



Geographical environment determinism for discovery of mineral deposits



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ABSTRACT

The spatial distribution of metallic mineral deposits discovered in China during 1901 to 2007 shows that nearly 85% of the total 2906 metallic mineral deposits with the magnitude greater than medium-size are located on the southeastern side of the famous Heihe-Tengchong “geo-demographic demarcation line”. This spatial pattern is consistent with the population distribution of China, indicating that the spatial distribution of discovered mineral deposits may be related to exploration level that is strongly restricted by the geographic environments. We found that the number of discovered deposits per unit area in explored regions increases with the exploration level, following a power-law model. From this model, if the geological, geochemical and geophysical exploration in the NW region of the geo-demographic demarcation line reaches the same level as that in the SE region of the line, about 2000 metallic mineral deposits with magnitudes greater than medium-size remain to be discovered in the NW region of China.

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1. Introduction

According to the standards for classification of the scales of mineral resource reserves in China (Ministry of Land and Resources of the People's Republic of China, 2000), during the period from 1901 to 2007, totally 2906 metallic mineral deposits with magnitudes greater than medium-size were found in China (National geological archives of China, 2007), of which those productively mined deposits have been the main domestic metallic mineral resource suppliers for Chinese economic development in the last 100 years.

About 85% of the total 2906 metallic mineral deposits are distributed at the southeastern side of the famous Heihe-Tengchong “geo-demographic demarcation line” (Figs. 1 and 2A), which is basically consistent with the distributional pattern of population in the country since 1930s (comparing Fig. 1 and Fig. 3). The geo-demographic demarcation line is also called Huanyong Hu Line (HH Line) in the literature. In 1930s, the population in China totaled 458 million, of which about 96% were concentrated in the SE side of the HH Line, and merely 4% in the NW side (Hu, 1935). After 70 years, Chinese population increased to 1.3 billion, but the population distribution is still consistent with that revealed by the HH Line (comparing Fig. 3 A and B). The data of 2000 China census show that the proportional distribution of the population at the two sides of the line was 94.1% to 5.9% (Ge and Feng, 2008).

As we all know, the geographic environments such as landforms and climate on both sides of the HH Line are greatly different, thus the difference in the population distribution between the two regions separated by the line since 1930s mainly can be attributed to the differences in economic and societal developments resulted from different geographic environments between the two regions. An important similarity between the spatial distribution of discovered mineral deposits and the distributional pattern of population in China is noteworthy, which implies that geographical environments such as landforms and climate have an important control on the regional discovery frequency of mineral deposits. Although the different styles of mineralization are not randomly distributed, either in time or in space (Robb, 2005), and the formation of certain types of mineral deposits and their distribution in any given region depend on the crustal evolution and tectonic setting of that region, the chances of discovering mineral deposits, especially deposits under cover, will depend on geographical environments as well as economic and political factors under a given technological progress. Geographical environments have a great impact on the coverage and intensity of geological, geochemical and geophysical surveys for mineral resources, thereby the spatial distribution of discovered mineral deposits can be considered as a function of the geological exploration level.

A key function of many quantitative mineral resource assessments is estimating the number of undiscovered deposits (Singer et al., 2001). Allais (1957) used the Poisson distribution to estimate the number of deposits per square kilometer in a relatively unexplored area from several explored areas. Most resource assessments

