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China's ion-adsorption rare earth resources, mining consequences and preservation

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ABSTRACT

The surface mining and heap leaching of China's unique ion-adsorption rare earth resources have caused severe environmental damage, and China needs to develop and implement an integrated rare earth resource management approach for a sustainable rare earth industry.

Rare earth elements (REEs) comprise of 15 lanthanides (atomic numbers between 57 and 71), scandium (atomic number 21) and yttrium (atomic number 39). REEs have become vital and indispensable components of many high-tech products, devices and technologies, including clean energy (e.g. solar cell and wind turbines), national security systems, and military and defense applications. China's rare earth reserve in 2011 was estimated at 18 million tons, accounting for 23% of the global reserves (see China's rare earth industry white paper) (Anonymous, 2012). By contrast, the United States Geological Survey's REE reserves data for China was 57.7% in 2008, 36.5% in 2010 and 48.3% in 2011. China's production of rare earth minerals increased by an annual average of 40% between 1978 and 1989 (Fig. 1) and has provided more than 90% of the world's supply since 2001 (Su, 2009; Chen, 2011; Anonymous, 2012). As a result, China's rare earth reserve has been steadily

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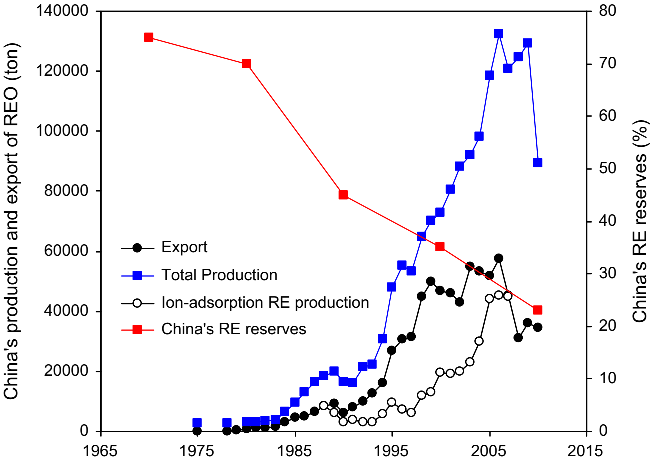
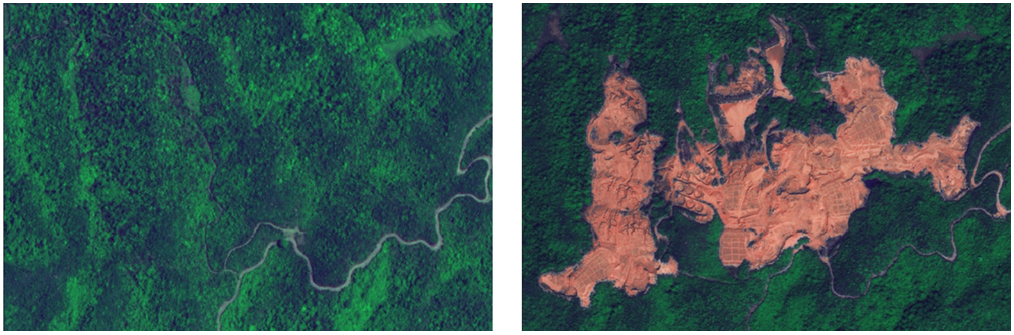


Fig. 1. China's rare earth reserves, production levels and exports.

Ion-adsorption rare earth mining in Ganzhou, Jiangxi Province; Photo by K. Wang, (2012).



