HIGHLIGHTS AND BREAKTHROUGHS

Regolith-hosted rare-earth elements: the phyllosilicate connection

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The analyses of all or some of the rare-earth elements (Sc, Y, and the Lanthanide Series) have been used to understand petrologic processes at many scales ranging from planetary studies to studies the earth's crust (e.g. McLennan and Taylor, 2012). Though thought to be insoluble or immobile at increased temperatures and pressures, the geochemical behavior of the rare-earth elements (REE) have varied relative to each other in many subtle ways. Specific rare-earth elements (Ce, Eu) have had distinct redox behaviors within crustal rocks. Their geochemical and mineralogic attributes have made them highly useful for many petrologic studies of the Earth's crust.

An entirely different picture of the REE's geochemical and mineralogic behavior has been evident in weathering and diagenetic systems. This general idea of the increased solubility of the REE due to weathering or diagenetic temperatures can be traced at least to the 1960s (Burkov et al. 1967). The release of REE from bedrock sources (granite and sedimentary rocks) and their precipitation as secondary REE-phases and/or REE as ion-sorbed has been described recently in the Piedmont regolith and in mined kaolin beds in the Georgia Coastal Plain (e.g. Bern et al. 2017; Cheshire et al. 2018). This increased solubility of the REE might be a paradigm shift relative to the conventional thinking about the occurrences of the REE observed from the petrologic and geochemical studies of crustal rocks.

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The REE have been regarded recently as critical metals for important technologies and products (e.g. batteries, magnets, wind turbines, LED, phosphor for screens; Lucas et al. 2015). The strategic nature of the REE has stimulated further thinking to understand both traditional occurrences of the REE as well as to explore for new and non-traditional occurrences for the REE. The REE have been mined from well-known deposits (e.g. Bayan Obo, China; Fan et al., 2016; Mountain Pass, California). Examples of recently studied nontraditional and sizeable occurrences of the REE included: the occurrences REE as diagenetically formed REE-phosphate phases in kaolin; the presence of REE in kaolin mine waste; and the sizeable amounts of the REE in coal, coal fly ash, heavy mineral sand deposits, alluvial sediments, and in deep sea sediments (e.g. Seredin and Dai, 2012; Hower et al., 2016; Bern et al., 2016; Cheshire et al., 2018; Elliott et al., 2018; Shah et al., 2018; Van Gosen and Ellefsen, 2018; Takaya et al., 2018; Liu et al., 2019).

The REE-enriched fractions of these heavy mineral sand deposits in southern Georgia and the resumption of REE mining at Mountain Pass are currently the only domestic sources of the REE being mined in US. Consequently, the US is highly dependent on international sources for the REE, particularly the HREE (Gd, Lu) used in many technologies, materials and other industrial uses and materials. Considerable amounts of the HREE are being mined from the extraction of HREE ion-sorbed regolith in SE China. The ease of extraction makes these deposits highly attractive as sources of the HREE. The ion-sorbed HREE accounts for approximately 70% and more of the current supplies of the HREE. A growing body of work is documenting the solubility, and the adsorption of these seemingly insoluble REE in sedimentary rocks, regolith, and low temperature regimes. Further study of their solubility will lead to the increased development of these non-traditional or novel deposits of the REE in sedimentary/regolith/soil systems.

Given the foregoing ideas regarding the increased solubility of the REE and their formation as ion-sorbed REE or formation as secondary REE-minerals in sedimentary and regolith settings, the paper entitled *The role of clay minerals in forming regolith hosted heavy rare-earth deposits* by Martin Yan Hei Li and Mei-Fu Zhou is a most welcomed contribution for many reasons. Li and Zhou took on the formidable task of trying to understand the role of clay minerals in adsorbing REE in the regolith-hosted REE deposits in SE China. Briefly, Li and Zhou found the halloysite-rich lower regolith adsorbed the REE and heavy rare-earth elements (HREE) weathered from the parent granite. These REE were later desorbed as the halloysite phases were transformed to kaolinite in the upper regolith. These released REE migrated or translocated to the deeper regolith containing halloysite. These combined mineralogical, geochemical, and the pedogenic processes forming this regolith were thought to have created the large concentrations of REE whose total REE on average is 2,500 ppm.

The sorption of metal ions at the interlayer sites of phyllosilicate minerals having high layer charge is known well. However, the sorption of REE by halloysite stressed the importance of edge/surface sorption processes and high specific surface area of the individual grains. These new results on regolith-hosted REE should stimulate further thinking and investigations regarding the about metal-phyllosilicate mineral sorption processes at the atom scale. Li and Zhou further noted that compounds forming stable complexes with halloysite would point to more environmentally friendly extraction processes to recover the REE from these clays.

Finally, this paper was also a welcomed contribution in that the authors provided a useful review of the site description to these regolith-hosted REE deposits. They noted the occurrences of ion-sorbed REE elsewhere in south China and other tropical settings (SE Asia, Madagascar, Malawi and Brazil). More interesting and germane to the *American Mineralogist* readership, the authors stressed the phyllosilicate mineralogy connection for understanding the ion-sorption of these seemingly insoluble REE. Li and Zhou's results should stimulate further thought on the release and sorption of these seemingly insoluble REE onto clay particles at the atom or nano-scale. This new model will be useful to find further REE prospects in regolith settings.

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