

THE EARTH AND ITS LIFE: SYSTEMS PERSPECTIVE

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Abstract. From the planetary point of view, the Earth can be imagined as a system comprised of intertwined natural populations propagated through time via recycling. This recycling, or 'birth/death' process, imposes age patterns on natural populations of the solid earth, hydrosphere, atmosphere and living entities. Mathematically, the concept is analogous to that of population dynamics in living systems. The populations of the Earth system form a hierarchical structure. The hierarchy of geological tectonic realms contains populations of $\leq 10^{24}$ – 10^{26} gr in size, with half-lives in the 10^7 – 10^9 yr time range. The approximate parameters for the oceans are $\leq 10^{24}$ gr and 10^2 – 10^7 yr, for the atmosphere $\leq 10^{21}$ gr and 10^{-2} – 10^7 yr, and for living systems $\leq 10^{14}$ – 10^{19} gr and 10^{-3} – 10^2 yr, respectively. In this perspective, and in departure from the GAIA hypothesis, the subordinate populations, such as those of living systems, are constrained to operate within limits imposed by the larger, and slower, hierarchies. They can overstep the imposed limits only on time scales shorter than the response time of the dominant populations. Isotopic record of past sea water shows that on time scales of 10^7 yr the solid earth, hydrosphere, atmosphere and life act as a unified system controlled by tectonics, that is by the hierarchy of the solid earth.

1. Introduction

The quest to unravel the mysteries of the origin and evolution of our surrounding world, and of life, is strongly influenced by personal views of the relative importance of deterministic vs probabilistic concepts of evolution and history. The deterministic attitude, which may or may not lead to formulation of an ultimate cause (god), implies a directional design. The probabilistic approach, although not excluding design in terms of processes rather than products, does not require directionality. I would like to argue, from a geological perspective, that these two concepts are not mutually exclusive, but complementary. The evolution of the Earth system can be viewed as a propagation of constituent populations through continuous 'birth/death' cycles. This concept is true whether the 'dead' inorganic or the 'living' organic matter is considered. The constituent populations are mutually interdependent and of variable sizes. On average, the larger the population the longer its life-span. The 'birth/death' cycles of large populations establish the limits, and the very basis of existence, for the operation of smaller populations. For subordinate populations, departures from such controlled steady-states are possible, but only on time scales shorter than the life-spans of the dominant populations. Thus an event, such as habitat destruction, may be of deterministic significance for a given living community, while at the same time being of only repetitive (probabilistic) significance for the controlling geologic cycle (e.g. earthquakes). The 'birth/death'

cycles, or population dynamics, and their interactions will be the recurrent themes of the subsequent discussion.

2. Conceptual Approach

An ideal natural population, characterized by a continuous ‘birth/death’ cycle, is usually typified by an internal age distribution pattern similar to that in Figure 1. The proportion of progressively older constituent units, such as human individuals, decreases exponentially. This exponential (power law) decrease is due to mortality

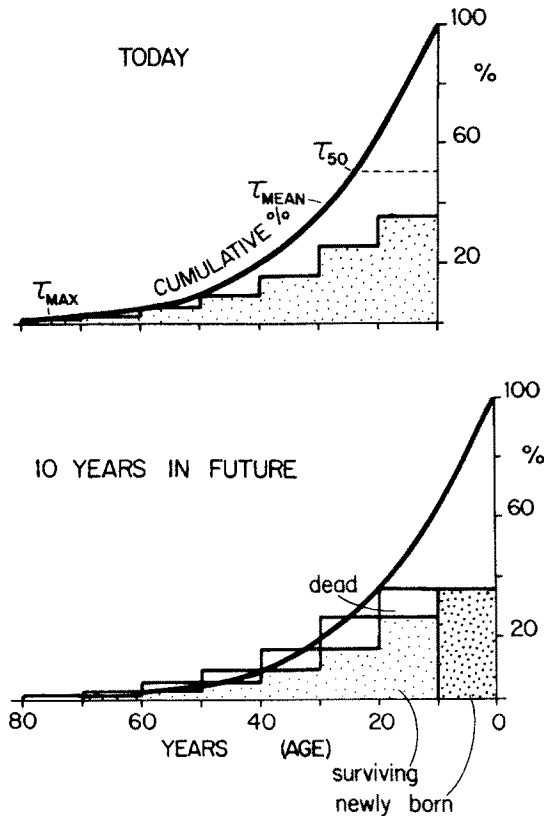


Fig. 1. Simplified theoretical age distribution for a steady-state living system. τ_{50} , τ_{MEAN} and τ_{MAX} as in the text. In this case, the natality/mortality rate is 35% of the total population for a 10 yr interval ($b = 35 \times 10^{-3} \text{ yr}^{-1}$). τ_{MAX} is arbitrarily defined as the 5th percentile. In practice, τ_{MAX} marks the point where the resolution of the data base becomes indistinguishable from the background. In general, the cumulative age distribution pattern for an ideal population with a stable age structure can be mathematically expressed as $A_{t^*} = A_0 e^{-kt^*}$, where A_{t^*} is the cumulative fraction of the surviving population older than the age t^* , A_0 equals 1 (one population), and k is the rate constant for the recycling process. The recycling proportionality constant b employed in this text is related to the above formalism as $b = 1 - e^{-kT}$, where T is time resolution (cf. Veizer and Jansen, 1979, 1985). Note that, in living as well as inorganic worlds, deviations from the above idealized age distribution pattern are frequent (cf. Veizer, in press), but such refinements are not essential for the general thesis of the present paper. Reproduced from Veizer and Jansen (1985). (By permission of the University of Chicago Press.)

being usually proportional to, or a first order function of, the size of the given age group. A cumulative curve of such an age histogram defines all necessary attributes of a given population. These are its *size* A (here 100%), *half-life* τ_{50} , *mean age* τ_{MEAN} , and *oblivion age* (or maximal life-span) τ_{MAX} (Figure 1). The above τ_{50} , τ_{MEAN} and τ_{MAX} , and thus the slope of the cumulative curve, are an inverse function of the mortality rate; the faster the rate the steeper the slope, because older individuals have a lesser chance of survival. For a steady-state extant population, natality per unit time equals combined mortality for all age groups during the same time interval. Consequently, the cumulative slope remains the same but propagates into the future (Figure 1 bottom). This natality (= mortality) rate is designated as the *average recycling proportionality parameter* b . Note that the 'birth/death' process is accomplished via internal (cannibalistic) as well as external recycling. In the internal recycling the entity propagates itself, whereas in the external recycling the components of a populations are 'dying' into an external reservoir (population), while others are being 'born' from an outside, not necessarily identical, source. For example, in a national population of people, the individuals are being 'born' and 'dying' by an internal birth/death process as well as by immigration/emigration. In the case of biogeochemical elements, a proportion is recycled cannibalistically (mother to embryo and infant), while the remainder recycles via the atmosphere and/or hydrosphere, biosphere and lithosphere. Some rocks of the oceanic crust recycle into the mantle directly (subduction), while others do so via an external continental loop. This internal and external recycling, singly or in concert, controls the above described age distribution patterns of natural populations, with the relative importance differing from one population to another. Note that it is the external component of recycling which molds the diverse populations into an interdependent *system*. A complete description of the dynamics of such a system would require resolution of the external from the internal recycling rates and not only their summation. Unfortunately, such ambitious goal is not yet within our grasp. The above statements constitute the minimal explanations needed for geological application of the concept, usually designated as *population dynamics*. Further details are available, for example, in Hutchinson (1978), Wilson and Bossert (1971), and Pielou (1977). The subsequent treatment of the solid earth, and of its hydrosphere, atmosphere, and biosphere is based on this unifying dynamic concept and on the sets, or hierarchies, of populations. The utilized approach is that of the white box model with emphasis on internal structure of the boxes (populations), but scant knowledge of their interconnecting fluxes. This contrasts with the familiar black box models, which have the opposite attributes.

3. Hierarchy of Geological Populations

According to the theory of global plate tectonics (Dietz, 1961; Hess, 1962; LePichon *et al.*, 1973; Scientific American, 1983) the upper layer of the solid Earth, the crust, is subdivided into several major global tectonic realms (Figure 2). These are:

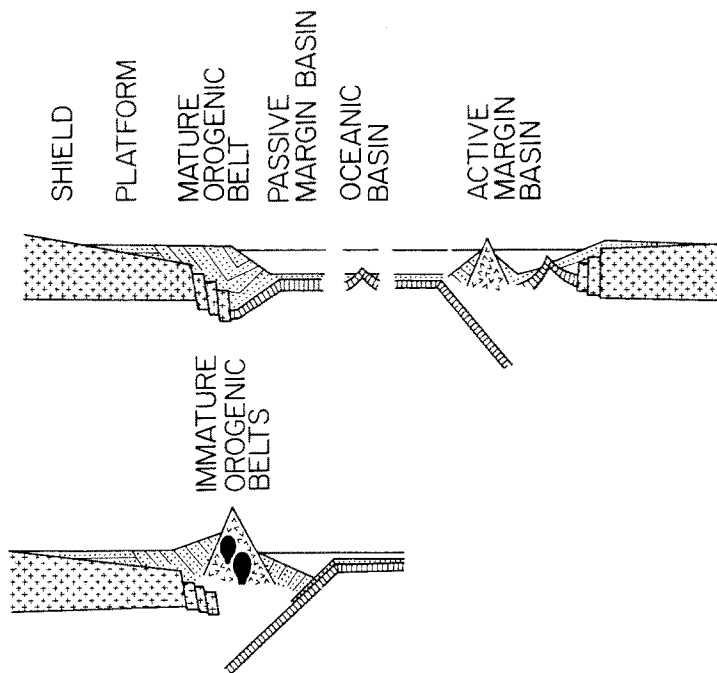


Fig. 2. Schematic presentation of major tectonic realms in the context of the global plate tectonics.

