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Facilitating the Critical Mineral Future: Valorization of Kaolin Mining Waste Through Partnerships

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In order to address the growing demand for critical minerals to supply the energy transition, industry-academic-government circles must engage in discussions about the state-of-the-art procedures for extant mining operations and the potential to coproduce critical minerals such as rare earth elements (REE), which are indispensable in many key components for the automotive, battery, and communications industries. One important reason to further establish critical mineral production is the desire to reduce U.S. dependence on international supplies and increase the economic potential in rural regions. This article highlights the outcomes of a recent Georgia Essential Minerals Workshop and recommends pathways for academic-government-industry partnerships to advance the exploration and production of critical mineral resources. These recommendations reflect the consensus of 45 technical attendees from academia, government, and industry, with a focus on evaluation of the kaolin mining industry in Georgia, USA, and the potential to extract REE from production streams, overburden, and mine tailings. This partnership model may serve other regions looking to meet critical mineral needs.

The first three authors were brought together by all being faculty in earth science departments at public R1 universities and having records of engaging research on rare earth elements (REE) and mining. Their expertise includes characterizing critical mineral speciation in complex heterogeneous matrices and waste valorization, such as REE extraction from coal fly ash (Wen et al., 2024). Additionally, Elliott and Schroeder each have 30+ years of working with kaolin-producing industries in Georgia, USA. Research foci of these geoscientists include REE occurrences in Georgia kaolins (Boxleiter and Elliott, 2023; Elliott et al., 2018), volcanic systems (Karpov et al., 2018), and weathered rocks of the southeast U.S. Piedmont (Schroeder et al., 2022). Perspectives included views from 20 workshop participants from the Georgia Mining Association (GMA). The GMA supports 40 industrial corporations in its mission to "provide information on legislative matters to the membership and to create a better understanding among the people about the importance of the mining industry."

Unifying this effort were university vision statements. The University System of Georgia's mission is to "provide an affordable, accessible, and high-quality education; promote lifelong success of students; and create, disseminate, and apply knowledge for the advancement of our state, nation, and world." The study of critical minerals presents a novel opportunity for universities to collaborate with industry and government on this societally pressing issue. The geoscientists involved in this workshop wanted to answer key questions related to the Georgia kaolin industry, including:

- What is the potential for coproducing REE from kaolin ore, mine tailings, overburden, or other kaolin production streams?
- What is needed to move from inferred resources to indicated resources?
- What technologies can be transferred from kaolin and other mining operations?
- What permitting variations are anticipated to maintain environmental compliance and stewardship?
- What outreach is needed to keep stakeholders involved during each stage of development?
- How can leaders ensure workforce training is inclusive and part of industry-academic-government partnerships?

Workshop outcomes consisted of several take-home points. Workshop participants emphasized that there is a long history and discovery of REE. A rich body of peer-reviewed REE literature exists, and we do not need to have recursive revelations. REE studies in volcanic systems and weathered rocks of the southeast U.S. Piedmont show near-surface mobility of

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REE. Biogeochemical processes (both natural and engineered lanthanophores) may concentrate abundances of REE, thus making it easier to mine. Two general pools are being mined globally: REE hosted in primary minerals (e.g., Mountain Pass, California, and Mission Mine, Georgia) and REE adsorbed on clay mineral surfaces (e.g., southeast China).

It has been demonstrated that the coarse grit fraction from kaolin feedstock contains a range of REE-bearing minerals (Boxleiter and Elliott, 2023). These host light and heavy REE in varied proportions. A rough valuation of grit from one Georgia kaolin deposit was made using a production rate of 10 tons per day, assuming literature-reported concentrations of REE and current market prices of REE. Not considering mining, processing, and transport costs, this inferred resource can be valued at nearly US$1 million.

A multi-scale approach is required for REE extraction strategies that span from molecular to field scales of understanding. Experience with extracting REE from coal fly ash points to the numerous steps and energy required to bring REE metals to market (Liu et al., 2023; Wen et al., 2024). It is likely that kaolin streams that include overburden, grits, mine tailings, and other complex REE-mineral associations will require multifaceted characterization using analytical resources at universities and government laboratories. There are numerous opportunities to route feedstock, specific REE yields, and byproducts to other profitable uses that maintain cradle-to-grave material fates and ensure environmental soundness.

There is a long and esteemed history of mining throughout the U.S., especially in Georgia, where practices have been exemplary regarding reclamation and safety compliance. A key advantage to considering the future of REE extraction from operations like kaolin mining is existing and mature infrastructure. Georgia ranks seventh in the nation in the production of industrial minerals, meaning that the technical knowledge, workforce, mineral processing infrastructure, and transportation needs are regionally in place. This positions Georgia for a full-scale exploitation scenario of REE on time scales much shorter than starting from scratch.

During the workshop, subgroups of personnel from academic, industry, and government entities were randomly assembled into breakout sessions to discuss the questions listed above and comments made during plenary sessions. The following consensus points were reached:

- REE production may be difficult to scale because a single operation may be unable to produce sufficient feedstock.
- REE production should be viewed as a multi-mineral resource extraction endeavor, with each feedstock supplying different REE and mineral components.
- Small-scale producers participate in co-operative scenarios to build "banks," similar to co-ops in agricultural markets.
- In addition to REE banks from kaolin mining ore streams and similar sources, enrichments may also come from coprocessing of waste from REE-bearing end products.
- Regulatory oversight needs to be evaluated at state and federal levels to identify barriers that may lead to intolerable economic and/or environmental thresholds.
- Valorization of waste streams contributes to economic national security, which enables the U.S. to establish supply chain demands.

These insights led to the following recommendations, which are intended to be guide posts for stakeholders, not only in the southeast U.S. but also in other regions around the world:

- Political will needs to bend and allow more direct partnering of industry-academic initiatives with government (e.g., U.S. Geological Survey).
- Enable basic research via industry-academic-government partnerships to characterize REE contents and occurrences in inferred resources. Consider kaolin mine tailing, grits, and overburden to be a fast track in this model.
- Establish regional consortia. This is promoted by the U.S. State Department's concept of Minerals Security Partnership, the goal of which is to "accelerate the development of diverse and sustainable critical energy minerals supply chains through working with host governments and industry to facilitate targeted financial and diplomatic support for strategic projects along the value chain."
- Establish consortia to organize workshops to bring stakeholders together, prioritize research and economic topics, provide continuing education for existing workforce, and train the next generation needed for sustainable growth.

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