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BOOK REVIEW

A VIEW OF NON-ANALOG WORLDS[1]

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I'll readily admit that I had promised to finish this book review before the beginning of the current academic year, having read it earlier this summer during our first field season. But, somehow the northern hemisphere summer has passed quickly and the leaves are now beginning to turn color in the northeast; it's only mid-September. Our concept of time goes back towards the dawn of civilization when early societies used a variety of astronomical means to track the seasons. The earliest Assyrian calendar was based on the lunar cycle, but such a means of keeping time necessitated the introduction of additional months in leap years to even things out. And, even though the early Romans tried to standardize their concepts of time defining months as having either 29 or 31 days (30 was an unlucky number then), the addition of an extra month every second year (i.e., Mercedonius) was necessary. In 45 BC, Caesar reformed the calendar which became known as the Julian calendar, comprised of months of either 30 or 31 days and a leap year. But, under this scheme, the date of the vernal equinox drifted. It wasn't until the Council of Trent (1545–1563) when Pope Gregory XIII authorized the reformation of the calendar that the Gregorian Calendar was conceived and adopted where every fourth year became a leap year (except for century years not divisible by 400). Even then, the Gregorian calendar wasn't universally adopted until 1918 when the Russians changed from their long-held Julian calendar. Why spend so much time talking about time and our concepts of time? Why not just get to the book review?

Since the discovery of radioactivity by Becquerel and the Curies and the development of geochronological techniques within the last 100 yr, geoscientists have recognized that time is as immense as the concept of the universe is to physicists. This concept of Deep Time has radically changed the way in which we view our planet and the timing of the abiotic and biotic processes involved in its evolution. The first radioisotopic scale was published in 1934, and advances in the identification and proof of a variety of decay series allowed for independent mineralogical assemblages from the same rock to be assessed, thereby confirming the numerical age of crystallization. It is this fact, that Earth has a very very long, almost incomprehensible, historical record, that Andy Knoll has outlined elegantly in *Life on a Young Planet.* We are grounded in the life and times that surround us; but we are asked in this book to abandon our perspectives and concepts of the time governing our lives to consider evidence and processes operating on scales without personal reference. The challenge is rewarding.

Andy Knoll is Fisher Professor of Natural History at Harvard University where he studied with Elso Barghoorn at Precambrian ''ground zero.'' His interdisciplinary investigation of the biological, chemical, and physical aspects of early life has resulted in the development of an Earth Systems approach to chronicling our planet, culminating in his election to the U.S. National Academy of Sciences early in his career. This interdisciplinary approach is reflected in the three precepts governing the presentation of the first three billion years of evolution on Earth. The first precept is the narrative history of life in Deep Time, where disparate facts are synthesized to provide a coherent picture for the reader. As he states, ''contemporary biological diversity is the product of nearly 4 billion years of evolution. We are part of this legacy'' (p. 3). Understanding what came before may help us to understand and change our personal reference. Science is not conducted in a vacuum. It is the result of personal interactions in various parts of the world over one's short, geologically instantaneous career. Knoll's second goal is to present this history as human enterprise. And, lastly, the synthesis. What grand themes can we identify during the evolutionary history of early life on our planet, and what might we expect to encounter elsewhere in the universe?

The book is comprised of 13 chapters that take the reader through basic concepts necessary to provide the geological and biological groundwork, setting the stage for an understanding of more complex and synthetic discussions that make up the remainder of the text. Precambrian rocks are not evenly distributed across the globe, nor are the same parts of this long history found on every continent. For a geoscientist this means only one thing—a good travel agent.

