Economic Deposits in Sedimentary Environments

István Dunkl

http://www.sediment.uni-goettingen.de/staff/dunkl/edu/sedi-ore-01.pdf

[1] Definitions, Mining economy in brief
[2] Deposits related to weathering / residual sediments
  laterite, bauxite, karst-bauxite, [3] Ni-laterite, regolith, gossan
[4] Placer deposits
  gold, zircon + rutile + ilmenite + REE, diamond, tin
[5] Chemical sediments
  Fe-sediments, Mn-sediments, phosphate
[6] Exhalative, infiltration and metasomatic deposits (SEDEX, Kupferschiefer,
  MVT-type deposits, Carlin-type gold deposits, sandstone-type U-ores)
[7] Combustable materials
  coal, [8] hydrocarbon (oils and gas), (tar sand, oil shale, gas hydrate)
[9] Mineral processing
Definitions

Economic Geology
OR
Ore Geology
OR
Geology of raw materials
OR
Lagerstättenkunde

Needed:
- petrography,
- mineralogy,
- general geology.

Today:
- general introduction,
- relations to other disciplines,
- definitions,
- history,
- mining economy
**What is Ore Geology?**

**What is ore?**

**Ore:** (1) a material from which we extract a metal and (2) this operation must be a profit-making one.

**ECONOMY**

- **Fundamental Geology**
- **Real World** $\$
- **Technology**

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'Ore is rock that may be, is hoped to be, will be, is or has been mined; and from which something of value may be extracted'

Halite (NaCl) and Bauxite (rich in Al2O3), with metallic element, but not necessarily used as a metal

---

**Industry mineral**

Ore is a solid naturally-occuring mineral aggregate of economic interest from which one or more valuable constituents may be recovered by treatment.
### The history of ore geology

<table>
<thead>
<tr>
<th>EPOCH</th>
<th>THE MAIN ASPECT:</th>
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<tbody>
<tr>
<td>Egyptian-Greek</td>
<td>mainly empirical</td>
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<tr>
<td>Roman Empire</td>
<td>well organized mining industry,</td>
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<tr>
<td></td>
<td>excellent descriptions</td>
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<td>Aristotele, Pliny</td>
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<td>Middle Age</td>
<td>mining + alchemy</td>
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<td>(Georg Bauer)</td>
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<td>Robert Boyle, Roger Bacon</td>
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<td>Industry Revolution</td>
<td>mining + monetary strategy + analytical</td>
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<td>synthese</td>
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<td>Post-industrial</td>
<td>new materials</td>
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<td>environment</td>
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</table>
Risk analysis aims at foreseeing the possible effects of market risk (reflecting the sensitivity to the uncertainty with forecasts of trends in a commodity prices and of turbulences in currencies and interest rates). Project risk (caused by the uncertainty with estimating ore reserves, recovery and dilution factors, capital and operating costs, time schedule, etc.) discovery risk (reflecting the low probability (1 - 2%) of an economic deposit, given the discovery of a mineral occurrence). Geologic risk (caused by the geologic variability in size, the grade, structure, etc. of mineral deposits that cannot be foreseen). Environmental risk (caused by industrial construction or production as such or by their outbursts and tailings) and political risk (due to changing political situations in the home country, in neighboring countries or in the countries where the products should be sold to).
Country Risk Ranking

RANKING
Geological, Financial, Political, Infrastructural

- A - Low risk
- B
- C
- D - High risk
Economy

Gold 1968 - 1999

USDollars per Troy ounce

[©The London Metal Exchange Limited]
Figure 2.—Prices (US$) for copper (Cu) and zinc (Zn) in real and nominal terms compared with major historical events.

Figure 3.—Price (US$) for aluminum (Al) in real and nominal terms compared with major historical events.