Satellite images of a rare earth mining site in Ganzhou on April 14, 2005, (left) and February 9, 2009 (right) (Guo, 2012).

decreasing from 75% in 1970 to 23% in 2011 (Chen, 2010a, 2011; Anonymous, 2012) (Fig. 1) while the world's demand is projected to rise to at least 185,000 t annually by 2015 (Humphries, 2012). As REEs are being used in more and more applications, the gap between the world's demand and supply is increasing (Stone, 2009; Service, 2010). Nevertheless, there are sufficient reserves of rare earths in the world to sustain global consumption needs for many years (Chen, 2011). The challenge will be in finding these new reserves and establishing the required infrastructure, mining and extraction procedures quickly enough while also ensuring the environment is not damaged (Hurst, 2010).

China's rare earth reserves which are of industrial grade are predominately in three categories, mixed bastnaesite and monazite (accounting for 83.7% of China's total REE reserves, located in Bayan Obo, Inner Mongolia), bastnaesite (10.6%, in Sichuan and Shandong provinces) and ion-adsorption clays (2.9%, in seven provinces of southern China) (Su, 2009). Rare earth ore deposits have relatively low concentrations ranging from 10 to a few hundred parts per million by weight, making them difficult to mine economically. Bastnaesite (with a formula of $(Ce,La)CO_3(F,OH)$) and monazite (with a formula of $(Ce,La,Nd,Th)PO_4$) ores are far more complicated and costly to extract than ion-adsorption clays. The light REEs (La, Ce, Pr, Nd, and Pm) are more abundant and concentrated than medium and heavy REEs (from Sm to Lu plus Sc and Y) and usually make up about 80–99% of a total deposit. Medium and heavy REEs have more applications and are of higher value than light REEs. Bayan Obo rare earth deposits are rich in light REEs (accounting for 97% of total rare earths of the deposit) whereas the ion-adsorption clays are rich in medium and heavy REEs (accounting for more than 80% of world's total medium and heavy REEs) (Su, 2009; Chi et al., 2012). Ion-adsorption rare earth deposits were first discovered in Ganzhou (115°11′–115°49′ E and 25°35′8″–26°20′53″N), China, in 1970. Initially, it was not considered as a mineral phase because it did not behave like any of the known phases of rare earth minerals. The ion-adsorption rare earth deposits were formed by chemical weathering decomposition and dissolution of granite and granite porphyry (containing relative high abundance of rare earth elements) and subsequent adsorption and enrichment on clay minerals during the migration and penetration process of rare earth mineral solutions. The minerals are therefore also called weathering crust elution-deposited rare earths. These particular types of deposits are sparsely distributed throughout seven adjacent provinces of southern China (Jiangxi, Guangdong, Fujian, Zhejiang, Hunan, Guangxi and Yunnan) and have not been found anywhere else in the world. The deposits are generally found in small mountains with a humus topsoil layer of 0.3–1 m, a full-regolith layer of 5–30 m (the main ore body, containing 0.03–0.15% REE in general), a semi-regolith layer of 2–3 m and a bedrock layer. Unlike other rare earth minerals which are in solid state mineral phase and tend to be symbiotic or associated with the radioactive elements uranium and thorium, ion-adsorption rare earth minerals occur at a simple trivalent cationic state, which is simply adsorbed onto clays and readily extracted by a simple leaching technique with an aqueous electrolyte solution (sodium chloride or ammonium sulfate) via an ion-exchange process: $2(Kaolin)^{3-}RE^{3+}+3(NH_4)_2SO_4 \rightarrow 2(Kaolin)^{3-}(NH_4)^{+}_{3}+RE^{3+}_{2}(SO_4)^{2-}_{3}$. Therefore, the extraction of ion-adsorption rare earths is carried out by surface/mountaintop mining followed by tank or heap leaching with sodium chloride or ammonium sulfate solution.

