The First Billion Years: When Did Life Emerge?

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There are three principal lines of evidence from which we can infer the timing of the origin of life on Earth: stromatolites, microfossils, and carbon isotope data. All indicate that life emerged earlier than ~3500 million years ago, but the details and exact timing of life’s beginnings remain unknown.

INTRODUCTION

Although the overall pathway of the origin of life seems well defined—extending from biogenetic elements to organic monomers, then polymers, then information-containing macromolecules encapsulated in cells (Schopf 2002)—the details of this event, the how and when of life’s beginnings, remain a mystery. Can the geosciences contribute to solving these problems?

Unfortunately, even the most detailed studies of the ancient rock record are unlikely to reveal the how of life’s beginnings. Because all biomonomers and biopolymers are geochemically unstable, it is implausible that evidence of intermediate stages in the emergence of life could be preserved in ancient rocks. As to the timing of life’s origin, the geosciences can provide only a partial answer—paleobiological studies of microbe-produced stromatolites, cellular microbial fossils, and carbon isotope evidence of microbial physiology have set a minimum date for life’s emergence. Such insight might be obtained by tracing biological signals back through time and, at a particular horizon in the rock record, see them vanish and be replaced in older units by evidence of planet-wide sterility. One might even hope to find carbonaceous deposits that could plausibly be interpreted as the residuum of a life-generating “primordial soup.” Such, however, is not the case. Here, again, the problem is one of preservation—not of remnants of life but of the geological record itself.

According to Garrels and Mackenzie (1971), the average lifetime of sedimentary rocks—those in which fossils typically are preserved—is about 200 million years (Myr), and about 50% of such units that have survived to the present are Phanerozoic (<550 Ma in age), the remainder dating from the earlier, ~4000 Myr long Precambrian. “About 90 percent of the Precambrian once deposited is gone” (Garrels and Mackenzie 1971, p. 275), preserved units petering out with increasing geological age to yield a severely depleted Archean (>2500 Ma) rock record. The age of the oldest-known sedimentary rocks—localized slivers of the highly metamorphosed Isua supracrustal belt of southwestern Greenland—is about 3800 Ma (Moorbath 2005). Only two thick ancient sedimentary sequences are known, those of the Pilbara Craton of Western Australia and the Barberton Greenstone Belt of South Africa and Swaziland, both with ages between ~3500 and 3000 Ma and both regionally metamorphosed to greenschist facies.

Given the markedly depleted Archean rock record and the fossil-destroying effects of metamorphism, it is not surprising that the early fossil record is sparse. Nevertheless, both of these thick Archean sedimentary sequences contain megascopic stromatolites, microscopic fossils, and carbonaceous matter of biological isotopic composition. Thus, the documented history of life extends to at least ~3500 Ma, earlier chapters in the story having been lost as the older rock record was geologically recycled and destroyed.

EARLY ARCHEAN EVIDENCE OF LIFE

Hints of Life >3500 Ma in Age

The carbon isotope composition of particulate graphite in metasediments of the ~3800 Ma old Isua supracrustal belt of southwestern Greenland has long been interpreted as evidence of biological activity, a view supported by a recent report of 13C-depleted detrital carbonaceous microglobules in this sequence (reviewed by Schidlowski 2001). Graphite particles have also been reported from rocks of similar age at Akilia Island, near the Greenland coast (Moorbath 2005). Yet the Isua rocks are metamorphosed to amphibolite facies and those at Akilia Island to even higher grade, conditions that can reset carbon isotope values, such that original compositions can only be inferred (Schidlowski 2001). Additional studies are probably needed before the reduced carbon in these ancient units can be regarded as a firm indicator, rather than only a strong hint, of the existence of life.