[Wellmer and Küsten, 1992]
Economy

Table 1.—Installation of glass fiber instead of copper wire for telecommunication system in the Federal Republic of Germany
(Source: Telekom, Germany, written communication, 1992)

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed glass fiber</th>
<th>Substitution of Cu</th>
<th>Substitution as percentage of German total Cu consumption</th>
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<tr>
<td>1989</td>
<td>141,885 km</td>
<td>~107,000 t</td>
<td>~9</td>
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<tr>
<td>1990</td>
<td>278,670 km</td>
<td>~210,000 t</td>
<td>~18</td>
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<tr>
<td>1991</td>
<td>268,981 km</td>
<td>~200,000 t</td>
<td>~18</td>
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Figure 12.—Comparison of the forecast of Malenbaum (1978) with the real development of the “intensity of use” factors of aluminum for the USA and Japan. Abbreviation: GNP, gross national product.
Figure 9.—Distribution of population and distribution of metal consumption in 1950 and 1990 compared between developing and developed regions. Numbers given are percentages.
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<thead>
<tr>
<th>Element</th>
<th>100-10%</th>
<th>10-1%</th>
<th>1-0.1%</th>
<th>1000-100 g/t</th>
<th>100-10 g/t</th>
<th>10-1 g/t</th>
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Geochemistry
Fig. 1.17 Diagrammatic representation of the continuity of different orebody types and approximate grades. (Source: King et al. 1982.)
Geochemistry

Trace element abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>Average crustal abundance (%)</th>
<th>Average minimum exploitable grade (%)</th>
<th>Concentration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>8</td>
<td>30</td>
<td>3.75</td>
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<tr>
<td>Iron</td>
<td>5</td>
<td>25</td>
<td>5</td>
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<td>4000</td>
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<tr>
<td>Gold</td>
<td>0.000 000 04 a</td>
<td>0.0001 a</td>
<td>250</td>
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</table>

a 1 ppm.

Needed for element concentration to an ore body:
- Source reservoir,
- Energy,
- Transport medium,
- Trap or barrier

[Bender, 1977]
Geochemistry

Figure 3-2
Zone of gold-bearing quartz, Laird prospect, Virginia. (From Park, 1936, Fig. 3.)

Figure 3-3
Big Geyser area near Healdsburg, California. The rock was originally Franciscan graywacke and argillite; it has been thoroughly altered to carbonates, chaledony, and clay minerals. (Photo courtesy of D. A. McMillan, Jr., Thermal Power Company.)
Economy

Cross section through the Palabora Complex pipes.

[Lombaard et al., 1964]
Economy

[Lombaard et al., 1964]
Definitions

Parameters to describe an ore body for mining and economic evaluations:

*in X, Y, Z space:*

- concentration (metal 1, 2... n)
- concentration (contaminant 1, 2...n)
- tectonics
- water table (+ or -)
- transport cost
- airing

*and:*

- separation cost (metal 1, 2...n)
- price (metal 1, 2...n)
- salary, energy, water
- TAX, land usage, land recovery, etc.
Economy

[Hutchinson]

Figure 11. Top: schematic representation of the log normal distribution of mineralization deposited from a moving hydrothermal solution. The ore zone (ore shoot) is defined on the basis of economics (cost of extraction and commodity price). Bottom: minerals and mineral chemistry show a zonation down-flow, which can be used to decide whether the mining is approaching the centre of the shoot or its edge. A faulted vein at D may therefore not be worth the effort of tracing farther to the right, but that at C will be because it is still high-grade ore.
Definitions

Fig. 1.16 Mining terminology. Ore was first mined at the outcrop from an open pit; then an adit was driven into the hillside to intersect and mine the ore at a lower level. An inclined shaft was sunk later to mine at even deeper levels and, eventually, a vertical shaft was sunk to serve operations to two orebodies more efficiently. Ore is mined by driving two haulage drifts at different levels and connecting them by raises which are then connected by sublevels. Ore is mined upwards from the lower sublevel to form a stope. Broken ore can be left in the stope to form a working platform and to support its walls (shrinkage stoping), or withdrawn and waste from the mill pumped in (cut-and-fill stoping). Ore between haulage and sublevel is left as supporting pillars until the level is abandoned. A shaft pillar is also left unmined. (After Barnes, 1988, Ores and Minerals, Open University Press, with permission.)

