Geosciences Critical Minerals Research and Capabilities

Penn State's Department of Geosciences offers expertise and experience relating to the exploration and characterization of critical minerals in sedimentary, igneous and metamorphic rocks, and mining waste. To understand how critical mineral deposits form, we apply foundational knowledge of:

- sedimentary basins and depositional environments,
- large scale tectonic controls on ore formation,
- fluid-rock reactions and transport,
- caldera lakes and hydrothermal systems, and
- metamorphic processes

We are also extending this understanding to Pennsylvania iron slags, the glassy waste product of historical and modern metal refining, as well as other mining and related industrial waste. In our home territory of the northern Appalachian Basin, we have built upon USGS research from the 1970s to better understand the occurrences of Li and REEs in coal underclay. Better predictions of the concentration, volume, distribution, and phase of these and other critical mineral deposits requires a combination of new data analysis with various micro-analytical techniques and understanding of the physical-chemical processes – this work can help us determine which aspects of geological history are most predictive in different basins and geological settings.

<u>Current avenues of research, capabilities, and associated questions include:</u>

1. Developing new geochronological and geochemical tools to aid exploration geologists, including mineral vectors for exploration work, understanding sampling uncertainty in exploration projects, and developing geochronology and geochemical tools to date economic ore formation and determine critical element provenance. We can measure ages and trace elements (including critical elements) in a wide variety of mineral phases with laser ablation micro-sampling, making accurate measurements into the low parts per million to parts per billion concentration level.
    a. **What key ingredients differentiate barren granite from Li pegmatite granites?**
    b. **Can Li isotopes be used to track the provenance of Li in volcanic provinces?**
    c. **Do lithospheric structures control REE transport from mid-crust to near surface?**
2. Using trace-element and U-Pb isotopic measurements of phosphorite deposits to determine paleo-environmental conditions of formation, and how REE-rich phosphorites form.
    a. **Are REE-rich phosphorites (>1000 ppm) economic for extraction, and what geologic processes are important for concentrating REE in phosphorites?**
    b. **What phases in phosphorites (skeletal or authigenic apatite; carbonates; organics) are the key hosts for REE?**
    c. **What controls the regional-scale expression of REE in a given phosphorite unit?**

3. Understanding the presence of Li and REEs in coal underclay and similar claystones, especially within the Pottsville and Allegheny Groups of the northern Appalachian Basin, and the role of paleopedogenesis in the chemostratigraphic distribution of critical elements within them.
    a. **What was the original source of Li and REE in the claystones?**
    b. **What mineral(s) hosts critical elements, and what clay mineral hosts Li?**
    c. **Were critical elements redistributed by paleopedogenetic and/or fluid flow/shallow surface hydrological processes? If so, can this genetic model be applied to other claystones and sedimentary basins?**
    Some researchers are working on similar questions for caldera hosted Li and REE deposits, e.g., McDermott Caldera, Nevada. A key question is what is the source of Li – magmatic/hydrothermal vs remobilization by near-surface hydrology from volcanic deposits.
4. Integrating observations from field geology with insights gained through application of equilibrium thermodynamics, geochronology, microbeam geochemistry and reactive-transport calculations. A particularly exciting prospect is the application of laser ablation inductively coupled mass spectrometry (LA-ICPMS) depth profiling to get high resolution spatial (temporal) history of fluid flow/magmatic processes recorded in accessory minerals.
    a. **Are REE-bearing accessory minerals (monazite, zircon and titanite) mobilized via interface-coupled precipitation-dissolution reactions?**
5. Characterizing a growing collection of historic and modern Pennsylvania iron slags (n>100, from ~25 different furnaces across the state) using electron probe microanalysis (EPMA) and LA-ICPMS. Because smelting processes are typically tuned to refine a single metal of choice, all other lithophile components of the ore are concentrated into the slag. These may include elements of economic significance, including critical minerals such as Li, Co, Ge, and REE. In addition, slag is rich in Ca and Mg, making it a good potential raw material for carbonation and carbon sequestration. Our preliminary data show that REE are present in significant concentrations (>1000 ppm) in numerous different historical slag localities.
    a. **What elements are potentially economic in historical and/or modern iron slags?**
    b. **What is the relationship between the critical mineral potential in different slags, and the geologic origin of the iron ore (e.g., magnetite skarns vs. sedimentary limonite)?**
    c. **What environmental concerns are associated with critical mineral extraction in slags? This might include heavy metals in the slag, acid waste from extraction, caustic materials associated with slag, or contamination in soils that host the slag.**
    d. **Are historical iron slags present in significant enough volumes to be economic?**
    e. **What critical mineral resources are associated with modern iron and steel slags?**
    f. **How can historical and modern iron/steel slags be reprocessed as a substrate for carbon sequestration?**

6. Understanding when more data are necessary, or where and how to best target data collection to reduce uncertainty, is important for assessing prospectivity and viability of mining operations in different contexts. By applying geological model-guided assessments of existing data, and contextualizing machine learning efforts with insight about geological history, we can improve the assessment and prediction of critical minerals in a manner that is adaptable and scalable. For instance, a key gap in REE/CM exploration is understanding how to extrapolate data from one scale to another (e.g., pore/grain-scale data to outcrop/basin scales and vice versa). Leveraging theoretical, geostatistical, and machine-learning approaches, we are working to identify the most effective workflows for closing data gaps, integrating disparate datasets (e.g., remote sensing vs. hand-sample data vs. micro-analytical data)), and implementing process-model informed data extrapolation to accurately characterize resource richness.
    a. **Can hyperspectral imaging detect potential REE/Critical Mineral-bearing deposits at outcrop scale to direct detailed characterization efficiently and improve the feasibility of using spatially localized/heterogenous deposits?**
    b. **Can data and models be appropriately integrated to streamline and speed up resource assessment and adapt to changing economic and technology needs?**
    c. **Can we integrate what we learn from the process-field observations to understand how mineral extraction can be more effective? – often, the optimized mineral extraction technique is an inverted form of what happened in nature**.

The Department of Geosciences' broad expertise in physical, chemical, and biological characteristics of igneous, metamorphic, and sedimentary rocks and mining waste, united by a shared interest in process-informed, quantitative prediction, positions us as highly adaptable, capable of pivoting and extrapolating insight across different basins and mineral systems as technology and economic outlooks shift in this rapidly changing field. This provides a unique opportunity for value-added insight through interdisciplinary studies and knowledge-transfer.

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