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NOTE ON THE DISTRIBUTION AND PREDICTABILITY OF MINERAL RESOURCES

by

J. W. BRINCK

1967

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Brussels

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Brussels, May 1967

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Corroborating evidence to justify such extrapolations on the basis of the, mostly roughly estimated, parameters of the ore reserves is sought in the results of a geochemical survey on recent stream sediments in the Oslo region, Norway, for the elements copper, zinc and lead.

Allowances being made for the special metallogenetic characteristics of the Oslo region, comparison of the respective reference distributions with the survey distributions indicate that the model of log-normal distribution of element concentrations in the lithosphere can be used advantageously for the, at least semi-quantitative, estimation of the mineral resources of these elements, both from their known ore reserves and, under certain favorable conditions, from regional geochemical surveys. In the second case, such surveys seem to permit a quick and inexpensive appraisal of the metallogenetic characteristics of the region surveyed and its prospects for the occurrence of ore-grade mineralization in comparison with the upper lithosphere as a whole.

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SUMMARY

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CONTENTS

NOTE ON THE DISTRIBUTION AND PREDICTABILITY OF MINERAL RESOURCES (*)

INTRODUCTION

Through mining history, adequate capital investment, aided by the introduction and development of new exploration, mining and mineral processing techniques, has resulted in a rate of discovery and development of new ore reserves which, for many mineral commodities, has often exceeded the short- or medium- term requirements.

Almost conventionally, ore reserves are considered as naturally defined, vanishing assets of mostly unknown, but certainly limited, magnitude. This consideration, in view of the long-term availability of sufficient raw materials for industry has been, and certainly will continue to be, a source of grave concern to mineral economists. So far, all predictions on the imminent exhaustion of the world's ore reserves have been answered by the mining industry with increased production and, apart from conjunctural fluctuations, remarkably stable prices. It therefore appears that such predictions were based on insufficient quantitative data on the mineral resources from which ore reserves of mineral commodities are developed continuously.

In this note a short summary is given on the concepts and methods of estimating mineral resources and an attempt made to increase the prognostic value of such estimates by the application of geostatistical interpretation methods to this problem.

1 — CONCEPTS AND METHODS OF ESTIMATING MINERAL RESOURCES

Defining *ore* as "any naturally occurring mineral aggregate from which one or more components can be extracted at a profit", an *ore reserve* can be defined as "a weighted quantity of ore".

By definition, ore is an economic concept and therefore the term should be used only with reference to the market price of the mineral product(s) to be extracted from the ore. The concentration of the desired component(s) in the ore is an important, but by no means constant, factor for its designation as such. The limiting concentration is determined by the processing costs for the marketable product, which should not exceed the contained value of the product in the ore. Processing costs here include all costs incurred in the production, due allowance being made for a reasonable profit. Variations in exploration, mining and processing costs resulting from differences in the size, type and location of ore deposits permit the profitable mining of a range of concentrations at a more or less equal cost price for the mineral product.

Consequently, ore reserves are primarily dependent on the demand at a given price level and only secondarily on the absolute availability of the desired mineral substance in its accessible terrestrial environment. If the price is right, allowing for a certain lead-time for prospection

(*) Manuscript received on March 17, 1967.

and development, production from ore reserves will follow. Apart from the hydrosphere and the atmosphere, where element concentration is mostly a matter of scientific record, the size of the ore reserves representing a capital investment will tend to show a close relation with the rate of production. As soon as the ore reserves have reached a sufficient size to sustain the foreseeable rate of production for a certain number of years, prospection slows down or may even cease completely, especially if the target is overshot by too successful exploration.

For most mineral commodities, the demand at any given time in history is closely related to the state of technological progress at that time. The market price, however, in a balanced mineral market, is determined mostly by the contribution of the marginal producer to the total production of a mineral product. It seems therefore reasonable to suppose that the size of the ore reserves of a mineral commodity will show an at least semi-quantitative relation with its natural availability at the marginal and higher grades of enrichment. Especially for mineral commodities with a long mining history, ore reserves may be rather indicative for this availability in the accessible part of the lithosphere, comprising roughly the upper 3 km of the earth's crust, with the majority of the ore reserves between surface and a depth of 1 km.

While *mineral resources* are defined as the total of all weighted concentrations of mineral substances in the accessible part of the terrestrial environment, the term *potential ore reserves* is normally reserved for those concentrations which would become ore for a given reasonably predictable techno-economical development. Here the end-use to which the mineral product is put, expressed in terms of utility or desirability value (gold, for example), in close relation to the availability and price of substitute products (copper-aluminium; uranium-fossil fuels) determines the price which the mineral market could possibly bear for a given product. In analogy with ore reserves, the limiting value on the element concentration in potential ore reserves would be the contained end-use value, which should be equal or greater than the processing costs up to and including this end-use stage. Cost savings in any of the processing stages therefore would lower the limiting grade for potential ore reserves. However, competition with cheaper substitute products may counteract this effect to the extent of turning what were once valuable reserves into mineral resources (many coal reserves).

With the foregoing definitions, we now should review the data from which quantitative estimates on the size and grade of mineral resources are normally made.

Starting with ore reserves, we know that the mining industry distinguishes several classes of ore reserves, often somewhat differently defined, but always indicating the decreasing confidence we can place in their reported grade and size or even their existence itself.

1.1 — Ore Reserves

The most common subdivision is the following :

1.1.1 *Proven (or measured)* (1) *ore reserves*

Here ore grade and tonnage have been determined by extensive development work and can be considered accurate to within ± 10-50 % at the 95 % confidence level.

(1) The term in parenthesis commonly is used in mineral resources estimates. Proven and probable ore reserves sometimes are reported as "indicated" or "reasonably assured reserves", whereas "inferred reserves" also are reported as "possible additional reserves".

