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Editorial: Micro-to nano-analytical challenges towards trace element characterization of ore minerals: new perspectives and applications for sustainable georesources

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Editorial on the Research Topic
Micro-to nano-analytical challenges towards trace element characterization of ore minerals: new perspectives and applications for sustainable georesources

The formation of mineral deposits is the result of a complex interplay of magmatic, tectonic and hydrothermal processes that are recorded by the trace element composition of ore minerals. Trace elements are incorporated into minerals during the ore-forming process through a variety of mechanisms, and changes in their geochemistry over time can indicate changes in the fluid and metal sources or variations in the physicochemical conditions during ore formation. The geochemical signature of minerals, if well understood, may be used in exploration as a vectoring tool towards high-grade mineralization, or to constrain fluid sources or metallogenic trends in terranes with a protracted geological history (Börner et al.; Rieger et al.; Steadman et al.). Besides forming discrete phases in high-grade ores, trace elements are also abundant in common ore-forming minerals, either as inclusions or substitutions within the crystal structure. These physically or chemically bound "invisible" trace elements are often difficult to detect by conventional microscopic methods, and can have a refractory behavior during ore-processing. In addition, the economic potential of "invisible" trace elements is currently underestimated, however, they may represent a future resource if their deportment among host minerals and their behavior during mineral extraction processes are understood (Cook et al.; Xu et al.). Many of these elements are often identified as "critical" due to growing demand caused by their specific application in electronics and renewable energies and potential supply chain disruption (Hayes et al.; McNulty and Jowitt). Improved knowledge of trace element behavior during ore formation and throughout the extraction process is therefore crucial for building a sustainable future. However, this requires a detailed mineralogical and chemical characterization at the micro- and nano-scale, which is the focus of the contributions to this Research Topic.

Several contributions evaluated critical element-hosting minerals, including pyrite (Rieger et al.; Börner et al.) and apatite (Steadman et al.), from specific ore deposits in an effort to understand their formation history. Rieger et al. demonstrate how laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) data of diagenetic pyrite and its statistical evaluation by principal component analysis can refine genetic models of multi-stage ore formation in complex sediment-hosted mineral systems, such as the Proterozoic George Fisher Zn-Pb-Ag deposit (Australia). The study by Börner et al. shows how trace element and S isotope micro-analysis of pyrite by LA-ICP-MS helps to reconstruct the fluid sources and ore-forming processes in high-K calc-alkaline igneous rock-hosted epithermal-porphyry environments. The authors conclude that fluid-rock interaction, phase separation, and mixing of magma-derived and meteoric fluids are key processes enhancing the Te and Au deposition in three prospects on Limnos Island (Greece). Steadman et al. show by hyperspectral cathodoluminescence (CL), geochemical and geochronological characterization of a series of apatites from the Ernest Henry iron oxide copper-gold deposit (Australia) that complex mineral parageneses and multiple geological processes of magmatic and hydrothermal origin are recorded by petrogenetic indicator minerals.

Two additional contributions focused specifically on the behavior of REEs (Cook et al.) and Sn (Xu et al.) in Fe-oxides. Cook et al. study the REE distribution from the micro-to atomic-scale in hematite and magnetite from the Olympic Dam Cu-U-Au-Ag deposit (South Australia) using a combined LA-ICP-MS and high-angle annular dark field scanning transmission electron microscopy (HAADF STEM) analytical approach. The results demonstrate that these common minerals cannot only contain REEs, both in solid solution and as nanoparticles, but also that REEs undergo complex processes of redistribution in response to later-stage overprinting events. An improved understanding of the mineral deportment of REEs in giant Fe-oxide bearing ore deposits has the potential to underpin innovative REE extraction opportunities. Using a comparable micro-to nano-scale approach employing electron probe micro-analysis (EPMA) and HAADF STEM analysis, Xu et al. investigate the incorporation of Sn into magnetite from the Dulong Zn-Sn-In skarn deposit (South China). Their observations help elucidate the early (Mg) stages of skarn formation. They show that Mg-Si defects form along (110) planes in magnetite prior to Sn-enrichment. Release of high volatile, F-rich fluids is interpreted to lead to precipitation of cassiterite inclusions along <111*> directions in magnetite. High resolution STEM imaging of beam-sensitive phases such as chondrodite, preserved as nanoparticles in magnetite, is achieved using the integrated differential phase contrast (iDPC) technique, which was for the first time successfully applied to ore minerals.

Two final contributions described novel methodological approaches, including a description of a workflow for examining byproduct critical element speciation in ore minerals (Hayes et al.) and new ways to statistically examine published trace element data (McNulty and Jowitt). Hayes et al. use a comprehensive analytical approach, combining scanning electron microscopy (SEM), CL imaging, EPMA and synchrotron-based micro-X-ray fluorescence (μ-XRF) and (micro) X-ray absorption near edge spectroscopy (μ-XANES) to study the incorporation of Ge into sphalerite by co-substitution processes. The results demonstrate how this novel non-destructive workflow can help to understand fundamental ore enrichment processes of byproduct critical elements, which can also guide exploration activities, resource quantification, and extraction. McNulty and Jowitt show how proxies for the exploration of byproduct critical element resources can be developed from a LA-ICP-MS database. The study demonstrates that Sb, Bi, Cd, Co, Se, and Te are concentrated in common Ni-, Cu- and Zn-sulfides of magmatic sulfide and volcanogenic massive sulfide deposits, which represent unrecovered byproducts in existing mining operations that have the potential to support the future supply of these critical elements.

The contributions to this Research Topic therefore demonstrate how the combination of micro-to nano-scale analytical techniques can help to widen our knowledge from fundamental ore-forming processes to more applied topics that contribute to a more sustainable and secure supply of critical elements for future generations.

Author contributions

MK, SH, CC, DF, and MR jointly wrote this editorial. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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