The reader first is brought to Siberia to learn about the Precambrian–Cambrian boundary above which a dramatic change in biological diversity is recorded whereupon a short discussion of Darwinian evolution and Punctuated Equilibrium ensues. Systematics, phylogeny, and physiology are used to present the argument that bacteria rule the world and that we have evolved into their world, not vice versa. Prokaryotic metabolisms form the fundamental ecological circuitry of life, underpinning everything that occurs in the biosphere. From here, the reader is brought to the Tree of Life and Woese's (1987) domains, focusing on the often overlooked diversity in the Archaea and Bacteria. Knoll proposes that such a tree provides not only an understanding of relationships between organisms, but also serves as a proxy to the environmental history of Earth because particular groups are restricted ecologically in space throughout time. This idea, in itself, provides biologists and paleobiologists with new insights into the linkages between various biogeochemical cycles.

Knoll's quest moves to Spitsbergen in the following chapter where Neoproterozoic rocks (800–600 Myr) preserve vestiges of life and the environments in which this life thrived before the Cambrian explosion. The 20 000 foot-thick section is used

[1] Life on a young planet: the first three billion years of evolution on Earth. A. H. Knoll. Princeton University Press, Princeton, New Jersey, USA. 2003. 277 p.

to explain basic sedimentology associated with marine environments and that Hutton's concept of uniformitarianism—the present is the key to the past—is understood to be about Earth *processes* rather than direct substitutable examples of the here-and-now into the deep past. These processes are reflected both in the abiotic sedimentary and the biotic paleontological record, and Knoll sets out to describe the microfossil assemblages within these rocks. To which group are they most likely comparable? The answer comes in a well-presented comparison of the morphology and life strategies (including mat-building and ooid boring) of extant cyanobacteria and the Neoproterozoic fossils. But, to cinch the comparison, the reader is brought to equivalent-aged rocks in the Grand Canyon where molecular signals (biomarkers) of archaea, bacteria, proterozoa, and algae have been identified. A brief discussion of the stable isotopes δ^{13} C and δ^{34} S is presented to alert the reader to cosmopolitan biological fingerprints throughout Earth history. The Archean (3.5 Byr) Warrawoona Group in western Australia provides the backdrop for an introduction to the laws governing relative and radioisotopic-dating techniques, including recent advances using the ion microprobe. All of these fundamental concepts and techniques are found universally in nearly all introductory-level undergraduate courses in geology. But their presentation is necessary not only for the casual reader, but also for those professionals who have had little or no exposure to modern geological principles.

It is in Australia that Knoll begins to interject his ideas and interpretations on the earliest evidence of life, and throughout the book the reader is treated to balanced, thought-provoking arguments on what we know, what we think we know, and what we really don't know. Although the Warrawoona Group has been interpreted to preserve the earliest evidence of life, Knoll demurs based on the work of van Kranendonk. Van Kranendonk (Brasier et al., 2002; Garcia-Ruiz et al., 2003) has mapped these cherts as hydrothermal in origin, forming beneath the sea floor, not on the sea floor. And, following a visit to the Natural History Museum in London as part of the research conducted while writing the book, Knoll re-examined thin-section specimens only to find the fossil structures to be minerogenic that may be draped by organic films. Bill Schopf (Schopf, 1993; Schopf et al., 2002) would contend otherwise, fueling the protocols of science. There is δ^{13} C evidence indicating that an early biosphere existed when these sediments were deposited, but skepticism abounds about the resiliency of biomarkers as far back as the Archean. Other localities are examined—the Barberton Mountain Land in Africa and the Akilia Island off the coast of southwest Greenland—and discussed as to whether or not early evidence of biological systems are preserved and whether or not δ^{13} C signatures within these rocks can be the result of chemical fractionation. If so, Knoll contends that these earliest biosignatures may not be as reliable as presently believed. Hence, if life was forged by the same physical and chemical processes that shaped the crust and the ocean, what features distinguish life forms?

