by E.G. Nisbet

Of clocks and rocks—The four aeons of Earth

Recognizing four aeons in the history of the Earth and the need for establishing the boundaries among them, the author sets a goal of historically useful nomenclature. If we pursue the importance of the history of life and its home, instead of a set of numbers itself, he feels that the Hadean-Archaeon boundary is best placed at the origin of life, the Archaeon-Proterozoic boundary was a transition with the dividing point best set in the rock, and the Proterozoic-Phanerozoic boundary is best placed in the rock at the level in the geological column when life became manifest. (Ed.)

Introduction

The naming of the geological column appears, at least at first glance, to be a simple matter to be sorted out quickly so that we can busy ourselves with our task of understanding the Earth and its history. Yet geologic nomenclature is surrounded by great controversy: there is the saga of the dispute between Sedgwick and Murchison over the Cambrian-Silurian boundary that was finally settled by the interpolation of the Ordovician, and there are still innumerable minor arguments about the position of other Phanerozoic boundaries. Some of these disputes are irrational and clouded by personal emotion, but there remains a basis of reality behind many of the arguments. More than that, there is the distinct possibility that those of us who are field geologists may have to live with unsuitable decisions and compromises passed down from lofty panels of elders.

The arguments are sustained, in general, by different philosophies of stratigraphy. It is for this reason that the matter is not trivial. The way in which we devise our nomenclature—our language—controls the way in which we think about the rocks. Our goal should be a historically useful nomenclature, not simply a sorting of the historical documents—the rocks—into separate piles. We should make a clear distinction between the history of the Earth, which is classifiable, and the calibrating device (time and its radiometric substandards), which is not classifiable.

The most major of the division of geological time are those between the formal aeons. I use the term aeon here not in the sense of 10^9 yr. This paper explores the problems of setting interaeon boundaries. In all cases there is no consensus, yet the debate is worth exploring, for in so doing we explore problems of basic stratigraphic philosophy.

The discussion originated in correspondence with Preston Cloud, Jr., who died recently. Cloud disagreed with some of my conclusions, but we shared a deep interest in the Precambrian. As a mark of respect for his massive contribution to our knowledge of the Earth's history, I have asked the editor of *Episodes* to reprint the opinions below, in the hope that others will take up the discussion.

The four aeons

I start with a statement: I recognize four aeons in earth history. These are the Hadean, the Archæon, the Proterozoic, and the Phanerozoic. The history behind this nomenclature is long and complex but has been summarized by Cloud (1976), who introduced the notion of the Hadean. In temporal terms, the names cover, respectively, the birth of the Earth, its youth, its middle period, and its recent history. In palaeontological terms the names apply roughly to the prebiotic Earth, the early history of life, the middle period of life, and the time of abundant multicelled organisms. The divisions are "rough" because the rationale behind the divisions is not yet agreed upon. In rough geochronological terms the names apply to the time before about 4 Ga, the time between about 4 and 2.5 Ga, the time from 2.5 Ga to 700 Ma, and the time since. Should palaeontological history become the basis of division, or should time lines be drawn to divide history, which is contrary to the notion that time is a calibrator, not the thing being classified? When we say that the Roman Empire finally fell in 1453 AD, we are concerned with the Roman Empire, not with the 1453 (which merely locates the fall). The history of life and its home is what we are studying, not a set of numbers.

The Hadean-Archæon boundary

Fortunately, there is no obvious problem with the beginning of the Hadean. We can set it as the beginning of the Earth's history. Whether one should place the beginning at the time of some presolar supernova or when the first lumps accreted to form the protoplanet is best left to the physicists.

The end of the Hadean is a different problem. We have three options. We can choose an arbitrary time—say 4 Ga. Alternatively, we can place the Hadean-Archæon boundary at the beginning of the geological record. Finally, we could choose the beginning of life.

The first option is to choose a time, say 4 Ga. I believe that such a choice would be deeply unsatisfactory. To choose an arbitrary time tells us nothing about the Earth. There is no advantage in ascribing a name to a number. We can imagine the numbers anyway: why tack on a name? There are deep practical objections too. One is that all of our clocks are simply that—clocks in need of calibration, not real time. Radiogenic clocks depend on isotopic abundances interpreted via measurements of decay constant. They are not absolute, but are subject to error both in the decay constant and in the measurement of isotopes, and are subject also to insecurity in that in some cases it is possible that the measure (for example, ^{14}C production) changes over time. It is an old stratigraphic principle that definition must be "in the rock," and this principle holds for radiogenic clocks as well as it does for fossil clocks. Isotopes are like ammonites: they give precision more easily than accuracy. We need a standard against which we can refer. Thus the only way to make an "age" the boundary is to choose a particular sample, with particular isotopic content, as the reference. We cannot just take a number.