Early Archean Stromatolites (>3000 Ma)

As used here, the term “stromatolite” refers to accretionary sedimentary structures, commonly thinly layered, megascopic and calcareous, inferred to have been formed by mat-building communities of mucilage-secreting microorganisms, mainly photoautotrophic microbes. Such structures can be difficult to differentiate from nonbiogenic look-alikes (geyserites, cave deposits, tectonically deformed sediments, and the like). Buick et al. (1981) and Walter (1983) proposed that a prime indicator of biogenicity is the presence of fossilized microbes within such a structure. To some, however,
this criterion falls short, since the mere presence of such microbes cannot prove that they actually built the structure. Moreover, because stromatolites typically are calcareous, their formative microbial communities tend to be obliterated by the growth of carbonate grains during diagenesis. Fossilized stromatolite-forming microbes have therefore been reported almost entirely from rare cherty stromatolites, in which the initial carbonate matrix was replaced by silica prior to cellular decay and destruction of the microbes by growth of carbonate grains. Thus, “it is probably conservative to estimate that less than one percent of all stromatolites ever described have a fossilized microbiota associated with them” (Grotzinger and Knoll 1999, p 316).

Because of the absence of microfossils in most stromatolites, it is perhaps impossible to prove the biogenicity of the vast majority of such structures, even those of the Proterozoic (<2500 Ma) Precambrian. Yet Proterozoic stromatolites are...
widespread and abundant, and their biological origin is backed by studies of their morphology, fine structure, environmental setting, and, in numerous examples, fossilized formative communities. In the Archean, however, because of the scarcity of preserved sediments, stromatolites are relatively rare. Nevertheless, recent studies show them to be appreciably more abundant and diverse than has generally been assumed (Fig. 1). Their biogenicity can be assessed by the same criteria we apply to stromatolites of the Proterozoic.

Two major conclusions can be drawn from the compilation of Archean stromatolitic occurrences shown in Figure 1. First, the temporal distribution of stromatolites between 2500 and 3500 Ma is more or less continuous and parallels the rock record. Thus, stromatolites are relatively abundant between 2500 and 3000 Ma and less common between 3000 and 3500 Ma. Second, conical stromatolites have been recorded in 17 of the 48 units listed (Hofmann 2000). Present in fully one-third of these deposits—notably including the Strelley Pool Chert and the Kromberg and Panorama formations, all >3300 Ma—such distinctive structures require “both highly motile [microbial] mat builders and penecontemporaneous mineral precipitation” (Grotzinger and Knoll 1999, pp 342-343). Thus, the accretion of such stromatolites, especially the conical structures found in 3.45 Ga rocks of the Strelley Pool Chert, “may have been facilitated by microorganisms” (Knoll 2003).

**Early Archean Microfossils (>3000 Ma)**

In recent decades, rules for accepting Precambrian microfossil-like objects as bona fide fossils have become well established. Such objects must be demonstrably biogenic, and must also be indigenous to and have formed at the same time as rocks of known provenance and well-defined Precambrian age. To address biogenicity—the most difficult of these criteria to satisfy—a nested suite of seven traits has been proposed (Buick 1990): characteristics identifying spheroidal or filamentous fossil microbes, the predominant Precambrian morphotypes, have been specified (Schopf 2004); and the usefulness of such traits has been documented (Schopf et al. 2005).

A prime indicator of the biological origin of microscopic fossil-like objects is the co-occurrence of distinctive biological morphology and geochemically altered remnants of biological chemistry. Thus, chemical data demonstrating that populations of “cellular microfossils” are composed of carbonaceous matter would be consistent with a biogenic interpretation. Available analytical techniques permit a one-to-one correlation, at micron-scale resolution, of cellular morphology and carbonaceous chemistry: ion microprobe (House et al. 2000) and Raman spectroscopy (Arouli et al. 2000) for specimens exposed at the surface of a sample, and two- and three-dimensional Raman imagery (Schopf et al. 2005; Schopf and Kudryavtsev 2005) for specimens in petrographic thin sections. Such imagery, new to paleobiology, provides the means to map the spatial distribution of carbonaceous matter and associated minerals in submicron-thick optical slices of fossil specimens. The technique provides detailed chemical maps that, if acquired sequentially throughout a fossil, can be “stacked” to produce an image showing the fossil and its matrix in three dimensions. Raman imagery has been used to correlate biological morphology and carbonaceous composition in putative microfossils from three particularly ancient deposits (Schopf et al. 2002). These are the >3300 Ma Kromberg Formation (Fig. 3 G, H) and the Strelley Pool (Fig. 3 J) and Apex cherts (Fig. 3 K-M). Raman point spectra have been used to support a biological interpretation for the oldest fossil-like objects known, those in the Western Australian ~3490 Ma Dresser Formation (Ueno et al. 2004).

