Pedogenic Enrichment of Rare Earth Elements in Lignites during the Paleocene-Eocene Thermal Maximum, Williston Basin, North Dakota

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Abstract

Rare earth elements (REE) and other critical mineral commodities are increasingly vital components in the manufacturing of modern products, especially those needed for electrified energy infrastructure and advanced defense technologies. The United States has little to no domestic production of these minerals and thus relies on foreign suppliers; a strategic vulnerability that the U.S. has looked to address through the identification of new and non-traditional sources. Coal is one alternative source that has been investigated for its potential to accumulate critical minerals, especially the heavy REEs (terbium, dysprosium) which are not major components of traditional igneous REE ores. Although the average total REE concentration of U.S. coal (66 ppm) is much lower than that of average upper continental crust (UCC; 182 ppm), some coals are considerably more enriched. The North Dakota Geological Survey has identified zones of enrichment exceeding 2,500 ppm REE (dry coal basis) in some Paleocene lignites, showing that the Williston Basin has the potential to host feedstocks exceeding the 300 ppm threshold which the U.S. Department of Energy has assessed could be economical in coal and coal byproducts. Several mechanisms have been proposed to explain REE enrichment in world coal, including the introduction of volcanic ash during the peat bog stage or a later influence from REE-laden fluids, whether ascending (hydrothermal) or descending (meteoric). Lignites exhibiting moderate REE enrichment occur in many stratigraphic positions throughout the Paleocene record of the Williston basin, but appear to often be the result of long-term, low-intensity weathering during the Quaternary as these lignites are frequently associated with an overlying permeable upland surface. Fort Union clastics, which contain relatively normal amounts of REE-bearing primary and secondary minerals, are subject to leaching by weakly acidic meteoric waters which transport REE and other elements into organic complexes in the underlying lignites. Although much of this enrichment appears recent and topographically controlled, a few stratigraphic intervals contain consistently high REE concentrations regardless of modern landscape position. One of these intervals is the Bear Den Member of the Golden Valley Formation, a weathering profile formed during the anomalously warm and humid climate of the Paleocene-Eocene thermal maximum. Intense pedogenesis during this event kaolinized and leached 10 meters or more of Late Paleocene strata, transporting REE downwards through the profile. Mudstones and claystones in lower portions of the Bear Den Member are commonly slightly enriched (>364 ppm REE; 2 times UCC) and lignites, where they occur, can be significantly enriched (>1,820 ppm; 10 times UCC) on a dry coal basis and several-fold higher on an ash basis. The REE concentrations reported from these lignites are amongst the highest, if not the highest, known to occur in North American coals.