This leads us to the second option: to take a sample at the beginning of the geological record. We could choose a particular

rock or mineral and arbitrarily decide that it was formed at the beginning of the Archaean. For instance, the oldest material known on Earth is an array of about 4.3–4.2-Ga-old zircon crystals from western Australia (for example, Compston and Pidgeon, 1986). Since that time, we may assume that "normal" postplanetary accretion geological processes have been going on. The merit of the definition is that it fits with the general, if ill-defined, notion of the difference between the Hadean and the Archaean; that in the Hadean the Earth was in its formative stage, subject to external influence, while in the Archaean, it was evolving through its own internal constraints as a closed system. However, this type of definition is unsatisfactory in that, almost inevitably, we will find some older material somewhere on Earth. We can be reasonably confident that we will not find evidence to move the Hadean/Archaean boundary (if defined in this way) younger than 4.2 Ga, but it is possible that we may find evidence in favor of moving the boundary to, say, 4.4 Ga. Thus any choice of a particular rock or mineral sample is, in essence, an arbitrary choice. That is not necessarily to say that it is a bad choice, but it may not properly reflect the essence of the distinction between Hadean and Archaean.

There remains a third option. With some important dissent, it is for the most part agreed that life began on Earth. Even if it did not, the molecular evidence is extremely strong that all life has a common ancestor or very small group of ancestors sharing genetic material. We strongly suspect that the beginning of life, or more precisely the construction of the first self-replicating organism, must have been a single well-defined event. Because biological processes occur extremely rapidly on a geological timescale, the colonization of all niches available to the first replicator must also have been an "event," which we will be unable to distinguish from the actual beginning of life at the resolution level of the geological record. Thus, in principle, the beginning of life might be a suitable datum for dividing Archaean from Hadean.

Is this anthropocentric reasoning? Is it valid to divide the geological aeons by something as apparently trivial (from the Earth's point of view) as the start of life? The answer to this is twofold. Life is important, since it is important to the observer. If there were no observers, there would be no definition. Secondly, it can be argued that life is, in a sense, the architect of the planet. Earth is different from Venus and Mars in large part because it is the home of life.

Thus, in good palaeontological tradition, I propose placing the Hadean-Archaean boundary at the moment of the first self-replication on Earth. Of course, we do not yet know when the moment was, but perhaps we will eventually be able to estimate the date of the event by using stable isotopic study of the geological record and molecular clocks. Because the geological record of this time is so sparse and so poorly understood, it is not a major disadvantage to define the boundary in this way; indeed, the definition may encourage a different perception of the Hadean and may stimulate research into the character of the late Hadean Earth.

The Archaean-Proterozoic boundary

One purpose in naming parts of the geological timescale is to encapsulate concepts, to label a particular phase of the planet's evolution. Our label, of course, governs our perception of that phase, so the label must be applied carefully. Yet the label is useful, not simply as a shorthand way of describing something, but also as a referent that helps us to place in context the innumerable details of the geology of an aeon. Thus we see an aeon as representing a length of time or a body of rocks (depending on our opinion) possessing characteristics that can in some way be distinguished from the characteristics of the next aeon. This problem of distinction is especially

difficult when one considers the Archaean-Proterozoic boundary. We can, according to personal prejudice, identify certain geological features that are mainly of Archaean aspect. These, to paraphrase the perceptions of the textbooks, include the typical granite-greenstone terranes, the predominance of tonalities amongst the granitoids, the relative abundance of komatiites, the relative scarcity of mature clastic sediment and certain other sedimentary deposits, such as redbeds and carbonates. Conversely, texts tend to characterize the typical Proterozoic as containing vast sedimentary basins rich in banded ironstones, or including the still-identifiable relics of major continental collisions, such as the Hudsonian terrane, or the Grenville. Whether these stereotypes are correct remains a moot point.

Alternatively, we can appeal to the logic behind the naming of Archaean and Proterozoic: the difference in the record of life. The Archaean has a very thin fossil record, produced by bacteria. In contrast, during the Proterozoic life took on a more modern aspect and is much more abundantly recorded in the surface inventory of carbonate.

How then to define the boundary?

Ideally, we should search for some distinctive change that took place to distinguish the two aeons. To return to analogy, in human history we can indeed say that the Roman Empire fell in 1453 AD; at the end of the Archaean we could perhaps search for some distinctive change of global extent and synchronicity. Our stereotype models identify several changes that took place in the middle period of the planet's history. These include: (1) the onset, or at least the preservation of general epicratonic sedimentation, although locally epicratonic sediments as old as 3.5 Ga are preserved; (2) clear evidence for the evolution of an oxygen-rich atmosphere, at least by the Late Proterozoic; (although there is considerable evidence for some oxidizing settings in the Archaean); and (3) a poorly defined but frequently discussed change in tectonic style, between an Archaean regime of granite-greenstone terranes and a Proterozoic regime of more modern aspect.

Whether or not the stereotype models are correct, there is a variety of ways to delineate the interaeon boundary. One possibility (Plumb and James, 1986) is to define the boundary as a number—2,500 million years ago is the most popular number (although based on radiometric numbers that normally date postdepositional events). This type of definition is wrong in principle, if not in the number chosen, because it contradicts the basic logic of stratigraphy. Cloud (personal communication) has emphasized the importance of not confusing time, the calibrator which is not classifiable, with history, which is classifiable.