[Evans, 1993]

[Gocht, 1978]
Economy

**Exploration project:**

- **Reconnaissance:** Regional prognosis (1 : 10 000 000 -- 1 : 50 000)
- **Prospection:** Locating mineralizations (1 : 100 000 -- 1 : 10 000)
- **General exploration:** Mineral deposit outlining, first resource estimate (1 : 20 000 -- 1: 1 000)
  (Some mining companies accept a 50 % error for calculations at this stage, some companies even a greater error than that.)
- **Detailed exploration:** Mineral resource estimate, pre-feasibility (1 : 5 000 - 1 : 100)
  (In this study it is estimated whether the deposit is worth of a feasibility study or not. Some mining companies accept at maximum a 20 % error in these calculations.)

**Four stages of a mine project after exploration:**

- **Feasibility study / Mine Decision**
  (After a feasibility study we can decide whether or not a mineral deposit is an ore deposit with an ore reserve that forms the economic part of the mineral resource.)
- **Mine construction**
- **Mine production**
- **Mine closure and rehabilitation**

[Jyrki Parkkinen]
Economy / Reserve estimation

The metal contents of a mineral deposit or an ore body is:

\[ M = G \times r \times L \times W \times H, \]

where:
- \( M \) = metal content in tons to be counted.
- \( G \) = grade in percentages.
- \( r \) = tonnage factor in tons/cub.meter.
- \( L \) = length in meters.
- \( W \) = width in meters.
- \( H \) = height in meters.

The cumulation of error in geological deposit research (or evaluation):

\[ TE^2 = GE^2 + FE^2 + PE^2 + AE^2, \]

where:
- \( TE \) = Total error
- \( GE \) = Geological error, due to the general indefinity of natural occurrences like non-regular structures, weathering, trends, phase differences, etc.
- \( FE \) = Field sampling error, due to unrepresentative, non-typical or small samples as compared with the original specimen, the deposit itself,
- \( PE \) = Preparation error, due to the continual reduction of samples,
- \( AE \) = Analytical error, caused mainly by calibration errors and measuring errors.

[Jyrki Parkkinen]
Sampling

Geological sample:
A piece of rock (= specimen) or any collection of pieces supposed to represent some geological entity or feature.

Statistical sample:
a small part of anything, intended to show the quality, style or nature of the whole.

Population:
Any infinite or finite aggregate of individuals.

Frequency distribution:
Statistics, the correspondence of a set of frequencies with a set of categories, intervals, or values into which a population is classified (Webster's, 1989).
### Economy / Reserve estimation

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<tr>
<th>Non-spatial data</th>
<th>Directional data</th>
<th>Spatial data</th>
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<td>Nominal or categorical</td>
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<td>Feature</td>
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**Classical statistics**  **Circular statistics**  **Spatial statistics**

[Jyrki Parkkinen]
Economy / Reserve estimation


[Bender, 1977]
Economy /
Reserve estimation

[Isaaks and Srivastara, 1989]
Economy / Reserve estimation

above: average thickness (bauxite deposit)
below: scatter of calculated thickness

[Földessy, 2001]
Geometrische Figuren zur Bestimmung der Einflussbereiche von Schürfproben.
A: Quadratische Blöcke bei gleichmäßigen Probenahme-Abständen.
B: Rechteckige Blöcke bei ungleichmäßigen Probenahme-Abständen.
C: Polygonale Blöcke durch Verbindung der mittleren Probenahme-Abstände.
D: Polygonale Blöcke durch räumliche Festlegung der nächsten Umgebung der Probenahme-Stellen.
E: Dreieckige Blöcke durch Verbindung von jeweils drei benachbarter Probenahme-Stellen.
F: Profilschnitte, konstruiert durch den Mineralisationskörper.

[Bender, 1977]
Economy / Reserve estimation

**Inverse distance method:**
Inverse distance is based on the assumption that the statistical weight of a point value correlates inversely with the distance from the point.

**Kriging:**
This method produces visually appealing maps from irregularly spaced data. Kriging attempts to express trends suggested in your data, so that, for example, high points might be connected along a ridge rather than isolated by bull's-eye type contours.

