

A WORKING MODEL OF THE PRIMITIVE EARTH*

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ABSTRACT. Knowledge of the sedimentary and biological record of pre-Paleozoic time, scanty though it still is, suggests a working model of early Earth history consisting of four successive modes (or Eons) punctuated by "events" in which surface conditions on the Earth changed relatively rapidly. The four modes are:

1. An interval (Hadean) for which no certain record has been discovered on Earth, though it has on the moon — ended 3.6 to 3.5 aeons ago by a world-wide thermal event, possibly cosmic as the moon may also have been affected.

2. An interval (Archean) characterized by rocks mainly or entirely of the greenstone-graywacke-granodiorite suite, relatively low in potassium and little differentiated, by the earliest suggestions of life, and by thin crust and no large continental cratons —ended about 2.6 aeons ago by the beginning of extensive cratonization.

3. An interval (Proterophytic) characterized by the formation of large continental cratons and upon them a gamut of differentiated sedimentary and igneous rock types, and by the oxidation of vast amounts of iron by photo-autotrophic procaryotic microorganisms, although the atmosphere remained reducing. This terminated around 1.9 aeons ago with the development of advanced oxygen-mediating enzymes that permitted the evasion of oxygen to the atmosphere and probably led quickly to the development of eucaryotes, mitosis, and sex.

4. An interval (Proterozoic in a restricted sense) characterized by an increasingly oxidizing atmosphere and oxidized sediments, especially red beds, and by an abundance of unicellular eucaryotes, but without differentiated multicellular animal life (Metazoa) —ended about 0.68 aeons ago by the appearance of an ozone layer in the atmosphere, by the onset of Metazoa, and perhaps by a climax of continental glaciation.

INTRODUCTION

Recent advances in geochronology, geochemistry, biogeology, microbiology, electron microscopy, and sedimentology converge with the increasingly genetic focus of pre-Paleozoic geology to illuminate the evolution of the primitive Earth with growing clarity. Scanty though it still is, we now have a presumptive record of life going back to the oldest sedimentary rocks, and one that we can unequivocally relate to known living organisms for at least the last 2 aeons (years $\times 10^9$). Broad trends in crustal evolution are now also clear, and some of these can be related to biospheric and atmospheric evolution. The larger need is for a consistent working model that will integrate present knowledge and well-reasoned inference about the interdependent variables so as to focus on the central problems and predict future directions of advance. Such a model, under study for some years now, is here outlined—not with any thought of finality, but as a framework for discussion and a focus for observation.

RATIONALE

Because time is continuous and without natural subdivisions, it becomes necessary in all historical science to identify events or broad

* In preparing this paper, I have drawn heavily on the data and ideas of others, especially the participants of the Third Penrose Conference at Laramie, Wyoming (September 1970, Cloud 1971) and those who preceded me on the program of the Geological Society of America at which this paper was presented (November 2, 1971). The research on which this paper is based was supported by NSF Grant Nos. GB-7851 and GB-23809 and by NASA Grant No. NGR-05-010-035. This is Contribution #27, Biogeology Clean Lab, University of California, Santa Barbara, California 93106

modalities that set off one part of the sequence from preceding and following parts so as to bring out historical trends. One doesn't simply divide human history or crustal evolution into units of equal length in years without evidence for a true cyclicity of events, which has yet to be demonstrated for geologically long intervals at a global scale.

Nevertheless, an historical system must be calibrated as well as punctuated, and this requires some kind of time sequence and nomenclature. The best sequence we can have is one that reflects real time quantitatively, as do the radiometric numbers which in recent years have contributed so importantly to the emergence of an interregional pre-Paleozoic stratigraphy. At the same time, it is important to discriminate between crustal evolution and the system with which we attempt to calibrate it, and I will do that here.

In speaking of crustal evolution, I include not only the historical sequence of the rocks themselves but also the evidence contained within them of the interrelated evolutions of biosphere, atmosphere, hydrosphere, and chemosphere. Indeed, what is known or reasonably inferred about each of these lines of evolution places constraints on what may justifiably be inferred about each of the others. When all such evidence is considered together and found to converge, a powerful fabric of credibility results, even where individual lines of evidence may be less-than-compelling.

