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Estimation of lead and zinc emissions from mineral exploitation based on characteristics of lead/zinc deposits in China

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Abstract: Nonferrous mining activities are some of the largest sources of heavy metals emissions into the environment and China is one of the largest producers and consumers of lead and zinc in the world. The cumulative productions and emissions of lead and zinc from mining-related activities in China were estimated. Up to 2007, the cumulative productions of lead and zinc in China were estimated to be about 6.69 and 12.59 Mt, respectively; and about 1.62 Mt lead and 3.32 Mt zinc emitted into the ambient environment during the mining, processing and smelting activities, representing 24.39% and 26.36% cumulative production, respectively. Among these three types of mining-related activities, mineral processing contributes the most to the total emission of 50.67% lead and 45.51% zinc.

Key words: lead/zinc deposit; lead; zinc; cumulative production; emission flux

1 Introduction

The nonferrous mining industry in China has been exploiting rich domestic mineral resources in order to sustain rapidly economic and social development. However, the increase of heavy metals in the environment caused by mining activities has added to environmental deterioration in recent decades [1]. Heavy metal pollution due to mining and smelting has become a national problem and an important research topic for environmental and nonferrous mining sciences.

Lead is normally found in association with zinc in ores, either hosted within the lead sulfide mineral galena or within the zinc sulfide mineral sphalerite. These source ores are similar in terms of mineral composition, geochemical behavior and outer electron configuration and they have a strong affinity for sulfur and similar mechanisms for the adsorption of ferromanganese oxides, clay and organic matter. Co-existing lead and zinc ores are mined together during industrial production [2]. About 250 types of lead/zinc ores have been discovered in the crust, of which one-third are sulfides or sulfates. Natural galena and sphalerite are the main sources used in the lead/zinc mineral industry.

Lead/zinc mining and smelting activities are some of the main sources of heavy metals emission to the environment [3−5]. According to a global inventory of trace element emissions by NRIAGU and PACYNA [6], about (357−857)×10^6 kg/a lead and (462−1 380)×10^6 kg/a zinc are released into the environment through mining and smelting activities. Globally, the extensive processing of lead ores is estimated to release about 300 Mt of lead into the environment over the past five millennia, mostly within the past 500 years [7]. World lead mine production has been increased from 3.11 to 3.88 Mt from 1998 to 2008, and zinc production has been increased from 7.63 to 12.07 Mt [8]. Elevated levels of lead, zinc and related hazardous elements released into the environment continue to impact air, water, soil, vegetables, food supplies and other resources and may threaten human health [9−16].

China's rich lead/zinc resources have facilitated ongoing annual increases in lead and zinc mine production [8]. Many studies on Chinese lead/zinc mining and smelting activities have emphasized reserves and production from the perspective of resource utilization [17−21]. In this study, the cumulative

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production of lead and zinc from lead/zinc ore exploitation and the environmental emission fluxes of lead and zinc from mining, ore-dressing and smelting were calculated. The areas that face potential environmental risks due to lead/zinc mineral activities were also considered.

2 Data and methods

Data resources used in this study included publicly published articles and journal papers, Chinese mining yearbooks 2004−2008, and a 2006 database of the China Atlas of Lead/Zinc Mineral Resources (1: 5 000 000).

Equations used for the calculation of cumulative production and emission flux included:

$$P_C=R_{TI}-R_R \quad (1)$$

$$F_{ME}=P_C-(P_C\times R_{MA}) \quad (2)$$

$$F_{OE}=(P_C-F_{ME})-(P_C\times R_{MA}\times R_{OA}) \quad (3)$$

$$F_{SE}=(P_C-F_{ME}-F_{OE})-(P_C\times R_{MA}\times R_{OA}\times R_{SA}) \quad (4)$$

where P_C is the cumulative production, the total amount of workable ores mined during a specific time; R_{TI} is the total identified reserves; R_R is the retained reserves, the actual identified reserves of mineral resources at a specific time; F_{ME} is the mining emission flux; F_{OE} is the ore-dressing emission flux; F_{SE} is the smelting emission flux; R_{MA} is the mining average recovery rate; R_{OA} is the ore-dressing average recovery rate and R_{SA} is the smelting average recovery rate.

