Investigation on joint mining of Rare earth elements and zircons from the Yangtze River, China

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Abstract—Rare earth elements(REEs) have attracted much attention in recent years. China is the leading supplier of REEs, thanks to its vast mineral reserves and technological innovation since the 1960s. In the same period, China's sand used in construction has also increased year by year. The integrated application of the full utilization of sand for construction and exploration and mining engineering of REEs have been the subject of many recent studies. This paper compares the main erosion areas of the Changjiang River. And the abundance of zircon, a by-product of heavy rare earth elements in different regions. Yichang station is considered as a possible mining site. According to the characteristics of mechanical separation process and hydrometallurgy, a comprehensive system of river sand mining and REEs extraction was designed. This system is well established in zircon mining(LCA). However, the REEs extraction of river sand is affected by mineral composition, which requires a large number of experiments to optimize the process. This area needs further research.

1.Introduction
In the 1980s, China began to develop science and technology innovation programs. This period gave birth to two revolutionary programs: Program 863 and the Later Program 973. “The Father of Rare Earths in China” (Peking University News, 2015), Professor Xu Guangxian (1920-2015) applied his previous research results on extracting uranium isotopes to the extraction of rare earths and developed the REEs extraction technology suitable for China's mineral resources (Hurst, 2010)[1]. That has made China the world's largest exporter of rare earths. Between 1978 and 1989, China's rare earth production increased by an average of 40 per cent per year (Hurst, 2010). Thanks to the factors of labor and reserves, China has occupied the absolute advantage in the global production of REEs in the new century (Canadian Chamber of Commerce, 2012)[8]. But China is not content to simply be the number one exporter of rare earths. More and more high-tech applications require even more rare earth resources. The high profits and geopolitical influence have driven China to retain more rare earths in its own market (Bourzac, 2011).[9]

This means there is a huge demand for REEs in China itself. However, rare earth ore mining operation from rocks itself is in a state of over-saturation. Considering environmental factors, it is possible to obtain rare earth as a byproduct from other extractions. Although it is not a major REE mining area, a significant amount of minerals find their way into the Yangtze basin as weathered sediment. In addition, REEs are generally concentrated in certain heavy minerals, especially xenotime and zircon (e.g., Garzanti et al., 2011)[4]. Like REEs high-tech applications, zircon's range of applications and value is also expanding. Zircon sand is applied as is or transformed to many industrial applications, like ceramics, precision casting, refractories, catalysts, fuel cells, fibre optics, nuclear power generation, water treatment and medical prosthetics. This reveals the potential of river sand as a raw material for resource
extraction, even though it is an unrecognized base material in our economic system. It also accounts for the largest volume of solid material extracted globally (United Nations Environment Programme, 2019)\[5\].

The extraction of REEs and Zr from river sands can be regarded as a means to optimize the production system. They both serve as important emerging resources. On the one hand, the value brought by REEs and Zr can be used for the restoration of the environment while ensuring the quality of building materials. On the other hand, the extraction of REEs and Zr from river sand is also in line with the concept of circular economy under the huge demand window.

This paper will analyze the characteristics and type distribution of the river sediment in the Yangtze River and try to plan the most representative and suitable drainage basin for mining. It will explore the possibility of incorporating the traditional zircon mining methods with REEs extraction methods, from extracted sand. To test the idea it would be necessary to design a systematic mapping of the Yangtze River hydrological and sand characteristics, and extracted sands would also need to meet the general building materials standards.

2. River sediment of the Yangtze River

“Cradle of Civilization”, “Mother River” and "Artery of the Earth" all refer to the Yangtze River, the third longest river in the world and the longest river in Asia, with a total length of 6,387 kilometers, originating from the southwest of Keladandong Peak in Tanggula Mountains on the Qinghai-Tibet Plateau (Chen, 2020). It spans a vast range of landscapes along with competing climatic and tectonic factors (Wang, Yan, Han, Wu, & Zhang, 2019). Therefore, according to the basin, the Yangtze River sediment also has the characteristics of heterogeneity.

The process of soil erosion mainly occurs in the upper reaches of the Yangtze River. Its total erosion area is 622,200 km². The upstream basin covers 352,000 km². Symmetrically, sedimentation is dominant in the middle and lower reaches (Chen, 2020). Before the Three Gorges Dam impoundment, more than 400 million tons of sediment were sent into the ocean by the Yangtze every year.

The distribution of elements in the sediments is diverse. Grain size and the abundance of hydrodynamically sorted heavy minerals affect geochemistry of the Yangtze River's sediments, including the rare earth elements (He et al., 2015).

