

MINERALIZATION THROUGH GEOLOGIC TIME: RECYCLING PERSPECTIVE

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ABSTRACT. In analogy to living systems, geologic entities (rocks, mineral deposits, tectonic realms, and domains) are involved in the processes of perpetual generation and destruction (“birth/death” cycles). This results in time distribution patterns akin to age structures in living populations, and the systematics is amenable to treatment by the concept of population dynamics. In this concept, the half life (τ_{50}) of generation/destruction—or recycling—of petroleum during the Phanerozoic has been ~ 87 Ma. In contrast, coal and gas attained their “modern” steady-state only in the Late Paleozoic, following the colonization of land by vascular plants. Subsequently, they have been recycled with half-lives of ~ 265 and ~ 120 Ma, respectively. The present-day age distribution of reserves of metallic ores suggests that the system attained a steady-state at $\sim 1.75 \pm 0.25$ Ga ago, coincident with the growth of continents to their near present-day cumulative size. The subsequent history has been mostly that of perpetual recycling, the rates varying with the genetic categories of ores rather than specific metals. The genetic categories, in order of their ascending recycling rates, are: (1) magmatogene, associated with mafic-ultramafic rocks ($\tau_{50} \geq 1700$ Ma); (2) metamorphic associations (≥ 1350 Ma); (3) volcano-sedimentary (~ 800 Ma); (4) chemical-sedimentary ($\sim 414 \pm 194$ Ma); (5) hydrothermal ($\sim 95 \pm 41$ Ma); (6) detrital-sedimentary ($\sim 50 \pm 20$ Ma), and (7) weathering crusts ($\sim 3 \pm 2$ Ma). This progression reflects the diminishing tectonic and geological stability of the host environments. The simulated overall metallogenic evolution of the Earth, deconvoluted for recycling, indicates five partially overlapping development stages. These are: (1) The greenstone belt stage, dominant in the Archean and petering out ~ 1.8 Ga ago, with gold mineralization, Algoma type iron ores, and massive sulfides; (2) the cratonization stage, with the peak in the Late Archean and Early Proterozoic, and containing the paleoplacer type Au and U deposits, the bulk of iron (Superior type) reserves, and related Mn deposits; (3) the rifting stage, at $\sim 1.8 \pm 0.3$ Ga ago, typified by mafic-ultramafic dikes and layered complexes, and related mineralization of Cr, Ni, Cu, Au, Fe as well as frequent base metal deposits, hydrothermal U, and volcano-sedimentary Mn; (4) the stable craton phase, ~ 1.7 to 0.9 (or 0.6) Ga ago, with common alkalic volcanism and plutonism but a dearth of mafic-intermediate volcano-plutonic associations and metallic ores. The significant ores have been of exogenic type confined to the cratonic sedimentary cover (unconformity U, chemical sedimentary Mn, and Zambian type Cu); (5) the Phanerozoic

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stage of continental dispersal, characterized by varied and frequent mineralization, particularly of hydrothermal type.

INTRODUCTION

Temporal distribution of mineral deposits is of general interest to geosciences because of theoretical and practical considerations. From the theoretical point of view, mineral deposits—representing the most fractionated products of endogenic and exogenic processes—may be a good reflection of their qualitative and quantitative changes through time. If so, they may reflect evolution of the terrestrial lithosphere, atmosphere, hydrosphere, and biosphere; all subjects of fundamental scientific importance. From a practical point of view, recognition of such relationships, although not providing direct pathfinders for discovery of deposits themselves, will lead to improvement of conceptual models.

The question hotly debated at present is not so much whether certain types of mineral deposits have been dominant during specific time intervals of terrestrial evolution, but whether this apparent time-bound character is a primary feature or a consequence of secondary phenomena, such as, for example, their preferential preservation or destruction due to diverse, usually tectonic, factors. The preferences range from stoutly steady-state views, including the denial of time-bound character of deposits, to entirely evolutionary concepts. The majority of authors have been wavering between these two limiting alternatives. Examples of reviews for metallic mineral deposits as related to geological time are: Pereira and Dixon (1965), Rundqvist (1968, 1984a, b), Bilibin (1968), Routhier and others (1973), Strakhov (1969), Stanton (1972, 1986), Watson (1973, 1976, 1978, 1984), Hutchinson (1973, 1980, 1981a, b, 1984), Laznicka (1973, 1981a, 1985a), Folinsbee (1975, 1982), Anhausser (1976, 1981), Anhausser and Button (1976), Boyle (1976), Veizer (1976), Smirnov (1977, 1982a, b, 1984), Tugarinov (1979), Routhier (1980), Sangster (1980), Lambert and Groves (1981), Strong (1981), Meyer (1981, 1985, 1988), Gustafson and Williams (1981), Franklin, Lydon, and Sangster (1981), Sidorenko (1981), Sawkins (1983), Radhakrishna (1984), Windley (1984) and many papers, particularly for single commodities, cited in these references. The age distributions of hydrocarbon reserves have been reviewed, for example, by Tissot (1979), Bestougeff (1980), and Bois, Bouche, and Pelet (1980, 1982).

The difficulties and disagreements in interpretation arise from the fact that any given time distribution is a consequence of both primary creative and secondary destructive phenomena. The resulting time distribution pattern is, therefore, a result of the relative importance of these antithetic processes and not of their qualitative presence or absence. Qualitative and semiquantitative considerations, implicit in all the above publications, are thus frequently inadequate to answer the primary versus secondary dilemma. To do so, quantitative assessment of the dispersal and/or remobilization of mineral accumulations is essen-

tial. In this paper, we shall employ the techniques of population dynamics to show that the first order age distribution patterns for reserves of hydrocarbons and metallic ore deposits are consistent with the concept of recycling, utilize the approach to estimate their probable recycling rates, and with the help of these quantitative estimates attempt to unravel major features of the evolution of mineralization through time.

INTRODUCTION TO THE CONCEPT OF POPULATION DYNAMICS

In its abstract meaning *population* is a natural grouping of related constituent *units*. A population is a dynamic phenomenon, with perpetual generation and destruction of units, and this “birth/death” cycle, or *rate of recycling*, generates a specific internal age distribution pattern. The process of recycling proceeds internally (cannibalistic recycling) and externally. Most natural populations are involved in both, internal as well as external recycling, and it is only their relative importance that varies from one population to another. For present discussion, an oil pool—or any other mineral commodity—can be in part remobilized into younger strata (cannibalistic recycling) and in part dissipated and replaced in the younger reservoirs by oil originating from disparate outside sources (external recycling). Both types of recycling, independently or in concert, control the internal age structure of the population.

The fundamental parameters essential for quantitative treatment of population dynamics are the population *size* (A_0) and its *recycling rate*. Because of unequal sizes of natural populations, A_0 is normalized in the subsequent text to 1 population (or 100 percent), and the recycling proportionality constants ($\underline{b}$ below) relate to this normalized size. In a steady-state situation, an ideal natural population is usually typified by an age structure similar to that in figure 1. The proportion of progressively older constituent units decreases exponentially, because “mortality” usually is a first order function of the size of the given age group. The internal age distribution of the population expressed as a cumulative curve defines its *half-life* τ_{50} , *mean age* τ_{MEAN} , and *oblivion age* (life expectancy) τ_{MAX} (fig. 1). Mathematically (for example, Lerman, 1979)

$$A_{t*} = A_0 e^{-kt*} \quad (1)$$

where A_{t*} is the cumulative fraction of the surviving population older than t^* , A_0 equals 1 (one population), t^* is age (not time), and k is the rate constant for the recycling process. In the subsequent text, the recycling rate is discussed in the form of a *recycling proportionality constant* $\underline{b}$, which is related to the above formalism as

$$\underline{b} = 1 - e^{-kT}$$

where T is the time resolution (see Veizer and Jansen, 1979, 1985; also fig. 1 for further details). In general, the larger the $\underline{b}$, that is the faster

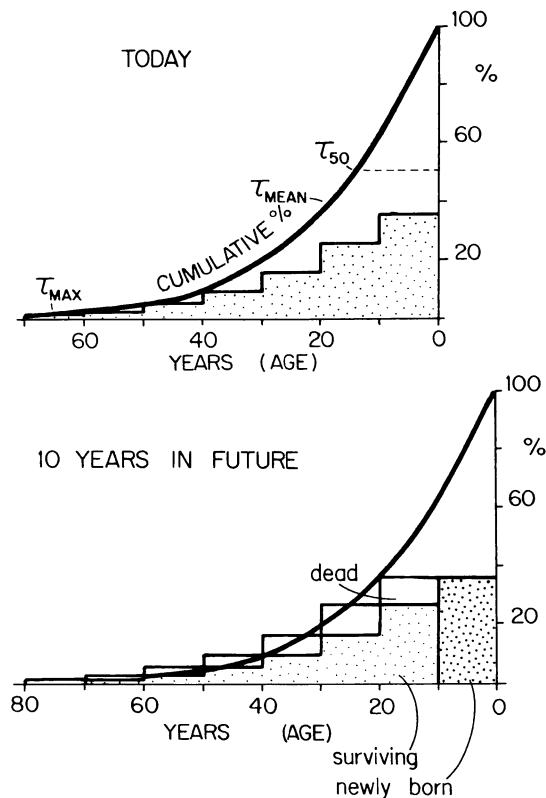


Fig. 1. An ideal internal age distribution pattern for a hypothetical human population with stable age structure. τ_{50} , τ_{MEAN} , τ_{MAX} as in the text. For a resolution T of 10 yrs, the recycling (natality/mortality) proportionality constant b equals $35 \times 10^{-3} \text{ yr}^{-1}$. Note that for the same population the b value varies inversely with time resolution, the latter denoted as a superscript. For example, b^{10} signifies the b calculated for $T = 10 \text{ Ma}$. τ_{MAX} is defined as the 5th percentile or the maximal life-span a unit will not exceed at the 95 percent confidence level of probability. In practice, the oblivion age τ_{MAX} marks the point at which the resolution of the database becomes indistinguishable from the background scatter. τ_{50} is the 50th percentile. Reproduced from Veizer and Jansen (1985) by permission of the University of Chicago Press.

the rate of recycling, the steeper the slope of the cumulative curve and the shorter the τ_{50} , τ_{MEAN} , and τ_{MAX} of the population. In other words, the chance of survival diminishes with increasing “mortality” rates. For a steady-state extant population, involved in a perpetual generation/destruction cycle, this cumulative slope propagates into the future (fig. 1 bottom).

In natural systems, three fundamental types of age distributions are ubiquitous (Pielou, 1969; Wilson and Bossert, 1971) (fig. 2). The ideal type discussed above is denoted here as the *type I* age distribution pattern.

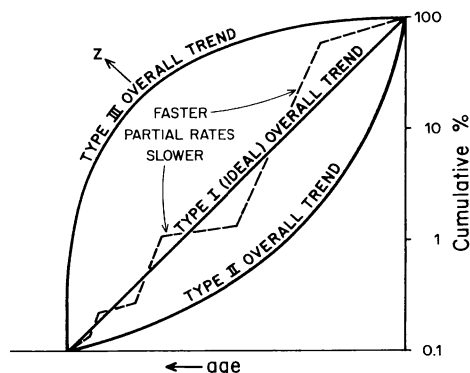


Fig. 2. Cumulative age distribution patterns for three ubiquitous survivorship trends. Note the semi-logarithmic plot, which transformed the cumulative curve in figure 1 into a straight line. The general equation for survivorship data can be expressed by the Weibull frequency distribution (Pinder et al., 1978; Odum, 1983, chap. 20), which follows the mathematical formalism

$$A_{i*} = e^{-(t^*/\ell)^z}$$

where ℓ and z are the scale and shape parameters, respectively. The former is related to mean ages as

$$\ell = \frac{\tau_{\text{MEAN}}}{>[1 + (1/z)]}$$

The shape parameter z is 1 for the type I age distributions (fig. 1), >1 for the type III distributions, and <1 for the type II distributions. Both parameters can be derived by a graphical linear regression technique (Hahn and Shapiro, 1967). Reproduced from Veizer (1988a) by permission of Wiley & Sons Ltd.

The *type II* pattern represents populations with an enhanced destruction rate of the young constituent units, with the chance for survival increasing with maturity. In contrast, the *type III* pattern represents populations with a suppressed destruction of the young units.