1.1.2 *Probable (or indicated)* (1) *ore reserves*

Exploration has roughly outlined these reserves but development work has not yet advanced sufficiently for tonnage and grade estimates to be regarded as more accurate than within 50-100 %.

1.1.3 *Possible (or inferred)* (1) *ore reserves*

These reserves are estimated on the basis of geological interpretation of yet unprospected areas in respect to known producing or well-prospected mineral deposits, mining districts or mineral provinces and therefore assume intimate knowledge and correct interpretation of all factors pertinent to the origin and distribution of such mineralizations.

It is especially in this class of ore reserves that more or less intelligent guesses show large differences between mining and geological estimates. In mining estimates the possible reserves are normally in the order of 10-20 % of the proven and probable reserves, whereas, the geologically inferred ore reserves often equal or exceed the measured and indicated ore reserves.

1.2 — Potential Reserves

The subdivision of *potential reserves* in practice can be limited to :

1.2.1 *Indicated potential reserves*

These include all non-commercial grade mineralizations from existing mines as well as from partially developed mineral deposits of marginal or sub-marginal grade.

Such reserves are often reported with the price-interval wherein they would become exploitable as ore.

1.2.2 *Inferred potential reserves*

These reserves are estimated similarly to inferred ore reserves.

The total of all ore reserves and potential reserves is then normally reported as "mineral resources".

As we have seen before, the "measured" or "indicated" reserve which serves as a basis for mineral resource estimates is a techno-economical concept with a variable, but almost coincidental relation to the abundance and distribution of a mineral substance in its natural environment. Even if the geological argumentation leading to the estimate is completely sound, the followed procedure will necessarily result in systematic underestimation until the last mineable reserve has been discovered. Without denying the considerable interest of such estimates for short-term economic planning, the medium- and long-term prognostic value of estimates of mineral resources would be considerably improved if we could find a more absolute criterion on which to base such estimates.

For this purpose we should explore the possibility of estimating mineral resources as a function of the distribution of element concentrations in their accessible terrestrial environment, independent of present-day economic considerations or the conditions for their exploitability — which for the majority of the inferred and potential reserves are not known anyway. In the following section this is done for element concentrations in the lithosphere, as the problem is related mostly to this particular environment.

(1) See foot-note on page 6.

2 — THE ABUNDANCE AND DISTRIBUTION OF ELEMENTS IN THE EARTH'S CRUST AS A BASIS FOR ESTIMATING MINERAL RESOURCES

The estimation of mineral resources as a function of the abundance and distribution of elements in the earth's crust brings this problem into the field of geochemistry.

Although ore deposits are hardly treated in the textbooks of general geochemistry, their existence is recognized and accepted as a logical consequence of the physico-chemical laws governing the distribution of elements in the earth's crust. Such a casual treatment of ore as a rock among other rocks could give the required basic criterion for the estimation of mineral resources, provided a common and generally acceptable yardstick could be found for their measurement against this common background. Much work in this field has already been done.

McKELVY (1960) and SEKINE (1962) have compared known ore reserves of elements with their natural abundance (clark) in the earth's crust. Although their results are obviously strongly influenced by technical and economic factors, the remarkable correlation they found to exist is highly indicative of a causal relation between ore deposits and their environment Qualitative explanations of the relation between ore deposits and the mineralizability of elements have been given by NIGGLY, GOLDSCHMIDT, RANKAMA and SAHAMA and many others. Contributions to the economic aspects of the subject have been made by the science of "applied geochemistry", which uses the concepts of geochemistry in mineral exploration (HAWKES and WEBB, 1962).

The use of geostatistical methods in geochemical prospection and the measuring of ore reserves (AHRENDS, DE WIJS, MATHERON, CARLIER, 1964) has in particular contributed much to our knowledge of element distribution in the earth's crust. It is mainly here that the still controversial concept of log-normal element distribution has been developed and put to the test. In short, this log-normality of element distribution means that the weighted frequencies of the logarithms of element concentrations in a series of weighted samples from different parts of a mineral deposit can be fitted into a normal or chance distribution (Gaussian curve).

Such log-normal element distributions have been found for many, if not all elements. The log-normality appears to be fairly independent of the size of the sampled environment and is found in all stages of mineral exploration from regional prospection with a very wide sampling grid, through systematic and detailed prospection to the measurement of ore reserves, with ever-decreasing size of the sampling grid. It has been demonstrated by COULOMB (1964) that the log-normal distribution found for uranium in several granitic areas studied, upon division of such areas into panels resulted into new log-normal uranium distributions in each panel, although generally with different median contents and standard deviations.

From these observations, the following properties of element distribution, on which consciously or unconsciously most modern mineral exploration is based, are indicated (1) :

— the element contents of a series of weighted subsamples in an area represented by one sample of a larger geochemical unit, in which the element contents are log-normally distributed, are log-normally distributed around the median element content in that sample;

— the element contents of regionalized samples from a geochemical unit in which the element contents are log-normally distributed also.

(1) For the sake of brevity no mention is made here of so-called anomalous element concentrations and composite log-normal distributions which are regularly found in mineral surveys. They normally can be explained from these properties by relating them to the element's distribution in a geochemical unit of a higher order than that represented by the sampled environment.

If a *geochemical unit* is defined as "a geological environment in which an element's concentrations are log-normally distributed", a logical consequence of this interdependence between element concentrations in different parts of the earth's crust is the assumption that the concentration and distribution of an element in any randomly chosen volume of rock is determined by its concentration and distribution in its geochemical unit, which ultimately might turn out to be its whole terrestrial environment, being the geochemical unit of the highest order.

There appears to be little reason to suppose that the element concentration in ore deposits would not confirm to this rule, as most of the above-mentioned observations have been made in relation with mineral exploration. If one looks at the distribution of ore deposits, the classical pattern of their occurrence as ore shoots forming an ore deposit; ore deposits often grouping together to form mineral districts, which in turn may form mineral provinces — instead of indicating a normal — or chance distribution of ore deposits in the earth's crust, can be much better fitted into a regionalized distribution, such as the log-normal distribution.