- (a) Basaltic oceanic crust and its overlying deep sea sediments;
- (b) Active margin basins separated from (a) by tectonic barriers (e.g. Sea of Japan, Caribbean, Mediterranean);
- (c) Passive margin basins (e.g. the Atlantic continental shelf and slope);
- (d) Immature orogenic (mountain) belts, such as the Andes or the Rocky Mountains;
- (e) Mature, or worn-down, orogenic belts (the Appalachians and the Hercynian mountain ranges of Europe represent imperfect, not yet entirely worn-down, examples);
- (f) Platforms, that is undisturbed flat lying sediments deposited on the stabilized crystalline basement of the continental crust (e.g. the North American midwest or the Russian platform); and
- (g) Shields, here understood as the crystalline and metamorphic basement of continents (e.g. the Canadian Shield).

The above delineated tectonic realms were selected because of the availability of quantitative data concerning the mass-age or area-age distributions for their constituent rocks. Alternative tectonic classifications are possible, but would not be grossly dissimilar from the one above. In general, the tectonic realms (a) and (b) are

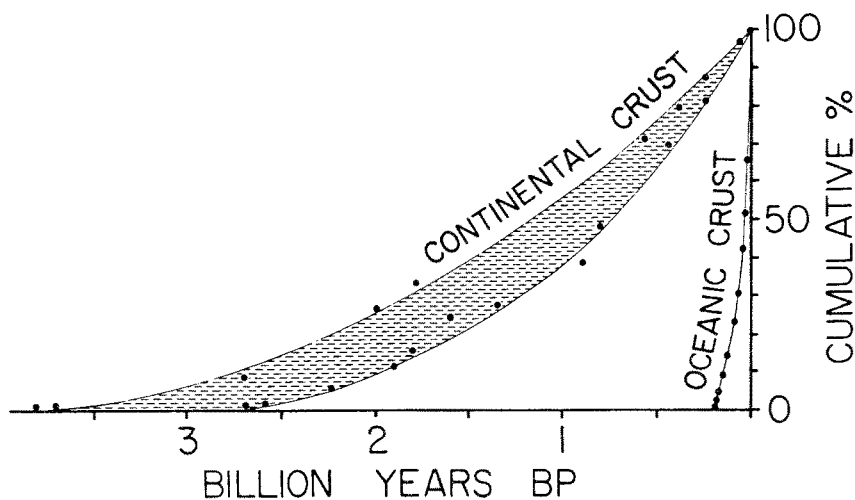


Fig. 3. Area-age distributions of oceanic and continental crusts. For age distribution patterns of other tectonic realms see Veizer and Jansen (1985).

mostly developed on basaltic oceanic crust, whereas (c) to (g) are associated with the crust of continental (granitic) type.

The mass-age or area-age distributions of rocks in these tectonic realms have been discussed in detail in Veizer and Jansen (1985) and here only the distributions for continental and oceanic crusts are reproduced for illustration (Figure 3). The cumulative curves for age distributions of rocks mimic the age distributions in living systems and both conform with the concept of population dynamics. The disparities between the living human and the 'dead' inorganic populations are mostly in their sizes (10^{14} vs 10^{24} – 10^{26} gr) and life spans (10^1 vs 10^7 – 10^9 yr), but not in the age distribution patterns.

The summary of the observed theoretical half-lives (τ_{50}) and recycling ('natality/mortality') rates is given in Figure 4. This figure demonstrates good agreement between the theory and observations, with half-lives diminishing as the rate of recycling increases. The calculated half-lives for the particular tectonic realms are the following: basins of active margins ≈ 27 Ma (million years), oceanic sediments ≈ 51 Ma, oceanic crust ≈ 59 Ma, basins of passive margins ≈ 75 Ma, immature orogenic belts ≈ 78 Ma, mature orogenic belts ≈ 355 Ma, platforms ≈ 361 Ma. The τ_{50} 's for continental basement depend on the resistivity of the particular isotopic dating system to later resetting and range from ≈ 673 Ma for K/Ar, through ≈ 987 Ma for Rb/Sr and U-Th/Pb, to ≤ 1728 Ma for Sm/Nd isotopic pairs. The maximal life-spans τ_{MAX} for these tectonic realms are usually 3.0–3.5 times their respective τ_{50} . This is less than the theoretically expected 4.0–4.5 times of τ_{50} and the discrepancy is a result of increased destruction rates for rocks approaching their expected life-span (see Veizer, in press, for further details).

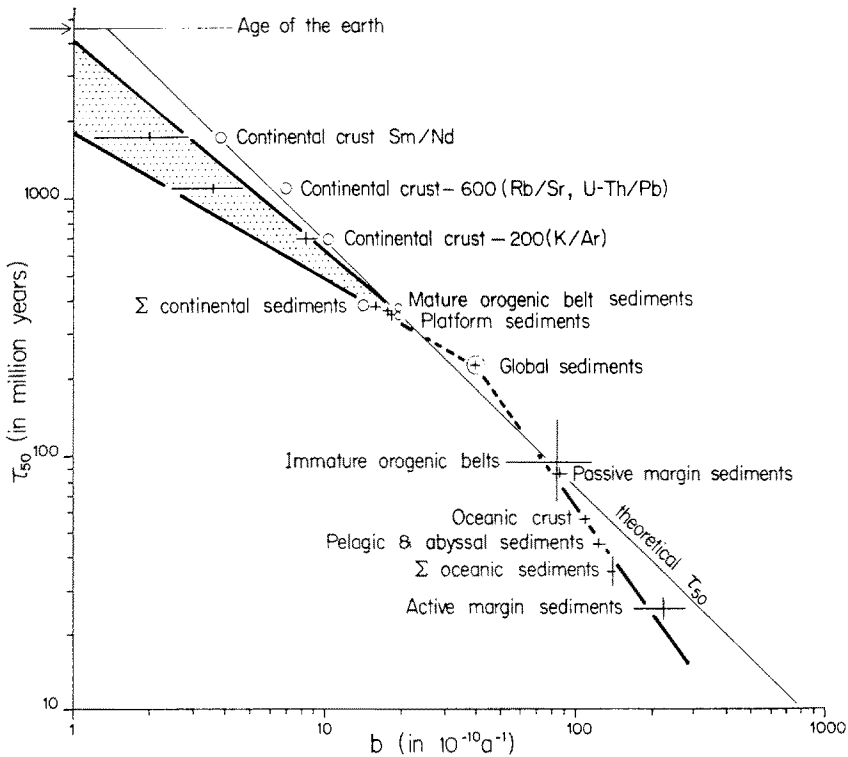


Fig. 4. Plot of the observed half-mass and half-area ages (τ_{50}) and of recycling rates (b) for major global tectonic realms. Crosses represent solutions for the 'preferred' logistic model of continental growth, where it is assumed that continents started to grow (or started to be preserved) at ≈ 4000 Ma ago. This was followed, ≈ 3000 – 2000 Ma ago, by a fast growth rate and subsequently the continents have been of a near present-day size. The circles give results for the steady-state (continents of present-day size) alternative. The two limiting solutions are identical at $b \geq 40 \times 10^{-10} a^{-1}$. For definition of b see Figure 1. Continental crust – 200, – 600 represent solutions for the bottom and the top enveloping curves in Figure 3. The Sm/Nd curve is not shown in this paper. Reproduced from Veizer and Jansen (1985). (By permission of the University of Chicago Press.)

The calculated data appear to separate the global tectonic realms into two domains, the continental and the oceanic one. The former comprises tectonic realms (e) to (g) and the latter (a) to (d). The oceanic domain, with τ_{50} in 10^7 yr range, represents a relatively fast cycling system, while the more massive continental domain operates more slowly on time scales of 10^8 – 10^9 yr. These two domains, or two interlocking wheels of different sizes and revolving speeds, interact in the process of mountain formation and destruction (orogenesis). Yet, orogenesis itself is a response to the operation of the oceanic cycle, as attested by recycling parameters for immature orogenic belts (Figure 4). Thus, the generation of oceanic crust from the mantle, its spreading, and the peripheral mountain building processes are all coupled phenomena and, following uplift, mountain ranges are eroded back into the oceans. In the terminology of the system science theory (e.g. Odum, 1983), the entire

continent-mantle system, interrelated via mountain building (orogenic) processes, represents an autocatalytic module and the orogenesis itself the autocatalytic loop.

The above discussion may invoke a notion of a steady-state Earth of infinite age. This, of course, is not the case. Any population, regardless of whether it is living or geological, may recycle and evolve simultaneously. Thus the hominid population branched out (was 'born') about four million years ago and has been expanding ever since via recycling of numerous generations. In contrast, the population of dinosaurs became extinct about 65 million years ago despite generational procreation. In the case of the Earth, it is widely accepted that our planet was 'born' ≈ 4.5 billion years ago, and during subsequent times generated, via internal differentiation, its present-day geological framework of continental and oceanic domains, as well as its hydrosphere, atmosphere, and biosphere. The evolution of the Earth is characterized therefore by a combination of recurring (cyclic) and superimposed unidirectional phenomena. The recurring, shorter term, phenomena leave behind only residual records and the long term trends, as they appear to us, are usually a compounded picture of such residual records. For example, the present day continental crust is a result of agglomeration of remnants from recurring episodes of orogenesis. In order to understand this long term evolution, it is essential to appreciate the time scales of the repetitive phenomena and their probabilities of preservation over geologic time. It is evident that tectonic realms of the oceanic domain are preserved only in a fragmentary fashion in geologic segments older than ≈ 300 Ma. The direct study of the oceanic tectonic domain must therefore be confined to this relatively recent time interval. Its preceding evolution can be reconstructed quantitatively only from attributes of some derivative property, the latter measurable over a longer time span and having time resolution of $\leq 10^7$ yr. In contrast, the evolution of the slowly recycling continental tectonic domain is discernible only on protracted time scales of 10^8 – 10^9 yr, regardless of whether it is studied through direct or derivative observations. The ideal book-keeping technique should therefore cover the bulk of the terrestrial life-span and have signal resolution on a variety of time scales. The isotopic properties of coeval sea water have a potential to serve as such a tool.