Natural processes, however, are discrete, and episodic phenomena and partial intervals usually have recycling rates faster or slower than the average rates (fig. 2) (see also Garrels and Mackenzie, 1971, chap. 10). Note that a given partial slope may reflect deviations in the rates of generation, destruction, or both. Usually the problem is not resolvable, although the *net* slope is mostly the result of a combined effect. As the population ages, the magnitude of this second order scatter diminishes to the level of the uncertainties in the data base (fig. 2), thus resulting in the loss of the quantitative record (oblivion age τ_{MAX}).

We refer to Veizer and Jansen (1979, 1985) for further details of mathematics and to Veizer (1988a) for an extensive discussion of the concept. Note also that this approach, in some analogy to thermodynamics, does not specify the nature of the processes involved. Any interpre-

tation of the calculated parameters ($\underline{b}$ values) must be inferred, therefore, from the geological context.

For geologic entities (crustal segments, mineral deposits, tectonic domains, fossils, et cetera), the age distribution patterns can be extracted from their stratigraphic and geochronological assignments. At present, only major features of the record can be interpreted quantitatively because the database is usually not of the desired reliability. It is our hope that this contribution will stimulate compilation of the required high precision inventories and thus facilitate a quantitative approach toward historical aspects of Earth evolution.

AGE DISTRIBUTION PATTERNS OF HYDROCARBONS

The age distribution patterns of petroleum, natural gas, and coal reserves (Tissot, 1979; Bois, Bouche, and Pelet, 1980, 1982; Bestougeff, 1980; Klemme, 1980; Ronov, 1985), reproduced in table 1 and figure 3, may serve as a good starting illustration of the methodology.

The present-day age distribution of petroleum reserves conforms well with the pattern predicted for an ideal type I population, and this is not surprising in view of the ease of its migration and dissipation. At steady-state, the calculated b^{10} is $\sim 78 \times 10^{-10} \text{ a}^{-1}$, which in absolute quantities amounts to recycling of $\sim 7450 \text{ bbl}$ per year. Consequently,

TABLE 1
*Present-day age distributions of global reserves of petroleum,
natural gas, and coal*
Based on the data of Bois and others (1982) and Bestougeff (1980).

	Petroleum %	Natural Gas %
Late Tertiary	17.7	14.5
Early Tertiary	13.5	12.2
Cretaceous	36.3	31.2
Triassic-Jurassic	18.1	13.5
Pennsylvanian-Permian	5.1	23.1
Silurian-Mississippian	6.7	4.4
Cambrian-Ordovician	2.6	1.1
Σ	$152.2 \times 10^9 \text{ m}^3$ $955 \times 10^9 \text{ bbl}$	$92.6 \times 10^{12} \text{ m}^3$ $3275 \times 10^{12} \text{ cft}$
	Coal %	
Tertiary	13.5	
Cretaceous	13.3	
Jurassic	16.8	
Triassic	0.4	
Permian	31.7	
Carboniferous	24.3	
Devonian	<0.1	
Σ	$10231 \times 10^9 \text{ t}$	

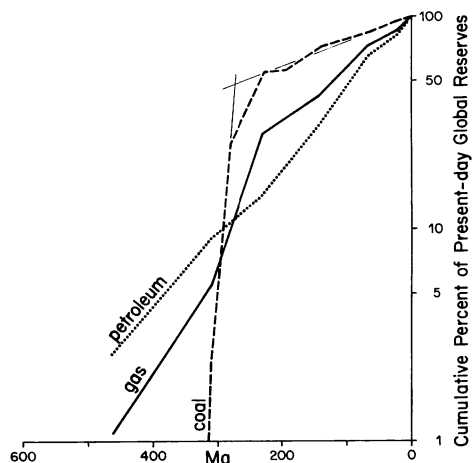


Fig. 3. Present-day cumulative age distribution patterns for global reserves of petroleum, natural gas, and coal. See table 1 for details.

the global half-life of storage/dispersal of petroleum reserves in the geological traps is ~ 87 Ma. The second order scatter, such as the Cretaceous and Devonian peaks, is discernible but the amplitudes are small. Consequently, recycling is the dominant factor on time scales $\geq 10^7$ yrs, smoothing the shorter term oscillations in the storage and/or dispersal rates of petroleum.

The present-day age distribution of coal (table 1, fig. 3) approximates the type III distribution. The best fit follows an approximation

$$A_{t*} = \left[1 - \left(\frac{t*}{350} \right)^{1.1} \right] 100$$

where A_{t*} is the cumulative percentage present at age t^* , the latter expressed in million years. This solution may indicate that the rate of destruction of coal deposits increases as they age. Alternatively, the rate of dispersal has been constant, but the rate of coal generation could have been very high during the Late Paleozoic times. The absence of pre-Devonian vascular land plants and the bimodal nature of the age distribution (fig. 3) clearly support the second alternative. The rapid colonization of the new niches by emergent land plants led to a proliferation of the late Carboniferous and Permian coal swamps. This, in turn, resulted in rapid coal generation and establishment of near steady-state reserves (saturation of the new niches) at the close of the Paleozoic. The subsequent generation/dispersal has been controlled by b^{10} of $\sim 26 \times 10^{-10} \text{ a}^{-1}$ ($\sim 26600 \text{ t a}^{-1}$) resulting in τ_{50} of ~ 265 Ma. Since less than one half-life elapsed from the emergence of this steady-state, the recycling process did not succeed in dispersing the huge initial Late

Paleozoic reserves. Given enough time (4–5 half-lives) this will be accomplished, and the resulting age distribution pattern will be that of type I. In reality, therefore, the present-day age distribution of coal is that of an immature type I population (post-Paleozoic) with an “indigested” memory of its initial growth stages. It will be shown in the text that such composite patterns are common also for metallic ore deposits.

The present-day age distribution of gas (table 1, fig. 3) shows a composite pattern of two type I populations. The mid-Paleozoic section has an age slope similar to that of the coeval petroleum ($b^{10} = 78 \times 10^{-10} \text{ a}^{-1}$), whereas the Mesozoic-Cenozoic portion has been controlled by b^{10} of $\sim 56 \times 10^{-10} \text{ a}^{-1}$ ($\tau_{50} \sim 120 \text{ Ma}$). Finally, the Late Paleozoic tangent indicates much faster rates of storage (or less dissipation) of gas than was the case during the preceding as well as subsequent times. Bois, Bouche, and Pelet (1982) attributed these large Late Paleozoic accumulations to entrapment of migrating gas beneath a tight Permo-Triassic evaporitic seal. We believe that an alternative interpretation is possible. During the early-mid Paleozoic times, generation of gas could have been mostly from marine sources, and, if so, its storage/dissipation rate has been governed by the same factors as that of petroleum. In the Late Paleozoic, a second (terrestrial) source of gas has been added to the already existing marine one. This led to the growth of composite gas reserves to near present-day steady-state value. The subsequent, Mesozoic-Cenozoic, steady-state has been characterized by the composite storage/dissipation b^{10} of $56 \times 10^{-10} \text{ a}^{-1}$ ($\sim 518 \text{ } 560 \text{ m}^3 \text{ a}^{-1}$), which is intermediate between that of coal and petroleum (fig. 3). As in the case of coal, the short elapsed time since the emergence of the Mesozoic-Cenozoic steady-state did not suffice for dispersal of the memory of the Late Paleozoic growth and of its preceding “marine” steady-state.

AGE DISTRIBUTION PATTERNS OF METALLIC ORE DEPOSITS

The present-day cumulative age distribution patterns of global economic accumulations of metals of all genetic categories are summarized in figure 4 and app. A. The observed overall picture indicates twofold evolution history, with a break at about 1.5 Ga ago. In our presentation (compare Veizer and Jansen, 1979, 1985), the cumulative data points are plotted at the end and not the mid point of each time interval. The actual break, therefore, may have been anywhere between 1.5 to 2.0 Ga but probably relates to the end of the Early Proterozoic at $\sim 1.8 \text{ Ga}$ ago (Hudsonian orogeny). In the subsequent discussion this break will be referred to as the *Proterozoic inversion*.

Concentrating first on the *post-inversion* section, the age distribution patterns of ores define an array of curves with progressively decreasing slopes from Al to Cr (fig. 4), consistent with the proposition that they reflect progressively diminishing rates of generation/destruction. Comparison with figure 2 establishes that all age curves conform to type I and type II preservational probabilities. Assuming steady-state, and disregarding the second order scatter, the rate of recycling for Al is

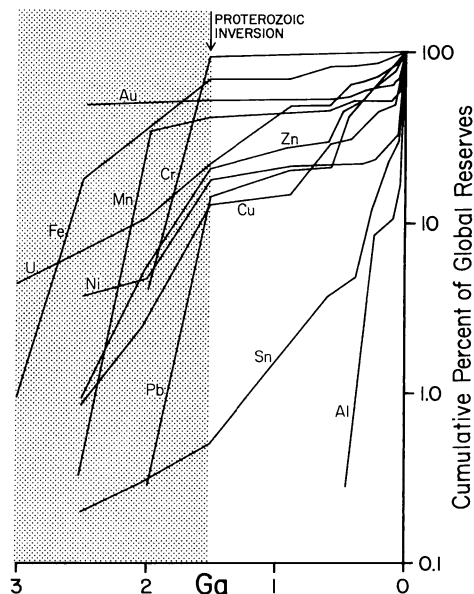


Fig. 4. Present-day distributions of global accumulations of metals. Reserves in this and subsequent figures denote the known economic accumulations and are based on inventories summarized in app. A.

very fast ($b^{10} = 150 \times 10^{-10} \text{ a}^{-1}$; $\tau_{50} \sim 40 \text{ Ma}$). This is to be expected, since generation/destruction of weathering crusts and soils, including lateritic and resedimented bauxites, is a rapid process on geological time scales. As a consequence, $\sim 45 \pm 5$ half-lives have elapsed since the time of the Proterozoic inversion, and the quantitative memory of the early bauxites deposits is lost from the geologic record. In contrast, the post-inversion rate of recycling for the deposits of Cr appears to have been essentially zero. As a result, the pre-inversion record is preserved almost intact. Almost the entire present-day global reserves of Cr are associated with the Late Archean-Early Proterozoic ultramafic layered complexes (app. A), which have been intruded into the stable cratonized shield areas (Windley, 1984). As will be discussed later, such shields have had slow rates of recycling. For other metals, the memory retention (hence reserves) diminishes as their rates of recycling increase, and these variable rates are a reflection of differences in geologic settings of the respective ore deposits. As will be demonstrated later, such geological complexities led also to the generation of type II global preservational probabilities (fig. 4).

The *pre-inversion* patterns of age distribution curves show large plunges in accumulated tonnages of most metallic commodities (fig. 4). As in the case of coal, such plunges in the tails of type I and II

populations may reflect an excessive growth of metal accumulations during the pre-inversion stage of terrestrial evolution or an increase in the rate of their destruction. In our view, the observed growth of metal tonnages reflects mostly, although not exclusively, the concomitant fast generation of the host environment, that is of the continental crust. The discussion of the rates of growth of continents through time is beyond the scope of this contribution. The topic has been reviewed recently, for example, in Taylor and McLennan (1985) and Veizer (1988a). These reviews, independent of mineral deposit criteria, suggest that the late Archean and early Proterozoic have been the most prolific times of generation (and cratonization) of continents, arriving at near present-day extent at about the time of the Proterozoic inversion. The age distribution pattern of mineral deposits is consistent with such interpretations.

