial idea was to bring together field, experimental, and theoretical studies in order to review and summarize the current ideas and recent progress on granite-related mineralization systems, we were caught by surprise realizing that participants were inclined to focus more on ore deposits related to granitic magmatism. This spontaneous shift from granites, the major intended focus of the symposium, to mineralization associated with them, spawned the idea for a special issue on this theme and ultimately to the nine papers assembled here, chosen from about 60 scientific contributions at the symposium. Around twenty oral presentations were given and forty posters were presented at the meeting; the 60 papers were grouped according to the current main granite-related ore systems, as follows; granite-pegmatite, skarn and greisen-veins, porphyry, orogenic gold, intrusion-related, epithermal and porphyry-related gold and base metal, iron oxide–copper–gold (IOCG), and special case studies.

Importance of granite-related mineralization systems: diversity of mineralization styles and related mineral deposits

Granite-related mineral deposits are diverse and complex and include different associations of elements such as Sn, W, U, Th, Mo, Nb, Ta, Be, Sc, Li, Y, Zr, Sb, F, Bi, As, Hg, Fe, Cu, Au, Pb, Zn, Ag, Ga, and other metals. Among these, deposits of rare earth elements (REEs) and other precious and semi-precious metals are vital to current technologies upon which society depends. Granite-related ore systems have been one of the major targets of the mineral exploration industry and have probably received more intensive research study over the last decades than any other type of ore deposits.

Many different authors have attempted to summarize metallogenic models for granite-related mineral deposits. However, due to the diversity of classes of ore-deposits, styles of mineralization and processes involved in their formation, major reviews focus only on individual classes highlighting the current status of investigation. Only very

few papers focus on experiments and modelling processes leading to metal enrichment, although significant physical and chemical studies have been conducted by Candela (1997), Linnen (1998), Piccoli *et al.* (2000), Cline (2003), Ishihara & Chappell (2004), Vigneresse (2007), among others. The main topics of interest discussed by these authors are: magma sources, emplacement mechanisms, diversification processes, diffusion-controlled element distribution, partition coefficients between minerals and melt, solubility and redox conditions.

Modern approaches, new paradigms, mixing and unmixing of magmas and related ore generation

In the last thirty years, growing evidence for the coexistence of acidic and basic magmas has reinforced the importance of basic magmatism in the evolution of granites (e.g. Didier & Barbarin 1991; Bateman 1995). From the contributions of modern fluid dynamics, we know that the mixing process is the interplay between thermal and/or compositional convection and chemical diffusion (Ottino 1989; Fountain *et al.* 2000). This is known as a

largely non-linear process and dependent on the viscosity and density of the end members involved.

Persistent inputs of relatively dense and low viscosity mafic magma into a high viscosity felsic magma chamber enhances convection, diffusion and redistribution of different elements through the different melts, and therefore distribution of rare elements throughout the chamber (Reid *et al.* 1983; Wiebe & Collins 1998; Wiebe *et al.* 2002). This process is known to be non-linear, chaotic and fractal (e.g. Poli & Perugini 2002; Perugini *et al.* 2003; De Campos *et al.* 2008).

To date, only a handful of experimental studies on magma mixing have been targeted on investigations with natural melts or magmas (Kouchi & Sunagawa 1984; Bindeman & Davis 1999; De Campos *et al.* 2004, 2008, 2010). This is partly due to the high temperatures and high viscosities involved. From these experimental results, we know that mixing between basalt and granitic melts may enhance diffusive fractionation of metals and trace elements, such as the rare earth elements, this being a potential additional mechanism for ore concentration (De Campos *et al.* 2008; Perugini *et al.* 2008).

As a counterpart to the mixing process, magmatic differentiation may also lead to liquid immiscibility. This has received limited attention as a major process leading to the formation of large plutons. Its importance, however, has been claimed by Ferreira *et al.* (1994) and Rajesh (2003) to explain the generation of coexisting ultrapotassic syenite and pyroxenite at the Triunfo batholith, Brazil, and an alkali syenite-pyroxenite association near Puttetti, Trivandrum block, South India. In the roof zone of granitic plutons, liquid immiscibility between aluminosilicate and hydrous melts controls the partitioning of B, Na and Fe to the hydrous melts. Veksler & Thomas (2002) and Veksler *et al.* (2002) experimentally confirmed the immiscibility of aluminosilicate and water-rich melts with extreme boron enrichment (5 wt%; Thomas *et al.* 2003). Veksler (2004) noted that more water-rich depolymerized melts in immiscible systems are strongly enriched in B, Na, Fe. Therefore, liquid immiscibility may concentrate the necessary elements for nodule formation in water-rich, highly mobile melt phases, which may percolate through crystal mush and coalesce in discrete bodies (Trumbull *et al.* 2008; Balen & Broska 2011; Ishiyama *et al.* 2011).

Regarding recent models for granite generation, it is important to analyse the new paradigm of discontinuous magma input in the evolution of felsic magmas and the related consequences to ore formation, as proposed by Vigneresse (2004, 2007). This model represents a substantial change in the concept of ore generation in which magma source,

emplacement mechanisms and magma mixing processes, together with diffusion/partition coefficients between minerals and melt, solubility and redox conditions, are the main control parameters for element distribution and, therefore, enrichment processes.

