MINING AND EXPLORATION FOR MINERAL RESOURCES

T. Nishiyama  
Kyoto University, Japan.

K. Kaneko  
Hokkaido University, Japan.

Keywords: Mineral exploration, geologic prospecting, ore deposits, magmatic deposits, hydrothermal deposits, sedimentary deposits, geophysical prospecting, magnetic survey, electric survey, radiometric survey, geochemical prospecting, geochemical anomaly

Contents

1. Introduction
2. Geologic Prospecting
   2.1. Ore Deposits Formed During Magmatic Process
      2.1.1. Separation and Concentration due to Crystallization in Basic Magma at Specific Places and at Specific Stages
      2.1.2. Separation and Concentration due to Immiscibility in the Melt
   2.2. Hydrothermal Deposits
      2.2.1. Porphyry-type Deposits
      2.2.2. Kuroko-type Massive Sulfide Deposits
      2.2.3. Skarn-type Deposits
      2.2.4. Vein-type Deposits
   2.3. Sedimentary Deposits
3. Geophysical Prospecting
   3.1. Gravity Survey
   3.2. Magnetic Survey
   3.3. Electric Survey
      3.3.1. Self-potential Method
      3.3.2. Resistivity Method
      3.3.3. Induced Polarization Method
      3.3.4. Electromagnetic Method
   3.4. Seismic Survey
      3.4.1. Reflection Method
      3.4.2. Refraction Method
   3.5. Radiometric Survey
4. Geochemical Prospecting
   4.1. Basic Principles
   4.2. A Few Practical Geochemical Explorations
   4.3. Fluid Inclusion and Isotope Studies
Glossary
Bibliography
Biographical Sketches

Summary
Depletion of mineral resources often induces social crises and sometimes causes wars. However, during the long history of human beings, total depletion of a single mineral has never occurred. New discoveries and technology are adding to the reserves of various mineral commodities at a rate that has exceeded depletion. Mineral exploration leading to the discovery of new ore deposits and products is one of the most important forces helping to fend off depletion. In section 1, the fundamentals and aims of mineral exploration are briefly introduced. In section 2, the characteristics and formative processes of mineral deposits are described for geologic prospecting. In sections 3 and 4, the geophysical and geochemical prospecting methods widely used for mineral explorations are described.

1. Introduction

The magnitude of the world's mineral production has increased sharply, and there is no sign that this growth is likely to stop in the near future. The growth rates of production and life expectancies of aluminum, crude steel, copper, zinc and energy over the past half century are illustrated in Figure 1.


Growth rates increased radically after 1950, especially between 1950 and 1973. On the other hand, life expectancies have remained nearly constant because new discoveries and technology add to the reserves of mineral commodities at a rate that has exceeded depletion, in order to satisfy growing demands. However, since the quantity of a particular resource in the Earth's crust is physically limited, it is questionable whether this condition is sustainable in the future. Therefore, most of our attention for the future has been focused on potentially recoverable resources and exploration (see Mining Engineering and Mineral Transportation).
Reserves, production and life expectancies are fundamental factors in forecasting the supply and demand of mineral commodities. Current statistical data for 35 minerals are summarized in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit</th>
<th>Production Reserve Lifetime Price Resources principal (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(P)           (R)          (R/P)         (US$/kg)</td>
</tr>
<tr>
<td>Al</td>
<td>1000t</td>
<td>130,619       25,000,000   191          1.45</td>
</tr>
<tr>
<td>Sb</td>
<td>t</td>
<td>73,762        2,100,000    28           1.39</td>
</tr>
<tr>
<td>As</td>
<td>t</td>
<td>46,800        1,000,000    21           1.39</td>
</tr>
<tr>
<td>Be</td>
<td>t</td>
<td>6,220         N.A.         N.A.         720.9</td>
</tr>
<tr>
<td>Bi</td>
<td>t</td>
<td>3,620         110,000      30           8.49</td>
</tr>
<tr>
<td>B</td>
<td>1000t</td>
<td>4,817         170,000      35           0.37</td>
</tr>
<tr>
<td>Cd</td>
<td>t</td>
<td>18,764        600,000      32           0.31</td>
</tr>
<tr>
<td>Cr</td>
<td>1000t</td>
<td>14,000        3,700,000    264          0.063</td>
</tr>
<tr>
<td>Co</td>
<td>t</td>
<td>29,900        4,500,000    151          37.52</td>
</tr>
<tr>
<td>Cu</td>
<td>1000t</td>
<td>12,288        340,000      28           1.67</td>
</tr>
<tr>
<td>Au</td>
<td>kg</td>
<td>2,540,000     45,000,000   18           9000</td>
</tr>
<tr>
<td>In</td>
<td>t</td>
<td>N.A.          2,600        N.A.         303</td>
</tr>
<tr>
<td>Fe</td>
<td>1000t</td>
<td>1,041,571     74,000,000   71           0.025</td>
</tr>
<tr>
<td>Pb</td>
<td>1000t</td>
<td>2,977         66,000       22           0.96</td>
</tr>
<tr>
<td>Li</td>
<td>1000t</td>
<td>N.A.          3,400        N.A.         4.47</td>
</tr>
<tr>
<td>Mn</td>
<td>1000t</td>
<td>20,400        680,000      33           2.26</td>
</tr>
<tr>
<td>Hg</td>
<td>t</td>
<td>3,663         120,000      33           4.06</td>
</tr>
<tr>
<td>Mo</td>
<td>1000t</td>
<td>142           5,500        39           5.9</td>
</tr>
<tr>
<td>Ni</td>
<td>1000t</td>
<td>1,045         40,000       38           6.01</td>
</tr>
<tr>
<td>Nb</td>
<td>t</td>
<td>23,600        3,500,000    148          6.61</td>
</tr>
<tr>
<td>Pt</td>
<td>kg</td>
<td>378,000       71,000,000   188          12,180</td>
</tr>
<tr>
<td>REE</td>
<td>t</td>
<td>82,000        100,000,000  1220         5.622</td>
</tr>
<tr>
<td>Re</td>
<td>kg</td>
<td>46,000        2,500,000    54           750</td>
</tr>
<tr>
<td>Se</td>
<td>t</td>
<td>1,480         70,000       47           5.622</td>
</tr>
</tbody>
</table>
The reserves of Ag, Au, As, Sr, Pb, Zn are not sufficient for even 25 years at the current rate of production. Reserve life expectancies of 12 minerals including Cu, Mn, Mo, Cd, Sn, etc., vary from 25 to 50 years. The total world reserves of other resources seem adequate for the next 50 years. As mentioned previously, new discoveries and advances in mining technology have added to the reserves of various mineral commodities. Reserves are not fixed. Additional reserves and cumulative consumption of 16 essential metals over the period 1970-95 are shown in Figure 2. For gold, using 1970 as the index (1970=100) of additional reserve, the 1970-95 increase in reserves is approximately sevenfold, and cumulative consumption has more than tripled. In other words, six times the gold reserves in 1970 were discovered and more than three times the 1970 reserves were consumed during 1970-95. Currently, discoveries and technologies to increase the reserves of many metals are divided in the following three categories.
Exploration strategies vary widely, dependent upon the mineral commodity species, the geologic and climatic environment, political and social restrictions, and available resources. Exploration programs focus progressively on decreasing size, from large to narrow research areas using methods increasing in cost per unit area, with a declining risk of failure. The principal programs from reconnaissance surveys into detailed ones include three stages: (1) conventional prospecting consisting of the search for directly observable natural features commonly associated with ore mineralization, or literature and geologic research with the selection of geologically favorable localities; (2) multistage coverage of the area selected involving detailed geologic mapping, geochemical and/or geophysical coverage, and/or the use of special techniques; (3) and finally a drilling program and/or underground exploration by shafts, drifts, and crosscuts.