A difficulty in trying to reconstruct pre-Paleozoic history has been our disproportionately greater level of information about crystalline rocks, in contrast to those of demonstrably sedimentary origin, and our slowness in learning to recognize the sedimentary origin of some crystalline rocks. Our best radiometric numbers are on intrusive rocks, and, although they cluster in most interesting ways, it now seems clear that near or seemingly correlatable intrusive events took place over different time intervals in different regions, that some of the most important ones may have been scores of millions of years between emplacement and final cooling, and that some numbers represent episodes of rejuvenation rather than initial crystallization.

For the punctuation of our geologic continuum, we seek trend-related events that have affected the entire Earth over relatively short intervals of time and left recognizable signatures in the rock sequences of the globe. Such attributes are more likely to result from events in atmospheric, climatic, or biologic evolution than in plutonic evolution and hence should be more characteristic of the sedimentary record than of the igneous or metamorphic record, although the latter must be included in any meaningful global assessment.

MAIN TRENDS IN CRUSTAL EVOLUTION

What broad modal trends and events stand out in the history of the primitive Earth, defining that history as beginning with the accumulation of the Earth as a solid body and ending with the appearance of differentiated multicellular animal life—whose elaboration comprises the stuff of conventional historical geology? And how can we array these

modalities and events into a consistently interrelated and testable system that gives us some feeling for the broad aspects of crustal evolution?

Four broad modes can be discerned, succeeded by a fifth, the Phanerozoic, representing geologically "modern" times. The oldest of the pre-Phanerozoic modes comprises the first aeon of Earth-history, from the time of accumulation of the Earth about 4.6 aeons or more ago to that of the oldest confidently dated rocks, about 3.5 to 3.6 aeons ago.¹ These oldest firmly dated rocks are generally gneisses and schists which appear to represent still older parent rocks in which radiometric clocks have been reset by some global and perhaps cosmic thermal event. We do not really know the age of deposition or original nature of these "basement" rocks but only that they are very old and that some are metavolcanic or metasedimentary, or both.

Indeed the only rocks we know with certainty to be older than about 3.6 aeons are a few that have been returned from the moon. On the moon these rocks are called pre-Imbrian. If and when the occurrence of rocks of this age is confirmed on Earth (and some believe it is already confirmed), we might find it preferable to call them Hadean, implying their basal position in the geologic sequence; or, perhaps, Selenian, in token of their lunar affinities.

The second great modality, and the oldest to be represented by unequivocally dated terrestrial rocks, is commonly designated as Archean. These rocks, roughly 3.6 to 2.6 aeons old, are "granitic" (commonly granodioritic) and gneissic complexes, ordinarily with relatively low ratios of potassium to sodium (Ronov and Migdisov, 1971; also A. E. J. and Celeste Engel, oral commun., September 1970), unless K-metasomatized; and enclosed or embedded in belts of greenstone and volcanoclastic graywacke-like sediments that are analogous in their implication of mantle sources and immature weathering to the volcanic-sedimentary complexes of modern island-arcs. Although similar rocks of younger age are common, their association, to the near-exclusion of other types (except ultramafics, charnokites, and other granulite facies rocks), seems to be a universal feature of this second major phase of Earth history. Archean folded terranes commonly, and perhaps generally, consist of contiguous subsiding belts without intervening anticlinal structures, often associated with ultramafics. Over most of the Archean earth, the crust appears to have been thin, cratonization weak, and roughly linear subsiding belts common. A few places, such as in west central Arizona, show essentially Archean styles of rock associations of much younger age. Such sequences must be viewed in the larger context of interregional geology.

The third big modal trend in early crustal evolution is an interval of marked cratonization, during which plutonic and sedimentary rocks alike became increasingly sialic and cratonal. It shows an abundance of

¹ Black and others (1971) have now published *preliminary* evidence suggesting an age approaching 4 aeons on amphibolitic gneisses from West Greenland; but, as these authors are careful to point out, the basic data can be interpreted in several ways, one of which implies an age not much greater than 3.6 aeons.