4. The Hydrosphere-Atmosphere Hierarchy of Populations

The present day oceans and atmosphere have masses of 10^{24} and 10^{21} gr, respectively (Lerman, 1979; Scientific American, 1983) and their compositions and evolutions have been treated comprehensively in Garrels and Mackenzie (1971), Holland (1978, 1984), and Walker (1977). The details of the age distributions of water and atmospheric masses are only partially known (e.g. Broecker and Peng, 1982), but there is little doubt that these age distributions conform with the exponential or power law patterns advocated above (Lerman, 1979). The yearly flux of river water into the oceans is $\approx 0.3 \times 10^{20}$ gr. Thus the evaporation-precipitation-runoff cycle is capable of recycling the whole ocean in ≈ 40000 years and this is designated as the *mean residence time* τ_{RES} . In most instances,

$\tau_{\text{MAX}} \geq \tau_{\text{RES}} \geq \tau_{50}$. Consequently, the probable half-life for the entire population of oceanic H_2O is about ten thousand years. The residence times for chemical and isotopic species dissolved in sea water range from $\leq 10^2$ to $\approx 10^8$ yr (e.g. Holland, 1978) and for the smaller populations of atmospheric constituents they are about 10^{-2} – 10^7 yr (Lerman, 1979). The corresponding half-lives for all of the above dissolved species and atmospheric constituents are therefore likely to be somewhat shorter than their residence times.

4.1. CONTINENTAL DOMAIN: DERIVATIVE SIGNAL IN SEA WATER

The chemical and isotopic composition of sea water reflects average global causes and not local phenomena. For this reason, a time record of its evolution is valuable. Unfortunately, there are no unequivocal samples of ancient sea water (and of air) preserved in the rock record. Its properties can be therefore deciphered only through derivative signatures inscribed in ancient marine sediments.

The present day fluxes controlling the composition of sea water are (Figure 5):

- (a) Continental river discharge, F_C ;
- (b) Interaction between sea water and oceanic basalts, mostly in hydrothermal cells of mid-oceanic ridges. This interaction is designated as the 'mantle' flux, F_M ;

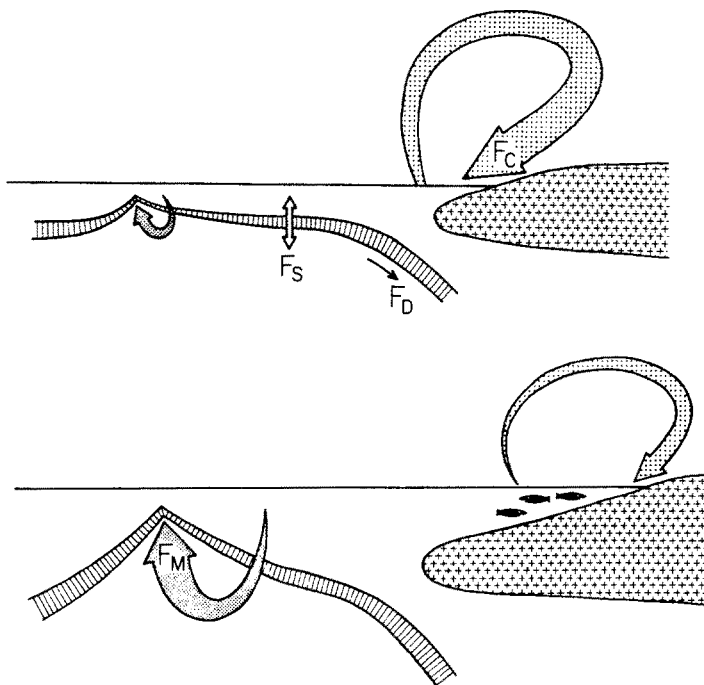


Fig. 5. Schematic representation of fluxes controlling the composition of sea water. F_C – 'continental' river discharge; F_M – hydrothermal and low-temperature 'mantle' flux, involving circulation of heated sea water through ocean floor basalts; F_S – sedimentary flux involving deposition of sediments and their interaction with sea water; and F_D – flux of sediments and water subducted into mantle.

- (c) Efflux via, and interaction with, sediments, F_S ; and possibly
 (d) Subduction of sediments and trapped water in subduction zones, F_D .

As already stated, in terms of water transfer the river flux is capable of recycling one ocean volume in $\approx 4 \times 10^4$ yr, whereas the 'mantle' flux requires $\approx 2 \times 10^7$ yr (Edmond and Von Damm, 1983). The estimates for the net unidirectional sedimentary (F_S) and subduction (F_D) fluxes are uncertain and probably small compared to those of the river and 'mantle' fluxes. Taking into account that sea water recycled through oceanic basalts has the concentration of solutes $\approx 10^3$ times higher than river water, the 'mantle' flux has, for some elements, the potential to match the magnitude of the river flux. The change in relative intensities of $F_C:F_M$ fluxes, that is in relative importance of the continental vs oceanic tectonic domain, results in secular (time related) evolution of chemical and isotopic composition of sea water. This evolution is, in turn, recorded in (bio)chemical sediments, such as carbonates. Consequently, the secular trends in the latter provide a direct weighted record of past perturbations. Tracers with differing signatures for these two fluxes are particularly suitable for such an approach. For example, the average Sr isotopic composition of river water is 0.711, whereas that of oceanic basalts is 0.703 (Figure 6). The sea water value of 0.709 therefore demands that the river flux of Sr outweighs its 'mantle' counterpart by $\approx 4:1$. In the geological past, sea water $^{87}\text{Sr}/^{86}\text{Sr}$ fluctuated between the above end-members. The river flux was probably non-linearly proportional to the size of the coeval continents (Figure 7A). In contrast, the intensity of water circulation through ocean floor basalts was probably proportional to mantle heat production and its dissipation. Thus the buffering of ocean chemistry when the Earth was young, with high mantle heat generation and small continents, should have been mostly by basalt (F_M), whereas during the later periods – characterized by large continents and less mantle heat production – the

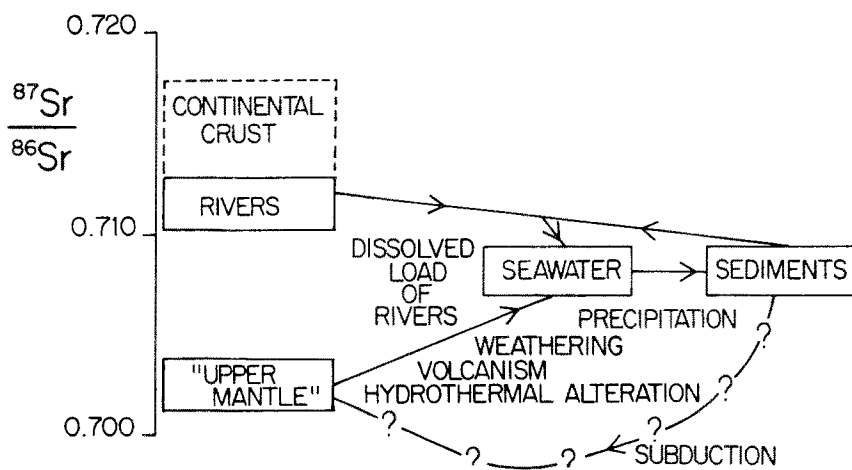


Fig. 6. Schematic presentation of Sr isotopic surficial cycle. Reproduced from Wadleigh (1982) and Wadleigh *et al.* (1985).