He et al. (2015) studied sediments covering the entire Yangtze River, collecting 30 confluences at major tributaries and main streams. Although these collection points are representative of different basins to a certain extent, they mainly demonstrate the contribution of tributaries to the main stream. In addition, the presence of ultra-dense minerals (e.g., zircon & monazite) has a strong influence on REEs distribution characteristics which in turn are subject to hydrodynamic sorting and concentration. Sediment of different streams as a whole may differ less than that of individual collection sites (Garzanti et al., 2010). For the collected samples, the main elements(X-ray Fluorescence Spectrometer), trace elements(ICP-MS) and isotopes(Thermal Ionization Mass Spectrometer) were determined. REEs (except Pm) and Zr compositions in sediments is collated here. In terms of cost-benefit project design, ZR can be regarded as the main product of the project and REES as the by-product. Moreover, ZR's main source of ore is zircon, itself generally concentrated HREEs (e.g., Garzanti et al., 2011). At a deeper level of enrichment, The HREE-enriched heavy minerals significantly influence the REE compositions, reflecting the control of provenance (e.g., Rollinson, 2013)\[8\]. But all the sediments show a similar type of pattern, with an enrichment in the light rare earth elements (LREE) and a relatively flat pattern in the heavy REEs (HREE; Gd to Lu). REES also vary in performance and are often difficult to assess in relation to strategic objectives. A specific value model needs to be further established and improved according to social needs. Therefore, a single quantitative order does not answer the question of the optimal location for REE mines. Because of the much more extensive information on its presence and because other heavy minerals can be expected to be concentrated with zircon, this paper only discusses these higher points in terms of the content of Zr.

Zirconium abundance levels of the sampling site in Nanjing is much higher than other sites, but there are construction costs (a bustling city, a large number of floating population and a high cost of labor).
And the reason why the value here is too high is not clear, there may be insufficient reserves. So this spot and its basin may not be a suitable location for mining. The value of Jinshajiang point is also relatively high. As the upper reaches of the Yangtze River, it is also the area with the most abundant sediment yield through erosion. Nd isotope data show that the major sources of sediment in the Yangtze appears to be within the lower and middle parts of the Yangtze Craton, as well as in the Songpan-Garze Terrane exposed in Eastern Tibet and Yunnan (He et al., 2015). Jinshajiang is the main river in Eastern Tibet. Compared with the sampling site in Nanjing (lower part of the Yangtze Craton), urbanization along the river is backward. As a result, mining costs are lower and social and environmental impacts are lower. [6] It is weak in sedimentation, so the value consumed by the process is the least. In terms of total reserves, it may be the most efficient extraction site. However, sediments are mostly suspended, which is difficult to collect. Because the existing design of zircon sand mining is applicable to riverbed sediment. The river sand produced by erosion is sparse and widely distributed and cannot be mined intensively. In addition, the turbulence of the Jinsha River itself is large and fierce (the total drop is 3,300 meters, and the hydraulic resources are more than 100 million kilowatts, accounting for more than 40% of the Yangtze River’s hydraulic resources), and the steep banks are not suitable for the construction of mining facilities. But the Jinsha River is the main source of sediment at Yichang Station on the main stream of the Yangtze River (Chen, 2020), which means that Yichang Station may be a better site even if it is not operated at the sampling site. There are already existing sand mining equipment, which greatly saves the cost. However, as mentioned above, this is only an overall analysis, and the specific site selection needs a detailed cost-benefit analysis. [7]

3. Mining and extraction process design

Placer deposits compared with rock mining; it has the advantage of processing process. The low-temperature REE deposits formed by erosion and weathering present fewer challenges in processing than the high-temperature deposits (e.g., alkaline igneous rocks). Beneficiation of such complex deposits to separate and concentrate the REE ore minerals remains a challenge (Goodenough, Wall, & Merriman, 2018). River sand is mainly a resource formed by weathering. Nature itself helps us with the sorting of minerals, which makes the overall design of the extraction process much simpler. Mineral sands are processed further as-mined and are not subjected to any comminution (Gupta and Krishnamurthy, 2005)[9]. Mineral Sands, for the most part, avoids the grinding step. Grinding is a necessary part of the rock mining process and accounts for 50% of the energy used in the extraction process (Wills and Napier-Munn, 2006).[10]

Figure 1 Basic flow sheet of ore processing modified from Voncken, 2016

Placer mines eliminate many of the cycle steps of pretreatment compared to hard rock ore (fig. 1). The number of cycles saved depends on the quality of the sand itself. But often simple screening may be required. Like rock, sand needs to be mined. Suspended sand is not collected efficiently, so sand is generally mined from the riverbed. Heavy mineral sands (placers) in wet environments are mined by dredging techniques, using bucket line and suction dredger (deep water), or bucket wheel device (shallow water). In dry conditions, open-air excavation is used. Drilling and blasting are generally not required but can be used when sand is strongly cemented (Voncken, 2016). Zircon sand is mined in two ways: dry mining (the inland deposits) and wet mining (using dredges) along the coastlines. Dry mining is the most common method and can be used for hard surface deposits, discontinuous deposits and small
tonnage and high grade deposits. Traditional earth-moving equipment (using scrapers, bulldozers and excavators) is used to dig up the sand and transport it to the processing plant. Wet mining usually requires the use of floating dredgers and concentrators in enclosed ponds, with the concentrator moving along behind the dredge within the pond. Alternatively, high-pressure water hoses could be used to break up sand dunes containing mineral deposits (Gediga, Morfino, Finkbeiner, Schulz, & Harlow, 2019). As the ore minerals of the rare earths are hardly magnetic, gravity separation and flotation will be the main separation technologies (Voncken, 2016). In addition, this property can also be used for zircon extraction, but the separation of zirconium and REEs requires a further process.