In spite of an extremely low ratio of ion-adsorption rare earth reserves (2.9% of China's total rare earth reserves), this type of rare earth accounted for 26% of China's total rare earth production between 1988 and 2007 (Su, 2009) (Fig. 1) and has reached 35% since 2009. Using traditional surface/mountaintop mining and heap leaching techniques it is estimated that for the production of 1 t rare earth oxide from ion-adsorption rare earth ores, 300 m^2 vegetation and topsoil are removed, 2000 t tailings are disposed into adjacent valleys and streams, and 1000 t wastewater containing high concentrations of ammonium sulfate and heavy metals is produced (Su, 2009). Removal of vegetation and topsoil, the resulting changes in topography, and soil compaction reduce infiltration and storm runoff absorbing capacities, leading to increased frequency and magnitude of flooding and other geological disasters during storm periods. As a result, surface/mountaintop mining for ion-adsorption rare earth ores has become the dominant driver of land-use change and degradation in southern China, causing permanent loss of ecosystem, severe soil erosion, air pollution, biodiversity loss and human health problems (Tang et al., 2000; Liu, 2002; Chen, 2010b; Anonymous, 2011b). The rare earth mining in Ganzhou region has left 302 abandoned mines and 191 million tons of tailings and the area of destroyed forests increased from 23 km^2 in 2000 to 153 km^2 in 2010 (see satellite images) (Guo, 2012). The reclamation for Ganzhou's rare earth mine-sites was estimated at least at 38 billion RMB (approximate U.S. $5.8 billion). This does not account for human health and environmental costs. In stark contrast, the total sales income of the entire Jiangxi Province's rare earth industry (51 enterprises in total) for 2011 was 32.9 billion RMB (Xinhua, 2012) and the Ganzhou's average annual profit from the rare earth industry has been only about 2 billion RMB over the past decade (see China Daily, 28th July, 2012). Biological, environmental and human health impacts of mountaintop mining activities have been well documented (Gilbert, 2010; Palmer et al., 2010; Holzman, 2011; Beggs, 2012; Bernhardt et al., 2012); the negative impacts and environmental degradation of surface/mountaintop mining are pervasive and irreversible and human health problems continue to develop even after the mine-site has been reclaimed to premined conditions (Palmer et al., 2010). In June 2011, the Chinese central government enforced a ban on surface mining and tank/heap leaching while implementing in-situ leaching for ion-adsorption rare earths (Anonymous, 2011a). This policy has been reiterated in the 2012 rare earth white paper (Anonymous, 2012). The in-situ leaching technology is advantageous in terms of surface vegetation clearing and soil excavation. However, the enforcement of in-situ leaching to tackle environmental problems associated with rare earth mining and extraction remains highly contentious (Zhao, 2000; Li and Shao, 2001; Liu, 2002; Li et al., 2010).

The alternative technique of in-situ leaching for ion-adsorption rare earth minerals was developed in the mid-1980s and the first plant began operating in 1997. The in-situ leaching does not require clearing of vegetation and forests or the removal of topsoil, instead drilling of leaching holes with a diameter of 0.8 m, a depth of 1.5–3 m and a distance of 2–3 m in between each leaching hole are used. The concentration of the leaching solution is generally 3–5% ammonium sulfate and the leaching takes 150–400 days. Clearly, removal of all the top soil and vegetation above the ore deposits and subsequent filling of valleys with ore tailings are avoided in the in-situ leaching process, although about one-third of the vegetation is still cleared and 7000 m^3 drilling slurry/ha is produced. The implementation of in-situ leaching requires comprehensive geological and geotechnical surveys to be carried out to obtain information on the hydrogeological structure of the mining areas, ore characteristics, occurrence, composition and grade, surrounding rock infiltration properties and to estimate the amount of ore. As a consequence, each mine requires a dedicated in-situ leaching program based on the geological survey. Otherwise, the recovery of resources could be as low as 5% (Zhao, 2000). The practice of in situ leaching has also revealed serious environmental problems including underground water contamination, mine collapses and landslides. Ammonium sulfate contaminations of 3500–4000 mg/L in the groundwater, elevated pH and increased concentrations of ammonium, sulfate and rare earths (e.g. 80–160 mg/L ammonium and 20 mg/L REEs) in the surface water have been reported (Liu, 2002). The pH of the surface and ground water increased by 11% and 17.8% near the in-situ leaching sites of Longnan and Xunwu of Ganzhou region (Du, 2001). Water contamination owing to increased pH, electrical conductivity, total dissolved solids, sulfate and other pollutants directly cause environmental degradation, including disruption of water and ion balances and stream biodiversity decline (Palmer et al., 2010). Sulfate pollution persists long after mining ceases through exacerbated nutrient pollution of downstream rivers and reservoirs and increasing microbial production of hydrogen sulfide, an extremely toxic substance for many aquatic organisms and plants (Palmer et al., 2010). In addition, capillary forces surrounding the leaching holes attract high concentrations of leaching solution back to topsoil layer, destroying surface vegetation and plants and making rehabilitation more difficult. More than 100 landslides reported in Ganzhou region were attributed to in-situ mining and leaching practices, at significant human costs and losses of ion-adsorption rare earth resources. The recorded number of fatal landslides triggered by environmental degradation worldwide between 2004 and 2010 was 2620 with a total of 32,322 recorded fatalities—most occurring in the Himalaya mountains and China (Petley, 2012). Landslide fatalities in China will continue to increase due to serious environmental degradation (Petley, 2012). The reclamation of finished in-situ leaching mines is conducted on a case-by-case basis and could be more costly than that of surface mining/heap leaching mines (Zuo, 2012).