relatively potassic granites and gneisses and plenty of clean quartzites and arkoses. Many of its platform deposits remain undeformed to the present day. This interval extended from about 2.6 to around 1.9 aeons ago. The ratio of potassium to sodium in granites and other rocks of this age is, as a rule, greater than that of older rocks. The oldest thick and extensive carbonate rocks occur near the top of this sequence. It terminates with a great episode of banded iron formation and is followed by the oldest red beds of consequence. Its sediments, although cratonal, are not subaerially oxidized. Rocks of this age have been designated by a confusing variety of terms, most commonly Lower Proterozoic (although Lower Proterozoic conventionally includes somewhat younger rocks as well). Inasmuch, however, as evolution of primitive plants (blue-green algae and bacteria) rather than animals is what is biologically important about this interval, we might cut the Gordian Knot of conflicting terminology by calling it Proterophytic and reserving Proterozoic for pre-Paleozoic rocks younger than about 1.9 aeons—an interval most of which is included in the Proterozoic of all classifications that employ that term. Although the Proterozoic, so defined, is not known to contain animal fossils, Protozoan remains are to be expected in its upper parts, and long-standing usage, although not strictly logical, does deserve to be conserved as far as practicable.

The fourth and last great modality observed, the Proterozoic proper (or Upper Proterozoic, if Proterophytic doesn't appeal), includes an aggregation in which oxidized sediments are conspicuous, and which is generally similar to Phanerozoic rocks except for the rarity of sedimentary calcium sulfate, the preponderance of dolomite over limestone, and the absence of Metazoan fossils, tracks, burrows, or after-death imprints. It includes rock types characteristic of the older sequences as well but is distinguished by the addition of oxidized cratonal sediments. It began around 1.9 aeons ago, when thick and extensive continental red beds first appeared, and lasted until about 680 m.y. ago, when the late pre-Paleozoic ice ages were waning, and the first authentic Metazoa are known.

These broad subdivisions of primitive crustal evolution can be recognized on every continent that has a good pre-Paleozoic sequence. They are also reflected, if somewhat unevenly, in the clustering of radiometric ages of plutonic rocks. But they must be integrated with other evidence to create geologic history and to discern potential turning points in that history.

In what remains of this paper, I shall attempt to relate some of these other elements to the broad features of crustal evolution suggested above.

INTERRELATION WITH ATMOSPHERIC AND BIOSPHERIC EVOLUTION

Source of atmospheric oxygen.—Consider the atmosphere, in particular its anomalous 21 percent of oxygen. No plausible model of atmospheric origin provides either a primary or a juvenile source of free

oxygen. Whether or not Earth accumulated with a residual atmosphere, the very low ratios of the noble gases in our present atmosphere, as compared with cosmic abundances, tell us that it has descended from one that accumulated as a consequence of the volcanic outgassing through time of originally occluded gases. Oxygen, not being among such gases, must have arisen through some secondary process. Plausible sources include the photolytic fission of the water molecule with escape of hydrogen from Earth's gravity field and the photosynthetic combination of CO_2 and H_2O , with sedimentary segregation of carbon (plus relatively minor additions from rock weathering). Both processes occur, and each has undoubtedly contributed some of the oxygen now in atmosphere and hydrosphere, and combined with other elements in sedimentary sulfates, ferric oxides, and other oxygen sinks. One way to assess the problem is to see whether a geochemical balance exists between oxygen and carbon in the present atmosphere, hydrosphere, and lithosphere. Unfortunately, we cannot make a similar test for oxygen and hydrogen, because no way has been found to measure independently the mass of hydrogen that has escaped Earth's gravity field, or, conversely, that has been added to our atmosphere by the solar wind.

Fortunately, numbers are available for oxygen and carbon that were compiled quite independently and for a different purpose. These are shown in figure 1, which was prepared from the data of W. W. Rubey

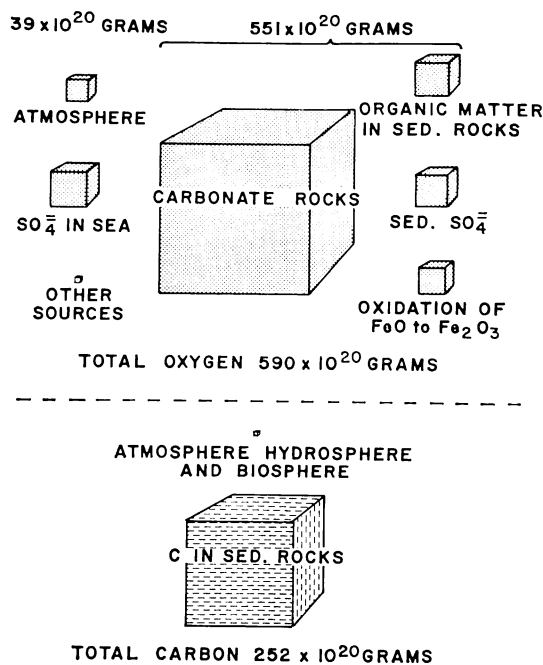


Fig. 1. Oxygen-carbon geochemical balance.