Quantitatively, for a log-normal element distribution the element's content and the dispersion of its concentrations in a given geological environment are determined by two parameters :

— the median element concentration γ

$$ln\ \gamma = \frac{\sum_{n=1}^{N} ln\ x_n}{N} \qquad [1]$$

in which x_n = element concentration in the n^{th} sample
N = total number of samples
(all samples here are given equal weight)

— the logarithmic standard deviation

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N} (ln\ x_n - ln\ \gamma)^2}{N}} \qquad [2]$$

From these two parameters the average element content $\overline{X}$ can be calculated from :

$$\overline{X} = \gamma e^{\frac{\sigma^2}{2}} \qquad [3]$$

in which e = constant with value 2.718 ...

With the above-mentioned properties of element distribution in mind, it is clear that element distributions found from different geological environments will not necessarily have the same median contents or standard deviations. The median concentration of an element in an ore deposit of that element will obviously be higher than its median content in a random chosen part of the earth's crust. Furthermore, it is a well-known fact that certain geological environments show a much more pronounced dispersion of element concentrations than others, which should be reflected in the standard deviation. It can be felt almost intuitively that the size of the samples, in respect to the size of the sampled environment, will also influence the value of the logarithmic standard deviation.

The absolute dispersion of an element in a given geological environment can be considered as the tendency of an element to occur in concentrated form (ore deposits). The absolute dispersion coefficient, which we would like to call the "specific mineralizability" of that element for the given environment, is related to the logarithmic standard deviation by the formula of MATHERON-DE WIJS (CARLIER, 1964) as follows:

$$\alpha = \frac{\sigma^2}{3\, ln \dfrac{D}{d}} \qquad [4]$$

in which α = specific mineralizability

D = linear equivalent of the sampled geological environment

d = linear equivalent of the average weighted sample.

For the derivation of the linear equivalent we must refer to the original paper of MATHERON. As a first approximation we can say that the linear equivalent of a volume with dimensions a$\geqslant$ b$\geqslant$ c$\geqslant$ is slightly less than a + b + c (CARLIER 1964).

$$D = 2.7 \ \text{a if b/a} = 1.00 \text{ and c/b} = 1.00$$

$$D = 1.99 \ \text{a if b/a} = 1.00 \text{ and c/b} = 0.00$$

$$D = 1.00 \ \text{a of b/a} = 0.00 \text{ and c/b} = 0.00$$

This relation, which is sometimes used for the comparison of the absolute grade contrast in different mineral deposits, could be equally used for the comparison of geochemical survey results from different geological environments.

If we know $\overline{X}$ and α for a given geological environment in which an element's contents are log-normally distributed, its probable resources at any given grade of enrichment can be inferred for any given possible individual size of the concentration. Consequently, by considering the range of concentrations from all ore deposits of an element as a class interval in the log-normal distribution and knowing the geological environment and average individual size of ore deposits, it would be possible to infer the total probable resources related with the ore reserves of the element (1).

Through the log-normal distribution, the parameters required for such calculations are related as follows:

$$P = \frac{r}{R} \qquad [5]$$

$$n_P \sigma = ln\gamma_r - ln\gamma_R \qquad [6]$$

in which:

P = the measured probability that a reserve r with a median element concentration equal or greater than γ_r will occur in a geological environment R with a median element concentration γ_R.

r = weight of the reserve, expressed in metric tons (area under the curve with median content $\geqslant \gamma_r$).

R = total weight of the geological environment R, expressed in metric tons (total area under the curve).

(1) Obviously, the chemical form in which the element will occur is not predicted.

n_P = number of logarithmic standard deviations equalling the difference between $\ln\gamma_r$ and $\ln\gamma_R$ for the indicated probability P (graphically represented in figure 1).

γ_r = median element concentration of the reserve *r*.

γ_R = median element concentration of the geological environment *R*; for the given median size of its ore deposits.

In order to demonstrate the applicability of this theoretical approach to the problem of estimating mineral resources the required parameters should now be defined quantitatively.

2.1 — The geological environment of ore reserves (R)

The geological environment of ore deposits in the lithosphere is formed by the accessible part of the earth's crust, which for most mineral commodities can be limited to the upper 3 km, with the majority of ore deposits between the surface and a depth of 1 km. Geologically this environment forms part of the granitic upper layer of the earth's crust, which on the continents normally extends to a depth of some 15 - 20 km (sial).

The apparently inhomogeneous distribution of ore deposits with depth does not necessarily indicate a natural chance with regard to the probability of ore-grade mineralization occurring with depth, even if many ore-forming processes are determined by near-surface or surface conditions. The constant recycling of crust material will tend to distribute such ore-grade concentrations to depths approximating to or equalling the thickness of the granitic layer. Apart from the increase in mining costs with depth, the observed vertical distribution of ore deposits can be explained by the fact that an ore deposit, in order to be discovered, should have a surface expression (outcrop, geological, geochemical or geophysical indication).

For many elements, such as Cu, Pb, Zn, Be, W, Ta, Nb, U, Th and many others, it is generally accepted that their present concentration and distribution has been determined essentially by geological processes in this granitic environment. Therefore we may regard this granitic layer as the geochemical unit for which all concentrations of the above-mentioned elements are log-normally distributed. Consequently, as a result of the second property of element distribution mentioned before, all measured element concentrations, which necessarily are limited to the upper part of this unit, can be considered as regionalized samples of this unit and should therefore be log-normally distributed also, even if their median content and specific mineralizability may be different from those of the unit as a whole [1].

For practical reasons we here will limit the environment of ore deposits to the upper 2.5 km of the emerged part of the earth's crust.