Chapter 5, The Emergence of Life, acquaints the reader with introductory biology, beginning with the earliest experiments of Stanley Miller and Harold Urey and then onto basic cellular organization. Within that context, the reader is introduced to the functions of both DNA and RNA and the difficulties these particular compounds would have faced to originate de novo. But once RNA was synthesized under one or more different possible catalytic reactions, evolution may have governed the trajectory of life. Evolution, though, wasn't perfect, and with mistakes in replication probably commonplace, a pool of natural variation was available on which selection could act. And, with selection pressures acting on both the RNA and the proteins synthesized by their activity, a ''protobiological'' merger could have followed, forming the first innovation by alliance, a theme that is reiterated throughout the book. As usual, there are not only unanswered and unanswerable questions about details of such a hypothesis, but alternative scenarios. Knoll presents all sides without firmly placing his foot in any camp, allowing the reader to ponder the merits of each. One way or another, cellular life forms began to play a role on Earth. And, that role is to begin changes on the planet that cannot be undone.

The Oxygen Revolution is designed to lead the reader up the stratigraphic column, back towards the Cambrian, with an examination of the Gunflint Chert in Ontario. This is the place where it all started with the collection of an unusual carbonaceous rock by Stanley Tyler in the 1950s that was sent to Elso Barghoorn at Harvard for examination. There *was* life before the ''Dawn of Life'' in the Cambrian, first changing our view of pre-Phanerozoic history (Barghoorn and Tyler, 1965). There is now relatively good age constraint on this sequence that is somewhat older than 1878 $\pm$ 2 Myr, based on a volcanic bed near the top of the section. Stromatolites in these rocks are different from those in other Precambrian areas, appearing more like sinters adjacent to mineral-charged springs than algal mounds formed within the tidal zone. And, unlike other microfossil assemblages, these fossils appear most similar to extant iron-metabolizing bacteria that are not common in today's oceans. At present, iron-loving bacteria are restricted in their habitats to unique chemical environments. In contrast, these bacteria are a persistent feature in the Archeoproterozoic (2.1–1.8 Byr ago) and before, indicating the near absence of free oxygen during this interval of time. Knoll not only presents the long-held arguments and evidence to support a low oxygen planet, but also the arguments of the opposition who contend that an oxygen-rich environment was in place much earlier than 2.2 Byr (Ohmoto, 1996; Canfield, 1998). Here, again, Knoll gives the reader a well-designed and illustrated set of arguments explaining the anomalous δ^{13} C, δ^{32} S, and δ^{34} S biogeochemical markers found in the record. His conclusion is that although oxygen may have been locally abundant in the Archean, it wasn't until the Proterozoic that it was sufficient in both the atmosphere and hydrosphere to impact global environmental and biological systems.

No paleontologist can miss a trip to Russia. The complex geology spread across much of the northern hemisphere provides endless opportunities to untapped resources if only you can get there from here. Knoll brings the reader back to Siberia where cyanobacteria dominate the carbonates and associated rocks in the Great Wall along the Kotuikan River. But the problem encountered in these rich fossil assemblages is how to differentiate the true biological signature of diversity. How can we say, with certainty, that the organisms seen here, some 400 Myr later than the iron-rich Gunflint cherts, are the same as those documented in older rocks based solely on morphology? Can the same morphotype have had different physiological requirements and pathways at different points in Precambrian time? And, what about convergence? Knoll discusses population stasis, Sewall Wright's ideas on the adaptive landscape, and Karl Niklas' models (Niklas, 1994) and concludes that when only one functional demand must be satisfied to ascend to your adaptive peak, then a single peak it is. ‘‘Bacteria can be famously single-minded’’ (p. 115).

The stromatolites and primary sedimentary structures found in the Great Wall section are different from those in older rocks. Here we see for the first time crinkly laminated algal mats, teepee structures, sheets of ooids, and stromatolite domes. The systematic diversity also is different. But, rather than ascribing it to evolutionary changes in the biota, he demonstrates that environmental change is the root cause of the differences seen in these rocks. These reflect changes in the ocean, resulting in a new array of sedimentary textures recording episodic changes in carbonate chemistry. And locked away with these sedimentary textures and bacterial remains might be some of the first traces of eukaryotes.