(1951), modified only to allow for larger deposits of ferric oxides than were then known. These numbers show an unexpectedly close geochemical balance between the combining equivalents of carbon and oxygen, with just enough carbon left over to account for the conversion of about 6×10^{20} g, or 6 geograms, of volcanic carbon monoxide to carbon dioxide (which seems low for consumption of oxygen by reduced volcanic gases). Of course, this estimate does not allow for the recycling of crustal materials beneath drifting continents, but that should not affect ratios, and it is these that are critical. The oxygen budget also presumably should include some O_2 resulting from rock weathering and some from outer atmosphere dissociation of H_2O —estimated respectively as 29 geograms and 89 to 100 geograms by G. D. Nicholls (Manchester, England, oral commun., 5 January 1972). Both these estimates, however, are only small fractions of the total O_2 budget, the physical dissociation estimate is very uncertain, and the consumption of O_2 in the conversion of volcanic CO to CO_2 is probably larger than suggested above—perhaps by some tens of geograms, which do not show in the estimated oxygen budget. Thus the near-balance observed between C and O_2 in figure 1 implies that photosynthesis was the main source of free oxygen and that rock-weathering and non-biological photolysis was comparatively unimportant.

Now it is time to see how the broad aspects of primitive crustal evolution may be integrated (fig. 2).

Hadean Time.—We have known that the solid parts of the solar system originated somewhat more than 4.5 aeons ago ever since the classic demonstration by Patterson (1956) that the isotopes of meteoritic and oceanic leads defined an isochron of that age (“primordial lead”), and the number has been revised only slightly upward. But the oldest unequivocally dated minerals on Earth are only 3.55 aeons old (Goldich, Hedge, and Stern, 1970), and they approach a similar age on several continents. It looks as though a thermal event of global scope had reset all the radiometric time-keeping systems about then. Available estimates indicate that this could not have been the heat of planetary accumulation and probably not radiogenic heating, because those processes should have had their main effects much earlier. The finding of similar numbers on the moon suggests that there may have been a relation, as I suggested before the lunar numbers were known (Cloud, 1968a)—perhaps a near approach of moon to Earth; or maybe an episode of bombardment by large meteorites, whose kinetic energy, converted to heat, produced magma pools and thermal metamorphism; or other cosmic event.

Archean and Proterophytic Time.—I suppose that if there had been an older atmosphere, hydrosphere, or biosphere, it would not have survived this thermal event, and that the beginning of a well-defined record of primitive Earth evolution dates from after that time. At least we know, from the evidence of thick and extensive sedimentary deposits approaching this age in eastern South Africa and Swaziland, that there

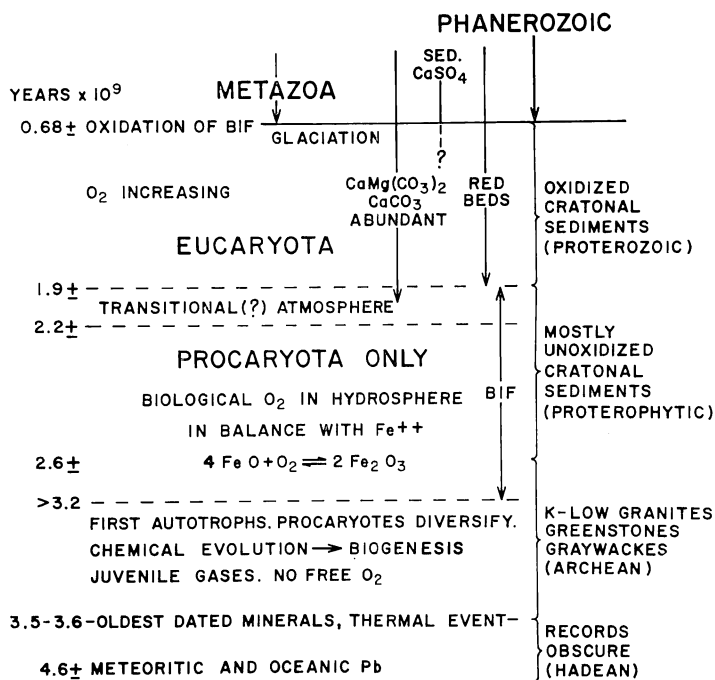


Fig. 2. Evolution of the primitive Earth.

was a substantial atmosphere and hydrosphere, and probably a biosphere, shortly after this 3.5 to 3.6 aeon event, whatever it was. The most recent number we have is a Rb-Sr isochron age of 3.38 aeons on Onverwacht sediments by the M.I.T. geochronology group (Hurley and others, 1971).