3 Results

3.1 Distribution and characteristics of lead/zinc minerals in China

Associated lead and zinc ores typically contain a much higher grade of zinc than lead. Chinese mines include few single lead or zinc deposits. The average grade level of the above-medium-sized lead/zinc mines in China is 6.48%, including 1.99% lead and 4.49% zinc [22]. As many as 50 elements are associated with the lead/zinc deposits, including sulfur, cadmium, copper, silver, gold, tin, antimony and so on. Silver is one of the main byproducts of lead/zinc ore, and silver from this source represents 60% of the basic reserve and 70% of the national production [23].

Although lead/zinc deposits of various types and metallogenic stages are widespread across China, most reserves are concentrated in Lanping in Yunnan province, the Sichuan−Yunnan region, the Nanling region, the Qinling−Qilian mountains and the Lang Mountain−Zhaertai region of Inner Mongolia. According to the government data (China statistical yearbook 2008) for 2007, the basic reserves for lead and zinc are 13.46 and 42.50 Mt, respectively. About 81% and 84% of them are located in the eight provinces/municipalities: Yunnan, Inner Mongolia, Gansu, Guangdong, Hunan, Sichuan, Qinghai and Guangxi (see Fig. 1). Lead/zinc mines in China include one super-scale mine (Lanping mine with reserves of more than 10 Mt), one ultra-scale (Fankou mine with reserves of more than 8 Mt), 44 large-scale and 133 medium-scale facilities. Large-scale and above-medium-scale deposits account for 5.1% and 22.3% of the mines, respectively. The 46 large and above large-scale lead/zinc mines account for 84.9% and 96.2% of lead and zinc reserves, and the top four largest mines (Lanping in Yunnan, Fankou in Guangdong, Changba in Gansu and Dongshengmiao in Inner Mongolia) account for 50.3% and 76.6% of all the lead and zinc reserves, respectively [20] (see Fig. 2). Of the various types of lead/zinc deposits in China, strata-bound deposits are most common, accounting for 52.3% of all the deposits. Other types of lead/zinc deposits include hydrothermal (25% of deposits), volcanic (14.7%) and skarn (7.6%) deposits. Underground mining is the most prevalent method for lead/zinc exploitation [20, 22].

China's lead/zinc smelting industry has developed fast based on its rich resources and low labor cost. Lead/zinc production bases in the Northeast are the earliest to develop and have made an active contribution to the development of China's lead/zinc smelting industry. In 1950s, the area has accounted for more than 80% of the lead production and trained skilled workers and professionals for other smelting companies. In the 2010s, according to the lists of enterprises in China's lead/zinc smelting industry, the smelting industry has shifted to production bases in Yunnan−Sichuan, Hunan, Guangdong−Guangxi and the Northwest (Fig. 3).

3.2 Status of China's lead/zinc resources in world

Lead/zinc deposits are scattered throughout the world with the exception of the Antarctic. According to US geological survey data for 2008, global retained reserves, basic reserves and reserves* of lead are 1 500, 170 and 79 Mt, respectively; for zinc, these values are 1 900, 480 and 180 Mt, respectively (see Table 1). Most identified reserves are concentrated in the four countries of Australia, China, the United States and Kazakhstan. These four countries host about 71.2% and 76.1% of all the world lead and zinc basic reserves and China accounts for 21.2% and 19.2%, respectively. Ranking second in the world is after Australia. From 1998 to 2008, the lead ore output has increased from 0.58 to 1.52 Mt at an average growth rate of 10.1% in China. Zinc ore output has increased from 1.27 to 3.91 Mt at an average growth rate of 10.2% [8]. Chinese lead and zinc production has ranked first in the world since 2003 and supplies both domestic demand and exports [23].

* Notes: According to the classification of solid fuels and mineral resources/reserves of China, retained reserves is the actual identified reserves of mineral resources as of a specific date; basic reserve is taken into account the feasibility of mining to the lead/zinc deposits economically; reserves is a portion of basic reserve been mined or easy to be mined.