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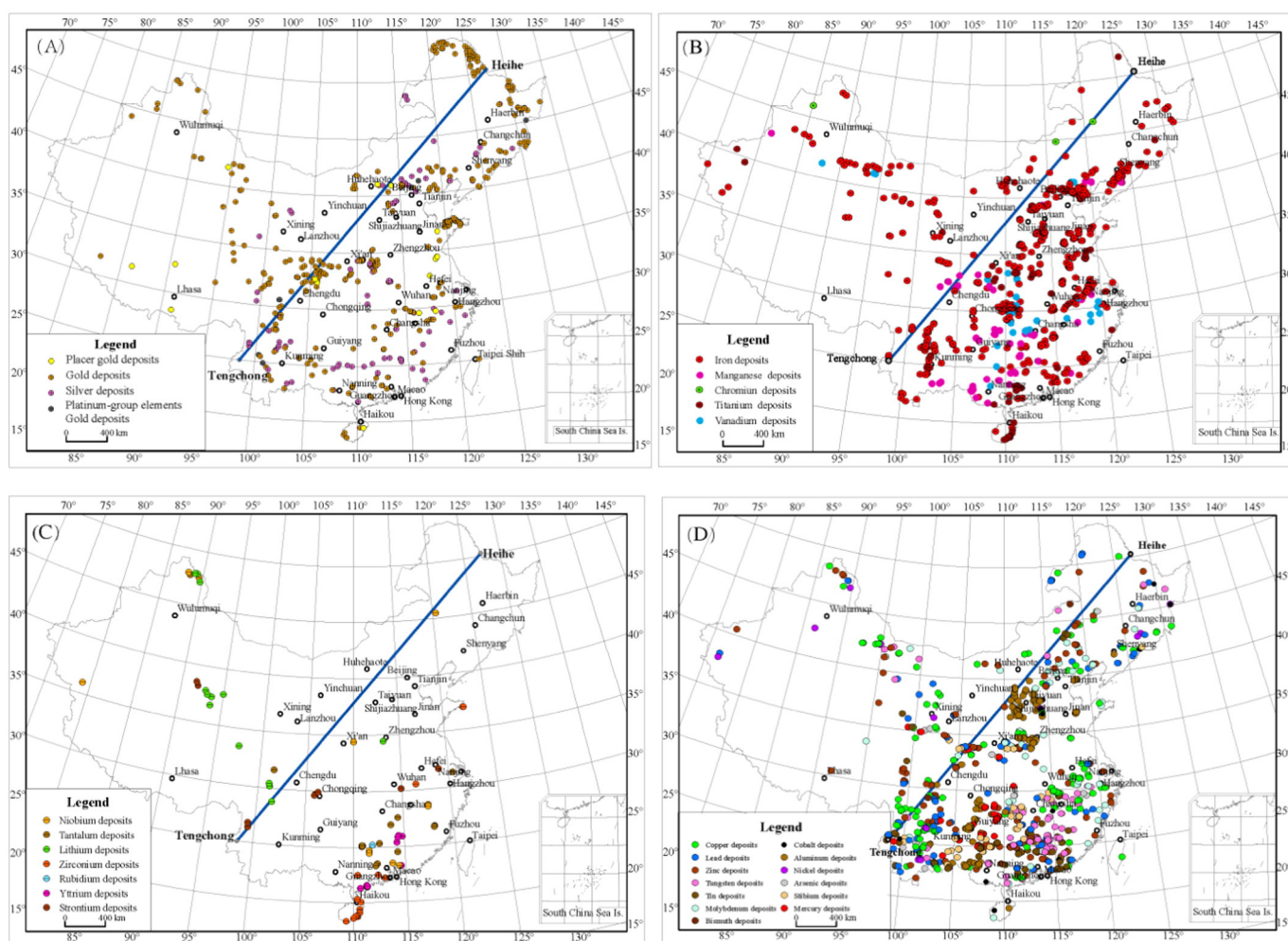


Fig. 1. Distributions of discovered 2906 metallic mineral deposits with magnitudes greater than medium-size in China during the period from 1901 to 2007 (compiled after National Geological Archives of China, 2007; Institute of Mineral Resources of Chinese Academy of Geological Sciences, 2009). (A) gold, silver and platinum-group element deposits; (B) iron, manganese, chromium, titanium and vanadium deposits; (C) niobium, tantalum, lithium, zirconium, rubidium, yttrium and strontium deposits; and (D) copper, lead, zinc, tungsten, tin, molybdenum, bismuth, cobalt, aluminum, nickel, arsenic, antimony and mercury deposits. The blue line is the HH Line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