New ore genetic models and related exploration models

Despite significant advances, due to new ideas and technologies, in the fields of igneous petrology (e.g. repeated magma intrusion, fluctuating redox through magma-crustal interaction), volcanology, geochemistry (e.g. formation of immiscible sulphide phases, salt melts and vapour-like fluid phases), geophysics, high P–T experiments, and numerical modelling, our present understanding of granite-related mineralization systems and related ore-bearing processes leading to metal concentrations is not yet sufficiently advanced. It is still poorly understood which parameters account for potential prospective targets for a given metallic resource. Despite much fundamental knowledge and new concepts in granite-related ore deposit geology we definitely need better genetic and exploration models. Critically, we need better understanding of the key features informing exploration targeting and discovery. In fact, future global needs for metal resources will require a subsequent surge in mineral exploration programmes, which inevitably rely upon reliable ore deposit models. Such improvement in models of ore formation is only possible through continuing multidisciplinary investigations.

This issue provides a range of studies that are broadly distributed in both space and time, highlighting granite-related ore deposits from Europe (Russia, Sweden, Croatia and Turkey), the Middle East (Iran), Asia (Japan and China) and South America (Brazil and Argentina) spanning from Palaeoproterozoic to Miocene. The nine papers selected for publication in this title fall under the following general themes:

Granite-pegmatite systems

The correlation between grain-size in orogenic granite/pegmatite magma and crystallization age is a topic that has not yet occurred to many petrologists. **Tkachev** (2011) discusses the evolution of orogenic granite-pegmatites through geological time. He focuses on pegmatite bodies both from Russia and other parts of the world. Based on data from the literature, this work quantitatively analyses distinct pegmatite generation intensity and/or evolutionary changes through geological time, bringing a new approach to the driving forces which have not previously been properly addressed.

Pedrosa-Soares *et al.* (2011) examine mineral resources related to the Araçuaí orogen in eastern Brazil. The most remarkable feature of this crustal segment is the huge amount of plutonic rocks of Late Neoproterozoic up to Cambro-Ordovician ages, depicting a long lasting succession of granite production episodes in an area of over 350 000 km². Granitic rocks cover one third of the orogenic region, and built up the outstanding eastern Brazilian pegmatite province and the most important dimension stone province of Brazil. This is an example of how granites themselves can represent an economic target of a region.

The role of devolatilization in final stages of granitic melt leading to the formation of tourmaline nodules in Cretaceous peraluminous plutons in Croatia is discussed by **Balen & Broska** (2011).

Skarn systems

Wang *et al.* (2011) analyse the distribution and migration characteristics of Au, Ag, Cu, Pb, and Zn during the ore-forming processes in a skarn deposit near Tongling in the Shizishan area, Anhui Province, China. In this area, ore fields are composed of skarn-type deposits formed around several magmatic plutons, emplaced at about 140 Ma. Self-affine and multi-fractal analyses were used to study the migration and to model changes in the distribution patterns of those ore-forming elements, during the skarn mineralization process.

Cathodoluminescence and fluid inclusions shed some light on the study of mechanisms and timing of generation of skarn mineralizations at contact aureoles in granitic plutons in central Japan (Fe–Cu–Pb and Zn) as demonstrated by **Ishiyama *et al.*** (2011) while **Wang *et al.*** (2011) applied fractal analysis to constrain ore-forming processes in skarns from China.

Iron oxide–copper–molybdenum systems

Delibas *et al.* (2011) focused on Fe–Cu–Mo mineralization in the central Anatolian magmatic complex, in Turkey. In this association volcanic rocks grade from basalt to rhyolite, whilst coeval plutonic rocks range from gabbro to leucogranite. Results of this work highlight the importance of magma mixing and metal unmixing, possibly related to stress relaxation during post-collisional evolution in late Cretaceous times.

Epithermal gold systems

Ebrahimi *et al.* (2011) describe Cenozoic epithermal gold prospects in silica, silica-carbonate and veinlets in felsic to intermediate volcanic and plutonic rocks in Iran. The coexistence of vapour-

dominant and liquid-dominant inclusions in the ore stage quartz, hydrothermal breccias, bladed calcite, and adularia suggests that boiling occurred during the evolution of the ore fluids. Mixing and boiling are two principal processes involved in the ore formation in this a low-sulphidation epithermal system.

Intrusion-related gold systems

The petrology and alteration geochemistry of Palaeoproterozoic intrusions that host Au deposits in Sweden is the main theme of the contribution by **Bejgarn *et al.*** (2011) who studied a structurally-controlled mineralization that occurs within zones of proximal phyllic/silicic and distal propylitic alteration. It comprises mainly pyrite, chalcopyrite, sphalerite with accessory Te-minerals, gold alloys, and locally abundant arsenopyrite. During hydrothermal alteration an addition of Si, Fe and K together with an increase in Au, Te, Cu, Zn and As occurred.

Regional geology

Rossi *et al.* (2011) examine the metalliferous fertility of the undeformed Carboniferous San Blas granitic pluton in western Argentina that was emplaced at shallow levels by passive mechanisms. The finding of alluvial cassiterite and wolframite in drainage from this pluton is evidence of the fertile character of this granite. The Sr/Eu ratio and other geochemical features characterize this pluton as fertile, evolved granite with the REE tetrad effect, typical of evolved granites with hydrothermal alteration (greisenization).

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