GENETIC CATEGORIES OF METALLIC MINERAL DEPOSITS

In order to understand the details of the age distribution patterns of metallic mineral deposits (fig. 4) it is essential to consider their fate in conjunction with the history of the host geological settings. We attempted to subdivide metallic deposits into nine major genetic categories, with a realization that such classification is, to a large degree, arbitrary. Any classification of populations as diverse as ore deposits is bound to encounter problems due to transitional nature of many genetic types, multiphase origins, heredity, and particularly due to nonuniform conceptual approach of the international scientific community. Nevertheless, some discretionary assignment of complex deposits is essential for statistical purposes. A more complex classification, while not less subjective, would lead to a proliferation of overlapping genetic types, each representing too small a sample for statistical treatment. The underlying philosophy of the present classification is the desire to assign each category to a broad tectonic setting within the context of global plate tectonics (Miller, 1980; Mitchell and Garson, 1981; Garson and Mitchell, 1981; Guilbert and Park, 1986). This, in turn, helps to delineate their subsequent geologic history and thus the pathways of preservation. The metal tonnages for many ore deposits, as reported in literature, vary immensely, and some countries do not release any quantitative data at all. Such missing data had to be estimated in order to avoid regional bias. Although admittedly inaccurate, the built-in error for these estimates is certainly less than that caused by exclusion of such deposits. The details of methodology utilized for collation of the ore deposit inventory have been discussed in Laznicka (1985a, b). The genetic categories selected for this study are:

1. magmatogene deposits associated principally with mafic and ultramafic rocks (mafic to ultramafic layered complexes, alpine type ultramafics);
2. magmatogene deposits associated with acid differentiates (granitic pegmatites);

3. volcanic deposits (metalliferous ore lavas);
4. volcano-sedimentary and similar deposits (submarine-exhalative, volcano-diagenetic, volcano-epigenetic);
5. hydrothermal-epigenetic deposits of all types (veins, disseminations, replacements, skarns);
6. detrital-sedimentary deposits (placers, paleoplacers);
7. chemical-sedimentary deposits (including diagenetic and ground water epigenic concentrations);
8. weathering crusts (laterites, karst accumulations, calcrete); and
9. high-grade metamorphosed and metamorphogenic ores.

The genetic diversity of each category, documented by examples, and the estimated reserves are summarized in app. A. Somewhat modified classification is employed for uranium ores.

We are conscious that evolving technology, new discoveries, conceptual exploration advances, and demand all result in perpetually changing cut-off grades and thus reserve estimates. For all these reasons, our treatment of the subject cannot avoid some arbitrariness. Consequently, the concept itself and its implications may be improved and modified in the future, in accord with specific requirements of potential users. Nonetheless, we believe that the approach and the database are sufficiently refined to enable reconstruction of at least the first order picture.

AGE DISTRIBUTION PATTERN OF ZINC DEPOSITS

The bulk of the deposits of zinc can be assigned to four major genetic categories, with total tonnages decreasing from chemical-sedimentary → hydrothermal → metamorphic → volcano-sedimentary type (app. A). Their present-day age distribution pattern serves as an illustration for ores of other metals. Our statistical population includes 250 Zn deposits accounting for 450 million tons of Zn. This represents approx 80 percent of the world's past Zn production and the presently known reserves. The tonnage-age distributions for genetic categories are summarized in figure 5. All genetic categories mimic the sudden decline of reserves during the pre-inversion times (fig. 4). Note also that all these curves show more second order structure than the compound (global) curve. This is a consequence of (A) episodic nature of generation of such deposits, (B) limitations of the statistical databases because of the smaller sizes (hence less representative data) for the genetic subpopulations, and (C) lumping of somewhat diverse genetic deposits into a single category. In terms of global reserves, ~69 percent of accumulations are associated with the Phanerozoic, ~25 percent with the Proterozoic, and ~6 percent with the Archean crustal segments. Consideration of the post-inversion pattern shows that the global reserves in progressively older crustal segments are dominated, in succession, by hydrothermal, chemical-sedimentary, volcano-sedimentary, and finally metamorphic categories of ore deposits. We shall argue

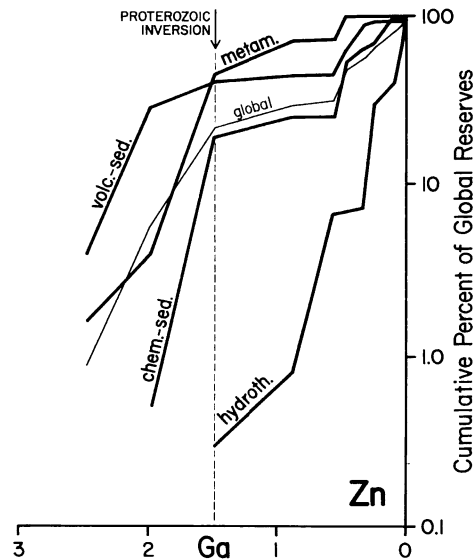


Fig. 5. Present-day age distribution of zinc ores. See app. A for the respective inventories.

later that this progression reflects the association of these genetic categories with progressively more stable tectonic environments, the diminishing recycling rates resulting in better preservation probabilities. At this stage, we only point out that any population composed of subsets with different rates of recycling (and half-lives) will yield an overall *global* age pattern of type II (figs. 2, 5). Space considerations preclude discussion of detailed age patterns for other metals (app. A), but they all have several features in common. Firstly, most display type II global post-inversion patterns (fig. 4). Secondly, apart from few exceptions to be detailed later, the sequence of post-inversion curves with progressively shallower age slopes is invariably in the following order:

weathering crusts $\geq$ detrital-sedimentary $\gg$ hydrothermal $\gg$
 chemical-sedimentary $\geq$ volcano-sedimentary $\gg$ magmatogene
 of (ultra)mafic affinities $\geq$ metamorphic genetic types.

This is not to say that within a single genetic category age curves for each metal are identical, but only that they vary within a specific range. The consistency of these patterns for a variety of metal commodities points to an underlying geological, likely tectonic, control of their generation/destruction probabilities. Further considerations must be therefore based on genetic categories rather than commodities, and we shall utilize this approach for subsequent discussion.

AGE DISTRIBUTION PATTERNS BY GENETIC CATEGORIES

Surficial deposits.—This group includes the “weathering crusts” and the “detrital-sedimentary” (placer) categories. The weathering crusts category is almost exclusively associated with the Quaternary and Tertiary terranes, with only few deposits persisting into older segments of the Phanerozoic Era (app. A). This is the case for Al, Sn, Zr, Cr, Ni, Fe, Mn, some Au, as well as for the subordinate base metal accumulations. The calculated recycling constants $\underline{b}^{10}$ for most weathering crusts are $\sim 900 \times 10^{-10} \text{ a}^{-1}$, except for Al, Fe, and Mn, where the rates are $200 \begin{smallmatrix} +110 \\ -50 \end{smallmatrix} \times 10^{-10} \text{ a}^{-1}$. The respective half-lives are therefore $\sim 3 \pm 2$ and 31 ± 12 Ma. The “detrital-sedimentary” ores of Al and Fe have a considerably slower $\underline{b}^{10}$ of $\sim 94 \begin{smallmatrix} +108 \\ -68 \end{smallmatrix} \times 10^{-10} \text{ a}^{-1}$, which results in a half-life of $\sim 50 \pm 20$ Ma. All the above are geologically very fast recycling rates, but they are hardly suprising, and common sense dictates their acceptance. The only major anomaly are the Witwatersrand-Elliot Lake type paleoplacers (Pretorius, 1981), which are ~ 1.9 to 3.1 Ga old, yet they account for the bulk of the present-day reserves of detrital gold and uranium (app. A). This paleoplacer type is dominated almost entirely by a few giant deposits and represents therefore a geological and statistical anomaly.

Hydrothermal ores.—The present-day age distribution of cumulative tonnages of hydrothermal ores is summarized in figure 6. Except for gold, uranium, and nickel, they all cluster around a relatively well defined type II age trend. At steady-state, the steeper portion of this pattern is consistent with recycling at $\underline{b}^{10} \sim 70 \begin{smallmatrix} +50 \\ -20 \end{smallmatrix} \times 10^{-10} \text{ a}^{-1}$ ($\tau_{50} \sim 95 \pm 41$ Ma) and the shallower one at $\sim \underline{b}^{10} \sim 14.2 \begin{smallmatrix} +2.2 \\ -0.8 \end{smallmatrix} \times 10^{-10} \text{ a}^{-1}$ ($\tau_{50} \sim 483 \pm 58$ Ma).

The hydrothermal deposits of gold, uranium, and nickel have clear bimodal secular distributions (app. A), with negligible net generation rates during the 1.5 to 0.6 Ga interval (fig. 6). If only the Phanerozoic deposits are considered, they all conform with the general type II age trend (see Au* in fig. 6). The Precambrian and Phanerozoic hydrothermal deposits of Au, U, and Ni are indeed not close genetic analogues. For gold, the Precambrian deposits consist mostly of gold-bearing quartz veins in the Archean greenstones (Boyle, 1976, 1979), representing metamorphic and thermal remobilizations and concentrations of this precious metal. In contrast, the Phanerozoic deposits encompass hydrothermal veins in the aureoles of ascending orogenic plutons. For uranium, the Proterozoic deposits are mostly localized in the sediments blanketing the cratons (Beaverlodge) and the basement roots of the former orogenic belts. These deposits share many common features with the unconformity genetic type (Marmont, 1988), and our assignment of uranium deposits to either hydrothermal or unconformity

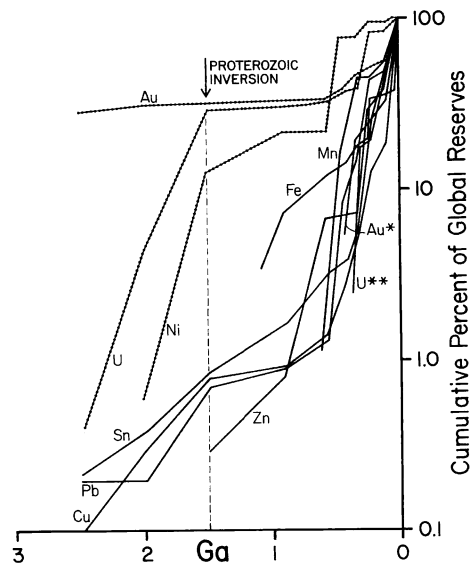


Fig. 6. Age distribution of presently available accumulations of hydrothermal ores. The accumulations of uranium in "infiltration in sandstones" category (app. A) are marked as U**. Au* represents the "Phanerozoic" populations for this metal. Because of optical considerations Ni* and U* are not plotted in the figure, although they would be similar to that of Au*.

category is undoubtedly somewhat arbitrary. The Proterozoic setting contrasts with the Phanerozoic one, where the deposits are mostly veins associated with orogenic zones (Jáchymov). A similar tectonic bimodality emerges also for the economically subordinate hydrothermal nickel deposits. The Proterozoic ores represent only local hydrothermal remobilization within the hosting mafic-ultramafic layered complexes (Falconbridge), while the Phanerozoic ones are again associated with orogens (Schneeberg).

Included in this category also are the "infiltrations in sandstones," or Colorado Plateau (western United States) type, uranium deposits. Such deposits are frequently located within the limits of the extant orogenic belts (Rackley, 1976), and the controlling step of their generation/destruction probability could have been the rate of generation/destruction of the hosting fluviatile sandstones.

Chemical-sedimentary ores.—The present-day age distribution patterns of chemical-sedimentary ores are summarized in figure 7. Most of these deposits (app. A) are related to intracratonic and stable shelf tectonic settings (Mississippi Valley type; Mt. Isa; Zambian copper belt; Superior, Minette and Clinton types of iron ores; South Ukrainian Mn basins).

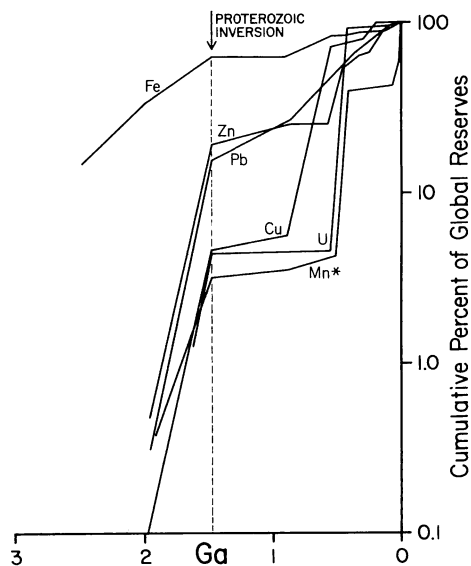


Fig. 7. Age distributions of presently available economic accumulations for chemical-sedimentary ores (compare app. A). Mn* represents the distribution of Mn ores without the Early Proterozoic Kalahari Basin and the Tertiary South Ukrainian tonnages. These two supergiants account for ~80 percent of the global reserves and thus represent geological and statistical anomalies.

The age distribution pattern of these deposits shows a considerable second order scatter. Nevertheless, the first order features (fig 7) show that, as for global patterns (fig. 4), the tonnages decline rapidly during the pre-inversion times. Iron, although following this decline, has a somewhat modified secular trend. The post-inversion limits on $\underline{b}^{10}$ are $\sim 16.6 \pm 14.4 \times 10^{-10} \text{ a}^{-1}$, with the respective half-lives of $414 \pm 194 \text{ Ma}$.