used multivariate statistical or numerical-statistical methods to estimate the number of undiscovered deposits (Singer et al., 2001). In addition, a discrete lognormal distribution that is close to the power-law model was recommended for estimating the densities of mineral deposits that could be used for probabilistic estimates of the number of undiscovered deposits and their total tonnages in permissive tracts (Singer, 2008; Singer and Kouda, 2011; Singer, 2013). Many studies have suggested that the spatial distribution of mineral deposits follows power-law (fractal) distributions (e.g., Carlson, 1991; Agterberg et al., 1993; Li et al., 1999, 2002, 2003; Raines, 2008; Deng et al., 2009; Ma et al., 2014). If the spatial distribution of mineral deposits follows statistically power-law (fractal) distributions, the number of undiscovered deposits should be estimated with a power-law (fractal) model rather than using the Poisson or discrete lognormal distribution assumption.

This study derived a power-law relationship between the number of discovered mineral deposits per unit area and the exploration level for mineral resources based on the data of the coverage and intensity of geological, geochemical and geophysical exploration for mineral resources during the period 1901 to 2007 in China and mineral deposits discovered in the country in that period, and the derived power-law (fractal) relation is applied to estimating the number of deposits undiscovered in the northwestern region of the HH Line.

2. Data used in this study

The data on the deposits and the exploration level used in this analysis were acquired from the 1:5,000,000 mineral resources map database of China (National Geological Archives of China, 2007), the Atlas of Geological Exploration Degree in China from 1901 to 2000 (China Geological Survey, 2004), and the 1:5,000,000 map of geological exploration degree for non-energy mineral resources (Institute of Mineral Resources of Chinese Academy of Geological Sciences, 2009). In about 100 years' geological exploration from the early 1900s to 2007, 2906 metallic mineral deposits with magnitudes greater than medium-size have been found in China (Taiwan Province is not included in the statistics), including 570 precious metal deposits (gold, silver and platinum-group metals deposits), 689 ferrous metal deposits (iron, manganese, chromium, titanium and vanadium deposits), 96 rare-metal deposits (niobium, tantalum, lithium, zirconium, rubidium, yttrium and strontium deposits), and 1371 nonferrous metal deposits (copper, lead, zinc, tungsten, tin, molybdenum, bismuth, cobalt, aluminum, nickel, arsenic, antimony and mercury deposits). The distributions of these deposits are shown in Fig. 1. The detailed description of the types of these deposits and their metallogenic and geologic settings can be found in Chen et al. (2007) and Xu et al. (2008).

According to exploration workload per unit area (including geological, geochemical and geophysical surveys at various scales as well as

