

## The geochemistry and mineralogy of responsible mining of rare earths.

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Responsible mining is often regarded as largely a socio-economic issue but although good behaviour and governance are important, the fundamental ore deposit geochemistry and mineralogy also influence many relevant factors. For example, energy use, water use, resource efficiency, financial profitability, potential environmental contamination, and the health, safety and well-being of the work force are all related to the minerals present; to their compositions, sizes, shapes, textural relations, solubilities, amenability to various beneficiation methods, and how strongly they are held together.

Rare earths, used in many green technologies, are particularly interesting to consider from this point of view. Following the recent supply problems and the designation of rare earths as 'critical' metals, a wide range of rare earth deposits are now under active exploration and development, ranging from fresh and weathered carbonatites and alkaline rocks, to beach sands, ion adsorption clays and even sea floor muds. These diverse deposits have large differences in the characteristics listed above and raise a question about whether some deposits are inherently more environmentally friendly than others.

For example, unconsolidated beach sands, such as those currently mined for monazite in India, do not need comminution and thus can require one third of the energy to process than a hard rock carbonatite deposit. However, the monazite in beach sands is mostly derived from granitic protoliths and contains typically several wt% ThO<sub>2</sub>, making it radioactive and problematic to store, ship and process. In contrast, rare earth fluorocarbonates in carbonatite deposits have some of the lowest Th contents of any of the rare earth minerals, and carbonatite monazite is also characteristically low in Th.

In order to make comparisons, metrics are required and it is necessary to balance the various factors, such as energy use, versus the other environmental impacts. The system of apportionment of these impacts when the REE are by-products also makes a large difference to the outcome. Mineral compositions and associations do vary within each deposit type and it is possible to develop a geometallurgical approach to environmental impact early on in an REE exploration project.

## Liquid-liquid separation at the onset of CaCO<sub>3</sub> formation

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Recent experimental characterizations of the early stages of calcium carbonate crystallization reveal an abundance of nanometer-sized prenucleation clusters that appear prior to formation of an amorphous intermediate phase. The prevailing interpretation of the clusters as thermodynamically stable suggests that the nucleation of calcium carbonate may follow a non-classical pathway.

This research uses replica-exchange molecular dynamics techniques to probe the initial formation and onset of order within hydrated calcium carbonate cluster species and lattice gas simulations to explore the more general behavior of clusters during phase separation. A two-phase thermodynamic model is also used to determine the free energy of the clusters as a function of size and to enable comparison with classical nucleation theory.

The results suggest that a spontaneous liquid-liquid phase separation may occur within the range of concentrations for which pre-nucleation clusters are observed. Coalescence of the nanoscale droplets results in the formation of a phase whose structure is consistent with that of amorphous calcium carbonate. The significance of these results is discussed within the context of classical and emerging non-classical phase-separation theories.