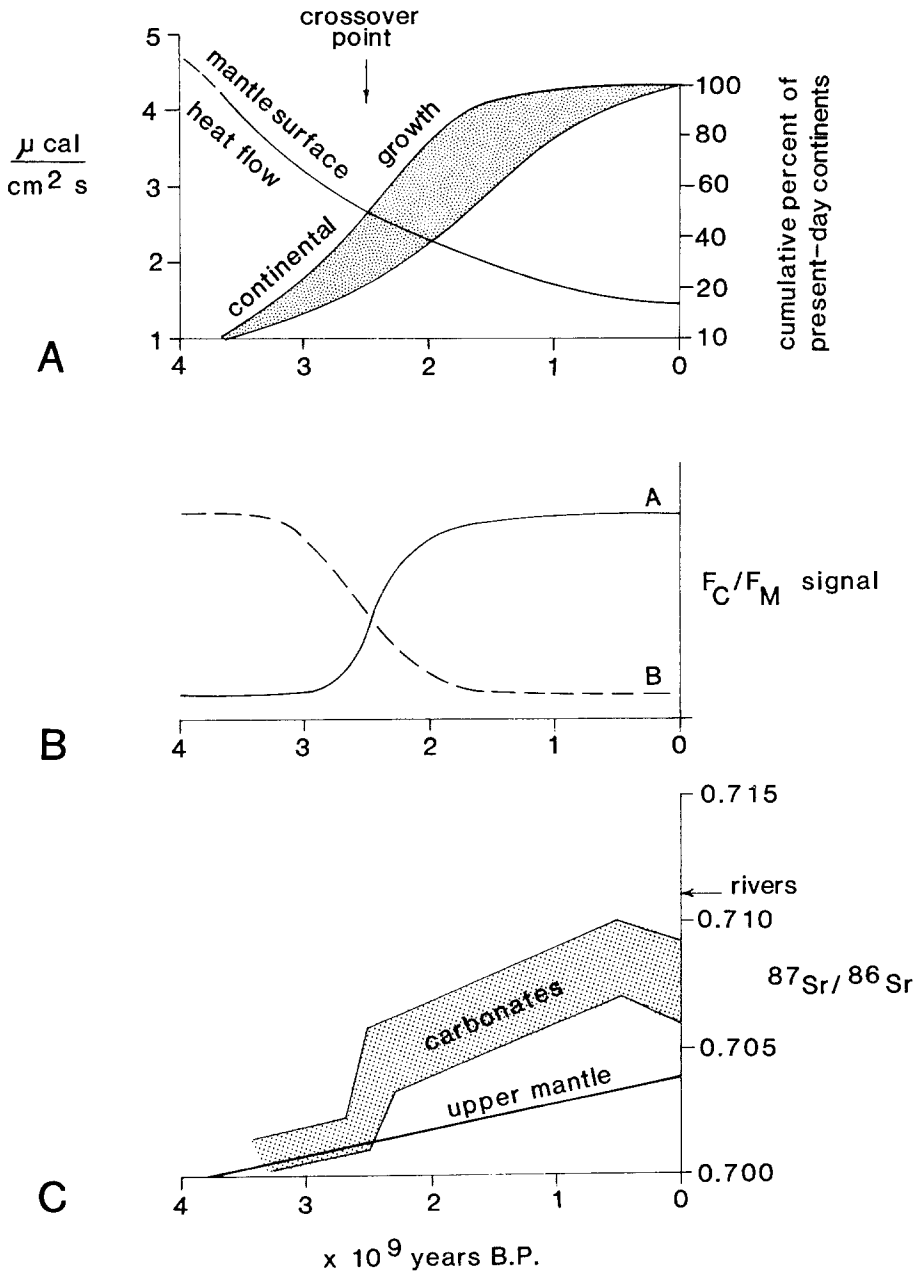


Fig. 7. (A) Schematic presentation of mantle surface heat flow and of areal continental growth during geologic history. (B) The expected F_C/F_M signal in sea water composition. This signal should be of type A if the transition results in a gain, and of type B if in a loss of an entity. Note that this general shape of the signal will evolve regardless of the details of the two exponential (or other type) curves of opposing slopes. For radiogenic isotopes (i.e., Sr) the flat parts of the curves will be modified by radioactive decay. (C) Schematic $^{87}\text{Sr}/^{86}\text{Sr}$ variations in sea water during geologic history based on the data in Veizer and Compston (1976). Note the departure of the 'sea water' curve from mantle values at ≈ 2500 Ma ago. Reproduced from Veizer (1984).

dominant controlling flux was the river flux (F_C). The resulting Sr isotopic signal should therefore approximate that of A in Figure 7B. Indeed, the first order (10^8 – 10^9 yr) $^{87}\text{Sr}/^{86}\text{Sr}$ secular trend, as observed in sedimentary carbonates, approximates the proposed signal (Figure 7C), with the transition from a ‘mantle’ to a ‘river’ buffered ocean apparently accomplished ≈ 2500 Ma ago.

The above observations, although open to alternative interpretations, are in good agreement with the available geologic record (e.g. Windley, 1984; Veizer, in press). The oldest continental-type rocks are known from the Isua area of Greenland and their age is ≈ 3800 Ma (Moorbath, 1977). The only older terrestrial materials are cores of some detrital mineral grains such as zircons (ZrSiO_4) from sediments in Australia, with ≈ 4200 Ma ages (Froude *et al.*, 1983). Following the ‘birth’ of the continental domain (population), its growth increased at first exponentially, but subsequently slowed down and approached a near steady-state situation at ≈ 1800 Ma ago. This growth pattern again resembles a population growth which approaches the *carrying capacity of the system*, as in living examples. Such growth pattern, designated as sigmoid or *logistic* in system science theory (e.g. Odum, 1983), is typical for autocatalytic modules, because the return flux in the autocatalytic loop is a quadratic function of the storage size. Consequently, as the storage (continents, biomass) grows, its decay (erosion, death) accelerates quadratically, eventually equalling the generation rate and the system reaches a steady-state. What is being argued at this stage is the relative importance of the generation of new pristine continental crust from the mantle, as opposed to the destruction of the existing crust, as a principal cause of this apparent continental growth pattern. If the rate of recycling of continental crust via mantle were diminishing in the course of geologic evolution, the proposed continental growth pattern could simply be a consequence of a preservation probability. It is likely that both causes were involved. Nevertheless, the lack of pre-3000 Ma detrital components in sediments of all ages (Veizer, 1983, in press; Miller and O’Nions, 1985) argues for a general scarcity of old continental crust and thus for accelerated growth as a major reason for continental buildup during the early, Archean, interval of terrestrial evolution.

4.2. OCEANIC DOMAIN: DERIVATIVE SIGNAL IN SEA WATER

The tectonic populations of the continental domain operate on time scales of 10^8 – 10^9 yr and the first order Sr isotopic curve therefore reflects the relative intensity of the river flux only on this time scale. Ever since continents, and rivers, became large enough to dominate the surficial cycle of Sr, sea water isotopic composition of this strontium never dropped back to mantle values. The ‘mantle’ flux, which reflects the operation of the faster, but smaller, oceanic domain, operates on time scales of 10^7 yr. This causes second-order oscillations of 10^7 years wavelength superimposed on the first-order, 10^8 – 10^9 yr, trend. Such oscillations have been detected as far back as the Archean, but the existing geochronology does not provide the desired time resolution on a routine basis until the appearance of shell secreting organisms at the beginning of the Phanerozoic (latest ≈ 570 Ma) (Figure

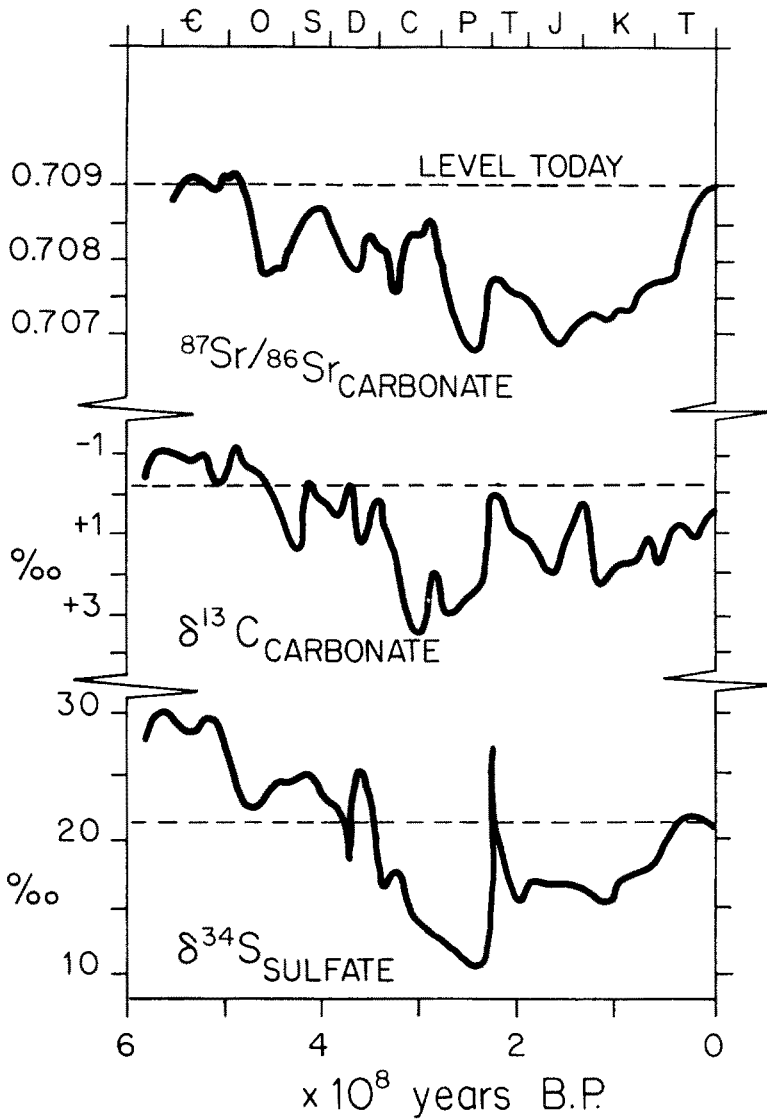


Fig. 8. Sea water isotopic age curves for the Phanerozoic (latest 570 million years) as recorded (a) in carbonates and in fossil apatites for Sr isotopes; (b) in carbonates for carbon isotopes; and (c) in evaporite sulfates for sulfur isotopes. Note the reversal of scale for carbon isotopes. Modified from Holser (1984) and Veizer (1984).