From a dry land surface of 150×10^6 km^2, a specific gravity of the crust of 2.7 and its depth of 2.5 km, the total weight of this environment can be calculated as 1×10^{18} metric tons.

From the dimensions of the environment, its linear equivalent D can be calculated as 24,500 km, assuming b/a = 1.00 and c/b = 0.00.

Thus : $R = 1.0 \times 10^{18}$

$D_R = 24{,}500$

---

(1) For element distributions found in relation to some ultra-basic rocks (Ni, Co, Cr in serpentinites, for example), the geochemical unit relating them to their distribution in the granitic upper layer of the earth's crust may be of a higher order than the latter and ore-grade reserve estimates by this method could lead to highly erroneous results.

2.2 — The median element content of the geological environment of ore reserves

Concerning the median content of an element in the environment of ore reserves we can use, with reasonable confidence, its average content in the earth's crust (clark) as determined from numerous analyses of common rock types forming the bulk of the earth's crust. The fact that extreme values are normally omitted from the clark calculations (GREEN, 1959) indicates that the clark of an element is a median value rather than an average.

For the examples given in this note, the following values are taken (GREEN, 1959) :

$$\gamma_{R,Cu} = 70 \text{ ppm (for copper)}$$
$$\gamma_{R,Zn} = 80 \text{ ppm (for zinc)}$$
$$\gamma_{R,Pb} = 16 \text{ ppm (for lead)}$$
$$\gamma_{R,U} = 3 \text{ ppm (for uranium)}$$

2.3 — The specific mineralizability of the elements in the geological environment of ore reserves

The specific mineralizability of the elements, to our knowledge, has never been calculated for the environment of ore deposits. Calculated values for the specific mineralizability of some elements in their ore deposits, which certainly cannot be considered representative for their environment as a whole are not very helpful in this respect. Therefore, we should try to approximate this value from available data on element distribution in the crust. Two sources of information are available here :

— the ore reserves,

— results of geochemical surveys.

If α_R is defined as the true specific mineralizability of the environment R, the specific mineralizability as approximated from the size of the ore reserves of an element could be referred to as α_r and from the results of geochemical surveys as α_s.

3 — THE ESTIMATION OF THE SPECIFIC MINERALIZABILITY FROM THE ORE RESERVES OF AN ELEMENT (THE "REFERENCE DISTRIBUTION")

The specific mineralizability of an element as calculated from its ore reserves has a very particular meaning in the estimation of mineral resources as it enables us to calculate the element's related mineral resources at any grade of enrichment and for any average size of these resources at a given enrichment. For this reason it is proposed to call the element distribution which is based on the parameters γ_R and σ_r (from which α_r is found) the *"reference distribution"* of an element.

For the construction of the reference distribution each individual ore reserve of an element is considered as a weighted sample in the class interval of ore-grade concentration. With the (estimated) median size of the ore-reserves ([1]), α_r is calculated.

The (estimated) median content ([1]) of the ore reserves is considered as the median content of the class interval. From the total weight of all ore reserves the measured probability of their

([1]) Both size and grade are shown to be log-normally distributed (PATTERSON, 1963).

occurrence in the weighted environment R is calculated [5]. The logarithmic standard deviation σ_r then can be found from [6], the specific mineralizability α_r from [4].

From the foregoing considerations on the conventional estimation of ore reserves it is obvious that the value α_r will approach the absolute value of α_R only if the ore reserves of an element truly reflect the natural availability of that element at the given ore-grade concentration. This generally may be expected to be the case for elements with a long mining history. For elements which are mined essentially as a by-product, or for which the occurrence in important placer deposits complicates the ore-grade estimation for their reserves as a whole, special precautions have to be taken for the estimation of α_r.

The following example shows the calculation of mineral resources (ore reserves + potential reserves) for uranium :

3.1 — Uranium

The total of all exploited and known uranium reserves (excluding the South-African reserves with an average content of 0.02 % U) can be estimated at ± 500,000 tons U in ore with a median content of 0.15 % U (range 0.085 - 0.35 % U).

The median individual reserve is estimated here as 4,000 tons U (range 100 - > 100,000 tons U) in ore with a specific gravity of 2.7.

The dimensions a > b > c of the median size ore deposit are estimated as b/a = 0.50 and c/b = 0.10, from which the linear equivalent d_r is found as 0.50 km (d = ~ 1.5 a).

Thus : $R_U = 1.0 \times 10^{18}$ tons

$r_U = 3.2 \times 10^8$ tons ore 0.156 % U (1)

$\gamma_{R,U} = 3.0 \times 10^{-4}$ % U (3 ppm)

$\gamma_{r,U} = 1.5 \times 10^{-1}$ % U (1 500 ppm)

$D_R = 24,500$ km

$d_r = 0.50$ km

$$\text{and : } P = \frac{3.2 \times 10^8}{1.0 \times 10^{18}} = \frac{1}{3.125 \times 10^9} \qquad [5]$$

$n_P = 6.16$ [figure 1]

$$\sigma_r = \frac{ln\ 1500 - ln\ 3}{6.16} = 1.00774 \qquad [6]$$

$$\alpha_r = \frac{1.0155}{32.36} = 0.03138 = 3.14\ \% \qquad [4]$$

From γ_R and σ_r we now can construct the reference distribution for all uranium concentrations with a median linear equivalent of 0.50 km. However, it is clear that the total amount of uranium contained in concentrations of this median size decreases with the lowering of the grade. To consider such lower-grade resources as potential reserves the opposite would be required.

(1) The average content as indicated from the estimated range of the class interval [3] (normally the median content is taken as the average for this calculation).

Therefore we have to increase the linear equivalent of such potential reserves as a function of the required size for the given grade of the potential reserves.