New market requirements and legislative changes are forcing the construction industry to improve its products - building materials that are used safely in sustainable buildings. This development led to changes in the production process and new requirements for the raw materials used. Unfortunately, most geologists, and even experts in raw materials, pay little attention to the needs of construction, the construction industry and its requirements for raw materials (Götze, Möckel, & Walther, 2012). Tailings will be used as construction sand, so attention should also be paid to the treatment of its physical and chemical properties. For example, cement requires the content of SiO₂ in the raw sand. Not only very pure sand qualities with >98 wt% SiO₂ are required, some applications need only 95, 88 or 70 wt% SiO₂. Taking into account transport and existing building materials standards (European Standard DIN EN 12620), it is important to ensure basic quality. At present times, it is uneconomic to process low quality source materials to produce mediocre products (Götze et al., 2012). However, the variety of building materials is also different, so the extraction process can be specified by a summary of the characteristics of the use (Table 1).

| Physical use | Physical and chemical use | Chemical use |
|--------------|---------------------------|--------------|
| Clay bricks  | Calcium silicate units    | Autoclaved aerated concrete |
| Concrete products | Ceramic products (pottery) | Cement |
| Grit         | Foundry sand              | Chemicals    |
|              |                            | Glass        |

| Mortar and render |
|-------------------|
|                   |

The size and shape of sand is a valid feature only if it is directly used in its original state. The grain size is of minor importance, if the sand is ground and used chemically (Götze et al., 2012).

The process of producing heavy mineral concentrate (HMC) from mined sand varies from person to person, depending on the specific mineral configuration of the deposit (Gediga et al., 2019). Extraction of heavy minerals from raw materials is usually achieved by wet gravity separation techniques such as helical separation, but integral foam flotation processes for gangue minerals are used in some hard rock operations. In the process of dredging, wet separation is carried out in floating concentrator. In dry mining, the feed preparation or mining unit plant (MUP) is mobile to minimize sand transport resistance. The mud produced by MUP is then pumped into the concentrator. Because of the multistage utilization process, there is little material available for backfilling. But considering that there is no backfilling process with construction sand, this aspect of the environmental impact is artificially minimized. The separation process is divided into two parts - Mineral Separation Plant (MSPS) and REE Separation Plant (RSP). The first separation was made according to the electrical, magnetic, and specific gravity properties of the heavy minerals. Other heavy minerals other than zircon inevitably appeared, but their use is beyond the scope of this paper. The active components of REE are separated mainly by gravity flotation, but flotation separation may be used earlier if gravity separation fails. In addition, the milling process is not required, depending on the quality of the HMC. After several times of separation, the sand used in construction will be separated from other active components, but the total efficiency needs further experiments and calculations. The secondary gravity separation and magnetic separation are to further purify the effective REE particles, in order to ensure the efficiency of subsequent
hydrometallurgy (Zhang, Zhao, & Schreiner, 2016). The core of the whole system is the separation technology using multiple differential stages, but the specific indicators of separation need to be adjusted according to the nature of the ore source.

4. Environmental impact considerations
The three outputs of the design -- sand for construction, REEs and zircon -- are currently irreplaceable and in long-term demand. Therefore, the core of environmental thinking is high efficiency and low impact.

The power component of this project can be referenced in a traditional zircon mining operation. Electricity generation relies on conventional combustion, a process that affects water eutrophication, summer haze (POCP), acidification (AP), ozone layer depletion potential (ODP), Eutrophication potential (EP) and global warming (GWP). The final data and degree can be presented by the sensitivity analysis of Gediga et al., 2019 (Table 4). Sensitivity analysis is used to assess how the results change when the values of the processes contributing the most change. Based on this, it was determined how the final impact would change if the power consumption varied by +/−30% (this value represents the true variability of power consumption considering the same mining mode (wet or dry) and the MSP produced in the same country).

5. Conclusion
Zircon, REEs and construction sand are in great demand in developing China. As one of the major rivers in China, the Yangtze River provides a large amount of sediment every year, given its large geographical span and complex distribution of chemical systems. Therefore, we chose zircon as the main research object, which is a heavy rare earth mineral that significantly affects the composition of REEs. It reflects the controlling effect of provenance area. The final results show that Yichang station may be a suitable mining site with a complete production system and excellent river sand resources. Then, according to the zircon mining and extraction system, the boundary of REEs and zircon combined extraction and river sand recovery system is preliminarily designed.

In terms of the nature of three resources, such research direction is the path to achieve environmental protection and sustainable development. However, the research focus is on the efficiency of the system, and more experiments and adjustments are needed to optimize the system.

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