8). That these variations are indeed a reflection of the operation of the oceanic tectonic domain is confirmed by a correlation of Sr isotopic composition of sea water with 'sea-level' stands (Figure 9). The latter are relative heights of paleosea-levels in relation to the present-day strandlines. Theoretically, a higher rate of heat dissipation from the mantle causes more volcanism and thus faster generation and spreading of

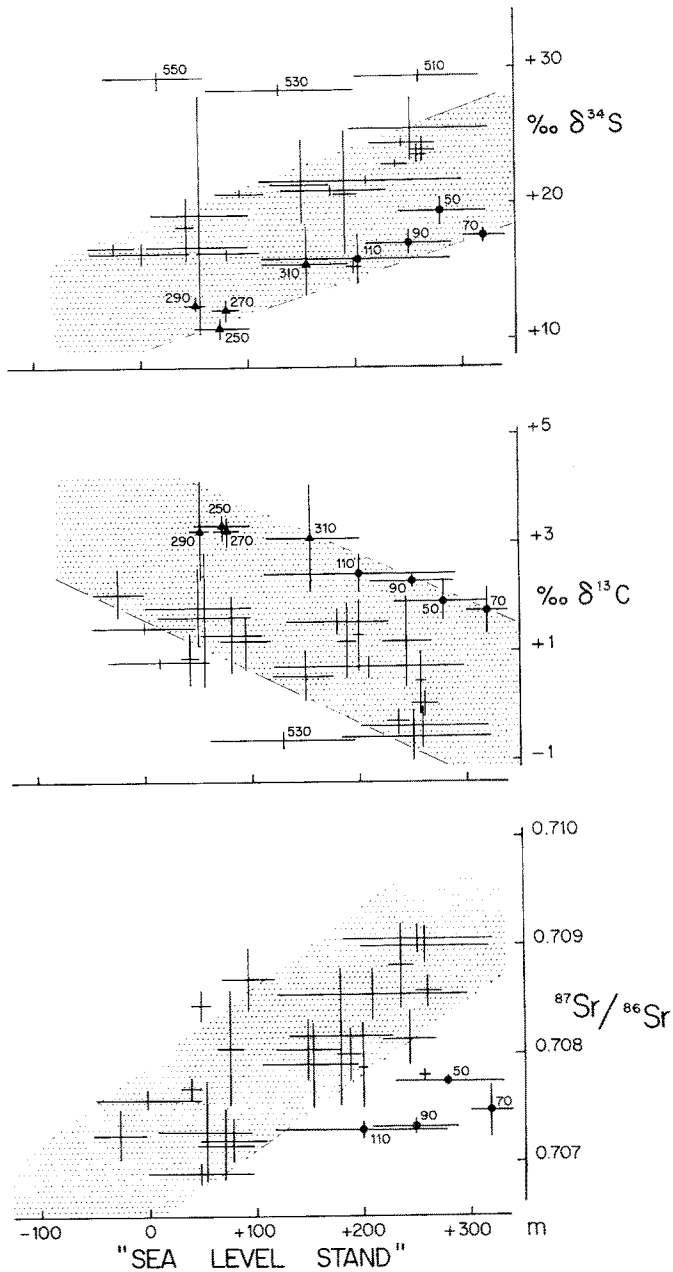


Fig. 9. Scatter diagrams of seawater $\delta^{34}\text{S}$, $\delta^{13}\text{C}$, and $^{87}\text{Sr}/^{86}\text{Sr}$ versus 'sea level' stands during the Phanerozoic. The isotope data are taken from the latest compilation of the curves in Holser (1984) and 'sea-level' stands from Vail and Mitchum (1979). The crossed bars represent the boundaries for a square which encompasses all variations for a given ≈ 20 Ma interval. The bars therefore signify the maximal limits of the observed variations, and their intersect signifies the midpoint (not average) of these variations. Numbers 70, 50, etc. mark the 70 ± 10 , 50 ± 10 Ma ages for those time intervals which depart from the norm. Reproduced from Veizer (1985).

the basaltic oceanic crust. This hotter young crust has lower density, causing high standing mid-oceanic ridges. The latter, in turn, displace seawater and cause marine transgressions over continental margins (Hays and Pitman, 1973). The 'sea-level' curve for the Phanerozoic should therefore be a direct reflection of the intensity of sea floor spreading in the geologic past. Higher spreading rates also demand more efficient cooling of the newly generated oceanic crust by more pervasive convective circulation of sea water (Figure 5). This factor introduces non-radiogenic basaltic $^{87}\text{Sr}/^{86}\text{Sr}$ into coeval oceans. However, contrary to expectations, the high 'sea-level' stands are associated with influx of radiogenic continental river-born Sr ($^{87}\text{Sr}/^{86}\text{Sr} \approx 0.711$). The observed correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ with 'sea-level' shows, therefore, that at times of fast spreading the denudation of continents increases to such a degree that 'continental' Sr overwhelms any hydrothermal increase in addition of 'mantle' Sr, the present-day balance being $\approx 4:1$. In other words, fast sea floor spreading leads to mountain building and increased erosion, as indicated already from the consideration of recycling rates. The Cretaceous ($\approx 140\text{--}65$ Ma BP) ocean appears to have been a major exception from the general Phanerozoic steady-state. Its non-radiogenic nature indicates very high influx of basalt-derived Sr. A massive intraplate volcanic activity, such as that from a multitude of Hawaiian-type island chains (e.g. Schlanger *et al.*, 1981), may have been the cause. Such volcanism does not necessarily result in tectonic compression and mountain building at the ocean-continent interface and a consequent influx of radiogenic ^{87}Sr .

5. Population Hierarchy of Living Systems

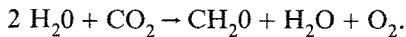
In terms of organic carbon (C_{org}) the mass of the *extant* global biosphere is perhaps $\approx 10^{18}\text{--}10^{19}$ g (Bolin, 1981; Bolin and Cook, 1983), with constituent populations being orders of magnitude smaller. The life-spans of these populations are from centuries to hours and their corresponding half-lives (τ_{50}) are therefore in the range of $10^2\text{--}10^{-3}$ yr. The general compatibility of internal age distributions in living systems with the pattern described in Figure 1 is well established and has been described, for example, in Deevey (1947), Valentine (1973), Pielou (1977), Hutchinson (1978), and Odum (1983). From the geological point of view, it is important to ascertain when the terrestrial biosphere first appeared and what was its subsequent evolution towards the present-day steady-state. The evolutionary aspects are treated in Schopf (1983) and this contribution will deal only with the origin and the size of the terrestrial biosphere.

5.1. THE ANTIQUITY OF LIFE

The oldest direct evidence for the existence of terrestrial life is the discovery of stromatolites (Walter *et al.*, 1980; Lowe, 1980; Groves *et al.*, 1981; Schopf, 1983), laminated organosedimentary structures produced by microbial biocenoses, in the ≈ 3500 Ma old Warrawoona Group of Western Australia and of filamentous prokaryotes from the same sedimentary sequence (cf. Awramik, 1981; Schopf, 1983;

Schopf and Parker, 1986). It appears that life on Earth spans almost the entire time interval represented by the preserved rock record. The oldest known rocks, the ≈ 3800 Ma old Isua metasediments, contain only disputed fossil-like artefacts (Pflug, 1978). These sediments are, however, strongly thermally altered and even a negative outcome of the present discussion should not be regarded as evidence for the absence of life. The great antiquity of life is supported also by arguments based on the inventory of terrestrial carbon, the fundamental building block of living systems.

The global inventory of carbon in the overall sedimentary, or exogenic, system of the Earth (comprising sediments, oceans, atmosphere and life) is $\approx 10^{22}$ gr, with the surficial exchange reservoirs (atmospheric CO_2 , dissolved marine bicarbonate, and extant biomass) accounting only for $\approx 0.1\%$ of this amount (Schidlowski and Junge, 1981; Schidlowski *et al.*, 1983, Bolin, 1981; Bolin and Cook, 1983). Consequently, the bulk of carbon resides in sediments either in its oxidized (carbonate rocks) or reduced (disseminated C_{org}) form, the present day relative distribution between these two oxidation states being $\approx 80:20\%$. The transfer of carbon from a carbonate reservoir into C_{org} is achieved through weathering of sedimentary rocks, liberation of CO_2 , and utilization of the latter in a photosynthetic reaction:



This results in generation of 'new' organic substances (C_{org}) in the exchangeable reservoirs. The bulk of the biomass is reoxidized to CO_2 after death and is thus involved in rapid recycling on time scales of 10^{-3} – 10^2 yr. Today, the fraction of C_{org} incorporated into sediments is $< 1\%$ and only this fraction is involved in the slow, 10^7 – 10^9 yr long, rock cycle. Thus the sediment-water (atmosphere) interface represents – in analogy to mountain belts – an interface of a small but fast active cycle with a large and slow passive cycle.

The $\delta^{13}\text{C}$, an arbitrary measure of the ratio of $^{13}\text{C}/^{12}\text{C}$ isotopes relative to the PDB standard, for gases originating in the interior of the Earth, the terrestrial mantle, is $\approx -6\text{‰}$ (DesMarais and Moore, 1984). In the absence of isotopic fractionation, all surficial reservoirs would inherit a comparable $^{13}\text{C}/^{12}\text{C}$ ratio. However, most ancient organic matter has $\delta^{13}\text{C}$ of about -25‰ . Although the actual ^{13}C depletion in organic matter is somewhat variable, and could have been generated by abiotic or chemosynthetic processes (Chang *et al.*, 1983; Schidlowski *et al.*, 1983), the remarkably consistent average $\Delta^{13}\text{C}_{\text{carbonate-organics}}$ of about -24 to -30‰ is likely due to RuBP, the key enzyme of the photosynthetic Calvin cycle, and hence to life. Assuming constant isotopic fractionation of 25‰ , the first photosynthetic life should have inherited $\delta^{13}\text{C}_{\text{org}}$ of about -31‰ (Figure 10). With increasingly larger amount of C_{org} stored in sediments, the $\delta^{13}\text{C}$ of the residual oceanic bicarbonate should become progressively heavier, reaching $\approx 0\text{‰}$ at a time when C_{org} attained $\approx 20\%$ of the total carbon pool (Broecker, 1970). The $\delta^{13}\text{C}$ of the coeval C_{org} should parallel this trend towards ^{13}C enrichment (Figure 10). However, the observed first order pattern resembles the present-day steady-state for