The Origin of Eukaryotic Cells begins with an outline of the early 20th Century hypothesis by Merezhkovsky (Khakhina, 1992) of endosymbiosis followed by the now textbook account of Margulis’ theory. The relationships established between the various symbionts can be tracked by where different algal groups sit on the tree of life. The acquisition first of a mitochondrial symbiont allowed for metabolic stabilization within the cell, whereas molecular evidence indicates that photosynthetic symbiosis must have occurred at least half a dozen times (e.g., Delwiche, 1999). These iterative relationships spread photosynthesis through the eukaryotic domain. But, there’s always a catch. There are organisms constructed of nucleated cells without either mitochondria or chloroplasts; the example given is *Giardia*. Knoll relates the stories of the pioneering molecular studies focused on eukaryotic phylogeny and the quandry posed by these organisms, and then presents the argument that their mitochondria were lost (although retaining mitochondrial genes) during adaption to an anaerobic habitat. In addition to molecular biology identifying nuclear genetic material of proteobacterial origin in the early basal branches within the tree of life, he adds the recent hypothesis of Martin and Müller (1998) wherein they propose that primitive mitochondria-free eukaryotes never existed. The precursor to all eukaryotes, then, was a prokaryote–prokaryote partnership between a methanogenic archaea, requiring H_2 and CO_2 for fuel, and a protobacterium, capable of both aerobic and anaerobic respiration. The methanogen produced organic molecules imported into the proteobacterium which, in turn, provided H_2 and CO_2 for the assembly of new organic matter. As changing atmospheric conditions reduced the available H_2 driven, in part, by increasing atmospheric O_2, the methanogens lost their wall and evolved a flexible membrane maximizing H_2 diffusion. Cytoskeletal proteins were manufactured to assist in stabilizing cellular contents, along with genetic transfer or loss, resulting in a new cellular organization. This evolutionary pathway may explain the presence of an unusual organelle found only in eukaryotes inhabiting anaerobic environments and responsible for anaerobic metabolism, the hydrogenosome (Bui et al., 1996). As new data are acquired, those genes found to be shared across domains and those restricted to specific domains lead to interpretations that there may be more than just two symbioses in the march towards the eukaryotic condition.

It is in southern China that the reader is next introduced to the fossil record of eukaryotes, a much younger record preserved in the phosphate mines of Guizhou Province (some 900 Myr younger than the Great Wall; 900 Myr is nearly twice the duration from the Cambrian to the present and 15 times the duration since the extinction of the dinosaurs at the K/T boundary event). This section contains a volcanic ash bed with an U-Pb age of 748 $\pm$ 12 Myr which is overlain by the fossiliferous Doushantuo Formation. Here, both macrofossils (lanceolate benthic algae and invertebrates) and microfossils (algae, eggs of invertebrates, and embryos) abound. In some beds, the phosphatically preserved microfossils literally form a sandstone. Knoll outlines the criteria necessary to identify such remains as eukaryotes and then examines the taphonomic processes that uniquely preserved these assemblages. This is exciting stuff, because evidence for the developmental biology of Neoproterozoic invertebrates and algae just isn’t found anywhere else before the Cambrian, to date. Single cells surrounded by a membrane, cells in pairs, quartets, octads, and other larger cellular masses arranged in geometric patterns that reflect oriented cell division are all present (Xiao and Knoll, 2000). Unfortunately, adults of these embryos are unknown; the mines in the Doushantuo Formation provide only a glimpse of invertebrates to come. But there are well preserved macroalgae, and Knoll surveys these in the remainder of the chapter acknowledging that the oldest of these are recorded in cherts from arctic Canada, at approximately 1.2 Byr. And, surprisingly enough, their closest living relatives are the Rhodophyta, implying that this clade must have diverged from other eukaryotes and evolved to this level by the Mesoproterozoic. Late Proterozoic physical evidence abounds for the green algae, as well as biogeochemical evidence for dinoflagellates, ciliate protozoans, and testate amoeba. Does evidence for eukaryotes appear abruptly at this time? The answer is no.