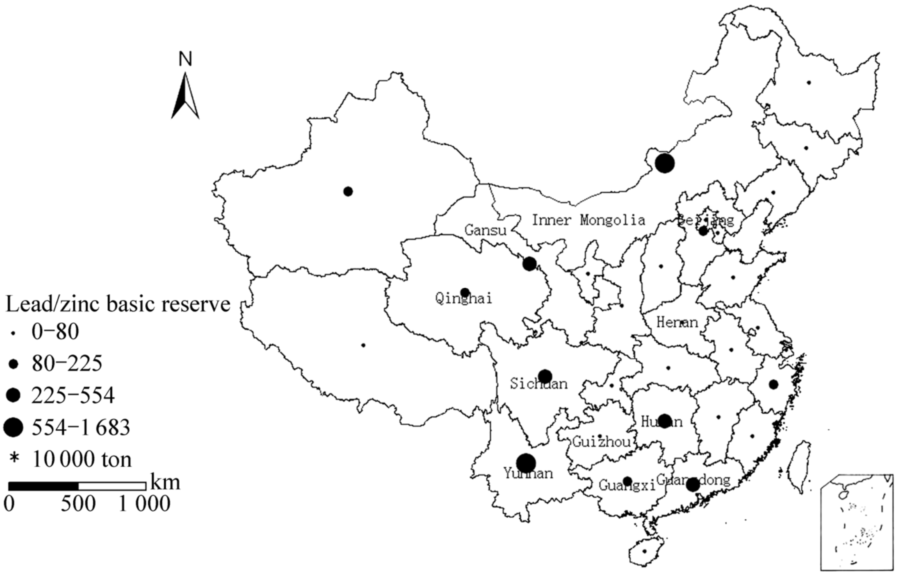

Fig. 1 Basic reserves of lead+zinc in each province/ municipality in China

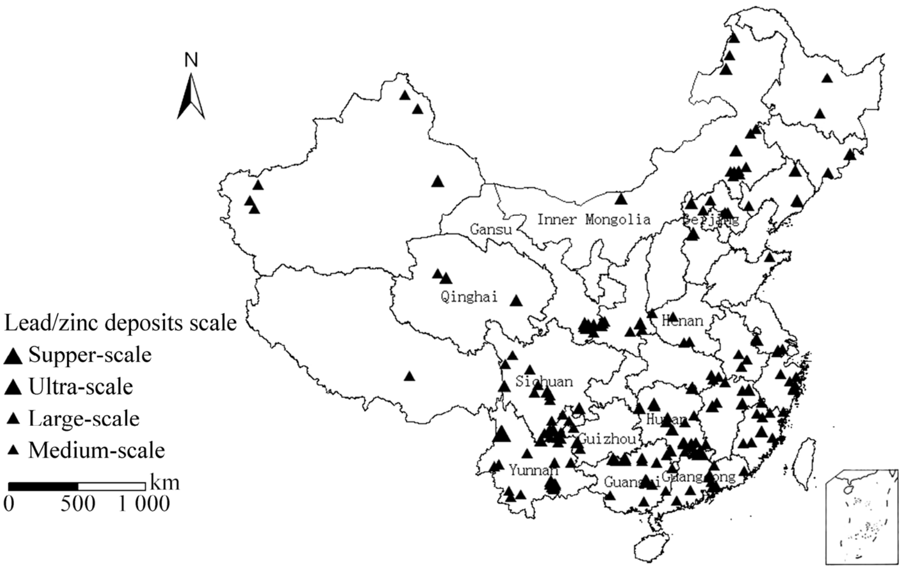

Fig. 2 Scale and distribution of lead/zinc mines in China

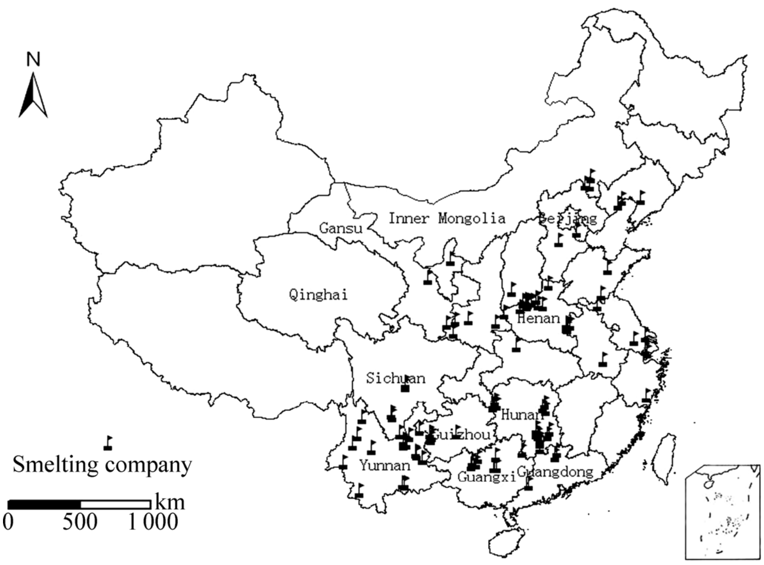

Fig. 3 Top 100 lead/zinc smelting enterprises in China

3.3 Cumulative production of lead and zinc

In 2003, mainland China had 735 lead mining sites and 797 zinc mining sites. The total identified reserves (R_{TI}) of lead/zinc were 130.24 Mt (including 39.57 Mt lead and 92.67 Mt zinc) [22]. The data for newly-identified reserves and retained reserves each year (2004−2007) from China mining yearbooks 2004−2008 are obtained. Based on Eq. (1), the P_C of lead and zinc in China is about 6.69 and 12.59 Mt, respectively (Table 2).

3.4 Flow direction and fluxes of lead and zinc

During the processing of mining, ore-dressing, smelting and commercial use, lead, zinc, cadmium and other associated elements can escape into the adjacent environment. Lead and zinc processing procedures release different fluxes of metals due to the differences in their production processes and average recovery rates.

3.4.1 Mining

Most lead/zinc deposits in China are mined underground by cut-and-fill mining, open stope mining and natural block caving mining [24]. The mining process involves entry driving, rise driving, slicing, punching, bursting, ore loading, transporting, spraying, ventilating, etc. In this process, crude ores release large amounts of dust, harmful gases, wastewater and barren rock. According to the R_{MA} (Table 3) and Eq. (2), about 0.49 Mt lead and 0.93 Mt zinc have escaped into natural environment during lead/zinc mining in China (seen in Fig. 4).

3.4.2 Ore-dressing