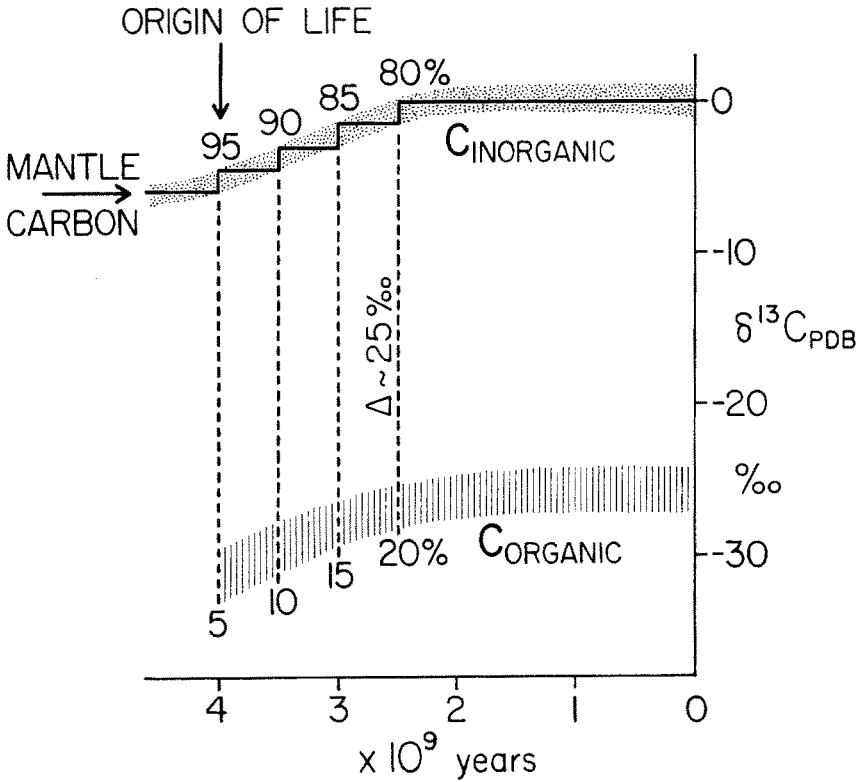


Fig. 10. Schematic presentation of $\delta^{13}\text{C}$ evolution for a theoretical exogenic cycle of carbon. In this instance, it is assumed that life originated ≈ 4000 Ma ago. 5, 10, 15, 20 are the percentage proportions of carbon which was sequestered into the reduced carbon reservoir (extant and buried C_{org}). $\delta^{13}\text{C}$ is derived as $\delta^{13}\text{C} (\text{‰}) = \{[(^{13}\text{C}/^{12}\text{C})_{\text{sample}} / (^{13}\text{C}/^{12}\text{C})_{\text{standard}}] - 1\} \times 10^3$. $\delta^{34}\text{S}$ is derived in a similar manner. The standard for C is PDB (Pee Dee Belemnite), and for S it is CDM (Canyon Diablo Meteorite).

the entire geologic record (Figure 11). This indicates not only a great antiquity of life but also its essential conservatism. To be exact, the uniformity of $\delta^{13}\text{C}$ in carbonates and C_{org} specifies only that the relative sizes of these two exogenic reservoirs of carbon have been constant. Considering that the global sedimentary mass attained its present day size ≈ 2000 Ma ago (Veizer, in press), the absolute sizes of the two C reservoirs should have been comparable to their present-day counterparts for at least the second half of the terrestrial life span. The isotope data do not constrain how much of C_{org} has been sequestered into the extant biomass, as opposed to the dead organic matter buried in sediments, at any given time in geologic history. It is therefore possible to generate scenarios with extant biomass smaller or larger than today, while keeping the total reservoir of reduced carbon constant. By the same token, the data are entirely consistent with the existence of a photosynthetic prokaryotic biosphere of $\approx 1/2$ (Hayes, 1983) to near present-day size (Schidlowski

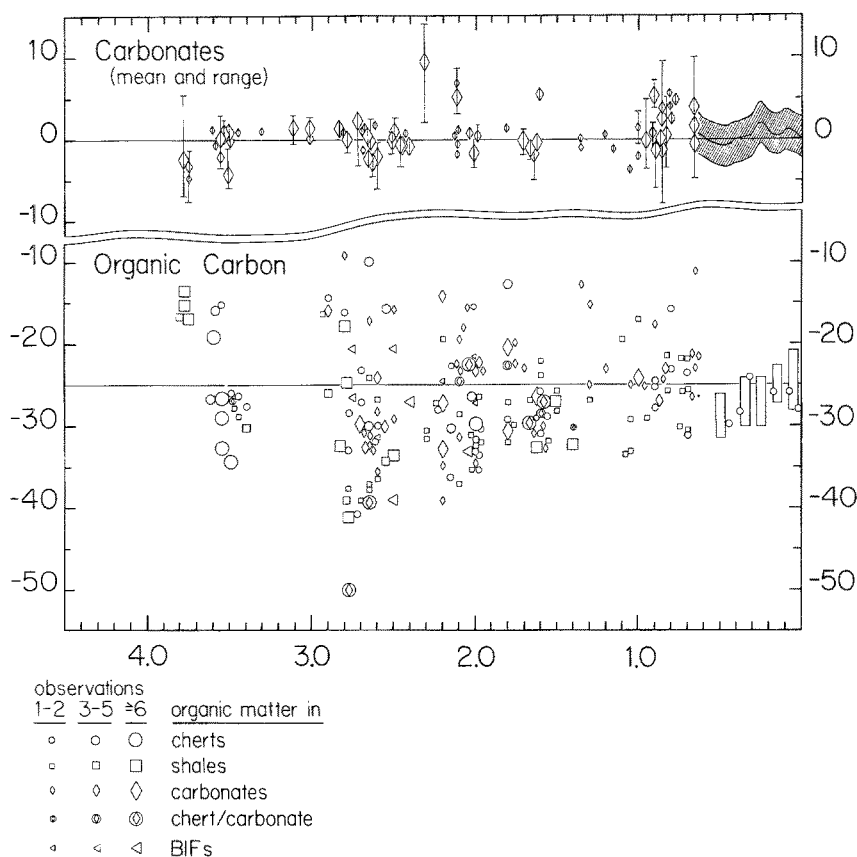


Fig. 11. Isotopic composition of sedimentary carbon as a function of time. The approximate constancy of the carbonate record is in marked contrast with the scatter of data points for organic carbon (kerogen) that reflects both primary variations and the later effects of diagenesis and metamorphism. The gross average for sedimentary organics of all ages is approximately -25‰ . The age trend for Phanerozoic carbonate values (mean and standard deviation) is according to Veizer *et al.* (1980), and that for kerogens of the same age is according to Galimov *et al.* (1975) and Welte *et al.* (1975). Bars imposed on the Phanerozoic kerogen record are standard deviations for selected age groups as reported by Degens (1969).

Modified from Schidlowski *et al.* (1983). (By permission of the Princeton Press.)

et al., 1983; Hayes *et al.*, 1986) as far back as 3500 (3800) Ma ago. The subsequent development may have been mostly that of recycling with ever increasing biological complexity. These propositions are perhaps unexpected but not entirely surprising. The limits on the size of the terrestrial biosphere, or the carrying capacity of the Earth, may be set, for example, by the supply of nutrients, such as phosphorus or nitrogen. This supply may be a function of their release from rocks by weathering and thus controlled by the rates of operation of the higher hierarchies of populations (solid earth and hydrospheric cycles). The emerging biosphere, because of the initial availability of nutrients, probably expanded exponentially, and rapidly reached the

limits imposed by nutrient supply. If this were the case, it is disturbing to note that no clear discontinuity is evident in the carbon isotope record (Figure 11) at ≈ 2.5 Ga ago; the times of transition from a 'mantle' to a river dominated ocean. Rivers are a prominent source of phosphorus (e.g. Meybeck, 1979), whereas mid-oceanic ridges are probably a sink for this nutrient (J. M. Edmond, pers. comm., 1986). Thus, the transition from phosphorus deficiency to abundance should have enhanced the size of the extant biomass, and perhaps the rate of its burial, with a potential to modify the carbon isotope record. Alternatively, the limits on the size of the terrestrial C_{org} may have been set by the overall oxidation-reduction balance of the surficial Earth (Holland, 1984), controlled possibly by mantle dynamics. The difficulty, or challenge, with this alternative is that in its extreme formulation it may obviate the need for the role of life in the ultimate redox partitioning of the exogenic carbon pool. Whatever the ultimate controls of the biomass, once the limits were reached, further propagation of life was maintained mostly by internal cannibalism, as expressed in the rapid oxidation-reduction cycle of the extant biomass.