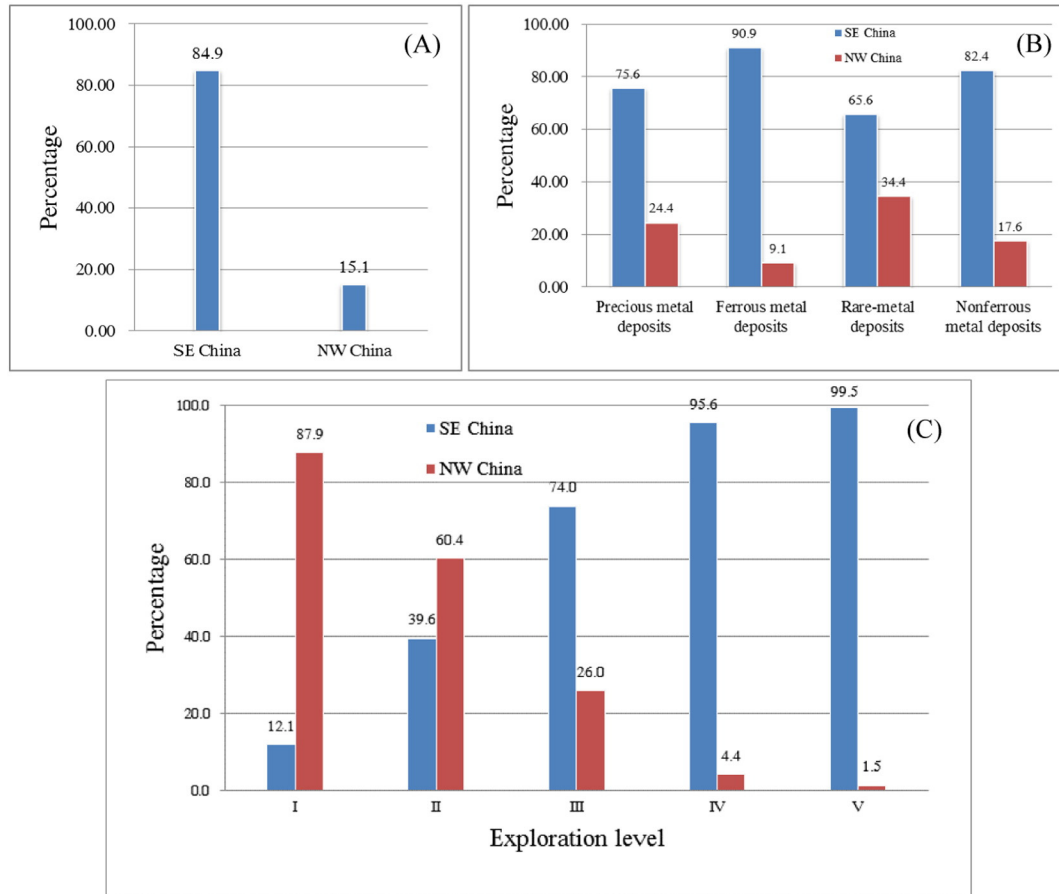


Fig. 2. Histograms showing discovered metallic mineral deposits with magnitudes greater than medium-size and proportional distribution of the class area accounting for total class area in exploration levels on both sides of the HH Line during the period from 1901 to 2007, (A) in total mineral deposits, (B) in different categories of the mineral deposits, and (C) in exploration levels: I - unexplored area; II - very low area; III - low area; IV - high area; and V - very high area.

other exploration works), the exploration intensity for non-energy mineral resources in China was classified into four levels (China Geological Survey, 2004), including very low ($L = 1$), low ($L = 3$), high ($L = 7$), and very high ($L = 19$), where the exploration levels (L) are normalized with respect to the exploration workload per unit area of the regions with very low exploration intensity. If we take into account the areas with no exploration workload ($L = 0$), the intensity of exploration can be divided into 5 levels: namely, unexplored area (I), very low area (II), low area (III), high area (IV), and very high area (V). Fig. 4A

shows the coverage and intensity of systematic geological exploration for non-energy mineral resources during the period from 1901 to 2007 in China.

3. Discussion and conclusions

For the four categories of the mineral deposits studied, the proportional distribution of the number of the deposits at the SE and NW sides of the line is 75.6% to 24.4% for precious metal deposits, 90.9% to