The Middle Proterozoic Roper Group (1492 $\pm$ 3 Myr) in Australia preserves an eukaryotic assemblage different from those in China, the Grand Canyon, or Spitsbergen, both as microfossils and molecular fossils (steranes). The microfossils are large spheres, up to 150 μm in diameter, that have tubes originating from their walls that often branch. These features are similar to those in living protists, and this feat, of modifying one’s shape during its life, is not a characteristic of bacteria-grade organisms. Which means that by 1.5 Byr, eukaryotes were in the oceans and had evolved a ‘‘sophisticated’’ internal organization. And that feature brings us to sex and the consequence of genetic variation within populations; and Knoll proposes the ‘‘just add sex’’ hypothesis as the trigger for eukaryotic diversification. Without that little step allowing for exchange of genes between organisms, and others (cytoskeletons, genetic regulation, etc.), I wouldn’t be writing this review and you wouldn’t be reading it. We all should be grateful for this evolutionary innovation.

Was the appearance of eukaryotes in the Middle Paleozoic, then, the beginning of a steady uninterrupted march to the Cambrian? The answer, again, is no. This is because the Late Proterozoic sedimentological record tells us of a number of alien global conditions that appear to play a role in the evolutionary process. These include moderate oxygen levels within both the atmosphere and surface sea waters, but a hydrogen sulfide-rich environment in the deep marine basins. Such water chemistries effect life in a multitude of ways. They limit the levels of available nitrogen, restricting growth of eukaryotes (cyanobacteria can fix their own nitrogen and would have been unaffected). But, when molybdenum is present in the water column, it can be used in nitrate reductase providing available nitrogen for metabolic processes. Knoll predicts that during these alien times, diversity and abundance of eukaryotes should be preserved in nearshore settings where rivers debouched into the ocean, providing concentrations of molybdenum that could be used to free up nitrates. The second alien condition may be even more difficult to conceive—a Snowball Earth—wherein changing global environments promoted severe extinction events. But, this story is postponed until Chapter 12 after a short interlude in Africa.

Namibia exposes rocks deposited at the very end of the Proterozoic (550–543 Myr) wherein some of the first evidence for macroinvertebrates (body fossils and ichnofossils) is preserved. These invertebrates, though, neither look familiar nor can be placed easily into extant (or extinct) clades (although shallow disks several inches in diameter are related to Cnidaria), and most have been placed into a group unto themselves—the Vendoza—commonly called the Ediacaran fauna (Narbonne, 1998). These fossils have a variety of complex, leaflike forms comprised of repeating tubular units, and Knoll describes the major taxa—*Rangea*, *Pteridinium*, *Swartpuntia*, *Ernietta*, *Charniodiscus*, *Charnia*, and *Dickinsonia* (if you're unfamiliar with these forms, use your internet browser; several museum websites picture these and other Vendoza). So, what are these creatures? Knoll speculates that all these forms were colonial animals broadly related to the Cnidaria and may have possessed symbiotic algae as in living taxa. Speculation aside, the remainder of the chapter is devoted to the level of evolutionary sophistication that can be documented in the ichnofossil assemblage. Trace fossils indicate the presence of bilateral symmetry in the invertebrate realm, whereupon Knoll evaluates the possible contenders. Finally, the reader is brought to the reason why there is a good post-Proterozoic fossil record; the innovation of biomineralization and its evidence in Namibia where the Nama reefs are preserved. Intermixed with the framework organisms—algae and cyanobacteria—are skeletalized animal fossils that come in a variety of shapes and sizes. But these animals are still distinctly Proterozoic in character. Those assemblages that mark the ''Dawn of Creation'' are nowhere to be found, at least here; it's necessary to move upsection to the Cambrian.