5.2. FATE OF BYPRODUCTS: THE CASE OF OXYGEN

The above scenario poses problems for the traditional view that evolution of the atmospheric oxidation state was controlled solely by advancing biological evolution. Although oxygen is not an inevitable byproduct of early photosynthesis and of C_{org} storage in sediments, the data are consistent with such an interpretation. The traditional view (e.g. Cloud, 1976; Scientific American, 1983) presupposed the gradual evolution of oxygen-producing photosynthetic biomass and, as a consequence, development of an oxygenic atmosphere-hydrosphere system, with a crossover point at $\approx 2100 \pm 300$ Ma ago. Recently, suggestive geochemical (Hayes, 1983; Schidlowski *et al.*, 1983) and morphological (Schopf and Walter, 1983; Schopf and Parker, 1986) evidence indicates that oxygen producing photosynthesis may have been in existence much earlier, perhaps even 3500 Ma ago. If so, the early sources of oxygen may have been substantial (Veizer, 1983), yet the sedimentological criteria indicate low oxidation state for the early hydrosphere-atmosphere system (cf. Walker *et al.*, 1983). In such a scenario, an effective sink(s) is required for the maintenance of low partial pressures of oxygen. On the early Earth such a sink could have been the previously advocated enhanced circulation of sea water through oceanic crust (Veizer, 1983). The present-day 'black smokers', submarine hydrothermal vents which discharge modified, oxygen-depleted, hot sea water are an eloquent testimony to the potential effectiveness of this process. The scenario appears to be supported also by the ubiquity of Fe^{2+} and Mn^{2+} in ancient sediments (Figures 12, 13) and by oxygen balance calculations. Since photosynthesis results in generation of two free oxygens for each C_{org} present either in the living biomass or buried in sediments, the total quantity of photosynthetic oxygen in the surficial terrestrial reservoirs should be twice that of C_{org} , that is $\approx 3.2 \times 10^{22}$ gr (Schidlowski and Junge, 1981). The known oxygen reserves in the hydrosphere-atmosphere system and in sedimentary products of iron and sulfur oxidation do not balance this production. It has been

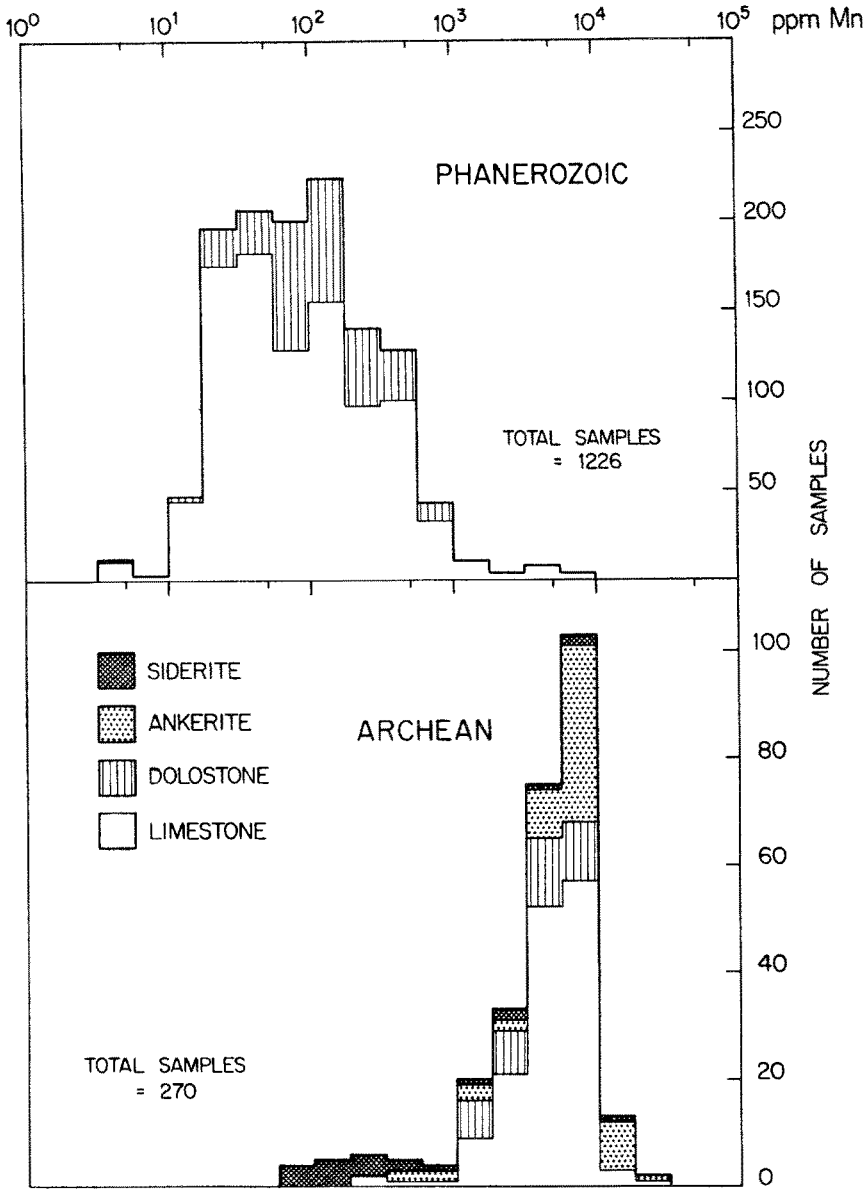


Fig. 12. Histograms of manganese (mostly Mn²⁺) distribution in Archean and Phanerozoic carbonates. Reproduced from Veizer (1985).

therefore proposed (Arrhenius, 1981; Ronov, 1982) that the missing oxygen has been reinjected into the interior of the Earth and the submarine hydrothermal systems (flux F_M) are the prime candidates for such oxygen 'scrubbers'. Note, however, that not all C may have been originally present as CO₂ (see the proposed 'mantle

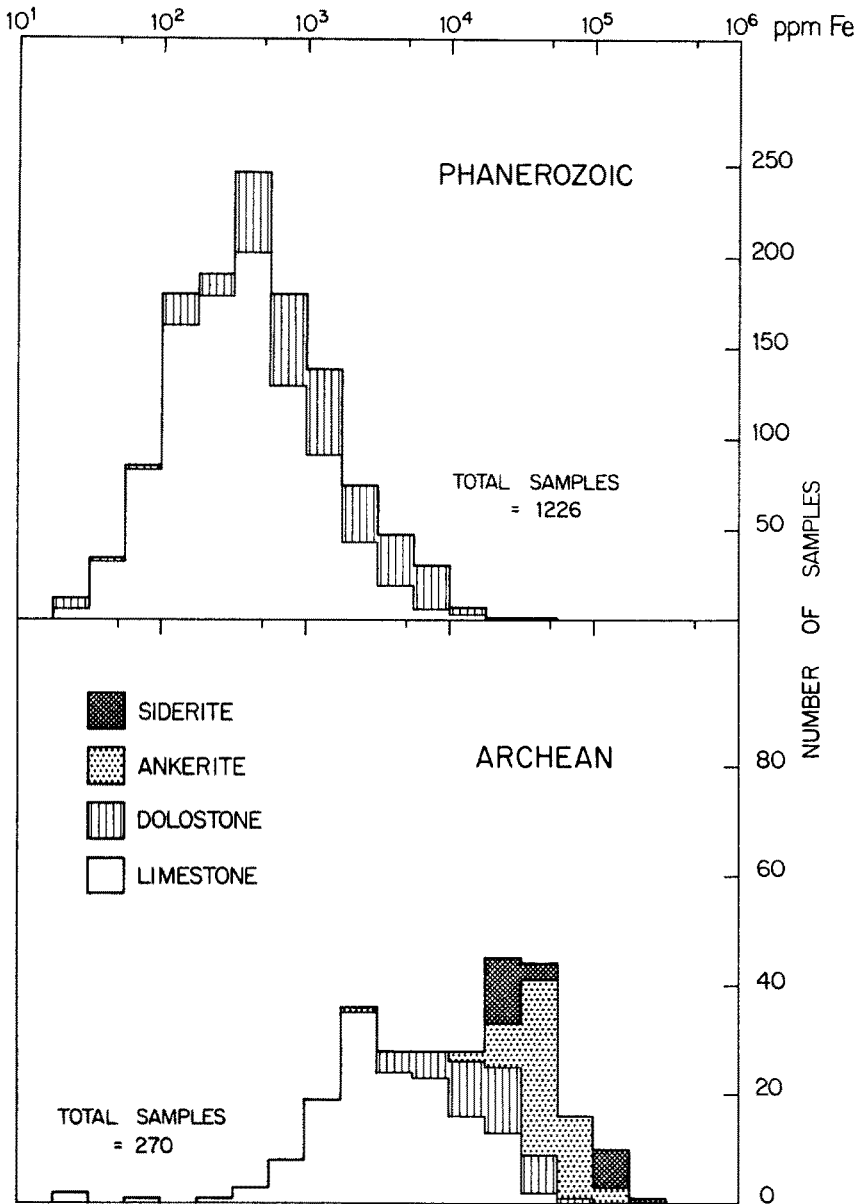


Fig. 13. Histogram of iron (mostly Fe^{2+}) in Archean and Phanerozoic carbonates. Reproduced from Veizer (1985).

dynamics' alternative of redox control in the previous section) and, if so, the apparent deficiency of oxygen may only be illusory. In this case, a proportion of the exogenic carbon pool may have existed from the start in a reduced form (see, for example, meteorites) and the ultimate role of life could conceivably be visualized as

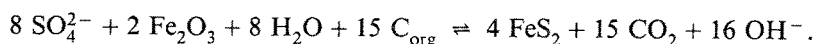
that of a catalyst in an essentially abiotic redox balance. Considering the heretical nature of this line of reasoning, I do not desire to pursue its consequences, but such a perspective would be consistent with the later discussed hierarchical interaction of populations within a system.

5.3. TECTONISM AND LIFE

Figure 11 demonstrates the essential stability of the biosphere on time scales of 10^8 – 10^9 yr. Superimposed on this steady-state are second and higher order oscillations of $\leq 10^7$ yr wavelengths. Because of time resolution problems, the second order oscillations in $\delta^{13}\text{C}$ have been deciphered for the Phanerozoic (Figure 8), and the higher order variations for the Tertiary and Quaternary (e.g. Sundquist and Broecker, 1985), intervals only. The observed 10^7 yr oscillations again correlate with 'sea-level' stands (Figure 9), clearly identifying tectonic processes of the oceanic domain as a causative factor. In the present context, it is important to note that the higher the 'sea-level', the lighter the $\delta^{13}\text{C}$ of sea water. This can be interpreted as an indication of a diminished sequestering of carbon into organic matter; the latter preferentially subtracting the lighter (^{12}C) isotope. The precise geological meaning of this relationship has yet to be deciphered. Nevertheless, the observation clearly poses problems for models suggesting large creation and burial of biomass at the times of high 'sea-levels' and thus of large epicontinental seas (Arthur *et al.*, 1985; Berner *et al.*, 1983; Mackenzie and Pigott, 1981). It may also pose problems for models which propose second and higher order biomass control through supplies of nutrients, such as phosphorus (Broecker, 1982). Times of high erosional rates (high $^{87}\text{Sr}/^{86}\text{Sr}$) should also be the times of maximal nutrient supply by rivers to the oceans and not vice versa. Whatever the detailed scenario, closer inspection of $\delta^{13}\text{C}$ data (Figure 9) indicates two limiting modes of operation of the carbon cycle. The 'heavy' isotopic mode (full circles), characterized by more pronounced generation and burial of organic matter, has been dominant during the Late Paleozoic and Cretaceous times. It may or may not be a coincidence that the two most important Phanerozoic mass extinctions, the terminal Paleozoic and Mesozoic ones (Raup and Sepkoski, 1984), coincide with the terminations of this mode of ocean operation.