Concentrated lead and zinc ores, which are the inputs for the smelting process, are obtained from crude ores by crushing and mill running. Lead and zinc sulfides are separated from their ores mainly by the process of flotation. Flotation requires a large volume of water and beneficiation pharmacy and releases large amounts of dust, tailings and waste water that contain high concentrations of lead, zinc, cadmium and other elements. Based on the R_{OA} (Table 3) and Eq. (3), about 0.82 Mt lead and 1.51 Mt zinc have escaped into the natural environment in China during the ore-dressing process (see Fig. 4).

3.4.3 Smelting

Lead and zinc are traditionally extracted from sulfide mineral concentrates by roasting, sintering and then smelting. Smelting is the reduction of oxides to elemental metal and is usually accomplished by pyrometallurgical methods with carbon (coke or coal) and carbon monoxide in a furnace. An alternative method commonly used for zinc is to leach the roasted zinc concentrate with sulfuric acid to form zinc sulfate, which is then purified to remove contaminating elements such

Table 1 Worldwide lead/zinc reserves

Country	Lead reserves				Zinc reserves			
	Reserves/Mt	Proportion/%	Basic reserve/Mt	Proportion/%	Reserves/Mt	Proportion/%	Basic reserve/Mt	Proportion/%
Australia	24	30.4	59	34.7	42	23.3	100	20.8
China	11	13.9	36	21.2	33	18.3	92	19.2
United States	7	9.7	19	11.2	14	7.8	90	18.8
Kazakhstan	5	6.3	70	4.1	14	7.8	35	7.3
Canada	0.4	0.5	50	2.9	5	3.9	30	6.3
Peru	3.5	4.4	40	2.4	18	10.0	23	4.8
All the world	79	100	170	100	180	100	480	100

Source: Mineral commodity summaries, 2009

Table 2 CP and TIR of lead and zinc in China

Year	R_R/Mt		New identified reserve/Mt		R_{TI}/Mt		P_C/Mt	
	Lead	Zinc	Lead	Zinc	Lead	Zinc	Lead	Zinc
2003	−	−	−	−	39.57	92.67	−	−
2004	−	−	1.82	3.05	41.39	99.31	−	−
2005	39.34	94.95	2.09	4.02	43.47	103.33	4.13	8.34
2006	41.41	97.11	2.55	4.87	46.02	108.20	4.61	11.09
2007	42.08	100.49	2.74	5.25	48.76	113.45	6.69	12.59