The enforcement of in-situ leaching regardless of the mine's characteristics could result in a very much lower recovery of the resources, massive groundwater contamination and potential landslides. We suggest that the technique used for the mining of ion-adsorption rare earth reserves should be solely based on hydrogeological and geotechnical conditions and ore concentration. The government should provide greater tariff benefits, compensation policies, regulation and support to encourage the use of in-situ leaching rather than to simply ban surface mining/heap leaching. The scattered distribution of ion-adsorption rare earth deposits and their ease of extraction through a simple heap leaching technique makes it extremely difficult for large-scale and centralized industrial production, for government authorities to carry out efficient overseeing of the industry and to stamp out illegal mining and extraction activities (e.g. local residents dig ore from mountains behind their homes and leach in their backyards). Preservation of sovereign non-renewable resources is a fundamental policy of industrial nations (Jia and Liu, 2011). China needs to implement an integrated rare earth resource management approach for meeting the global demands, preserving resources for future generations and protecting the environment (Chen, 2010b). This integrated approach would involve issues of ecology, resource management, scales of production, the most appropriate mining technology, marketing, and would require state controlled regulation. Firstly, China needs to establish stricter industrial and environmental standards and laws for regulating the development of China's rare earth industry (prospecting, mining, extraction, tailings, run off and remediation). Secondly, China needs to achieve a centralized management of RE resources by eliminating illegal mining, consolidating rare earth enterprises, establishing production scale threshold for ion-adsorption rare earth mining enterprises, and setting production caps. A highly centralized management is especially important for the ion-adsorption rare earth resources, owing to scattered distribution and the simple and easy extraction of this particular mineral by individuals. To prohibit illegal mining and extraction, stricter laws and enforcement systems are required. Thirdly, by developing an integrated rare earth market, pricing and distribution system, China needs to strengthen environmental laws and enforcement authorities and encourage investment in environmental programs associated with the rare earth industry. To achieve the coordinated development of the rare earth industry, the Association of China Rare Earth Industry (ACREI) was officially founded in Beijing in April, 2012, aiming at coordinating, overseeing and regulating the development of China's rare earth industry while protecting the environment. Finally, but not least, China should seek the world's support with the higher consuming nations taking the lead in helping (assisting) China to implement strict environmental standards and measures in general, and in particular in strengthening regulations on the rare earth industry to preserve the resources and to protect not only China's environment but that of the world, as the global impacts are felt by every nation (Liu and Diamond, 2005).

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