The volcanism and outgassing associated with the heating of Earth's outer shell at that time probably gave rise to a very large fraction of all the gases that ever reached the surface of the Earth—perhaps 10 to 30 percent of the volume of the present atmosphere and hydrosphere. An atmosphere of juvenile gases (CO, CO₂, H₂O, N, HCl, and probably some H, NH₃, and minor gases), in the absence of free oxygen, provides ideal circumstances for the chemical synthesis of large organic molecules, leading to the origin of life. In the absence of an ozone screen, high-energy UV radiation would impinge on Earth's surface waters, and organic compounds produced could accumulate without serious threat of oxidation. Many important steps in chemical evolution leading toward a living cell have been repeated in the laboratory by biochemists and biophysicists, experimenting with likely models of the primitive atmosphere—the common and essential feature of the successful experiments being the absence of free oxygen. Although a living cell has not as yet resulted from such experiments, the only serious remaining question (and the quite unanswerable one in the face of a variety of con-

ceivable routes) is, “exactly what pathway did lead to the evolution of the first living organism?”

The first living cells, in any case, almost certainly inhabited an oxygen-free environment and fed on organic substances of non-biological origin or on one another. They were, technically speaking, anaerobic heterotrophs. But evolution would not have gone very far without the emergence of an organism that could manufacture its own food products, using sunlight or chemical energy to activate the process—an autotroph. When that happened, we should expect to see a diversification of the morphologically simple and essentially asexual forms of life we designate as Procaryota to signify their rudimentary nuclear structure and cellular organization.

An interesting question is: “What happened when the first of these early autotrophs became an oxygen-releasing photo-autotroph—oxygen being poisonous to all forms of life in the absence of suitable oxygen-mediating enzymes?” Unless it simultaneously evolved a full complement of advanced oxygen-mediating enzymes, it would have been in grave need of some chemical oxygen-acceptor in the surrounding physical environment. Water-splitting photo-autotrophs which today lack oxygen defenses survive by attaching their oxygen waste-products to the sulfide ion, converting it to sulfate, or to other suitable and available reduced ions—but we do not see in the older geologic record the large deposits of the oxidized products of these substances that we would expect to see if they had then been important oxygen sinks.

Instead we see vast deposits of banded iron formation (BIF) of near global distribution in sedimentary rocks older than about 1.8 to 1.9 aeons. This mainly siliceous BIF (especially between about 1.9 to 2.2 aeons ago) is commonly thick, of great lateral extent, relatively rich in hematite, most commonly low in phosphorus, and primarily a chemical blanket-deposit from open waters of broad extent. Excepting rare, mostly restricted, and often earthy younger deposits, commonly with discontinuous banding and characteristically associated with volcanism and narrow, subsiding, euxinic trenches, typical BIF is not known from rocks younger than about 1.9 aeons.

The extensive, time-limited, blanket deposits of hematitic and magnetitic BIF pose a geochemical dilemma. How could the iron have been transported over such large areas had the atmosphere (and hydrosphere) been oxidizing, and how could it have been precipitated in the absence of free oxygen? The dilemma is resolved by calling on ferrous iron in solution to serve as an oxygen acceptor for the early photosynthesizing microorganisms. In the absence or rarity of free O_2 in the atmosphere and hydrosphere, ferrous iron would be freely transported in solution wherever waters moved. Biological O_2 production in the hydrosphere in fluctuating balance with a sink of ferrous iron would account for its precipitation as insoluble ferric oxide, as well as for the banding and varying facies of BIF (these being products of varying levels of local oxidation and distance from sources of oxygen). I must note that

there are interesting and perhaps significant differences between Archean and Proterophytic BIF that sometimes lead to differences of opinion about origin—but that story, interesting though it is, would be discursive here. I emphasize instead only that the presence of thick and extensive BIF of the Algoma and Lake Superior types, and the essential absence of red beds, characterizes a long episode of sedimentation and biological evolution that ends with the third major modality of crustal evolution, the Proterophytic.