Despite such data, questions have been raised (Brasier et al. 2002) about the biogenicity of fossils reported from the ~3465 Ma Apex chert (Schopf 1993)—sinuous microbe-like filaments composed of carbonaceous cell-like segments (Fig. 3 K-M)—primarily because of their preservation in chert of hydrothermal origin (Van Kranendonk 2006). Recently, however, additional specimens, some identical to described Apex taxa (Ueno et al. 2004), have been discovered in three other hydrothermal cherts: the ~3490 Ma Dresser (Ueno et al. 2004), ~3240 Ma Kangaroo Caves (Rasmussen 2000), and ~3200 Ma Dixon Island (Kiyokawa et al. 2006) formations. Moreover, microbes of similar size and shape are abundant in hydrothermal settings today (e.g. Renault and Jones 2000), even at abyssal depths (Jannasch and Wirsen 1981).

Representative Early Archean microfossils are illustrated in Figure 3. These and fossils reported from the other >3200 Ma units listed in Figure 4 are all composed of carbonaceous matter. All satisfy specified biogenicity criteria (Schopf 2004). All exhibit distinctive biological morphology: spheroidal specimens are juxtaposed in adpressed pairs (Fig. 3 D-F) or in well-defined colonies (Fig. 3 I, J), presumptive evidence of biologic cell division; and filamentous forms (Fig. 3 K-M) are composed of boxlike chert-filled segments defined by carbonaceous walls, presumptive cell lumina (cellular cavities) that are an identifying characteristic of filamentous microbes.
Some 40 types of bona fide microfossils, comprising six distinct categories, have been reported from the Archean (Schopf 2006). All are morphologically simple—rod-shaped bodies, unornamented coccoids, or sinuous tubular or uniseriate cellular filaments. Such fossils, common also in Proterozoic biological communities, evidence a microbial evolutionary continuum that extends from the Early Archean to the present.

**Early Archean (>3000 Ma) Carbon Isotopes**

**FIGURE 4** summarizes paleobiological data from thirteen geological units in the two extant, relatively thick, Early Archean sedimentary sequences, those of the Pilbara Craton and the Barberton Greenstone Belt. As shown, ten of these especially ancient units contain stromatolites; eleven contain microbial fossils; nine have available carbon isotope data, including measurements on individual fossils in the oldest unit, the ~3490 Ma Dresser Formation; and five have provided Raman spectra and/or images of the carbonaceous components of microfossils.

In **FIGURE 5**, carbon isotope data from an extensive suite of Precambrian deposits show that over this vast sweep of geological time, average $\delta^{13}C_{PDB}$ values for carbonate carbon center at $-0\%$, whereas those for biologically produced carbonaceous organic carbon are centered at $-25 \pm 10\%$. As shown in **FIGURE 6**, the Early Archean microfossil-bearing deposits exhibit essentially identical $\delta^{13}C_{PDB}$ values—about $0\%$ for carbonate carbon and $-27$ to $-32\%$ for the particulate carbonaceous kerogen. As in the Proterozoic, the values measured are consistent with carbon isotope fractionation by autotrophic microorganisms ($-25 \pm 10\%$) and, thus, with a biological origin for the reduced carbon (cf. Hayes et al. 1992).
SUMMARY

Taken together, the evidence from stromatolites, microfossils, and carbon isotopes seems irrefutable: life was extant, and indeed flourishing, as early as ~3500 Ma ago. Where does this leave us regarding the time of life’s emergence? Certainly, life began before 3500 Ma, during Earth’s first billion years, but exactly when and how remain unknown. Most “origin-of-lifers” would set the date at around 4000 Ma. But that estimate will ultimately be placed on firm footing only by discovery of direct evidence from Earth’s earliest rock record.

ACKNOWLEDGMENTS

This article is based on a longer, extensively referenced article (Schopf 2006) that includes discussion of the complete Archean (2500 to 3500 Ma) paleobiological record as now known. I thank J. Shen-Miller, W. Barker, and J. Valley for suggestions for improvement of an earlier version of this contribution. This work was supported by NASA Exobiology Grant NAG5-12357 and by CSEOL, the IGPP Center for Study of the Origin and Evolution of Life at UCLA.

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