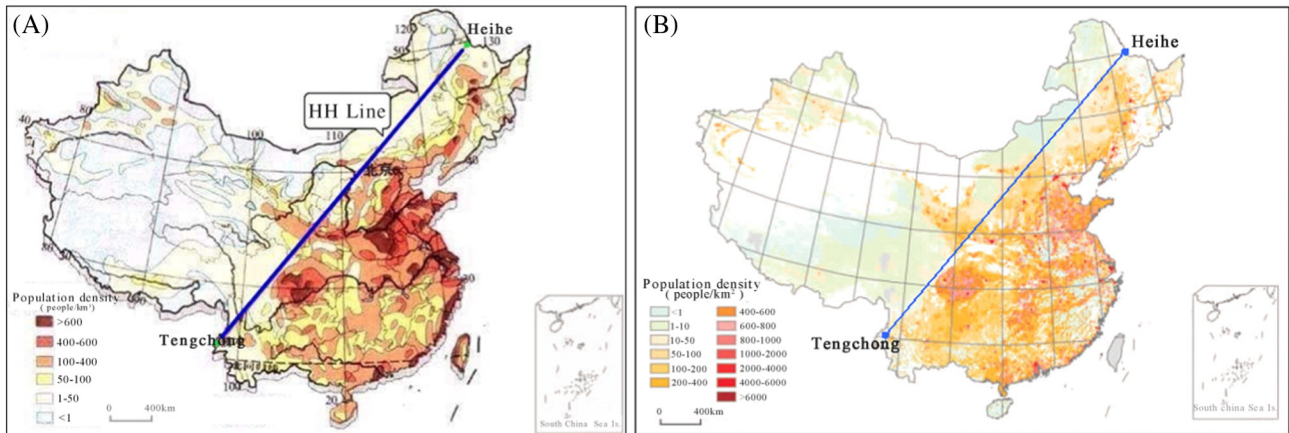


Fig. 3. (A) Distribution of population densities of China in the 1930s (modified after Hu, 1935). (B) Simulated population density of China in 1998 on a 1-km resolution grid with DMSP/OLS nighttime light image (after Zhuo et al., 2005). The blue line is the HH Line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

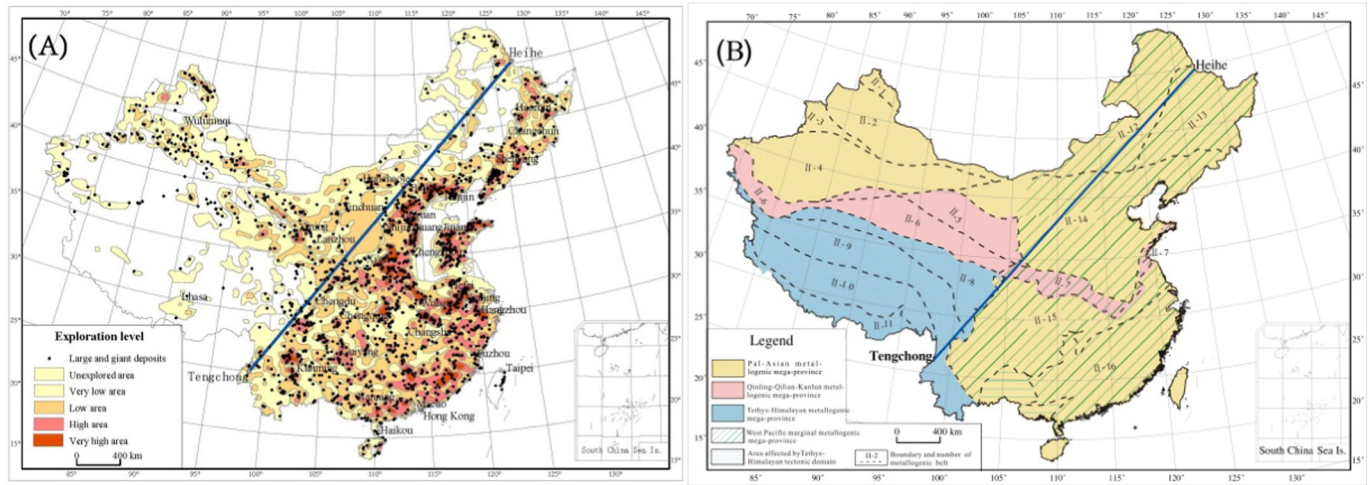


Fig. 4. (A) Map of the exploration level for non-energy mineral resources during the period from 1901 to 2007 in China (compiled after China Geological Survey, 2004; National Geological Archives of China, 2007; Institute of Mineral Resources of Chinese Academy of Geological Sciences, 2009). Exploration depth is generally within 500 m below the surface. Definition of the geological exploration level for non-energy mineral resources see the text. (B) Sketch map of metallogenic provinces in China (modified from Fig. 2 of Xu et al., 2008). The blue line is the HH Line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

9.1% for ferrous metal deposits, 65.6% to 34.4% for rare-metal deposits, and 82.4% to 17.6% for nonferrous metal deposits, respectively (Fig. 2B). The area with the exploration levels III, IV and V accounts for total class area in the SE region of the HH Line is respectively 74.0%, 95.6% and 99.5%, while in the NW region of the line it is merely 26.0%, 4.4% and 0.5%, respectively (Fig. 2C). The areas with unexplored level (I) and very low explored level (II) are mainly distributed in the NW side of the HH Line, accounting for 87.9% and 60.4% of total class area, respectively (Fig. 2C). From the comparison of Fig. 1 with Fig. 4, it is obvious that the chances of discovering mineral deposits can be strongly restricted by the geographic environments, which is not obviously related to the geologic tectonic settings. Statistically, for the entire continental region of China, the discovery of mineral deposits is mainly dependent on the degree of geological exploration, i.e., the higher the exploration level, potentially the more the discovered deposits in the geologically permissive range of mineral resources.