[Golden Software, Inc.]
Economy / Reserve estimation

Major gridding methods

Inverse distance to a power

Kriging

Minimum curvature

[made by Surfer - Golden Software, Inc.]
Economy

**Variogram:**
A two-point statistical function that describes the increasing difference or decreasing correlation, or continuity, between sample values as separation between them increases.

The term variogram is sometimes used incorrectly in place of semivariogram. The two differ only in that the semivariogram uses each pair of data elements only once, whereas the variogram uses all possible data pairs. Semivariograms are usually used instead of variograms, but opposite vector directions (for example, north and south) are recognized as representing the same thing and having identical ranges, sills, nugget points and the like.

[Schlumberger]
Vorratsschätzung von Abbauflöcken.

Grundlage zur Beschreibung der räumlichen Beziehung von Proben einer Lagerstätte ist das Variogramm

\[
2 \gamma(h) = \frac{1}{N(h)} \sum [Z(x) - Z(x + h)]^2,
\]

wobei \( Z(x) \) der Erzgehalt im Punkt \( x=(x_1, x_2, x_3) \) ist, \( h \) ein Vektor \( h=(h_1, h_2, h_3) \) und \( N(h) \) die Anzahl der Probenpaare, die in der (gerichteten) Distanz \( h \) vorhanden sind. \( \gamma(h) \) beschreibt, wie ähnlich die Erzgehalte benachbarter Probenpunkte sind.

Typisches Beispiel eines Variogramms einer Blei-Zink-Lagerstätte ist in Abb. II.17 gegeben. Bis zu einer Entfernung von ca. 35' (Reichweite, „range“) ist eine positive Korrelation der Probengehalte vorhanden. Die Proben, die weiter als die Reichweite voneinander entfernt liegen, können als unabhängig betrachtet werden. Anisotropien in der Lagerstätte machen sich dadurch bemerkbar, dass die Variogramme in verschiedenen Richtungen unterschiedlich sind. So ist die Reichweite einer sedimentären Lagerstätte in vertikaler Richtung meist viel kleiner als in horizontaler.

[Abb. II.17. Typisches Variogramm der Probenahmen in einer Blei-Zink-Lagerstätte (Probeninflußbereich ca. 35 Fuß).]

[Gocht, 1978]
Economy

Variograms / Definition

\[ 2Y^x(h) = \frac{1}{n} \sum [g(x) - g(x+h)]^2 \]

where:
- \( g(x) \) = value of parameter at point \( x \)
- \( g(x+h) \) = value of parameter at \( h \) distance from point \( x \)
- \( n \) = number of unique pairs of observations

\[ n = \frac{y(y-1)}{2} \text{ where: } y = \text{number of points} \]

(if \( y = 500 \), \( n = 124,745 \) pairs)
(y>50 !!!  min. 50 data recommended)
The variogram characterizes the spatial continuity or roughness of a data set. Ordinary one dimensional statistics for two data sets may be nearly identical, but the spatial continuity may be quite different.

Variogram analysis consists of the experimental variogram calculated from the data and the variogram model fitted to the data. The experimental variogram is calculated by averaging onehalf the difference squared of the z-values over all pairs of observations with the specified separation distance and direction. It is plotted as a two-dimensional graph.
Economy

Two synthetic data sets to demonstrate spatial variability:

Figure 1.3 Data Set A Contour Plot

Figure 1.4 Data Set B Contour Plot
Economy

Figure 1.3 Data Set A Contour Plot

Figure 1.4 Data Set B Contour Plot

Figure 1.5 Data Set A Variogram and Model

Figure 1.6 Data Set B Variogram and Model

[Golden Software, Inc.]
Economy

Variograms / Trend

[Statios]
Economy

Variograms / Geometric anisotropy

[Image of a colorful map with a color scale and a graph showing variograms with labels for Vertical Variogram and Horizontal Variogram, along with a line labeled Sill.]