5.4. TECTONISM, LIFE, AND ATMOSPHERE

The negative correlation between $\delta^{34}\text{S}$ and $\delta^{13}\text{C}$ (Figures 8, 9) (Veizer *et al.*, 1980) is a consequence of the coupling of sulfur and carbon surficial cycles (Garrels and Perry, 1974). The actual geological scenario is not well understood, but the chemical coupling can be written (Holser, 1984) as



The net effect is the utilization of oxygen from SO_4^{2-} for oxidation of C_{org} into CO_2 . The complementary reduction of sulfur, from SO_4^{2-} to H_2S , and ultimately pyrite, is bacterially mediated and results in an appreciable isotopic fractionation effect, with the light ^{32}S isotope concentrated in the reduced sulfur phase. By analogy with the

carbon cycle, when geologic storage of reduced sulfur is large the remaining sulfate in the oceanic reservoir is heavy (depleted in ^{32}S). Because of the above sharing of oxygen, an increase in generation and burial of organic carbon results in enhanced oxidation of reduced sulfur and vice versa. This explains the observed negative correlation between $\delta^{13}\text{C}_{\text{bicarbonate}}$ and $\delta^{34}\text{S}_{\text{sulfate}}$ (Figures 8, 9). As in the case of carbon, the oceanic sulfur cycle operates again in two limiting modes, but with a reversed signature (see Figure 9).

The correlations in Figure 9 demonstrate unequivocally that, on 10^7 yr time scales, the solid earth, hydrosphere, atmosphere, and biosphere act as a unified system. Consequently, the ‘living’ and ‘inorganic’ hierarchies of populations should not be envisioned as independent entities. Furthermore, the data show that the solid earth and its internal tectonic cycles are the dominant causative hierarchy. Tectonism apparently controls ‘sea-level’ stands, variations in chemical and isotopic composition of ocean water ($^{87}\text{Sr}/^{86}\text{Sr}_{\text{carbonate}}$), organic productivity and burial ($\delta^{13}\text{C}_{\text{carbonate}}$), and – via atmospheric linkage of C and S cycles – the $\delta^{34}\text{S}$ of marine sulfate. Although not yet understood in their precise geological scenarios, the data hint at a considerable buffering capacity and robustness of the terrestrial exogenic system in general, and of its life in particular. This buffering is a consequence of the linkage and interdependence of a multitude of diverse exogenic cycles.

6. The Earth System: Perspective and Design

The preceding discussion indicated that, from the point of view of the entire planetary system, the common thread to diverse physical phenomena is the concept of population dynamics. The populations discussed in this contribution span at least 13 orders of magnitude in mass (10^{13} – 10^{26} gr). The age distributions of their constituent units conform to the exponential (power law) systematics typical of populations propagated by recycling, that is through ‘birth’ and ‘death’ of the constituent units. Overall, the annual recycling rates appear to have been several orders of magnitude ($\approx 10^{-6 \pm 4}$) smaller than the population sizes. In general, the life-spans (τ_{MAX}) and half-lives (τ_{50}) of large populations appear to have been long and those of small populations short (cf. also Odum, 1983). The observed τ_{50} ’s ranged from 10^9 – 10^7 yr for the geologic tectonic realms, to 10^8 – 10^2 yr for the oceans, 10^7 – 10^{-2} yr for the atmospheric constituents, and 10^2 – 10^{-3} yr for the living systems (Figure 14). Viewed in this perspective, all populations are integral constituent parts of an all encompassing unity. However, the concepts of systems and of population dynamics do not require propagation of the present-day steady-state. The diverse constituent populations are in a constant intercourse on a variety of spatial and temporal scales, with some populations in *apparent* steady-state, others growing or declining, and still others being born or dying. In this scenario, the grand system design appears to have been a unity, with perpetual, statistically self-regulated, internal motions. It is beyond the scope of my experience to contemplate

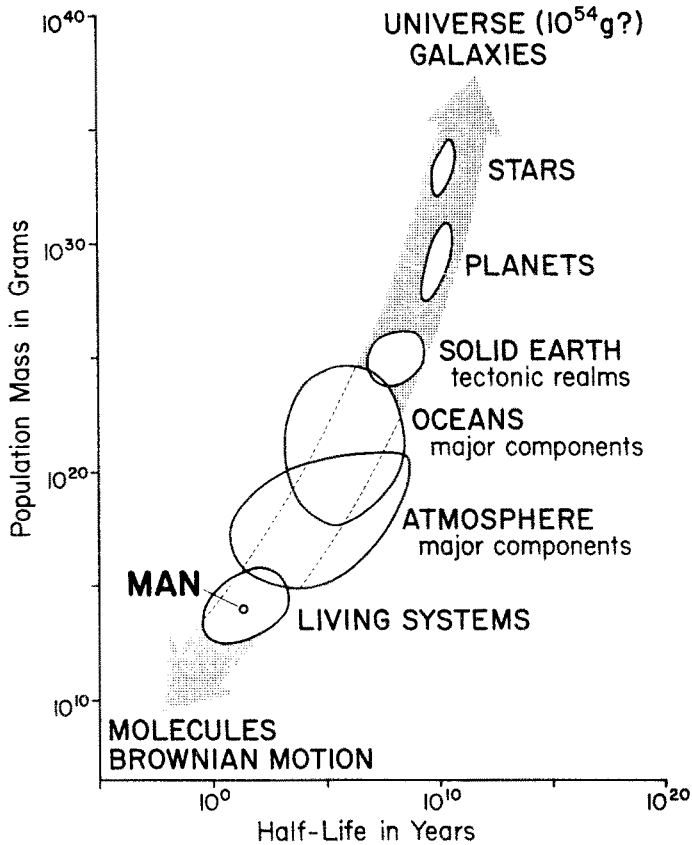


Fig. 14. A generalized plot of population sizes vs their half-lives. The estimate for the mass of the Universe is from Wilson (1969). See also Odum (1983, Chapter 27) for a comparable dimensionless presentation.

whether the concept of population dynamics can be extended to populations of microscopic and subatomic, as well as megascopic (e.g. galactic populations of stars, population of galaxies in the universe, 'many universes') sizes. The age distributions of stars in galaxies appear to be dominated today by old rather than young constituent units (P. J. E. Peebles, pers. comm., 1985). If so, the concept is not applicable to gigantic dimensions. Alternatively, our Universe, with its constituent galaxies and stars, is in a youthful stage of a very long 'life' cycle, and thus still populated by units 'born' as an early response to its 'big bang birth' (cf. Figure 15).

The previously documented interdependency of inorganic and living worlds is consistent with the view that life is an important parameter in planetary evolution. However, in contrast to the GAIA hypothesis (Lovelock, 1979) that life regulates the terrestrial exogenic system for its own benefit, I propose that life is constrained by limits imposed by the interdependent larger populations. In the first instance, the

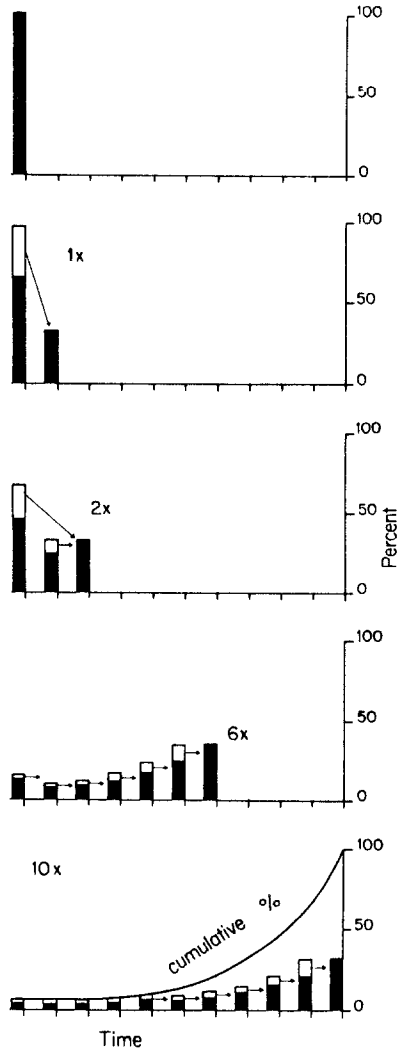


Fig. 15. Schematic presentation of the present day exponential (power law) cumulative age distribution of an entity generated via recycling in a steady-state population. The upper three cases may be indicative of age distributions in populations of galaxies and stars.

development of a suitable planetary system is controlled by vagaries of stellar evolution. Secondly, geological evidence from this planet clearly points out that tectonism controls the biosphere and not vice versa. Temporary departures from these controls are possible, but only on time scales shorter than those of the controlling larger populations. Nevertheless, I do believe that within the broad limits erected by the dominant populations, life exerts substantial modulating influence and acts as a catalyst. This catalytic effect, resulting in acceleration of otherwise sluggish inorganic processes, is responsible for the maintenance, for example, of the atmospheric blanket of oxygen and thus for our own existence and well being.

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