The choice of a number as a boundary denies the basic principle of stratigraphy that the definition is in the rocks (Hedberg, 1976). Moreover, the use of an abstract concept, 2,500 million years, is not only theoretically bad but has important practical problems. Two Archaean rock units of very major importance lie very close to the 2,500 Ma boundary: the Great Dyke in Zimbabwe and the Hamersley sequence in western Australia. Each time an accepted value for an isotopic decay constant is changed, so too do all the ages derived from that constant change. Thus the Great Dyke oscillates uncomfortably from Archaean to Proterozoic; potentially the Hamersley sequence will do likewise. Consider again the events of AD 1453. Whether the citizens of Constantinople were Byzantines or Turks did not depend on the inaccurate choice of the year of Christ's birth as our AD 1; rather, their fate depended on the battle between the last Emperor and the Sultan. We must define our aeons with reference to the rocks, not to some abstract number. Thus the arbitrary choice of a number for the Archaean-Proterozoic boundary must be rejected. A definition in the rocks is essential.

Cloud (1976) sees few boundaries but mostly transitions. Consequently, it is valid to denote a transitional interval between the

Archean and the Proterozoic, when extensive epicratonic sedimentation began and, geochemically, continent-dominated, not mantle-dominated, sediment becomes the major part of the sedimentary to geochemical record. On the other hand, one can also argue that although the change from one regime to another was transitional, it is possible to define an arbitrary set point in the rock. Such a set point could, for instance, be the cooling age of the Great Dyke (Nisbet, 1982) or the age of an ash layer in the Hamersley sequence (Compton and others, 1981). Both these ages are close to 2,500 Ma, and the rocks are both of major local importance and can serve to distinguish Archean from Proterozoic in their respective cratons. Alternatively, it is possible that some process, such as sea-level fall, may have induced a global unconformity (for example, Cheney and others, 1990). The set point would represent rocks close to 2,500 Ma, but the definition would be in the rocks (even if only locally). Such definitions are reproducible, and the interface boundary, as placed in rocks, would not change each time decay constants are reassessed. The boundary would be locally useful in a stratigraphic sense and would also provide a global isotopic standard. The exact numerical age of the chosen rock would, in a sense, be immaterial: the isotopic systematics provide an event as a standard for worldwide comparison.

There is undoubtedly a transition from Archean to Proterozoic. Although there is disagreement about the ways of handling this transition, I believe that any definition of the Archean-Proterozoic boundary at 2,500 Ma without reference to the rock is not only bad in principle but causes difficulty in practice. I thus oppose the conclusions of Plumb and James (1986). The choice of a rock is better, the most appropriate reference being the cooling age of the Great Dyke, or a point in the Hamersley succession.

The Proterozoic-Phanerozoic boundary

The Phanerozoic is the time of manifest life; more particularly, it is the time when the fossil record is dominated by multicellular animal and plant life. If so, a critical question to ask is when did the metazoans first begin? Either one can define the onset of the Phanerozoic as the beginning of the large-scale preservation of obvious fossils—hard parts—in the geological record, or one can define the Phanerozoic as beginning when large forms of life became obvious on the surface of the planet. Cloud (1988) made the bold proposal that the record of metazoans begins with the Ediacaran, and thus that the Phanerozoic should also begin with the Ediacaran System, not the Cambrian. If this proposal is accepted, the term "Precambrian" would fall, if not into disuse, at least to informal status.

How valid is this proposal? In a strict sense, it is inescapable because it was in the Ediacaran that individual organisms first became "manifest"—that is visible to human eyes (or at least to those of the field geologist who eventually came around to collect the fossils). Thus we are strictly led to a definition of the Proterozoic-Phanerozoic boundary at the start of the Ediacaran. This is the strong view of Cloud (1988). However, two counter-arguments can be made. The first is that geologists, unlike many of the organisms they study, are not very adaptable. To delete the Precambrian may be as impossible as getting rid of the Tertiary now that the Primary and Secondary are gone. Secondly, there is molecular evidence (if molecular clocks are "regular") that some part of the eucaryote genome is of great antiquity (Vossbrinck and others, 1987; see also Cavalier-Smith, 1987). This does not imply that metazoans are old, nor does it mean that there is any reason to suspect abundant large fossils prior to the Ediacaran, but nevertheless there remains an uneasy suspicion that

pre-Ediacaran rocks may indeed produce manifest life (Conway-Morris, 1985). Thus ambiguity remains. The radical option of shifting the start of the Phanerozoic to the base of the Ediacaran is attractive, but a more cautious retention of the basal Cambrian boundary is probably safer. The matter's worth pursuing: no doubt some new palaeontological light will one day illuminate it, but geologists are conservative and loath to abandon the Precambrian.

Conclusion

There are thus four aeons of Earth history, best divided according to events in the history of life, as it is life that is the most truly distinctive feature of the planet. The first boundary, Hadean to Archean, is best set at life's origin. The second, Archean to Proterozoic, is recognized as a transition with the dividing point best set in the rock. The third, Proterozoic to Phanerozoic, is placed in the rock at the level in the geological column when life became manifest. In detail there is uncertainty; nevertheless, we must distinguish between the history of the planet, which is classifiable, and the calibrating device (time and its substandards) which is not classifiable.

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