For iron, the post-inversion $\underline{b}^{10}$ is very slow ($\sim 3.7 \times 10^{-10} \text{ a}^{-1}$; $\tau_{50} \sim 1870 \text{ Ma}$). In this case, the “indigested” memory of the huge pre 1.8 Ga Superior type reserves (United Nations, 1970; James and Sims, 1973; James and Trendall, 1982; Melnik, 1982; Gross, 1983; and Trendall and Morris, 1983) still dominates the present-day age pattern.

Volcano-sedimentary ores.—This category of ores encompasses deposits generated in the oceanic (or transitional) tectonic domain subsequently incorporated into the continental tectonic domain. Examples are the massive Fe–Cu–Zn–Pb sulfide deposits (Kuroko type and deposits in ancient greenstones) for base metals, Algoma type iron ores, Cyprus-type Fe–Cu ores, and ophiolite-hosted Mn deposits (app. A). In contrast to the chemical-sedimentary category (fig. 7), the observed age distribution curves for the volcano-sedimentary ores (fig. 8) show that the phase of rapid generation has been mostly the Late Archean and not

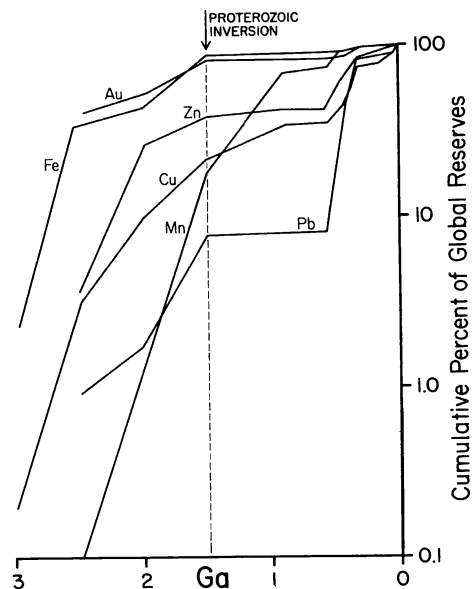


Fig. 8. Age distributions of presently available accumulations for volcano-sedimentary ores (app. A).

the Early Proterozoic. In addition, the post-inversion record is consistent with a somewhat slower recycling rates, with a $\underline{b}^{10}$ of $\sim 8.6 \pm 12.4 - 7.4 \times 10^{-10} \text{ a}^{-1}$. This yields a range of τ_{50} from $\sim 330 \text{ Ma}$ to values in excess of the terrestrial life span. However, the mean τ_{50} appears to be $\sim 800 \text{ Ma}$.

Deposits associated with mafic-ultramafic complexes.—The temporal distribution of global metal accumulations in deposits genetically related to mafic-ultramafic complexes is summarized in figure 9. This presentation illustrates that generation of almost the entire present-day tonnage was related to the 2.7 to 1.7 Ga interval (Bushveld, Sudbury, Great Dyke). Economic metals in this category are found almost exclusively in few supergiant deposits, and they cannot be treated therefore as a statistical continuum. Even disregarding this qualification, the calculated post-inversion recycling rates are minimal ($\underline{b}^{10} \leq 4 \times 10^{-10} \text{ a}^{-1}$) ($\tau_{50} \geq 1700 \text{ Ma}$). The Late Archean-Early Proterozoic incidence of mafic-ultramafic complexes (and ores) is well documented (Windley, 1984, chap. 4; Naldrett, 1981), and any correction for destroyed (recycled) old deposits would only magnify this anomaly.

Ore deposits in highly metamorphosed terranes.—This category encompasses deposits of variable origins, which in some cases are difficult to decipher through the metamorphic veil (Both and Rutland,

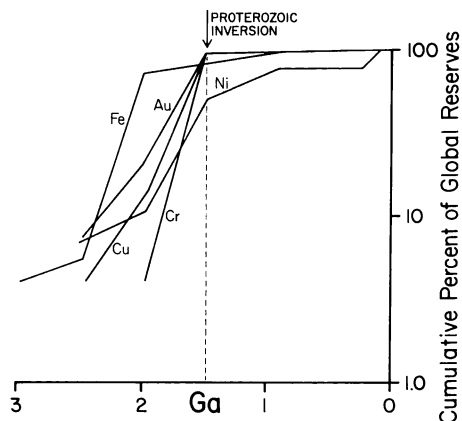


Fig. 9. Age distribution of presently available accumulations for ores associated with mafic-ultramafic complexes (app. A).

1976). As was the case for the mafic-ultramafic hosted ores, the metal tonnages are usually dominated by a few giant accumulations (Broken Hill, New South Wales; Rössing), and the statistical treatment of recycling would not be appropriate. With the exception of uranium, the bulk of the present-day tonnage is of the Late Archean-Early Proterozoic ages, with metamorphic iron ores prevalent mostly in the Archean (≥ 3 Ga) terranes (fig 10). Again, in analogy to the previous category, the indicated post-inversion recycling rates (U excepted) are negligible, with $b^{10} \leq 5 \times 10^{-10} \text{ a}^{-1}$ ($\tau_{50} \geq 1350 \text{ Ma}$).

Special types of mineral deposits.—Several types of mineral deposits listed in app. A, such as the pegmatite, carbonatite, or alkaline intrusions related deposits are too infrequent for statistical treatment and will not be considered further. The statistics for the uranium unconformity deposits is more complicated. Depending on the genesis and the reserves of the Olympic Dam deposit, the category may be dominated by a single supergiant. In this case, however, the plethora of deposits of all sizes and of comparable age brackets (Marmont, 1988) suggests that giant deposits are an integral feature of the mineralization process, and their inclusion will only magnify but not alter the shapes of secular distribution patterns.

Synopsis.—A summary of the present-day age distribution patterns for the discussed genetic categories of ore deposits is given in figure 11. As a first order observation, the weathering crusts, detrital-sedimentary and hydrothermal categories have type I to type II age distribution patterns. Their age slopes for the young age segments are very steep, and they have a subdued (narrow band) second order structure. In contrast, the chemical-sedimentary to metamorphic categories have type III age distributions, having steep slopes in the old segments. They

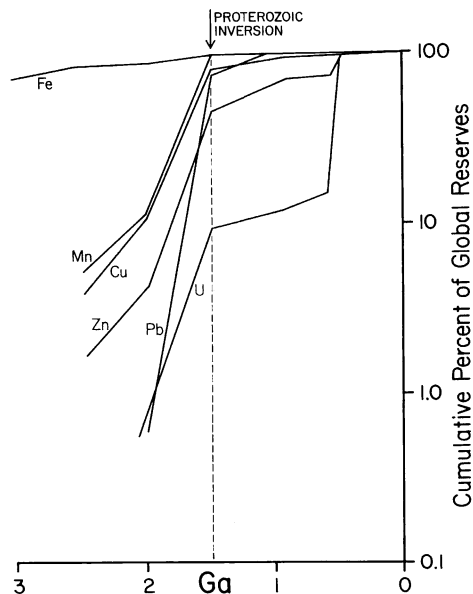


Fig. 10. Age distributions of presently available accumulations for metamorphic ores (app. A)

also have a pronounced second order structure. All these features are, in our view, a consequence of recycling. We accept (Taylor and McLennan, 1985; Veizer, 1988a) that, following a stage of an enhanced growth during the late Archean and early Proterozoic, the continental crust attained its near present-day steady-state size at about the time of the Proterozoic inversion ($\sim 1.75 \pm 0.25$ Ga ago). The emergence of the host tectonic settings resulted in concomitant generation of the associated mineral deposits as reflected in the steep slopes of type III distributions. Subsequently, each genetic type has been generated/dispersed differentially, with rates increasing from the metamorphic ores to the weathering crust category. The higher the rate of recycling the steeper the age slope, the more advanced the obliteration of the initial growth stage memory, the more attenuated the second order structure, and the more complete the transformation of type III—in reality immature type I with “indigested” growth memories—into the mature type I and II patterns. The critical b^{10} essential for the latter transformation is that between the calculated rates for the hydrothermal and the chemical-sedimentary ores ($70 \pm_{22}^{50} \times 10^{-10} \text{ a}^{-1} \geq \times \geq 16.6 \pm_{5.3}^{14.4} \times 10^{-10} \text{ a}^{-1}$). A b^{10} value of $\sim 40 \times 10^{-10} \text{ a}^{-1}$ ($\tau_{50} \sim 225$ Ma) has been proposed by Veizer and Jansen (1985) as a boundary limit between the fast cycling oceanic tectonic domain (ocean basins $\rightarrow$ imma-

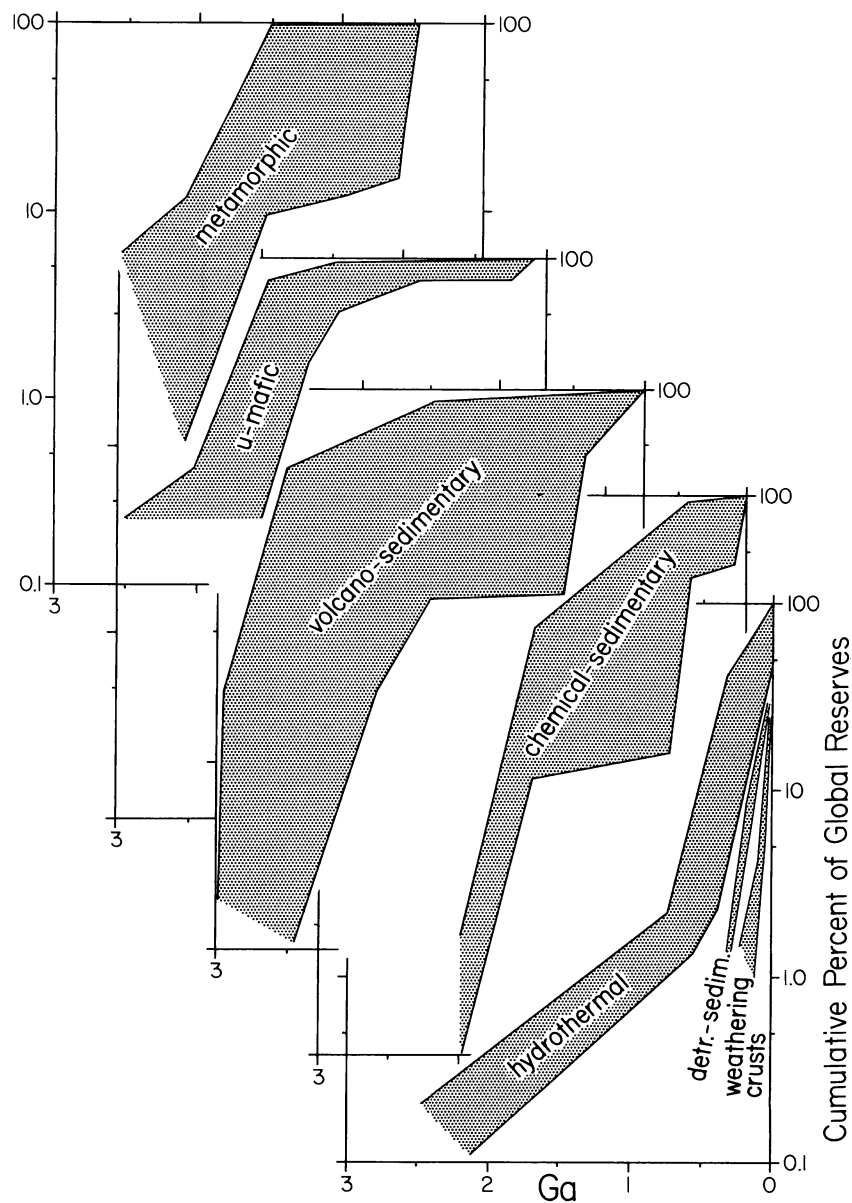


Fig. 11. Generalized present-day age distribution patterns for the discussed genetic categories of ores (see figs. 6-10). Excluded from consideration are the Precambrian populations of hydrothermal U, Ni, and Au, chemical-sedimentary (Superior type) ores of Fe and their metamorphosed equivalents, and detrital-sedimentary (Witwatersrand type) ores of Au and U.

ture orogens) and the slow cycling continental domain (orogenic roots → platforms and shields) (see also fig. 12). With the exception of the ephemeral surficial deposits, these are indeed the envisaged geological settings for the discussed genetic categories of ores. Consequently, the generation/destruction of the host tectonic realm is likely the rate controlling step of the generation/dispersal of its constituent rocks and of the entombed mineral deposits. In the subsequent section, we shall attempt to substantiate this proposition from theoretical considerations.