Power-law (fractal) distributions are usually used to model frequency-size statistics of an event in many situations of scientific interest (Clauset et al., 2009). In general, a power-law (fractal) distribution is of the form (Newman, 2005)

$$p(x) = Cx^{-\alpha} \quad (1)$$

where $p(x)$ is the number of objects with size x , and C and α are constant. The scaling exponent α could be a fraction and is usually called the fractal dimension. According to a broad general idea, the power-law (fractal) distribution is not restricted to the size of geometric shapes; x in Eq. (1) may be an arbitrary measure of magnitude of an event or a variable of interest (Li et al., 1999, 2011). In the following discussion, we will examine whether the number of discovered mineral deposits per unit area in explored regions as a function of the exploration level follows power-law distributions.

As shown in Fig. 5A, the number of discovered deposits per unit area from explored regions for a given exploration level (deposit density d at the i th explored area) and the exploration level (L) are shown as a log-log plot for the four levels of explored areas (the statistics does not take into account the area with unexplored level I). Here, a uniform grid resolution of 2×2 km is used for the statistical analysis of the number of discovered deposits — exploration level relation. The result shows that the density of discovered deposits as a function of the exploration level can be expressed as

$$d = cL^a \quad (2)$$

where c is a constant of proportionality and a is the slope of the straight

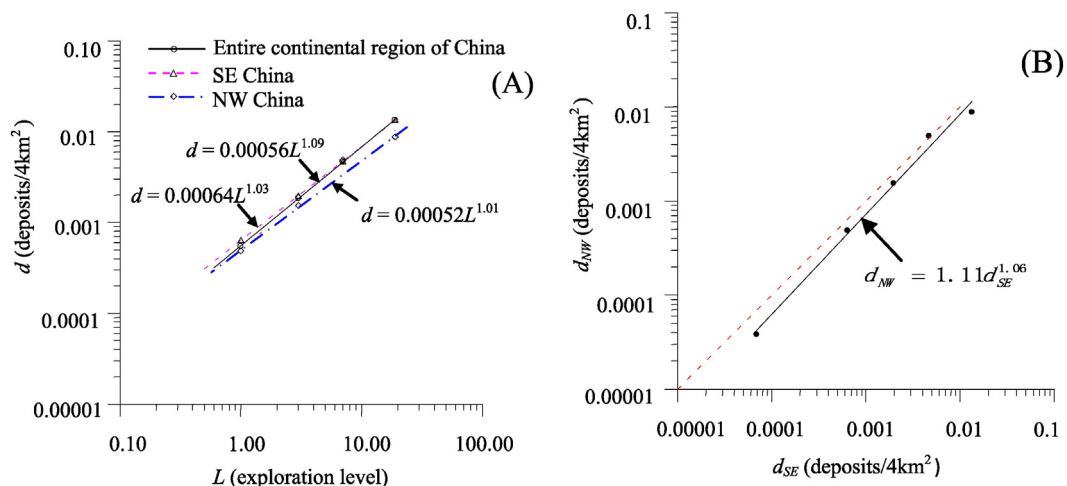


Fig. 5. (A) Relationship between the number of discovered deposits per unit area from explored regions (d) and the exploration level (L). (B) A log-log plot comparing the density of discovered deposits in NW China (d_{NW}) and in SE China (d_{SE}). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1

Numbers of mineral deposits with magnitudes greater than medium-size in the NW region of the HH Line, estimated using Eq. (2) under the assumption of the equal exploration level between the two regions separated by the line.