2. Geologic Prospecting

Geology provides the framework in which mineral exploration and the integrated procedures of remote sensing, geophysics, and geochemistry are planned and interpreted. Mineral resources have been formed by a variety of processes and in various places throughout the 4600 million year history of crustal development. The mineral deposits can, for convenience, be classified into three types based on their formative processes from magmatic to surface genesis, magmatic process, the process of solution-dominated ore genesis, and the transport of particulate matter at the earth's surface.

2.1. Ore Deposits Formed During Magmatic Process

Certain formations of igneous rocks may become concentrated into bodies of sufficient
size and richness to constitute valuable mineral deposits such as chromium, platinum and REE. Representatives of magmatic concentration are many and widespread, but the products yielded are not numerous. Chemical and mineralogical evolution is attended by the formation and segregation of two groups associated with ultra-basic and acidic magma.

### 2.1.1. Separation and Concentration due to Crystallization in Basic Magma at Specific Places and at Specific Stages

The resulting concentrations of these minerals occupy predictable parts of layers of igneous rocks (e.g. platinum, chromite, ilmenite and magnetite deposits). The mineral deposits formed by early magmatic segregation are generally lenticular and of relatively small size. Commonly, they are disconnected pod shaped lenses, stringers, and bunches. Less commonly and more importantly, they form layers in the host rock. The most famous example of this type of deposit is the Bushveld Igneous Complex in South Africa, where stratiform bands of chromite of remarkably uniform thickness lie parallel to the pseudo-stratification of the enclosing mafic igneous rocks and can be traced for several kilometers (Figure 3). Even more remarkable is another thin layer of pyroxenite, the "Merensky Reef" horizon, bounded above and below by thin layers of chromite that contain economic quantities of platinum. Currently this layer has supplied most of the world's demand for platinum.

![Figure 3: Chromite Deposits and Platinum Deposits (Merensky Reef)](by Jensen, M.L. and Bateman, A.M. (1979). Economic Mineral Deposits, p.85, John Wiley & Sons, New York.)

### 2.1.2. Separation and Concentration due to Immiscibility in the Melt

Nickel-copper deposits associated with basic and ultrabasic rocks and REE, niobium-tantalum deposits associated with alkali rocks are well known as typical of this group. Although metallic oxides do not or rarely form immiscible phases in silicate magma, it has been proved that an immiscible sulfide melt, which concentrates copper and nickel, occurs during crystallization. The Sudbury irruptive, which has for a long
time been the most important source of nickel, is formed in this manner. Deposits consisting of nickel-copper ores, with accompanying platinum, gold, silver, and other elements are in a stratiform complex composed of the lower norite and the upper micropeegmatite (Figure 4).

Figure 4: Geological Map of Sudbury Region (After South et al., 1969.)

Carbonatite consisting of alkaline rocks such as nepheline syenite is also an example of immiscible liquid segregation. The carbonatites of economic importance are mostly associated with a source of rare-earth elements, Nb, Ta, U, Th, Zr and Hf etc.

Bibliography


Biographical Sketches

Takashi Nishiyama (born 1939) is a professor emeritus at Kyoto University and at the time the research for this article was started, a professor of Department of Energy and Technology, Graduate School of Energy Science, Kyoto University. He studied in Mining Engineering Department at Kyoto University and obtained a degree of Dr. Eng.
Katsuhiko Kaneko (born 1950) is working as a professor of Division of Environment and Resources Engineering, Hokkaido University. He studied in Mining Engineering Department at Kyoto University and obtained a degree of Dr. Eng. He also worked for the Department of Resources Engineering, Kumamoto University, for eighteen years.