Assuming, for this example, that a potential reserve with a grade of 2/3 $\times$ median ore-grade should contain at least 2.5 $\times$ the amount of uranium in the median-size ore reserve and using these factors for each lower-grade potential reserve, we can calculate a set of d_r values, which we will number $d_{r,1-q}$ as follows :

Median resource ton U	Median grade % U	linear equivalent d_r
4,000	0.150	$d_{r,0} = 0.50$ km
10,000	0.100	$d_{r,1} = 0.78$ km
25,000	0.067	$d_{r,2} = 1.22$ km
62,500	0.044	$d_{r,3} = 1.89$ km
156,250	0.030	$d_{r,4} = 2.93$ km

Substituting $d_{r,q}$ for $d_{r,0}$ in equation [4] we find $\sigma_{r,q}$.

Substituting $\sigma_{r,q}$ for $\sigma_{r,0}$ in equation [6] we find $n_{P,q}$ which gives the probability P_q, from which the resources r_q can be calculated by equation [5] as follows (1) :

	Known examples with similar grade
$r_1 = 1.9 \times 10^9$ tons $\times$ 0.1 % U = 1,900,000 tons U	Blind River - Canada
$r_2 = 1.2 \times 10^{10}$ tons $\times$ 0.067 % U = 8,000,000 tons U	France - Sweden
$r_3 = 6.7 \times 10^{10}$ tons $\times$ 0.045 % U = 30,000,000 tons U	Many phosphate deposits
$r_4 = 3.3 \times 10^{11}$ tons $\times$ 0.030 % U = 100,000,000 tons U	Ranstad - Sweden

Each estimated resource includes all resources of a higher median content. In the same way estimates could be made from the reference distributions for other elements, such as copper, zinc and lead, which are given below.

3.2 — Copper

The total of all exploited and known copper reserves is estimated from the total amount of copper produced up to 1963 plus 20 $\times$ the annual production of 1963, giving 219 $\times$ 10^6 tons Cu in ore with a median grade of 1.7 % Cu (range 0.6 - 4.55 % Cu) (US BUREAU OF MINES, 1963, US BUREAU OF METAL STATISTICS, 1958).

The median size copper ore deposit is estimated as 65 $\times$ 10^6 tons copper ore (range 10 $\times$ 10^6 - 1,000 $\times$ 10^6 tons ore).

(1) Owing to the uncertain value of $\overline{X}_{K,U}$ the material imbalance as indicated in [3] is disregarded.

The dimensional parameters a > b > c of the median size ore deposit are estimated from a number of major ore deposits (BATEMAN, 1949) as b/a = 0.61 and c/b = 0.19 from which the following parameters of the reference distribution are calculated :

$$d_{r,Cu} = 1.2 \text{ km}$$

$$\mathrm{P}_{r,Cu} = \frac{1}{7.75 \times 10^7}$$

$$n_P = 5.55$$

$$\sigma_{r,Cu} = 0.9886$$

$$\alpha_{r,Cu} = 0.032864 = 3.29 \ \%$$

3.3 — Zinc

The total of all exploited and known zinc reserves is estimated, by the above mentioned method, as 174 × 10⁶ tons Zn in ore with a median grade of 4.3 % Zn (range 2.0 - 19.0 % Zn).

The median size zinc ore deposit is estimated at 10 × 10^6 tons of ore.

The dimensional parameters a > b > c of the median size ore deposit are estimated from a number of individual ore shoots as b/a = 0.56 and c/b = 0.10. If we ignore the generally higher specific gravity of zinc ore, the following parameters of the reference distribution are calculated :

$$d_r = 0.784 \text{ km}$$

$$\mathrm{P}_{r,Zn} = \frac{1}{2.47 \times 10^8}$$

$$n_P = 5.77$$

$$\sigma_{r,Zn} = 1.0884$$

$$\alpha_{r,Zn} = 0.03819 = 3.82 \ \%$$

3.4 — Lead

The total of all exploited and known lead reserves is estimated at 155 × 10^6 tons Pb in ore with a median grade of 5.0 % Pb (range : 1.0 - 25.0 % Pb).

The median size lead ore deposit is estimated at 10 × 10^6 tons of ore.

As most lead is exploited in combined lead-zinc deposits, the same parameters a > b > c are accepted as for zinc ore deposits, b/a = 0.56 and c/b = 0.10. If we ignore the generally higher specific gravity of lead ore, the following parameters of the lead reference distribution are calculated :

$$d_{r,Pb} = 0.784$$

$$\mathrm{P}_{r,Pb} = \frac{1}{3.23 \times 10^8}$$

$$n_P = 5.81$$

$$\sigma_{r,Pb} = 1.3835$$

$$\alpha_{r,Pb} = 0.0617 = 6.17 \ \%$$

To check whether or not this theoretical approach to the estimation of mineral resources has any practical value, we now should investigate whether similar resources estimates can be made from element distributions as found from geochemical surveys.

The parameters $\overline{X}_s$ and α_s, as found from geochemical surveys, then could be used against the reference distributions of the specified elements in order to estimate the more or less favorable potential for ore deposits of the surveyed environment with respect to the world's potential as indicated from the reference distribution.

If sufficient survey data became available it would then be possible to reverse the process and infer an element's mineral resources (including ore reserves) from its median content and specific mineralizability in the earth's crust.

4 — THE ESTIMATION OF THE SPECIFIC MINERALIZABILITY FROM GEOCHEMICAL SURVEYS

The most exact way of determining the specific mineralizability of an element in the upper 2.5 km of the earth's crust would be a systematic sampling program at different underground levels of the upper crust, which for obvious reasons cannot be considered. Survey results from existing mine works can also be ruled out as a source of significant information. Here, the sampled environment can be expected to be too much biased in favor of mineralization to be of much value to estimates on a world-wide scale.