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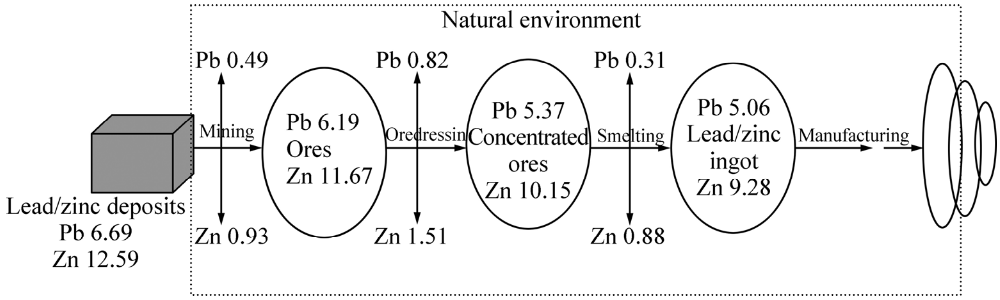

Fig. 4 Flow direction and fluxes of lead and zinc among lead/zinc exploitation in China (Unit: Mt)

Table 3 Average recovery rates of Chinese lead/ zinc mineral exploitation [20]

Element	R_{MA}/%	R_{OA}/%	R_{SA}/%
Pb	92.85	84.7	94.27
Zn	93.85	87.56	91.34

as Cu, Cd, Co and Ge. Lead and zinc refining use pyrometallurgical (e.g., fractional distillation) or electrolytic processes. According to the R_{SA} (Table 3) and Eq. (4), about 0.31 Mt lead and 0.88 Mt of zinc have escaped into the natural environment during smelting processes in China (see Fig. 4).

After smelting, the resultant lead/zinc ingots are manufactured into a variety of products. Although some traditional uses of lead are declining (petrol and architectural/plumbing applications), others (storage batteries) are increasing. Zinc applications, especially for galvanizing and die casting, are expected to remain steady. Although some lead, zinc and other metals are also released into environment during the processes of manufacturing, servicing and circulation, this study focuses on lead and zinc emissions due to mining through smelting. Through the three processes evaluated, about 1.62 Mt lead and 3.32 Mt zinc escape into the environment, representing 24.39% and 26.36% of the P_C for lead and zinc, respectively. Ore-dressing procedures produce the greatest fractions of lead and zinc release (50.67% and 45.51%, respectively). Tailings from ore-dressing contain high levels of metals that easily move into the environment through wind and rain erosion [25].

4 Discussion

a has a long history of lead/zinc mining and smelting. Massive reserves of lead/zinc deposits are widespread in several areas in China. Due to the favorable characteristics of China's lead/zinc mineral resources and economic incentives, major lead/zinc mining, ore-dressing, smelting and matching operations are based in Yunnan-Sichuan, Hunan, Guangdong-Guangxi, Henan, Northwest and Northeast, with a total capacity that accounts for more than 85% of the total amount in China (Fig. 5).

The lead/zinc mineral resources are highly favorable for exploitation due to their wide distribution and concentration. At the same time, the rapid development of industrial applications for lead and zinc has caused demand to increase consistently since 2000, and imports of lead/zinc ores and concentrates have increased each year (see Table 4). The calculation of the emission flux from the smelting process does not account for imports and therefore somewhat underestimate lead and zinc fluxes to the environment. For example, in 2006 alone, about 0.41 Mt lead and 0.36 Mt zinc were unaccounted for.

Before the end of 1970s, primitive mining, ore-dressing and smelting technologies yielded significantly lower average recovery rates than those described here. In addition, small-scale rural mines in rural areas were plagued by lower efficiency, illegal operations, inaccurate statistical data, abandoned waste and so on. Therefore, the emission fluxes and the cumulative production may be somewhat underestimated. The lead and zinc mining industries expanded rapidly and intensively after late 1970s, and this period was accurately represented by the data and parameters in this study. In other words, the estimates presented here are representative of China as a whole. They provide a reliable basis for environmental management and control of medium-scale and above-large-scale lead/zinc mining, which inflicts severe environmental and health damage, as currently practiced and regulated. Lead, zinc and associated elements have mainly accumulated in resource-rich, intensive smelting areas such as Yunnan−Sichuan, Hunan, Guangdong−Guangxi, the Northwest and the Northeast. The environment in these regions poses potential health risks, and some environmental health effects have been detected [10−11, 26−28]. Greater environmental and health protections should be implemented in these areas.