DISPERSAL OF TECTONIC REALMS

An essential corollary of the concept of recycling is that different tectonic realms have variable, but *statistically* predictable, rates of generation/dispersal and thus survival probabilities (Veizer and Jansen, 1985). With the passage of time, their record is lost at a pace inversely proportional to the recycling rates, and the respective half-lives are summarized in figure 12. For example, the 95 percent probability (oblivion age τ_{MAX}) that a mountain range (I.O.B.) will be reduced to its root is ~300 Ma. This can come about either through dispersal by geologic processes (erosion) or through incorporation of remnants into a successor tectonic realm, in this case the mature orogenic belt. The latter represents the isostatically equilibrated root of the former mountains. The root, in turn, should eventually disperse as well, or its remnant may be incorporated into the next tectonic successor, that is the metamorphic basement. At each transition, the rate of recycling controlling further dispersal will be that of the successor realm. Since these realms are progressively more stable, the b will diminish, and the resulting concave upward trend of preservation will start to resemble

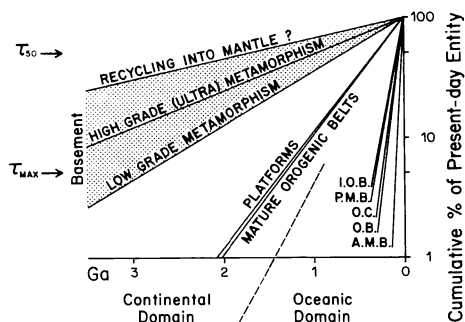


Fig. 12. Preservation probability for major global tectonic realms, with half-lives in parentheses. Explanations: AMB-active margin basins (27 Ma), OIB-oceanic intraplate basins (51 Ma), OC-oceanic crust (59 Ma), PMB-passive margin basins (75 Ma), IOB-immature orogenic belts (78 Ma), mature orogenic belts (roots) (355 Ma), platform (361 Ma), basement (673, 987, and 1728 Ma, respectively). Reproduced from Veizer (1988 b) by permission of Pergamon Journals Inc.

the type II age distribution pattern (fig. 13). The probability of transition from one tectonic realm into another is not known, but for theoretical consideration we assume that it is coincident with τ_{MAX} . If a specific genetic type of mineral deposits, such as the hydrothermal aureoles around ascending plutons in young mountain ranges, were generated within this tectonic realm and subsequently dispersed with its host tectonic environment, the age distribution pattern of these deposits should follow the “*orogenic*” pathway (OP) in figure 13. A similar argument could be advanced for deposits formed initially in the sedimentary cover of platforms and/or mature orogenic belts (for example, the Mississippi Valley type deposits), which may have been subsequently incorporated into metamorphic basement. This will be designated as a “*platform*” pathway (PP) in the subsequent text. Finally, mineral deposits formed within the continental crust itself (for example, layered mafic-ultramafic complexes) should follow the “*basement*” (BP) preservational pathway (fig. 13). In real geological situations it is sometimes difficult to discern the nature and history of the precursor deposits in high-grade metamorphic terranes. For this reason, such deposits have been assigned into a separate category. As a consequence, the high-grade metamorphic stages in the OP and PP pathways are forbidden by definition. Only the deposits not subjected to high-grade metamorphism retain their genetic identity. The dispersals of such deposits should therefore follow the modified pathways, designated here as OP* and PP* (fig. 13).

The predicted and the observed *post-inversion* patterns for secular distribution of ores show a fair degree of agreement (table 2, fig. 11, 13).

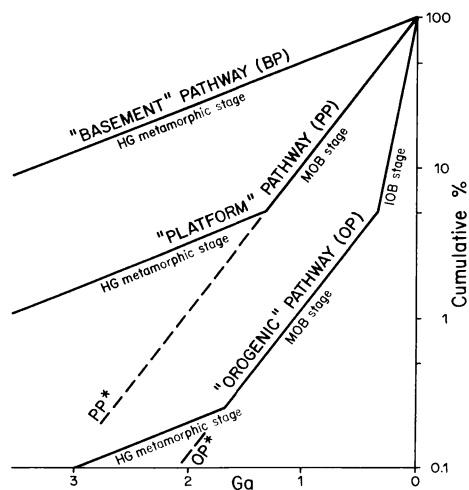


Fig. 13. Theoretical patterns of preservation of composite tectonic realms. See the text for discussion of the respective pathways.

TABLE 2

Synopsis of the observed and theoretical recycling rates for deposits of metallic ores

Observed dispersion pathways for genetic categories of mineral deposits			Theoretical dispersion pathways based on recycling of tectonic realms		
category	$\bar{b}^{10}$ in 10^{-10}a^{-1}	τ_{50} in Ma	pathway	$\bar{b}^{10}$ in 10^{-10}a^{-1}	τ_{50} in Ma
Surficial deposits					
weathering crusts					
most metals	900	3 ± 2	ephemeral, not directly related to tectonic settings		
Al, Fe, Mn	$200 \pm \frac{110}{50}$	31 ± 12			
detrital-sedimentary (placers)	$94 \pm \frac{169}{88}$	50 ± 20			
Hydrothermal			Modified orogenic pathway (OP*)		
IOB stage	$70 \pm \frac{50}{20}$	95 ± 41	IOB stage	85 ± 35	78
MOB stage	$14.2 \pm \frac{2.2}{0.8}$	483 ± 58	MOB stage	19.3	355
Chemical-sedimentary	$16.6 \pm \frac{14.3}{5.5}$	414 ± 194	Modified platform pathway (PP*)	19.0	361
Volcano-sedimentary	$\sim 8.6 \pm \frac{12.4}{7.4}$	$\sim 800 \pm \frac{2700}{300}$	Basement pathway (BP)		
Mafic to ultramafic associations	≤ 4	≥ 1700		$7 \pm \frac{3.2}{3.0}$	$987 \pm \frac{241}{350}$
Highly metamorphosed associations	≤ 5	≥ 1350			

In addition, the theory predicts that the recycling rates encountered within the continental domain ($\bar{b}^{10} \leq 40 \times 10^{-10} \text{a}^{-1}$) are too sluggish for development of either clear type II distribution patterns or for the "digestion" of the stock of the initial old (pre-inversion) deposits. Faster $\bar{b}$'s, or duration of recycling longer than the time elapsed since the attainment of the post-inversion steady-state ($1.75 \pm 0.25 \text{ Ga}$), would be required for such a task (fig. 13). As a result, the chemical-sedimentary, volcano-sedimentary, "(ultra)mafic" and "metamorphic" categories (fig. 11) still retain a considerable memory of their growth stages in the respective age distribution patterns.

The patterns in figure 13 do not consider the fate of mineral resources in the present-day oceans. Marine mineral resources, such as manganese nodules, are only ephemeral transient phenomena prone to destruction rather than to transfer into continental tectonic milieu. Only an incorporation of these deposits into the respective successor tectonic environment (immature orogenic belt, mature orogenic belt, basement and its cover) enables their inclusion into the geologic record on land. It is only from this moment that such deposits become accountable, and their theoretical preservational pathways should again conform to those outlined in figure 13.

MINERALIZATION THROUGH THE TIME

Accepting that the first order features (slopes) of the present-day age distribution patterns for mineral commodities are a reflection of recycling, correction for this recycling is an essential precondition for any discussion of secular evolution. The age distribution of hydrocarbons again provides an initiation into the concept.

Phanerozoic evolution of hydrocarbons.—The straight line age distribution of present-day petroleum reserves (fig. 3) is consistent with a proposition that an "invariant" long-term recycling rate has been almost the sole control of the age slope. Deconvolution of this first order recycling (app. B) to a Phanerozoic steady-state yields some superim-

posed temporal oscillations in the *net* generation/destruction rates (fig. 14), these oscillations reflecting the subdued second order scatter around the “straight line” in figure 3. We are not yet in a position to advocate specific geological causes for the first order recycling ($b^{10} \sim 78 \times 10^{-10} \text{ a}^{-1}$), and, considering the ease of petroleum migration and dissipation, they likely are complex and multiple. It is of interest, however, that the second order structure suggests that the Devonian and the Cretaceous times were the prime intervals of petroleum accumulation, whereas the Late Paleozoic and Cenozoic periods were deficient in this commodity. From correlation with “sea-level” curves it also appears that high petroleum yields have been related in some way to high “sea-level” stands (fig. 14). An appealing proposition is the model that invokes large epicontinental seas with high organic productivity and burial during high “sea level” stands (Tappan, 1968; Scholle and Arthur, 1980; Arthur, 1982; Woodruff and Savin, 1985; Berger and Vincent, 1986). Globally, high rates of burial of organic matter depleted in ^{13}C should shift the residual dissolved carbon in the ocean toward heavier $\delta^{13}\text{C}$. The $\delta^{13}\text{C}$ secular curve for Phanerozoic oceans (Veizer,

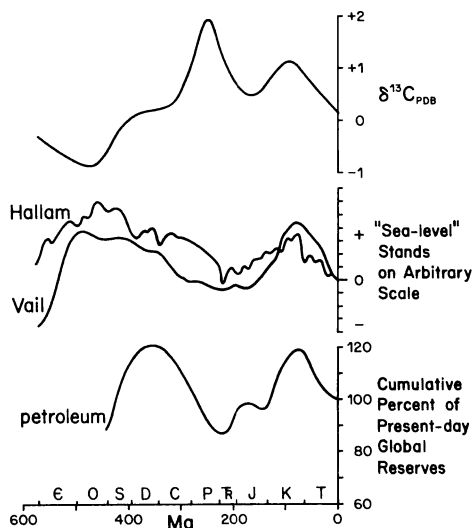


Fig. 14. Deconvoluted Phanerozoic distribution of petroleum, first order “sea-level” stands (Vail, Mitchum, and Thompson, 1977; Hallam, 1984), and variations in $\delta^{13}\text{C}$ of marine bicarbonate (Veizer, Holser, and Wilgus, 1980). The deconvolution for petroleum is at an invariant, $b = 78 \times 10^{-10} \text{ a}^{-1}$. Note that the deconvoluted reserves in figures 14 and 15 relate to all existing accumulations (cumulative percentages) present at a given time. Thus the total reserves in Devonian times may have been ~ 1.2 times of those today, but they comprised not only petroleum generated from, and retained in, Devonian rocks, but also all petroleum still surviving in older rocks. Similarly, today’s reserves represent a cumulative total surviving today in host rocks of all ages. The *net* rate of generation/destruction for a given interval of time ($d(\%)/dt$) is a tangent to the slope of deconvoluted reserves, with a positive slope denoting net generation and a negative one net destruction of reserves.

Holser, and Wilgus, 1980; Lindh, ms) lends some support to this interpretation for the Cretaceous but is entirely at odds with the Paleozoic record (fig. 14) (compare also, Berner, 1987). Consequently, the coincidence of high petroleum reserves with high "sea-level" stands may be more a consequence of the ubiquity of reservoirs and traps on the extensive shelves (the plethora of frequently dolomitized reefs and evaporites) than of the plentitude of source rocks. The causal relationships are therefore far from simple, and the propagation of the Cretaceous-like models as a Phanerozoic norm is not warranted; a cautioning note voiced already on the basis of Sr isotope data (Veizer, 1985).

A similar deconvolution of the second order structure for coal (at invariant b^{10} of $26 \times 10^{-10} \text{ a}^{-1}$) shows that the Late Paleozoic, and to a lesser extent the Jurassic, have been the intervals of massive coal formation whereas the Triassic represents the times of net dispersal (fig. 15). In our interpretation, colonization of land by vascular plants resulted in the attainment of a "modern" steady-state not only for coal but also for natural gas reserves (fig. 15). If so, the coincidence of its second order Devonian with Cretaceous peaks with the petroleum rich intervals and of the Permian peak with the coal interval hints that these "excess" reserves may have been sourced by marine and terrestrial organic matter, respectively.