Therefore, the only level practically available for such surveys appears to be the earth's surface. In order to obtain from this marginal environment a set of samples that could be expected to be more or less representative of the underlying 2.5 km of the crust, several conditions have to be fulfilled and many environmental factors, reflecting the interaction between the lithosphere, hydrosphere and atmosphere, have to be considered.

1. The surveyed environment should be representative of a geochemical unit of a high order.
   a) In the sampled environment, through tectonic movements and/or erosion, rocks that were formed at different levels of the crust should have become freshly exposed.
   b) To be more or less representative of the crust, igneous rocks, of granitic composition mainly, should prevail over metamorphic and sedimentary rocks.
2. The samples should be representative of the underlying 2.5 km of the crust.
   a) The optimum size of the samples can be estimated, in analogy with the appraisal of the potential size of mineral deposits from outcrop data, as depth = 1/2 × outcrop length.

      To be more or less representative of a depth of 2.5 km, the outcrop sample therefore should have a linear equivalent of at least 5 km.
   b) The influence of the interaction between the lithosphere, the hydrosphere and the atmosphere on the element concentration in the sample should be negligible or accounted for.

Although all of the above-mentioned conditions could bear a more detailed explanation, we will here limit ourselves to the problem of obtaining representative samples with a linear equivalent of 5 km. As samples of the indicated optimum size would be rather impractical for handling, such samples have to be replaced by the best obtainable samples for the given conditions. Different ways can be followed to obtain average element concentrations for such large samples :

— Systematic chip or channel sampling of the exposed surface of the sample area, resulting in a number of sub-samples from which an average or median content could be obtained, would apparently give valid results. However, to be really representative of the sampled environment, the costs and time involved in the sampling would be prohibitive. The proper weighing of the influence of the encountered geological conditions (contacts, veins, etc..) on the element concentration in the sample area would require a rather elaborate geological interpretation of the sample area. In general, such surveys, in order to be fast and cheap, can be expected to give unfavorable, low results.

— By sampling recent stream sediments, nature has largely solved the problem of proportional representation of all rocks present in a drainage basin. Here the whole geological environment is sampled. However, by forming a geological environment in itself, other problems are created, such as proper sediment mixing, the influence of different erosion resistance of the rocks present in the basin, gravity separation and chemical dissolution.

These problems have been discussed before, for the distribution of beryllium in the Oslo region, Norway (BRINCK - HOFMANN, 1963). Although errors due to the above-mentioned factors were found to occur, their influence in this area was not sufficient to interfere seriously with the geochemical interpretation of the survey results.

Therefore, if applicable, this method should be preferred above rock sampling for this type of regional survey.

4.1 — Estimation of the specific mineralizability for copper, zinc and lead in the Oslo region, Norway

For the reasons just mentioned, use is made in this test of the distribution of copper, zinc and lead as found from analyses (1) on the same samples from which the beryllium distribution in the Oslo region was determined.

4.2 — Sample Analysis

The analyses for Cu, Pb and Zn were made in 1963 at the JRC/Ispra by Dr. K. WEBER and his staff by X-ray fluorescence, using an automatic-coupled pulse-height discriminator (WEBER - MARCHALL, 1963). The — 100 mesh fraction of the recent stream sediment samples, which had only partially been used for the determination of Be, was pulverized to pass a 200 mesh sieve and the X-ray samples were prepared from this — 200 mesh material. Unfortunately, the detection limit for uranium with the followed standard procedure is around 30 ppm U, thus giving insufficient data for this test purpose.

4.3 — The geological environment of the geochemical survey

In a geologic sense, the Oslo region can be considered as a rectangular area, with a length of some 320 km and a width of 60 km, extending from the south coast of Norway, west of the Oslo Fjord to Lake Mjösen in the neighborhood of the village of Lena.

The area consists mainly of freshly exposed igneous rocks of Carbo-permian age, surrounded by pre-cambrian and palaeozoic metamorphic and sedimentary rocks. After glaciation of the area during the Pleistocene, some quaternary sediments were deposited in the deeper valleys and lower plains of the region.

(1) BRINCK, WEBER, HOFMANN, MARCHALL, DE WOLDE, publication in preparation.

In the total sampled area of 2186 km^2 (146 samples) the different geological units are represented as follows :

Quaternary sediments	6.3 %
Carbo-permian igneous :	
granites	35.5 %
nordmarkites	19.5 %
syenites	11.3 %
volcanics	9.7 %
Palaeozoic rocks	10.4 %
Precambrian rocks	7.3 %
Total :	100.0 %

During the geochemical survey abundant Zn mineral indications were observed and several abandoned zinc mines were located. No mineral indications for lead were found, but it can be expected that lead may be associated with the zinc mineralizations as usual. Copper mineral indications were not observed during the survey, but some copper concentrations of a non-commercial nature are reported in the literature. It may be expected that these conditions will be reflected in the element distributions found from the survey.

From this description the following environmental and sample parameters can be calculated :

— The size of the environment $S = 19{,}200$ km^2

$D_S = 380$ km

— The average sample size $s = 15$ km^2

$d_s = 7.75$ km

4.4 — The Element Distributions

4.4.1 *Copper*

— The survey distribution

$$\gamma_S = 89 \text{ ppm}$$

$$\sigma_S = 0{,}6119$$

from which $\alpha_S = 0.0376 = 3.76$ %

— The dimensional corrected survey distribution

Substituting d_r for d_s in equation [4] we find $\sigma'_S = 0.8053$.

With γ_S and σ'_S as parameters we now can construct the "dimensional corrected survey distribution" and compare the indicated probability for the occurrence of ore deposits in the surveyed area (P'_S) with the same probability for the world as a whole, as indicated by the "reference distribution" (P_r).

from [6]

$$n'_P = 6.515$$

$$P'_S = \frac{1}{2.9 \times 10^{10}}$$

Defining F as a factor which indicates the favorability of a surveyed area with respect to the absolute favorability for the occurrence of ore grade concentrations of a predetermined size in the environment R, the factor f can be used to indicate this favorability with respect to the "reference distribution" of the element.