The microorganisms of this time (and life then was wholly micro-biological) were probably limited to deep-planktonic and stromatolite-building protonucleate and non-mitosing cells—the procaryotes. Since, moreover, all living mitosing or eucaryotic cells are either obligate aerobes or dependent on obligate aerobes, it seems likely that eucaryotes could not have evolved until a suitable level of atmospheric oxygen arose. The BIF, the absence of substantial red beds, the presence of widely distributed detrital uraninite and pyrite, and the probable nature of the biosphere converge to imply that the atmosphere anterior to about 1.9 aeons ago contained only trivial and transient amounts of free oxygen.

The advent of advanced oxygen-mediating enzymes, releasing the photosynthesizers of the time from dependence on the ferrous iron sink, was more than a major development in biochemical evolution. It necessarily had pronounced, geologically near-instantaneous, global responses that should be observable in both stratigraphic and biologic evolution. The previously iron-dependent photosynthesizers would now be freed of such dependence. They could flourish throughout all parts of the hydrosphere that were both within the photic zone and sheltered from UV in the range of 2400 to 2600 angstroms. Ferrous iron would be swept out of solution in a final episode of blanketing ferric oxides and other oxygen-sinks would be wiped out. Oxygen could begin to accumulate in the atmosphere provided (and as rapidly as) some of its carbonaceous by-product was sequestered. With high-energy UV still impinging on Earth's surface, highly reactive ozone and atomic oxygen, as well as molecular oxygen, would be available for the oxidation of reduced substances then abundant at the surface of the Earth and in the atmosphere.

Proterozoic Time (restricted).—Evidence that the oldest major episode of atmospheric oxidation began about 1.8 to 1.9 aeons ago is seen in the continental red beds of this age on most continents. The youngest blanket deposits of BIF seem to be older than the oldest prominent red beds. The carbon counterpart of this oxygen influx may be seen in the roughly 1.8 to 1.9 aeon metacoals or shungites of Soviet Karelia and Siberia as well as in volumetrically more important carbonaceous sediments of this age elsewhere.

Continuing refinement of the evidence, especially in the Canadian Shield, suggests that there may have been a transitional interval of perhaps as much as 300 m.y. between the almost completely anoxygenous

atmosphere of older pre-Paleozoic time and the freely (but not highly) oxygenous atmosphere in which the first important red beds formed—the occurrence of thin red siltstones and shales in the Cobalt Group and younger Huronian beds has been summarized by Roscoe (1969, p. 81-82). But the massive onset of thick and extensive red beds and the termination of the blanket deposits of BIF are near enough in time to suggest a common relationship to the emergence of a substantially oxygenous atmosphere about 1.9 aeons ago. Eucaryotes may have evolved (the evidence is equivocal) at about the same time. Thus we seem to have an event of relatively short duration and global extent that separates long trends in atmospheric, biospheric, and lithospheric evolution.

I suggest that this is the kind of event we have been looking for, that it is probably real if not yet precisely placed in time, and that we should use it to delimit major divisions of pre-Paleozoic crustal evolution. Whether we choose to call these divisions Proterophytic and Proterozoic, Lower and Upper Proterozoic, or something else, is of no substantive concern, although eventually geologists will have to submerge these inconsequential differences and agree on names if they want to communicate clearly.

The beginning of substantial evasion of O_2 from hydrosphere to atmosphere thus marks the beginning of our fourth main pre-Paleozoic evolutionary package—the terminal sequence of dominantly cratonal and oxidized sediments. The oxygen did not come all at once, however. To assert, as some have done, that all the oxygen now in the atmosphere could arise abruptly following the onset of photosynthesis is to fail to recognize the reversible nature of the photosynthetic reaction (basically $CO_2 + H_2O \rightleftharpoons CH_2O + O_2$), such that oxygen can accumulate no faster than a chemically equivalent mass of carbon is sequestered (nor until the oxygen sinks of the time are filled). We see suggestions of the gradual accretion of O_2 in these younger pre-Paleozoic rocks in the continuing abundance of carbonaceous sediments, in the succession of red beds, and in the abundance and wide distribution of carbonate rocks of this age.