This paper has been designed to advance the concept. Further geological inferences must therefore await accumulation of the appro-

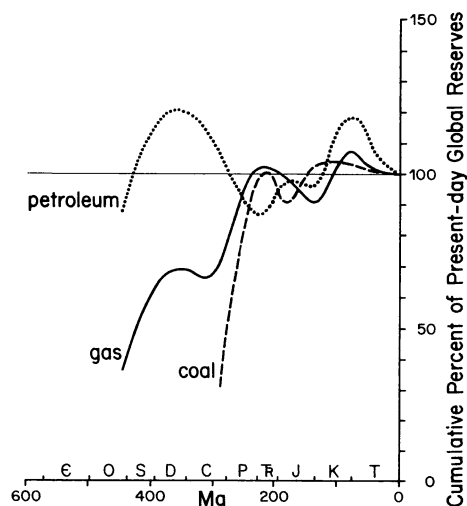


Fig. 15. Deconvoluted patterns for global reserves of petroleum, natural gas, and coal throughout the Phanerozoic. The deconvolution for coal is at invariant $b^{10} = 26 \times 10^{-10} \text{ a}^{-1}$. For gas, the deconvolution follows invariant $b^{10} = 56 \times 10^{-10} \text{ a}^{-1}$ for the 225 Ma time interval, $78 \times 10^{-10} \text{ a}^{-1}$ for the ≥ 310 Ma segment, and the 225-310 Ma tangent is interpolated. See the text and figure 14 for further details.

appropriate databases. At this stage, we only point out that the invoked quantitative scenario (fig. 15) is consistent with the general geological experience, thus buttressing the overall feasibility of our theoretical approach.

Evolution of ore deposits.—In contrast to the easily recyclable liquid and gaseous hydrocarbons, the age distribution patterns of metallic mineral deposits show more variability in both the first order slopes and the second order scatter, particularly for the slowly cycling genetic categories (fig. 11). In the preceding text we argued that the first order slopes for the genetic categories have likely been controlled by the rates of generation/dispersal of the host tectonic realms (table 2). Exceptions are the very fast cycling surficial deposits (placers and weathering crusts), which—irrespective of their tectonic setting—are only a transient phenomenon of the geologically ephemeral hydrologic cycle. For the purpose of simulation, we, therefore, “unrecycled” the theoretical preservational probabilities of the OP*, PP*, and BP pathways (fig. 13) to a steady-state, that is to a horizontal line at 100 cumulative percent (see app. B for details). Each genetic category of ores is assumed to have been controlled by one of these pathways (table 2). Any observed deviations and scatter are treated as superimposed geological anomalies. While admittedly an oversimplification, the approach provides a self-consistent and geologically reasonable model for “unrecycling” the present-day age patterns of the ore deposits.

The first order scenario emerging from these simulations is collated in figure 16. If considered in the context of continental tectonic evolution—as sketched, for example, in Windley (1984, chap. 19) and Radhakrishna (1984)—the overall mineralization history and tectonic development can be grouped into five principal stages:

1. The greenstone belt tectonic style dominant in the Archean and waning in the Early Proterozoic. Its typical mineral deposits have been the hydrothermal gold as well as the volcano-sedimentary Algoma type iron and massive sulfide ores (Zn, Cu).

2. The cratonization stage, coexisting with, and eventually superseding the greenstones, with chemical-sedimentary iron (Superior type) and manganese (Kalahari, gondites) and with the detrital-sedimentary gold and uranium (Witwatersrand type), paleoplacers. Generation and cratonization of continental crust has been at its maximum at $\sim 2.5 \pm 0.5$ Ga ago and attained its near present-day steady-state $\sim 1.75 \pm 0.25$ Ga ago.

3. The rifting stage, affecting the previously stabilized continental crust at $\sim 1.8 \pm 0.3$ Ga ago, with ubiquitous mafic-ultramafic volcanism and plutonism. The typical mineralization involves base metals (Pb, Zn > Cu) of the chemical-sedimentary and hydrothermal types (Mt. Isa), ore deposits associated with mafic-ultramafic complexes (Sudbury), volcano-sedimentary Mn (Birimian of western Africa), and hydrothermal (Beaverlodge) and unconformity (Lake Athabasca) ores of U in

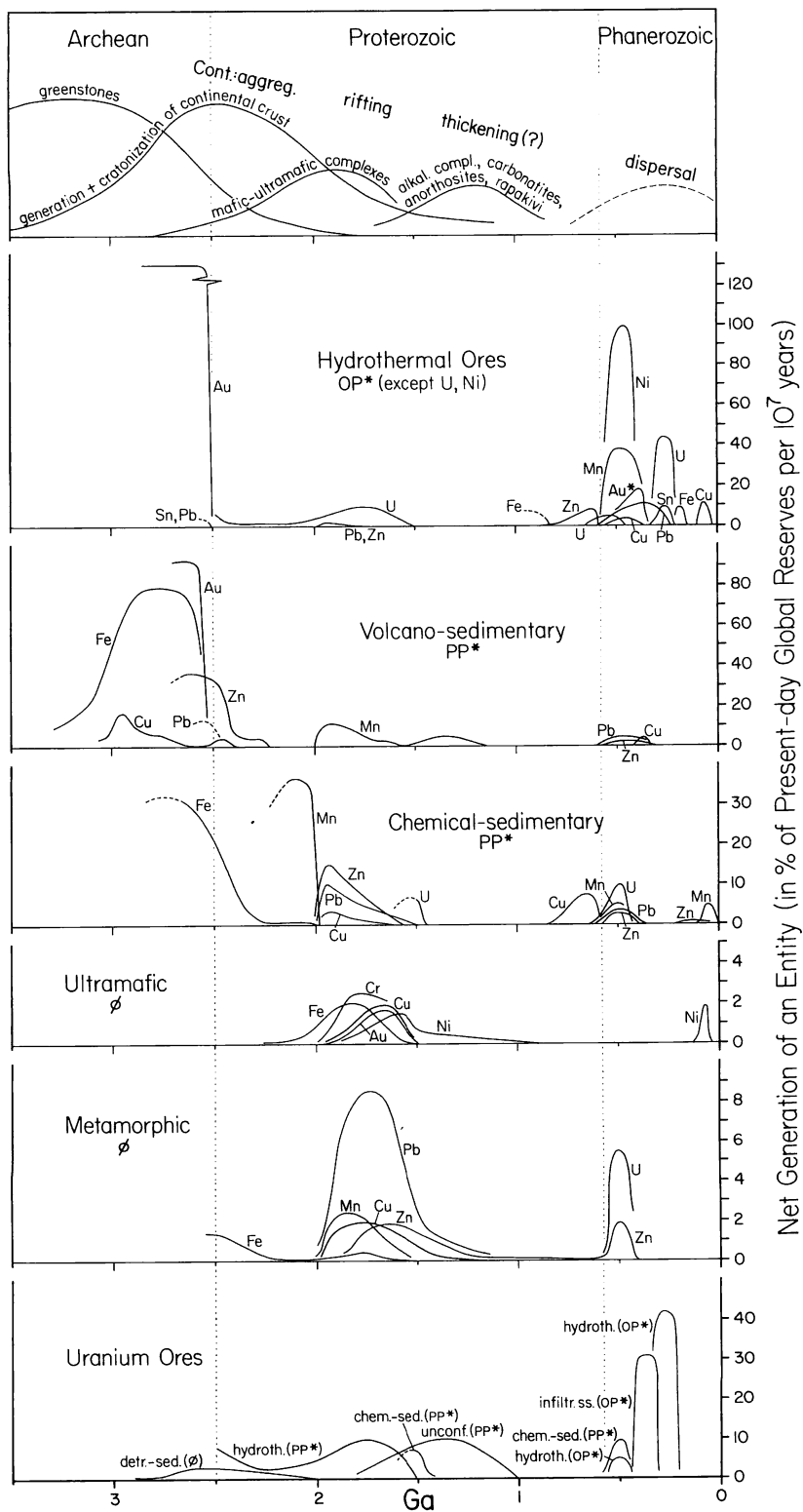
sediments overlying the reactivated basement. In addition, metamorphic equivalents of the above types are ubiquitous.

4. The mid- to late-Proterozoic phase of stable cratons, covering the $\sim 1.7 \pm 0.1$ to ~ 0.9 (or possibly 0.6) Ga time span, with common alkalic volcanism and plutonism but with a dearth of mafic to intermediate volcano-plutonic manifestations as well as of metallic ores. We again emphasize that this refers only to the net generation and does not preclude the existence of concomitant mineral deposits (Sullivan). Nevertheless, the reality of this gap has been repeatedly emphasized in studies of global metallogeny (Hutchinson, 1980; Meyer, 1981, 1985; Rundqvist, 1984a), and in Canada the time interval has been referred to as the Helikian volcanogenic gap (Hutchinson, 1980). Significant ore deposits in this phase have been mostly of exogenic type, and they have been confined to the cratonic sedimentary cover. Examples are the unconformity uranium, manganese (Moanda), and copper (Damara-Katanga of southern Africa).

5. The Phanerozoic stage, characterized by abundant and varied mineralization, particularly of hydrothermal type, the latter frequently a reflection of granitoid plutonism in Paleozoic orogenic belts. This ubiquitous mineralization may reflect an intensification of tectonism, orogeny, and ore generation after the dormant stages of the mid- to late-Proterozoic times, attest to the operation of plate tectonics in its present-day diversity and mode, and be a consequence of the dispersal of the pre-existing Proterozoic supercontinent(s).

The above secular evolution resembles a pattern of self-organization in living and technological systems (Odum, 1983). In these instances, the initial small intensively competing structures (pioneer or opportunist stage) are superseded by development of large dominant arrangements (K or steady-state strategists), their dislocation and ossification, and finally dispersal. Whether the progression from greenstone (1) $\rightarrow$ cratons (2) $\rightarrow$ their fracturing (3) and inertia (4) $\rightarrow$ and eventual dispersal (5) reflects a similar pattern of self-organization for the mantle-crust system is conditional upon the universality of the general systems theory.

While the evolution of endogenic ore deposits reflects principally the tectonic factor, sedimentary deposits may have been influenced also by the evolving exogenic system. To a degree, this may have been the case for the *exogenic* deposits of uranium, iron, manganese, and perhaps copper. For uranium, our modelling (fig. 16) confirms the frequently cited associations of the detrital-sedimentary ores with the Late Archean-Early Proterozoic terranes, the unconformity ores with the Middle-Late Proterozoic, the chemical-sedimentary ores (Kolm shales) with the Early Paleozoic, and the sandstone type ores with the second half of the Phanerozoic time intervals (Robertson, Tilsley, and Hogg, 1978; Dahlkamp, 1980; Nash, Granger, and Adams, 1981; Toens, 1981; Hutchinson and Blackwell, 1984). This progression, the Proterozoic



petering out of iron ores, the appearance of manganese deposits (differentiated from iron ores) and of red-bed copper ores are all believed to have been related to life, its diversification into new niches, and particularly to its role as a source of oxygen for the coeval atmosphere-hydrosphere system (Stanton, 1972; Veizer, 1976; Derry, 1980; Tilsey, 1980, 1981; Nash, Granger, and Adams, 1981). We do subscribe to this general scenario, and no amplification is intended in this paper. We wish to point out, however, that the quantification of the actual atmospheric P_{O_2} levels is still model dependent, and the proposed uncertainties are of several orders of magnitude (Holland, 1984; Grandstaff and others, 1986). Furthermore, contrary to the general consensus, the geologic history of this P_{O_2} could have been controlled as much by the varying rates of seawater cycling through the oceanic crust as by the advances in biological innovations (Veizer 1983, 1988a,c).

CONCLUDING REMARKS

The propagation of natural systems through time is accomplished via perpetual generation/destruction (recycling) of units in their constituent populations. In this paper, we strived to demonstrate that the present-day secular distribution patterns for mineral deposits (hydrocarbons and metals) are consistent with age structures generated by such recycling systems. In order to advance this point, non-steady-state aspects of continental evolution have not been given the desired consideration. We are keenly aware that evolution and recycling are not competing, but complementary concepts (Veizer, 1988a). The next step in the development of a comprehensive quantitative model should therefore concentrate not only on the refinement of the recycling aspects but also on the theory of the superimposed long-term evolution. We made only a tentative step in this direction. Nevertheless, the modelling yielded a quantitative scenario compatible with the general geological experience and with the patterns of metallogenic evolution espoused by the previous authors (Meyer, 1981, 1985, 1988). This leads us to believe that our methodology merits further consideration, refinement, and accumulation of advanced databases as a prelude to a more sophisticated treatment of the subject.