Exploration level	Number of known deposits in SE China	Known deposits density in SE China (number of deposits per 4 km ²)	Number of known deposits in NW China	Known deposits density in NW China (number of deposits per 4 km ²)	Number of Estimated deposits for NW China	Number of deposits to be discovered in NW China
Unexplored (I)	7	0.000069	28	0.000038	8	
Very low (II)	194	0.000640	224	0.000485	210	
Low (III)	800	0.001973	220	0.001540	848	
High (IV)	760	0.004695	36	0.004885	791	
Very high (V)	653	0.013453	2	0.008772	666	
Total	2414		510		2523	2013

Note: Taiwan Province is not included in the statistics.

line fitted to Eq. (2). The result indicates that, in explored regions, the number of discovered deposits per unit area increases with the increase of the exploration level following a power-law (fractal) model. The relation of d against L derived from explored regions can be extend to adjacent unexplored or poorly explored regions, which can be utilized to estimate the number of deposits undiscovered within geologically permissive areas in the unexplored or poorly explored regions.

Consequently, let d_{NW} and d_{SE} denote respectively the density of discovered deposits in the NW and the SE China, the relationship between d_{NW} and d_{SE} can be described as

$$d_{NW} = cd_{SE}^a \quad (3)$$

where c and a are constants determined from the actual data. d_{NW} and d_{SE} in regions for five levels are shown in Fig. 5B as a log-log plot, which shows that the relationship between d_{NW} and d_{SE} follows quite closely a straight line which is fitted using Eq. (3) by $d_{NW} = 1.11d_{SE}^{1.06}$. In Fig. 5B, the data point nearest to the lower left represents the density of known deposits in unexplored region (level I) and the point nearest to the upper right stands for the density of known deposits in the well-explored region (level V). Obviously, if the density of deposits in the NW region of the HH Line is equal to that in the SE region of the line ($d_{NW} = d_{SE}$), the relationship between d_{NW} and d_{SE} will be a straight line of a unit slope through the origin of coordinates (red dashed line in Fig. 5B).

As shown in Fig. 4B, the metallogenic provinces in China are divided into 16 belts on a broad scale and with respect to tectonic environments in China (Xu et al., 2008). Comparing Fig. 4 A and B, we can see that, although differences in the crustal evolution and tectonic setting exist between the two sides of the HH Line, the coverage and intensity of geological survey and exploration for non-energy mineral resources during the period from 1901 to 2007 do not strictly follow the distribution of the metallogenic belts because of the restriction of geographic environments, the distribution of the discovered mineral deposits is not obviously related to a particular metallogenic belt on the whole, and some of the four categories of the discovered deposits that concern the 28 kinds of mineral resources were found in almost all of the metallogenic belts (comparing Fig. 1 with Fig. 4B). Thus, if the explored level in the NW China is the same as that in the SE China, in the NW China likely many deposits would be found which are at least equal to that in the SE China.

By assuming that exploration levels in the NW region of the HH Line are the same as those in the SE region of the line, it is estimated that at least 2523 mineral deposits with magnitudes greater than medium-size should be discovered in the NW region (Table 1). Subtracting the number of the known deposits in the NW region (510) from the number of the estimated deposits for the NW region, and then there are at least 2013 metallic mineral deposits with magnitudes greater than medium-size to be found out in the region, which is a huge potential mineral resources. In Table 1, the numbers of estimated deposits in unexplored

(level I) and very-low explored (level II) areas in the NW China are lower than the number of the known deposits in these areas, because at assuming equal explored level in the NW and the SE China, the area of the regions with explored levels I and II will relatively decrease, and that of regions with explored level greater than II will relatively increase with the increase of the degree of exploration in the NW China, which results in decrease of numbers of deposits that remain to be discovered in the regions with explored levels I and II in the statistics.

It is important to note that in the estimate of potential metallic mineral resources in the NW China, no technical or economic risk is considered. The mineral resource development for this region will depend on the market demand, technical development and the scale of the un-revealed deposits, and the negative impact on environment should be minimized. This estimate of potential metallic mineral resources for the NW China is based on the data of known deposits and explored levels, which would be somewhat modified with the accumulation of data on the deposits and explored levels. However, the controlling effects of geographical environments on the discovery of mineral deposits and the rule of increase in density of discovered deposits with the explored level revealed by the power-law (fractal) model will not change.

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