Proterozoic-Phanerozoic transition.—We come now to a convergence of events in biospheric, lithospheric, and perhaps atmospheric evolution which, I believe, logically marks the termination of primitive Earth evolution and the beginning, geologically speaking, of essentially modern times. I take this as the logical transition from Proterozoic to Phanerozoic, that is from pre-Paleozoic to Paleozoic times. Of course it is not a sharp line, any more than any other geological “boundary” of more than regional extent; but it seems to me to be an interval of profound transition in evolutionary style that deserves serious attention in establishing local boundaries of convenience.

I refer to that convergence of events to be seen in the onset of Metazoan life, the appearance of sedimentary sulfate as a common rock type, the waxing and waning of extensive mainly late pre-Paleozoic

glaciations,² and the consequent lowering of water tables and oxidative enrichment of the BIF protosols that we see especially in North America. The wasting of the late pre-Paleozoic (and locally early Paleozoic) glaciers perhaps also gave rise to the initial epicontinental floods of Phanerozoic time.

These several developments are consistent with the suggestion that there may have been a noticeable increase in atmospheric oxygen around 680 m.y. ago³—perhaps from around 1 percent present atmospheric level, where an effective ozone screen appears (for example Berkner and Marshall, 1965), and a large increase of photosynthetic populations is conceivable to substantially more than that. One reason for supposing that this may have been the case is the fact that, of the two essential preconditions for the emergence of a Metazoan grade of life, that of a eucaryotic level of cellular evolution had long previously been realized. The most probable explanation for the relatively abrupt appearance of the Metazoa at this time (Cloud, 1968b) is, thus, the triggering effect of the attainment of a sufficient level of free oxygen, as originally suggested by Nursall (1959) and later by Berkner and Marshall (1965). The relatively rapid diversification implied during basal Paleozoic or Ediacarian time (an interval of perhaps 100 m.y. or more) becomes comprehensible if one visualizes a polyphyletic origin, with relatively uncontested adaptive radiation into previously unoccupied ecologic niches.

That such an emergence and adaptive radiation of the Metazoa should define the base of the Paleozoic (and, of course, the Phanerozoic) would hardly be questioned if it were widely accepted as a reality. I think it probably is a reality and that, as the evidence is critically reviewed by others, it will become generally accepted as such. It is, of course, reinforced by other aspects of crustal evolution already alluded to. The oxidative enrichment of the banded iron formation and the relatively abrupt onset of thick and extensive sedimentary sulfates would be logical consequences of the suggested increase in oxygen. The glaciation (if it is real and nearly synchronous) could have been triggered by a reduction in CO₂ (and the greenhouse effect) related to the suggested increase in O₂.

It is also a prediction of the mechanism suggested that there should be substantial deposits of carbon of late pre-Paleozoic and early Paleozoic age. It is of interest that the fine clastics associated with tillites and dropstone breccias of this age are often relatively carbonaceous. Ronov and Migdisov (1971, p. 176, fig. 9) have also documented a marked in-

²These glaciations, sometimes taken to imply an improbable global freezing, may reflect instead an episode of relatively rapid drift of continents over the polar regions or a clustering of continental crust around one or both poles. They are not critical to the model, but they cannot be ignored, and, if true, they would be consistent with it.

³Stratigraphic and radiometric data elaborated by Evans, Ford, and Allen (1968) imply that this age, earlier given by the author as 640 m.y. from Soviet data, must be increased to the number here given. Geochemical similarities between fossiliferous volcanogenic sediments and associated dated intrusives indicate near contemporaneity of sediments and intrusives dated at 680 m.y. in the British Midlands.

crease in the carbon content of sedimentary rocks of the Russian and North American platforms beginning at about this point in geologic time.

The needed testing of this and other predictive aspects of the model is a task for the future. So is its refinement and local subdivision into conventional time and time-rock units. But I venture the judgments: (1) that the four major subdivisions suggested reflect real modal trends; (2) that they deserve to be designated by formal names comparable to the now generally accepted fifth and final major division of geologic time, the Phanerozoic Eon; and (3) that, over the next few decades, we shall see the emergence of a more detailed historical geology anterior to the Phanerozoic, in which modern principles of sedimentology and biogeology will play an important part, along with geochronology and the more traditional tools of pre-Paleozoic geology.

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