Chapter 11, Cambrian Redux, brings the reader back to Siberia along the Kotuikan River. The evolutionary relationships among animal phyla are explored, and developmental biology is reviewed. The animal tree is climbed beginning with the Sponges (diversified in the late Proterozoic, yet uncommon), Cnidarians, and the Bilateria. This latter group is presented in some detail, recounting the primary division into Deuterostomes, Ecdysozoa, and Lophotrochozoa, and the lines of descent within the groups. The Burgess Shale fauna is briefly included and identified as stem taxa to what evolves thereafter, with the summary contention that the 50 Myr of time over which body plans recognizable as arthropods, brachiopods, mollusks, and chordates evolved can't really be considered a ''Cambrian Explosion.'' Can it? And Knoll contends that because these ''50 million years reshaped more than 3 *billion* years of biological history'' (p. 193), it doesn't really matter (just about the same way that the last 60 million years, from the K/T boundary event to now, might just not really matter). Explanations for these evolutionary innovations must be found elsewhere, at the interface of developmental biology and ecology. Much of the remaining text is devoted to ''Evo-Devo'' and the role that regulatory genes play in the ''tool kit'' of development. But, there is tension in the debate; the tension exists between paleontological evidence and molecular clocks (Wray et al., 1996; Knoll and Carroll, 1999). This tension concludes the chapter. Knoll asks if it is parsimonious to extrapolate rates of molecular change based on vertebrates deeper into the animal-family tree? Theoretical answers to this question have animals diversifying significantly earlier than the physical evidence, but recent analyses using genetic divergence in echinoderms still leaves a gap between the theory and the empirical. The only three options to reconcile the differences—high rates of early genetic divergence, undermining our ability to read ''time'' from molecules; genetic estimates are actually good, and the fossil evidence is missing; and both are correct, but telling two different stories—are provided. The conclusion is that ''the problem remains unsolved,'' as, indeed, it does.

Hard luck and trouble seems to be the theme recounting the evidence for ecological change in the Late Proterozoic. In Spitsbergen, southern China, Australia, Namibia, Canada, Boston, and elsewhere, the Late Proterozoic sedimentary record indicates a global ice age at this time. The global ice age didn't chill just once, but Knoll believes that glacial maxima and minima occurred at least four times. Physical and chemical evidence for what has been termed ''Snowball Earth'' is presented to the reader (Hoffman et al., 1998), and the δ^{13} C record is explained. This hypothesis has now been debated for nearly a decade, and the details of the latest iteration, as well as the issues still under contention, are well presented. The events that occurred over this ~200 Myr interval are used to set the stage, the crucible, for the biological revolution found in Cambrian strata. After pointing out the hydrological problem associated with the coming and going of low-latitude sea ice and the deposition of tillites within a global system that would be shut down under the contentions of the hypothesis, and the problem of the carbon isotope record (related to methane production; his arguments result in alternative explanations that can be explored), Knoll proposes the ''slush ball'' variation of the hypothesis. Irregardless, the biological signal preserved in the cap carbonates indicates that even though there were refugia for the late Proterozoic marine biota, climate shifts pruned the eukaryotic tree through ecological stress.

The Vendoza are uniquely limited in space and time, appearing in the fossil record after the last of Knoll's four ice ages. To date, there is no evidence for them in any older part of the sedimentary record. Hence, if ecological stress pruned the eukaryotic tree during hard times and allowed for the recovery of the eukaryotic lineage during good times, why are the multicelled animals found only after the last glaciation? Knoll suspects it is the level of atmospheric oxygen. He explains the relationship between body size and available oxygen via diffusion (Krogh's biophysical rule) and then discusses how cnidarians (and probably Vendobionts) circumvent the rule. The reader is brought back to the geochemical record and presented evidence for increased oxygen levels just after the youngest of the global ice ages. A second line of independent evidence for this increase is provided by the sulfur isotope record which, when all is said and done, points to the ''hunch'' that evolution in the animal kingdom was driven by oxygen. The last question proposed is the why. Why is there such a sudden appearance at the Cambrian boundary? The answer may have to do with a sharp excursion in the C-isotope signal at the boundary, signaling hard times, once again, for the biosphere. Knoll believes that mass extinction can explain both the stratigraphic gap and the radical difference between the Ediacaran and Cambrian animals, and that the subsequent evolutionary pathway traveled reflects the interplay between ecology and development (although there are others who would disavow the role ecology may have played and their sentiments are presented).