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Fig. 16. Summary of deconvoluted patterns of mineralization during geologic history. See app. B for mathematical background and qualifying statements. Note that this presentation gives the *net rates of generation* (positive derivatives of $d(\%)/dt$) of a commodity for a given time interval and not, as in the preceding figures, the total quantities of economically accumulated metals in rocks of all ages existing at any given time.

APPENDIX A

Inventory of present-day age distribution of metallic ores

The utilized database, which includes the already extracted as well as the remaining quantities of ores, is from the updated and expanded version of MANIFILE (Laznicka, ms and 1973, 1975, 1981b, 1985b). The estimates approximate the situation up to about 1981. The only exceptions are the estimates for uranium, where recent major discoveries (Olympic Dam, South Australia) completely revamped the existing inventories. Consequently, the uranium inventory represents the 1985 stand. The cut-off grades and methodology of statistical compilation are listed in Laznicka (1973), except for iron. The cut-off for the latter was at ~27 percent.

The age distribution patterns of mineral commodities are strongly influenced by the existence of giant deposits, which frequently dominate the total reserves (Halbouty and others, 1970; Hobson and Tiratsoo, 1981; Laznicka, 1983). No magic approach eliminates this complication. Frequently, geologic time intervals or geographic regions containing such giant deposits are also characterized by a plethora of deposits of all subordinate size categories (Laznicka, 1973). This is the situation for hydrocarbons, base metals, iron, non-detrital gold, alumina, and some uranium deposits (Laznicka, 1983). The observed anomalies are therefore real, regardless of whether or not the giant deposits are included in the statistics. Their exclusion would diminish the magnitude of the anomalies but would not eliminate them. In this case, because of the gradational continuity from giant to lesser deposits, we believe that generation/destruction of gigantic accumulations is an integral part of mineral deposit evolution. Consequently, there is no attempt to exclude deposits larger than some arbitrary size from the overall statistics. In other instances, the size distribution of deposits is polymodal, with no continuum between the giant and the smaller deposits, even taking into account that the statistical distribution of mineral deposits may

TABLE A-1

*Present-day age distribution of zinc ores
based on 250 deposits accounting for ~80
percent of the world's past Zn production
and presently known reserves. In subsequent
tables this will be abbreviated
to (N = 250, ~80 percent)*

Age in 10 ⁶ yrs	Deposit Category					Global Cumulative %
	Volcano- sedimentary	Hydrothermal	Chemical- sedimentary	Weathering crusts	Metamorphic	
	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	
0-38	5387	43510	2660	4200		100.0
38-100	305	35440	2040			87.6
100-225	1800	12400	47000		10	79.2
225-325	1749	29850	7120		108	65.6
325-435	19250	380	16568			57.0
435-570	13577	216	44046	900	21873	49.0
570-900	136	7800	397		470	31.1
900-1500	2022	620	9901		19470	29.1
1500-2000	10500	390	30300		32100	22.0
2000-2500	18900	45	876		1900	5.7
2500-3000	3009				1254	0.9
≥3000	36					
Total tonnage (10 ³ t)	76671	30651	60908	5100	77155	450485
% of global tonnage	17.0	29.0	35.7	1.1	17.1	100.0
Examples	Kuroko New Brunswick Kidd Creek	Grund (Harz) Leadville Naica	Mississippi Valley type Shale type Mt. Isa	Karst type (reworked) Laterites (Vazante)	Broken Hill (New South Wales) Tetereault Gamsberg	

reflect power law or fractal dimensions (Turcotte, 1986). This is the case for metamorphosed deposits of Pb and Cu, paleoplacer Au, deposits of Zr, Ni, Cr, Mn, and for syn-sedimentary and metamorphic deposits of U. The implications of this polymodality for statistical treatment are discussed on case by case basis in the text.

TABLE A-2
Present-day age distribution of lead ores
($N = 250$, ~85 percent)

Age in 10 ⁶ yrs	Deposit Category					Global Cumulative %
	Volcano- sedimentary	Hydrothermal	Chemical- sedimentary	Weathering crusts	Metamorphic	
	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	
0-38	1685	36539	974	275		99.9
38-100	150	13918	89			84.3
100-225	1305	4575	16168			78.7
225-325	210	29300	12130			70.0
325-435	7022	6100	14166			53.6
435-570	4768	6891	38282	197	408	42.8
570-900	15	442	201		280	22.8
900-1500	25	218	11481		6350	22.4
1500-2000	1075	455	17500		19000	15.3
2000-2500	150	10	273		172	0.3
2500-3000	158	211				0.1
≥3000						
Total tonnage (10 ³ t)	16613	98659	108229	472	26180	250153
% of global tonnage	6.6	39.4	43.3	0.2	10.5	100.0
Examples	Kuroko New Brunswick Kidd Creek	Pribram S. Eulalia Linars	Mississippi Valley type Sandstone type Shale type (Laisvall)	Karst type (redeposited)	Broken Hill, (New South Wales) Gamsberg	

TABLE A-3
Present-day age distribution of copper ores
($N = 120$, ~70%)

Age in 10 ⁶ yrs	Deposit Category					Global Cumulative %
	Magmatogene (ultramafic-mafic)	Volcano- sedimentary	Hydrothermal	Chemical- sedimentary	Weathering crusts	
	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	
0-38		4200	57740	680	3697	100.2
38-100		3453	195080	80		88.1
100-225	30	4465	20600	491		52.3
225-325		1521	21350	23340		47.7
325-435	225	21815	9000	810		39.4
435-570		4237	4200	3778		33.6
570-900		1145	1500	83935		31.3
900-1500		8418	300	1360		15.5
1500-2000	30000	8050	1600	5500	236	13.2
2000-2500	3600	4700	650	70		2.8
2500-3000	1500	2053	400			0.9
≥3000		135				
Total tonnage (10 ³ t)	35355	64192	312420	120044	3933	553289
% of global tonnage	6.4	11.6	56.4	21.6	0.8	100.0
Examples	Noril'sk Sudbury Bushveld	Massive sulfides Kuroko type Greenstone type (Kidd Creek, Noranda) Cyprus type New Brunswick Rio Tinto	Porphyry coppers Chibougamau Skarns (Christmas)	Red beds and shale type Mt. Isa Udokan Zambian Copperbelt	exotic infiltrations (Exotica)	Caraiba O'okiep Manitouwadge

TABLE A-4
Present-day age distribution of gold ores
(*N* = 200, ~80%)

Age in 10 ⁶ yrs	Deposit Category							Global Cumulative %
	Magmatogene (mafic and ultramafic)	Volcano- sedimentary	Hydro- thermal	Detrital- sedimentary	Chemical- sedimentary	Weathering crusts	Metamorphic	
	t	t	t	t	t	t	t	
0-38		3	8495	12350	2	8		100.0
38-100		6	8254	30				75.7
100-225	1	13	1982		220			66.0
225-325		5	1705				2	63.4
325-435		360	3408					61.4
435-570	7	170	1327	2	260		3	57.0
570-900		12	53				5	54.9
900-1500		38	76				390	54.8
1500-2000	990	1200	250	300			28	54.2
2000-2500	175	502	1400	10			37	51.0
2500-3000 ≥3000	98	1670	11200	28700				48.6
Total tonnage (10 ⁴ t)	1271	5979	38150	41392	482	8	465	85747
% of global tonnage	1.5	4.6	44.5	48.3	0.6		0.5	100.0
Examples	Ni-Cu sulfide type Sudbury	Massive sulfide type Shale Au Morro Velho Timmins	Comstock Lode Mother lode Shear lodes in Archean greenstones	Placers and paleoplacers Witwatersrand Tarkwa Jacobina	Gold in black shales/schists (Victoria, Australia)	Madagascar	Manitouwadge (by-product of massive sulfides)	

TABLE A-5
Present-day age distribution of tin ores
(*N* = 120, ~80%)

Age in 10 ⁶ yrs	Deposit Category						Global Cumulative %
	Magmatogene (pegmatites)	Volcano- sedimentary	Hydrothermal	Detrital-sedimentary	Weathering crusts	Metamorphic	
	10 ⁴ t	10 ⁴ t	10 ⁴ t	10 ⁴ t	10 ⁴ t	10 ⁴ t	
0-38			1996	11520	500		100.2
38-100			1585				33.5
100-225			2688				26.0
225-325			1637				13.2
325-435	13		150				5.4
435-570			39	100			4.6
570-900		85	141			210	3.9
900-1500	200		67				1.8
1500-2000			40				0.5
2000-2500			20				0.3
2500-3000 ≥3000		20	13				0.2
Total tonnage (10 ⁴ t)	213	105	8376	11620	500	210	21024
% of global tonnage	1.0	0.5	39.9	55.3	2.4	1.0	100.1
Examples	Manono Fabulosa	Halsbrücke Canadian Shield (massive sulfide by-products)	Llallagua Potosí Cornwall Erzgebirge	Alluvial placers: Sundaland Australia	Eluvial placers: Sundaland		

TABLE A-6
Present-day age distribution of zirconium ores

Age in 10 ⁶ yrs	Deposit Category			Global Cumulative %
	Magmatogene (pegmatites and alkalic intrusions)	Detrital-sedimentary	Weathering crusts	
	10 ⁴ t	10 ⁴ t	10 ⁴ t	
0-38		22252	5000	99.9
38-100		20		27.8
100-225	2000			27.8
225-325				22.5
325-435	7500			2.7
435-570				2.7
570-900		5		2.7
900-1500	38	1000		2.7
1500-2000 ≥2000				
Total tonnage (10 ⁴ t)	9538	23250	5000	37795
% of global tonnage	25.2	61.5	13.2	100.0
Examples	Lovozero Ilmaussaq	Beach placers: Florida Australia	Poços de Caldas	

TABLE A-7
Present-day age distribution of nickel ores
 (N = 120, ~80%)

Age in 10 ⁶ yrs	Deposit Category					Global Cumulative %
	Magmatogene (ultramafic and mafic complexes)	Volcanic (ultramafic flows)	Hydrothermal	Weathering crusts and Detrital- sedimentary	Metamorphic	
	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	
0-38				59800		100.1
38-100			10	4066		35.9
100-225	4698			1440		31.5
225-325			75	1500		24.9
325-435						23.2
435-570			180			23.2
570-900						23.0
900-1500	4175		30			23.0
1500-2000	12000		40		750	18.5
2000-2500	770		2			4.8
2500-3000	1701	1950				3.9
≥3000						
Total tonnage (10 ³ t)	23344	1950	337	66860	750	93187
% of global tonnage	25.0	2.1	0.4	71.7	0.8	100.0
Examples	Sudbury Noril'sk	Western Australia Timmins area	Ni, Co, Bi association (Schneeberg) Cobalt remobilized ores (Sudbury)	New Caledonia Philippines Larymna Brazil	Selebi-Phikwe Thompson	

TABLE A-8
Present-day age distribution of chromium ores
 (N = 80, ~90%)

Age in 10 ⁶ yrs	Deposit Category			Global Cumulative %
	Magmatogene (ultramafic and mafic bodies)	Detrital- sedimentary	Weathering crusts	
	10 ³ t	10 ³ t	10 ³ t	
0-38		188	25200	99.9
38-100				99.3
100-225	17794			99.3
225-325	700			98.9
325-435	7000			98.9
435-570	14200			98.8
570-900	1290			98.5
900-1500	500			98.5
1500-2000	4500000			98.5
2000-2500	190000			4.0
2500-3000	2248			
≥3000	2379			
Total tonnage (10 ³ t)	4736111	188	25200	4761499
% of global tonnage	99.5		0.5	100
Examples	Alpine type ultramafics Bushveld Great Dyke	Placers Oregon Philippines	Laterites: Philippines Cuba New Caledonia (by-products)	

TABLE A-9
Present-day age distribution of iron ores
(*N* = 150, ~75%)

Age in 10 ⁶ yrs	Deposit Category								Global Cumulative %
	Magmatogene (ultramafic and mafic)	Volcanic	Volcano- sedimentary	Hydrothermal	Detrital- sedimentary	Chemical- sedimentary	Weathering crusts	Metamorphic	
	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	
0-38				15	988	98	1473		100.2
38-100		563		180	25	13600	200		99.0
100-225			118	790	34	6614	50		93.7
225-325				25	530	410			90.8
325-435			1873	45		4303			90.4
435-570			100	28		921			88.0
570-900		60	2366	60		37000			87.6
900-1500	1200		216	90		990		13	72.5
1500-2000	600	2390	22800			64000		210	71.5
2000-2500	5100		5100			40000		40	37.5
2500-3000	80		17800			28000		154	18.5
≥3000	300		780					1470	1.0
Total tonnage (10 ⁶ t)	7280	3013	51153	1233	1577	95936	1723	1887	263802
% of global tonnage	2.8	1.1	19.4	0.5	0.6	74.3	0.7	0.7	100.1
Examples	Grenville Bushveld (titanio- magnetites)	El Laco Kiruna?	Lahn Dill Algoma	Siegen Bilbao Rudnary	Magnetite sands in New Zealand	Minette Lake Superior Clinton	New Caledonia Mayari Surigao	Dover, N.J.	