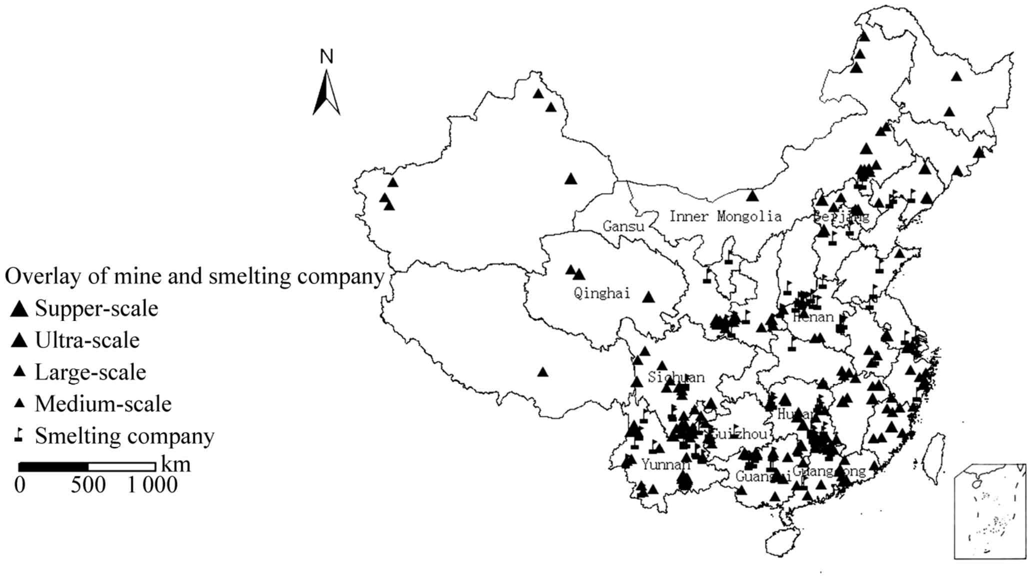

Fig. 5 Distribution characteristic of lead/zinc mining and smelting industries in China

Table 4 Chinese import dependence for lead/zinc ore concentrate

Year	Pb			Zn		
	Import quantity/Mt	Domestic output/Mt	External dependence/%	Import quantity/Mt	Domestic output/Mt	External dependence/%
2000	1.87	6.70	21.11	0.39	17.80	2.14
2001	2.38	6.76	26.06	3.27	16.93	16.17
2002	2.33	6.41	26.69	3.92	16.24	19.46
2003	4.07	9.54	29.91	3.73	20.29	15.52
2004	4.99	9.97	33.33	3.08	23.91	11.41
2005	6.18	11.42	35.11	2.84	25.48	10.03
2006	7.16	13.0	35.52	4.14	27.00	13.30

Note: External dependence = import quantity/(domestic output + import quantity)

5 Conclusions

1) Massive reserves of lead/zinc deposits are widespread in several areas of China. Due to the favorable characteristics of China's lead/zinc mineral resources and economic incentives, major lead−zinc mining, ore-dressing, smelting and matching operations are based in Yunnan−Sichuan, Hunan, Guangdong−Guangxi, Northwest and Northeast.

2) In 2007, about 6.69 Mt lead and 12.59 Mt zinc have been mined in China. As the result of the three processes of mining, ore-dressing and smelting, about 1.62 Mt lead and 3.32 Mt zinc escape into the environment, representing 24.39% and 26.36% of lead and zinc P_C, respectively.

3) Ore-dressing procedures are the largest contributor to the total emission fluxes for lead (50.67%) and zinc (45.51%).

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基于中国铅锌矿资源特点的铅锌环境释放通量估算

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摘 要：有色矿业活动是重金属释放进入环境的重要来源，而中国是世界上重要的铅、锌生产和消费大国之一。估算中国铅、锌矿产资源开发活动中铅、锌的累计采出量和环境释放通量。截至 2007 年底，在中国大陆铅、锌累计采出量分别为 6.69 和 12.59 Mt。通过铅锌矿采矿、选矿和冶炼 3 种方式进入周围环境的铅、锌通量分别为 1.62 和 3.32 Mt，分别占铅、锌累计采出量的 24.39%和 26.36%。在上述 3 种矿业活动方式中，选矿活动对铅、锌的环境释放通量贡献最大，分别占 50.67%和 45.51%。

关键词：铅锌矿；铅；锌；采出量；释放通量

(Edited by FANG Jing-hua)