Thus :

$$\frac{P'_S \times S_R}{P_r \times S_S} \qquad [7]$$

and

$$f_{S,Cu} = 21.1 \text{ (1)}$$

The factor $f_{S,Cu}$ indicates that the probability of finding a copper ore deposit of the referenced median size and grade is about 20 × higher for the Oslo region than for a randomly chosen area of this size.

— The indicated world's ore-grade copper resources

Substituting $\frac{D_R}{d_r}$ for $\frac{D_S}{d_s}$ in equation [4], we find :

$$\sigma''_S = 1.057$$

Substituting γ_R for γ_S in equation [6], we find :

$$n''_P = 5.19$$

$$P''_S = \frac{1}{1.07 \times 10^7}$$

indicating that the world's ore-grade copper resources could be about seven times as great as the presently known copper ore reserves, as estimated above. This appears quite reasonable if we consider the total environment to a depth of 2.5 km, as well as the fact that this estimate is based on only one observed value of α_S.

4.4.2 *Zinc*

— The survey distribution :

$$\gamma_S = 272 \text{ ppm}$$

$$\sigma_S = 0.7068$$

from which

$$\alpha_S = 0.0428 = 4.28\ \%$$

(1) S_R = dry land surface of the earth (150×10^6 km^2)
S_S = surface of the surveyed region (19,200 km^2).

— T h e   d i m e n s i o n a l   c o r r e c t e d   s u r v e y   d i s t r i b u t i o n :

Substituting d_r for d_s [4]

$$\sigma'_S = 0.8904$$

from [6] $$n'_p = 5.680$$

$$P'_S = \frac{1}{6.683 \times 10^8}$$

and from [7] (1) $$f_{S,Zn} = 2\ 900$$

The high value of $f_{S,Zn}$ reflects the observation that zinc ore deposits do occur in the Oslo region. The favorability here is determined essentially by the high median content of the region with respect to the clark of zinc.

— T h e   i n d i c a t e d   w o r l d ' s   z i n c   o r e - g r a d e   r e s o u r c e s

Substituting $\frac{D_R}{d_r}$ for $\frac{D_S}{d_s}$ [4] : $\sigma''_S = 1.152$

Substituting γ_R for γ_S [6] : $n''_P = 5.45$

$$P''_S = \frac{1}{4.46 \times 10^7}$$

P''_S indicates that the world's ore-grade zinc resources, as estimated from α_S, could be $\pm$ 5 times as great as the presently known zinc ore reserves, indicating that apart from a high γ_S, no special favorable conditions for zinc mineralization seem to be required for the occurrence of ore deposits.

4.4.3 *Lead*

— T h e   s u r v e y   d i s t r i b u t i o n

$$\gamma_S = 21 \text{ ppm}$$

$$\sigma_S' = 1.0166$$

from which $$\alpha_S = 0.088634 = 8.86\ \%$$

— T h e   d i m e n s i o n a l   c o r r e c t e d   s u r v e y   d i s t r i b u t i o n

Substituting d_r for d_s in [4] : $\sigma'_S = 1.2815$

from [6] : $n'_P = 6.06$

$$P'_S = \frac{1}{1.4 \times 10^9}$$

and from [7] (1): $f_{S,Pb} = 1\ 800$

The high value of $f_{S,Pb}$ here is determined essentially by the high specific mineralizability and indicates that favorable conditions for the concentration of Pb exist in the area (zinc ore mineralizations).

(1) See foot-note p. 19.

— The indicated world's ore-grade lead resources

Substituting $\frac{D_R}{d_r}$ for $\frac{D_S}{d_s}$ in [4] : $\sigma''_S = 1.6577$

Substituting γ_R for γ_r in [6] : $n''_P = 4.849$

$$P''_S = \frac{1}{1.68 \times 10^6}$$

P''_S indicates that the world's ore-grade lead resources as estimated from α_S could be 220 × as great as the presently known lead ore reserves. The value of α_S therefore may be considered too high and it seems that better than normal conditions for mineralization will not necessarily result in the formation of ore deposits.

5 — SUMMARY AND CONCLUSIONS

The estimation of ore reserves and mineral resources is conventionally based on the size of "proven" and "probable" ore reserves and such estimates therefore are closely linked to the state of technological progress at any given time in history. The estimates show a variable, almost coincidental, relation to the natural abundance and distribution of the elements in their terrestrial environment. In order to increase the long-term prognostic value of such estimates, an attempt is made to relate an element's resources (including ore-grade reserves) to its natural abundance and dispersion in its geological environment.

Assuming log-normality as a property of element distribution, an element's resources at any grade of enrichment, for any given possible average size of the individual reserve, are determined by its mean concentration ($\overline{X}$) and "specific mineralizability" (α) (absolute dispersion coefficient of MATHERON-DE WIJS) in the environment, which here is taken as the upper 2.5 km of the emerged part of the earth's crust.