TABLE A-10
Present-day age distribution of manganese ores
(*N* = 120, ~90%)

Age in 10 ⁶ yrs	Deposit Category							Global Cumulative %
	Magmatogene (carbonatites)	Volcano- sedimentary	Hydrothermal	Chemical- sedimentary	Weathering crusts	Metamorphic		
	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t	10 ⁶ t		
0-38		675	2000	1106940	1880			100.1
38-100	200	8974	3100	200900	78			62.7
100-225		413	1400	3190	631			55.4
225-325		93		2650				55.2
325-435		19159	3500	110				55.1
435-570		47479	1800	130099				54.3
570-900		11462	250	1855				48.2
900-1500		158003		1200				47.7
1500-2000		52000		10600		2000		42.2
2000-2500		3200		1050000		111000		36.3
2500-3000		358				8352		0.3
≥3000						6810		
Total tonnage (10 ⁶ t)	200	301816	12050	2507544	2589	128162		2952361
% of global tonnage	—	10.2	0.4	84.9	0.1	4.3		99.9
Examples		Ophiolitic assoc. Olympic Peninsula Birimian (Ghana, U. Volta, Mali) Moanda	Komaneche Philipsburg Siegen	Nikopol' Kalahari Chiatura	Cartersville New Caledonia	Gondites Langban Lafaiete, Brazil		

TABLE A-11
Present-day age distribution of aluminum ores (bauxites)

Age in 10 ⁶ yrs	Deposit Category		Global Cumulative %
	Detrital- sedimentary	Weathering crusts	
	10 ⁶ t	10 ⁶ t	
0–38	1354	2000	99.8
38–100	274		17.7
100–225	92		11.0
225–325	304		8.8
325–435	61		1.4
Total tonnage (10 ⁶ t)	2085	2000	4085
% of global tonnage	51.0	49.0	100.0
Examples	Amazon basin Guyanas Russian platform	Guinea Southern India Arkansas	

TABLE A-12
Present-day age distribution of uranium ores
(N = 150, ~80%)

Age in 10 ⁶ yrs	Deposit Category									Global Cumulative %
	Magmatogenic (alkalic intrusion)	Continental volcanics (including volcanic sediments)	Detrital- sedimentary	Chemical- sedimentary	Infiltrational in sandstones	Unconformity type	Weathering crusts	Hydrothermal	Metamorphic	
	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	10 ³ t	
0-38		10	2		70			5		100.0
38-100	20	15		4	400		60	25		96.7
100-225				15	400			5		85.0
225-325	5	10			30	5		120		74.5
325-435					200			2		70.3
435-570	1			300				10	300	65.3
570-900						10		5	10	49.9
900-1500	30		8			1000		5	10	48.3
1500-2000	5	15		15		60		60	30	22.9
2000-2500			400					10	3	10.3
>2500			300					1		7.5
Total tonnage (10 ³ t)	61	50	710	354	1100	1075	60	248	353	3991
% of global tonnage	1.5	1.2	17.8	8.4	27.6	26.9	1.5	6.2	8.8	100.0
Examples	Lovozero Ilmaussaq Catalao	Poços de Caldas Makkovik Baker Lake	Elliot Lake Witwatersrand Jacobina Moeda	Phosphorite type Ranstad Lodève Oklo	Western U.S. type	Jabiluka Roxby Downs Athabasca region	Calcrete type: Yeelirrie	Beaverlodge Mary Kathleen Zhelezye Vody Jachymov	Rössing Bancroft	

APPENDIX B

Deconvolution procedure

The notations and mathematical basis of the concept are those of Veizer and Jansen (1979, 1985). As in these references, we let $A_p(t)$ be the amount generated during the p 'th period and still present at time t . The solution for the original amount present $A_0(t)$ is

$$A_0(t) = A e^{-kt} \text{ and} \\ A_p(t) = A(e^{pkT} - e^{(p-1)kT})e^{-kt} \quad p = 1, 2, \dots, P; \quad (1)$$

where P equals the number of periods, T is the duration of a period (resolution), $t = 0$ is the beginning, and $t = PT = \text{today}$.

Note that at $t = 0$ the

$$A_0(0) = A = \text{the original amount.}$$

At $t = PT$ (today), the original amount present is given by

$$A_0(PT) = A e^{-kPT}$$

and the amount formed during p 'th period and present today is

$$A_p(PT) = A(e^{pkT} - e^{(p-1)kT})e^{-kPT} \quad p = 1, 2, \dots, P;$$

Let C_p be the cumulative amount created during the first p periods and still present today. The C_p is given by

$$C_p = \sum_{i=0}^p A_i(PT) = A e^{-kT(P-p)}. \quad (2)$$

Note that $C_p = A = \text{total cumulative amount present today.}$

As shown in Veizer and Jansen (1979) $\underline{b}_T = 1 - e^{-kT}$. Thus $e^{-kT} = 1 - \underline{b}_T$ and (2) becomes

$$C_p = A(1 - \underline{b}_T)^{P-p}. \quad (3)$$

We shall utilize coal data (table 1) for demonstration of deconvolution ("unrecycling") at an invariant $\underline{b}$. In this case P equals 450 periods (the age of the Earth), the assumed resolution T is 10^7 yrs, and $\underline{b}^{10} = 26.2 \times 10^{-10} \text{ a}^{-1}$. Thus $\underline{b}_T = 0.0262$.

From (3)

$$A = \frac{C_p}{(1 - \underline{b}_T)^{(P-p)}} = \frac{C_p}{(1 - \underline{b}_T)^{450-p}}$$

For $p = 450$ (today)

$$A = \frac{C_{450}}{(1 - \underline{b}_T)^{450-450}} = C_{450} = 100\%$$

For $p = 443$ (the end of the Cretaceous at ~70 Ma ago)

$$A = \frac{C_{443}}{(1 - \underline{b}_T)^{450-443}} = \frac{C_{443}}{(1 - \underline{b}_T)^7}$$

since $C_{443} = 86.5\%$ (table 1)

$$A = \frac{86.5}{(1 - \underline{b}_T)^7} = \frac{86.5}{(1 - 0.0262)^7} = 104.04.$$

Thus the pre-70 Ma reserves of coal were 104.04 percent of today's cumulative reserves, reflecting the deviations of the data from a perfect fit to exponential decay. Similarly, for $p = 432$ (the end of the Triassic at ~180 Ma)

$$A = \frac{56.4}{(1 - \underline{b}_T)^{28}} = 90.67, \text{ et cetera.}$$

To obtain values of A for every 10 Ma interval we utilized linear interpolation. For example

$$C_{444} = C_{443} + \frac{1}{7} (13.5)$$

The above deconvolution procedure has been utilized for all models with invariant $\underline{b}^{10}$, that is for hydrocarbons and the PP* and BP pathways of metals.

The deconvolution along the OP* pathway has been calculated as follows. Suppose for all periods up to period P_B we have a recycling at $\underline{b}_{T_i}$ (slow) and for the periods starting at P_B to today (period P) the recycling has been at $\underline{b}_{T_f}$ (fast). Then

$$A_p = \frac{C_p}{(1 - \underline{b}_{T_f})^{p-P_B} (1 - \underline{b}_{T_i})^{P_B-p}} \quad \text{for } p < P_B \quad (4)$$

$$A_p = \frac{C_p}{(1 - \underline{b}_{T_i})^{p-p}} \quad \text{for } P_B \leq p \leq P \quad (5)$$

Substituting age (a) for p and specifying the time of inversion (B) in yrs

$$A_a = \frac{C_a}{(1 - \underline{b}_{T_f})^{B/T} (1 - \underline{b}_{T_i})^{(a-B)/T}} \quad \text{for } a > B$$

$$A_a = \frac{C_a}{(1 - \underline{b}_{T_i})^{a/T}} \quad \text{for } a \leq B$$

The calculated rates for $T = 10$ Ma periods represent simple derivatives

$$\frac{d(\%)}{dt} = \frac{A_p - A_{p-1}}{T} \quad (6)$$

The rates in figure 16 represent only the positive derivatives, that is the times of growth. The rates of net dispersal (negative derivatives plotting below the zero axis) are excluded from this figure because of drafting considerations.

In detail, the age distribution patterns for hydrothermal deposits have been deconvoluted along the OP* pathway (table 2), except for the Proterozoic U, which—because of its association with platform sediments—has been deconvoluted along the PP* pathway. The chemical-sedimentary and the volcano-sedimentary categories have been deconvoluted along the PP* pathway, despite a better agreement of the latter with a BP pathway (table 2). The rationale for this choice has been the observation that the ores are a component of the sedimentary cover and not of the basement. Should a BP pathway be utilized, it would eliminate the base metal peaks (except for the Archean-early Proterozoic Zn), but Au, Fe, and Mn peaks would only be diminished. No correction for recycling has been utilized for ores of (ultra)-mafic and metamorphic associations and for U-Au paleoplacers. In all these cases, their total reserves are controlled by only a few giant deposits. The databases are therefore insufficient for statistical treatment. Nevertheless, whatever their recycling rate—and some dispersal must have occurred—it would only amplify the existing anomalies. In short, even with the most conservative assumptions, these deposits should be regarded as a quantitatively unique phenomenon of the Late Archean-Early Proterozoic Eons; a conclusion widely accepted by the geological community. For other categories of uranium mineralization, the unconformity and chemical-sedimentary ores have been deconvoluted along the PP* pathway, the infiltrations in sandstones (Colorado Plateau type) along the OP* pathway, and the hydrothermal ores along the OP* (Phanerozoic ores) and the PP* (Proterozoic ores) pathways. Uranium ores are summarized in a separate category in order to illustrate the succession of genetic types through time.

In this presentation, the absence of a peak indicates only that the *net* generation rate of a commodity has been negligible, zero, or negative. It does not necessarily follow that generation of new mineral deposits must have been negligible at such times, but only that it has been matched by concomitant dispersal of the pre-existing old ones. Because of this consideration, our methodology may err in the direction of downplaying the existence of peaks. Furthermore, if in doubt, we always opted for a minimal upgrading, via deconvolution of recycling, of the tonnages still preserved today (the “ultramafic,” “metamorphic,” and U-Au paleoplacers deposits). The volcano-sedimentary ores are the only exception from this rule, and the consequences are stated above. Overall, therefore, figure 16 downplays the existence and the magnitude of the peaks. It may underestimate the evolutionary component and artificially favor the role of recycling and of steady-state interpretations. We prefer to err in this direction, because it enhances the validity of the surviving peaks.

Note also, that the actual shapes of the peaks between interval endpoints are to a degree an artifact of extrapolation. Extraction of the second order structure for the Precambrian, with intervals of 330 to 500 Ma duration, would require time resolution similar to that of the Phanerozoic Eon (10^7 yrs). Unfortunately, such a database is not yet available. Furthermore, the unequal time resolution has consequences for the calculated apparent rates of the net generation/destruction of ore deposits. The apparent rates of geological processes are inversely proportional to the duration of the observational time interval. This is mostly because non-events and destructive events (non-deposition and erosion) account for progressively larger proportion of longer time intervals (Schindel, 1982; Gingerich, 1983; Veizer, 1984; Plotnick, 1986). On average, the Phanerozoic intervals are $\sim 1/5$ of the Precambrian ones. At 10^7 – 10^8 yrs. resolution, this could result in only slightly faster *apparent* rates of net generation of geologic entities for the Phanerozoic than for the Precambrian (fig. 1 in Sadler, 1981). Nonetheless, even a reduction of the Phanerozoic peaks to $\sim 1/5$ of the projected amplitude would not eliminate the overall

pattern. Consequently, the observed diversity and frequency of mineral deposits during Phanerozoic times is not solely a reflection of a record with better time resolution. Similarly, it is not an artifact of preservation, since our deconvolution procedures should have corrected for such phenomena.

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