Mineralogy, paragenesis, and mineral chemistry of REEs in the Olserum-Djupedal REE-phosphate mineralization, SE Sweden

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ABSTRACT

The rapidly growing use of rare earth elements and yttrium (REE) in modern-day technologies, not least within the fields of green and carbon-free energy applications, requires exploitation of new REE deposits and deposit types. In this perspective, it is vital to develop a fundamental understanding of the behavior of REE in natural hydrothermal systems and the formation of hydrothermal REE deposits. In this study, we establish a mineralogical, textural, and mineral-chemical framework for a new type of deposit, the hydrothermal Olserum-Djupedal REE-phosphate mineralization in SE Sweden. An early, high-temperature REE stage is characterized by abundant monazite-(Ce) and xenotime-(Y) coexisting with fluorapatite and subordinate amounts of (Y,REE,U,Fe)-(Nb,Ta) oxides. During a subsequent stage, allanite-(Ce) and ferriallanite-(Ce) formed locally, partly resulting from the breakdown of primary monazite-(Ce). Alteration of allanite-(Ce) or ferriallanite-(Ce) to bastnasite-(Ce) and minor synchysite-(Ce) at lower temperatures represents the latest stage of REE mineral formation. The paragenetic sequence and mineral chemistry of the allanites record an increase in Ca content in the fluid. We suggest that this local increase in Ca, in conjunction with changes in oxidation state, were the key factors controlling the stability of monazite-(Ce) in the assemblages of the Olserum-Djupedal deposit. We interpret the alteration and replacement of primary monazite-(Ce), xenotime-(Y), fluorapatite, and minor (Y,REE,U,Fe)-(Nb,Ta) oxide phase(s), to be the consequence of coupled dissolution-reprecipitation processes. These processes mobilized REE, Th, U, and Nb-Ta, which caused the formation of secondary monazite-(Ce), xenotime-(Y), fluorapatite, and minor amounts of allanite-(Ce) and ferriallanite-(Ce). In addition, these alteration processes produced uraninite, thorite, columbite-(Fe), and uncharacterized (Th,U,Y,Ca)-silicates. Textural relations show that the dissolution-reprecipitation processes affecting fluorapatite preceded those affecting monazite-(Ce), xenotime-(Y), and the (Y,REE,U,Fe)-(Nb,Ta) oxide phase(s). The mineralogy of the primary ore mineralization and the subsequently formed alteration assemblages demonstrate the combined mobility of REE and HFSE in a natural F-bearing high-temperature hydrothermal system. The observed coprecipitation of monazite-(Ce), xenotime-(Y), and fluorapatite during the primary REE mineralization stage highlights the need for further research on the potentially important role of the phosphate ligand in hydrothermal REE transporting systems.

Keywords: Rare earth elements, hydrothermal, monazite, xenotime, allanite, apatite, Olserum, Sweden

INTRODUCTION

In recent years, the global demand for the rare earth elements and yttrium (REE) for the rapidly growing green and carbon-free energy and information technologies has prompted extensive re-evaluation of REE deposits, and new research on the geochemical transport behavior and enrichment processes of these elements. Primary enrichment of REE to form mineral deposits can result from magmatic processes, such as in peralkaline silica-undersaturated rocks, peralkaline granites, pegmatites, and in carbonatites (e.g., Chakhmouradian and Zaitsev 2012, and references therein). Importantly, carbonatite-associated REE mineralizations are in most cases further enriched in the REE through late-stage hydrothermal fluid mobilization. Prominent examples include the mineralization in Lofdal, Namibia (Wall et al. 2008) or the mineralization at the Fen complex, Norway (e.g., Andersen 1984). In addition, ample evidence supporting a combined magmatic-hydrothermal origin is also present for other deposit types, such as the Strange Lake REE-Zr-Nb deposit, Canada (e.g., Salvi and Williams-Jones 1990; Gysi et al. 2016), and several REE enriched magmatic-iron oxideapatite deposits (e.g., Harlov et al. 2002, 2016; Jonsson et al. 2016). There are also several recognized deposits that primarily formed by hydrothermal processes. These include for instance the Bayan Obo REE-Nb-Fe deposit, China (e.g., Chao et al. 1992; Smith and Henderson 2000; Smith et al. 2015) and the REE deposit in the Gallinas Mountains, U.S.A. (Williams-Jones et al. 2000). The importance of hydrothermal REE transport and deposition is also highlighted by new experimental evidence for the high solubility of REE and high field strength elements (HFSE), such as Zr, Nb, and Ta, in certain hydrothermal fluids (e.g., Migdisov et al. 2009, 2011; Loges et al. 2013; Timofeev et al. 2015, 2017).