In order to test the applicability of this approach to the estimation of mineral resources, "reference distributions", derived from the conventionally estimated world's reserves of copper, zinc, lead are compared with copper, zinc and lead distributions found from a regional geochemical survey in the Oslo region Norway, with the following results :

	Reference distribution (from ore reserves)	Sample distribution (from Oslo Region)
Median content :	γ_{Cu} = 70 ppm	γ_{Cu} = 89 ppm
	γ_{Zn} = 80 ppm	γ_{Zn} = 272 ppm
	γ_{Pb} = 16 ppm	γ_{Pb} = 21 ppm
	γ_U = 3 ppm	γ_U = not available
Specific mineralizability :	α_{Cu} = 3.29 %	α_{Cu} = 3.76 %
	α_{Zn} = 3.82 %	α_{Zn} = 4.28 %
	α_{Pb} = 6.17 %	α_{Pb} = 8.86 %
	α_U = 3.13 %	α_U = not available

Allowing for the specific metallogenetic conditions in the sampled area, the estimates seem to confirm the applicability of the method to estimation of mineral resources. An example is given for the estimation of probable mineral resources related to the known uranium ore reserves, exploitable at a price of less than \$ 8.00 lb U_3O_8, with the following results :

Probable resources tons U	Individual size tons U	Median grade % U	Remarks (examples of deposits with similar grade)
500,000	4,000	0.15	Known reserves
1,900,000	10,000	0.10	Blind River Canada
8,000,000	25,000	0.067	Sweden - France
30,000,000	62,500	0.045	Many phosphate deposits
100,000,000	156,250	0.03	Ranstad - Sweden

In view of the fact that at Ranstad-Sweden a geological reserve of $\pm$ 1,000,000 tons U in ore with an average grade of 0.03 % U has been found, from which at present uranium concentrates can be produced at a price of \$ 15.00 - 20.00 lb U_3O_8, part of these indicated probable uranium resources can be considered as probable potential uranium reserves.

It should be remarked that this interpretation would be valid only if the granitic upper layer of the earth's crust could be considered as the "geochemical unit" for the considered element. This probably is the case for elements as Cu, Zn, Pb, U, Be, W, Ta, Th and many others.

As an interesting incidental result of the acceptance of log-normality as a property of element distribution, the particular distribution of ore deposits and the high efficacity of modern mineral exploration methods (applied geochemistry in particular), can be explained from this basic law.

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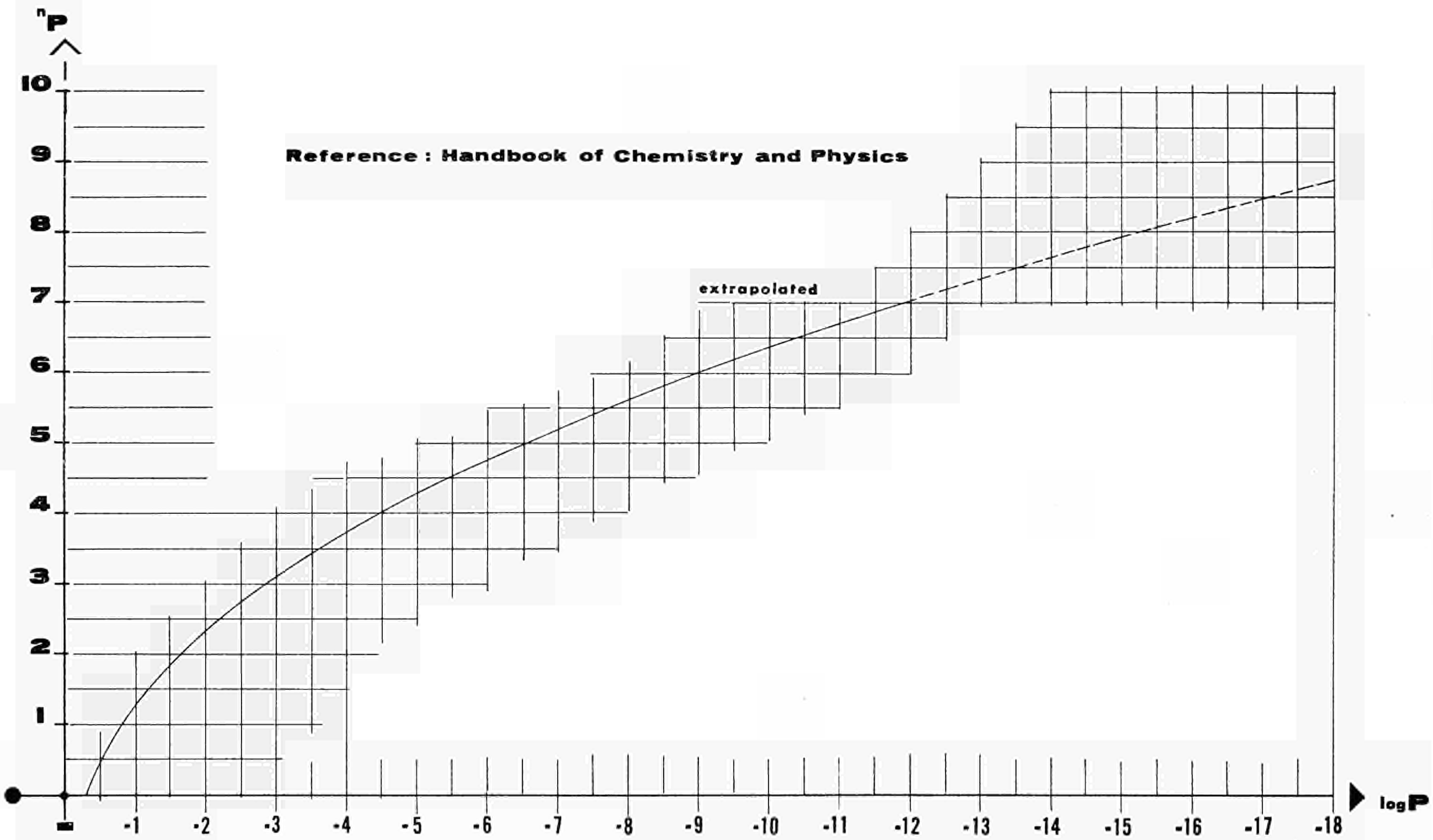
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FIGURE 1

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E R R A T U M

NOTE ON THE DISTRIBUTION

AND

PREDICTABILITY OF MINERAL RESOURCES

by

J.W. BRINCK

Please read the last paragraph page 8 as follows :

" - The element contents of regionalized samples from a geochemical unit are log-normally distributed also."

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