The story of the first 3 Byr of life essentially ends here on Earth, but may not end elsewhere. Paleontology ad Astra explores the possibility that life exists elsewhere in our solar system. In the mid-90s, newspaper headlines were made when NASA scientists proclaimed they had discovered biological evidence in a Martian meteorite. The announcement rocked the scientific community, no pun intended. Knoll recounts the events that unfolded that year and what has been learned since then. There is no argument over the meteorite originating from Mars, but two assumptions must be made before the hypothesis concerning evidence of extraterrestrial life in this rock can be accepted. These are that the organisms must have lived in small cracks within the planet's crust, and the biological record has survived intact for nearly 4 Byr. What the reader has learned in the foregoing chapters, then, must be applied to this argument because this ''is where terrestrial experience'' frames the debate. Knoll proceeds to discuss the carbonate mineralogy of the meteorite—ALH-84001—concluding that the minerals, themselves, indicate that these fissures acted as conduits for mineral-charged fluids. The minerals may provide clues to the physical conditions, but not the biological conditions. And even the organic biomarkers (polycyclic aromatic hydrocarbons) are ambiguous. True, minute quantities of PAHs are in situ and not terrestrial contaminants, but there is no evidence that they are biological in origin. What these biomarkers tell us, though, is that *if* life existed on Mars, it may have left ''a molecular calling card.'' Knoll continues the story with an examination of the interpreted microfossils and details the debate over whether such small structures—about 100 nm—could be biological in origin. Is there life on Mars?

Knoll focuses on what we do, don't, and hope to know about these (or any) extraterrestrial life forms. Astropaleontological interpretations must be based on three criteria. Do the morphological or chemical patterns found in these rocks make sense in terms of known biological processes as opposed to a strictly abiotic origin? Do we know all of the possible forms life may take in theoretical morphospace? That is, how would we recognize an unfamiliar biological form? The biology may be different, but the underlying chemistry and physics place constraints on what any organism can do. Of the four lines of evidence presented to support the interpretation of Martian life, only the case for the unusual crystals of magnetite in the carbonate globules has survived. To some workers, the features found in these crystals only could be the result of biological processes, providing the smoking gun resolving debate. But, as science marches on, such magnetite structures recently have been synthesized in the laboratory, and the support for a biological origin is declining. Which leaves only the last option to a paleontologist: another travel agent and another road trip. This time, to Mars.

The Epilogue to the book is retrospective. And, as such, I'd hate to ruin the ending to an intriguing story. Suffice it to say that *Life on a Young Planet* provides the advanced undergraduate and graduate student and their mentors across a wide array of disciplines the principle reference wherein 3 Byr of evolutionary innovation and stasis, and the reasons for change, are melded into a fascinating story of Earth history: a story to which many students in Historical Geology are introduced early in their college career and forget after the exam. (Introductory biology students often are not exposed to deep time and, consequently, have little or no concept of the subject material. This is even more reason why this book should be read by them.) Why might it be difficult for students to remember what they've learned about the very deep past? Maybe it's because the few short hours devoted to this part of our planet's history (just about as many hours as it will take you to read the book) just doesn't seem real enough. Billions of hamburgers are more real than billions of years. And those organisms that follow the ''Cambrian Explosion,'' trilobites, rugose corals, brachiopods, ichthyostegids, and dinosaurs, hold our attention much longer than microbial mats. But, as Knoll states so eloquently, all that came after we evolved into their world. Without them, we wouldn't be here as we are today, contemplating the intricacies of perceptible and imperceptible time.

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