[Statios]
Economy

Variograms / Cyclicity
Economy

Directional variograms

Figure 6.2 Directional variogram plots with Tolerance set to 30°. From left to right: Direction = 0°, 30°, 60°, 90°, 120°, 150°.

[Golden Software, Inc.]

[Földessy, 2001]
Economy

Cash flow through exploration to production

[Edwards and Atkinson, 1986]
Economy

Fig. 11.1 Stages and expenditure in a mineral exploration programme (timing and expenditure are for a medium-sized mine). (After Eimon 1980.)

[Edwards and Atkinson, 1986]
Economy

[Gocht, 1978]
Economy

Figure I-3. Geologic-economic classification of mineral reserves and resources. (Adapted from U.S.G.S. sources.)

[Bender, 1977]
<table>
<thead>
<tr>
<th>Erkannt - Demonstrated</th>
<th>Prognostisch - Undiscovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemessen - Measured</td>
<td></td>
</tr>
<tr>
<td>Sicher - Proved</td>
<td>Gefolgt (Vermutet) - Inferred</td>
</tr>
<tr>
<td>Wahrscheinlich Probable</td>
<td>Hypothetisch - Hypothetical</td>
</tr>
<tr>
<td>C1</td>
<td>Spekulativ - Speculativ</td>
</tr>
</tbody>
</table>

*FG*: ± 10%  
*AS*: > 80%  

Schema für Bergwerke

Schema für Regionen


*FG* = Fehlergrenze.  
*AS* = Aussagesicherheit.

[Bender, 1977]
### Economy

#### COPPER RESERVES

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative production since 1946 in million tons</th>
<th>Copper Reserves in million tons contained Copper</th>
<th>Static life in years</th>
<th>Gross increase of reserves since 1946 in million tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>123.7</td>
<td>390.1</td>
<td>54.2</td>
<td>403.8</td>
</tr>
<tr>
<td>1974</td>
<td>116.5</td>
<td>348.0</td>
<td>46.3</td>
<td>354.5</td>
</tr>
<tr>
<td>1973</td>
<td>109.0</td>
<td>348.0</td>
<td>49.4</td>
<td>347.0</td>
</tr>
<tr>
<td>1972</td>
<td>101.9</td>
<td>348.0</td>
<td>53.9</td>
<td>339.9</td>
</tr>
<tr>
<td>1971</td>
<td>95.9</td>
<td>348.0</td>
<td>54.6</td>
<td>333.5</td>
</tr>
<tr>
<td>1970</td>
<td>89.1</td>
<td>280.3</td>
<td>47.0</td>
<td>259.4</td>
</tr>
<tr>
<td>1969</td>
<td>83.7</td>
<td>279.2</td>
<td>51.0</td>
<td>252.4</td>
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<tr>
<td>1968</td>
<td>77.7</td>
<td>288.3</td>
<td>56.7</td>
<td>256.0</td>
</tr>
<tr>
<td>1967</td>
<td>72.6</td>
<td>195.0</td>
<td>36.7</td>
<td>157.6</td>
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<tr>
<td>1966</td>
<td>67.3</td>
<td>195.0</td>
<td>38.5</td>
<td>152.3</td>
</tr>
<tr>
<td>1965</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1961</td>
<td>33.8</td>
<td>170.6</td>
<td>40.2</td>
<td>104.4</td>
</tr>
<tr>
<td>1956</td>
<td>25</td>
<td>142.2</td>
<td>45.7</td>
<td>57.6</td>
</tr>
<tr>
<td>1951</td>
<td>11.2</td>
<td>130.3</td>
<td>51.6</td>
<td>31.5</td>
</tr>
<tr>
<td>1946</td>
<td>110.0</td>
<td></td>
<td>50.6</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4a. Copper. Cumulative production, proven reserves, static life, gross increase in world reserves from 1946 to 1975.
Economy

Summary

Definitions,

Related disciplines,

Effect of politics, trends in world market and technology

Major factors of concentration:

- Source reservoir,
- Energy,
- Transport medium,
- Trap or barrier

3D variations

Kriging,

Variogram,

Cash flow trends of mining