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Earth's Early Atmosphere and Oceans, and The Origin of Life

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Preface

Surface conditions on the Early Archean (and Hadean) Earth were critical to the origin of life. This is not a recent realization, and origin-of-life considerations have long figured prominently in geological analyses of Earth's earliest history. Several detailed treatments over the past century have discussed prebiotic processes based on assumed conditions, analyzed the (sparse) geologic data from earliest times, quantitatively explored chemical processes on and in the Earth and in its atmosphere, and attempted theoretical reconstructions of processes responsible for the formation and early evolution of the planet. Some of these efforts have also been applied to the other terrestrial planets and/or have been informed by knowledge of conditions throughout the solar system. In many of these efforts the analysis may not have given sufficient weight to one or more factors marginal to the expertise of the analyst, though in general there is a good awareness that the problems are complex and rely on information and constraints from a very broad range of disciplines. A recent spate of books discussing the origin of life suggests both a renewed interest in the topic, and perhaps no need for yet another. That a geologist feels an inclination to add to the discussion may seem misdirected. After all, isn't this a biological problem? On the contrary, I suggest that a careful consideration of the (essentially) geologic conditions leading up to life's origins can lead to a better understanding of where and how life began, and I am not the first (Rutten 1962). This book will cover such considerations in some detail and will also explore some essentially biochemical aspects which I don't believe have been previously discussed.

I will not suggest that my expertise across disciplinary boundaries is necessarily superior to those who have attempted an understanding of early Earth and the origin of life, and especially not as detailed in particular fields. However, as one who has a long-standing interest in astronomy, an abandoned goal of becoming a biochemist, degrees in chemistry and geology, research experience in geophysics and geophysical modeling, and a tendency to approach problems as a generalist, I may be better able to appreciate the range of constraints that help define the problem. A previous attempt at describing the origin and evolution of Earth's atmosphere (Shaw 2008) was somewhat limited by publication constraints, though it contains some of the ideas explored herein. In addition, even in the last few years, there have been developments/discoveries that have affected my thinking, even as I have given more thought to particular aspects of the problem.

This book will not be a critique of past efforts, though it will use and discuss them. There are several aspects of the problem that have been covered in great detail by others, and I make ready reference to those works without repeating previous expositions. I agree with the substance of the vast majority of what has been uncovered and parsed by previous work, and brief expositions of these results will often serve as starting points for my own interpretations. On the other hand, there are many points where I depart from the conventional wisdom, as well as a number of ideas that, if not completely novel, are essential to understanding the origin of conditions conducive to the emergence of life.

The book is divided into three parts. First I discuss the processes and results of the degassing and early processing of Earth's volatile inventory. Next I discuss various aspects of life processes, focusing on the requirements for the earliest emergence of life, including a possible pathway to the generation of the essential complex feedback processes thought to be characteristic of life. The third part examines processes of atmospheric evolution following the emergence of life, especially the development and consequences of photosynthesis, oxygenic photosynthesis in particular. There is a final chapter which examines the implications of the first three parts for understanding the geological and planetological record in terms of atmospheric and surface evolution.

Acknowledgments

My interest in these topics goes back to my school days, but became more focused during a course in economic geology taught by Eric Cheney at the University of Washington in 1969 or 1970. His detailed exposition of banded iron formations included implications for Earth's early atmosphere that I found fascinating. Randall Gresens, who taught a course in geochemistry at UW, was instrumental in teaching me that even apparently outrageous ideas are worth examining, and creative thinking is paramount. A few years later I just missed being a colleague of Preston Cloud, arriving at the University of Minnesota shortly after he had left. But, while teaching a course jointly with V. R. Murthy at UM, I was reminded of Cloud's work and the special features of BIF, and how they could tell us something about the Archean atmosphere. It was a couple of decades later when I had the time to return to thinking about and expanding on these matters at Union College. Brian Cohen in the Biology Department at Union provided invaluable assistance introducing me to the databases and tools of molecular biology. Kurt Hollocher read an earlier version of the manuscript and provided very useful comments. Dean Wendy Sternberg could not have known that providing a little travel support to an emeritus faculty would lead to a book contract, but it was a key step in a lengthy process.

I would like to thank my geologist daughter Katherine F. Shaw for her continued encouragement and for helping with illustrations. My philosopher son, J. Clerk Shaw, provided a nice bit of inspiration by having his own book published last year. And I especially want to thank the light of my life, Paula Fenimore Shaw, with whom I have shared the joys and sorrows of life for nearly 50 years.

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Chapter 1
Introduction

Oparin (1938) provided the first modern, comprehensive treatment relevant to the origin of life. He was not interested in geologic details, many of which were unavailable at that time. His basic premise was that widespread reducing conditions on Earth's early surface were necessary (accurately so, I believe) for the abiotic processing of CHNO compounds in order to yield the building blocks of life, i.e. prebiotic compounds. His work eventually gave rise to a host of experimental studies that reveal the surprising ease with which numerous biologically important compounds can be produced. One of the most striking results of this body of experimental work is the correlation between the compounds resulting from prebiotic chemical processes and those actually used by extant life, including essentially all the monomers (amino acids, nucleotides, simple sugars, etc.) which comprise the complex polymers of all organisms.

Coincidentally, just as these chemical results were being generated in laboratories, Rubey (1951, 1955) carried out the first careful analysis of the origin of Earth's atmosphere using geological reasoning. From sound uniformitarian arguments he concluded that the excess volatiles of Earth's surface, including those now bound in rocks as carbonate minerals and organic-rich sediment, could be accounted for as the result of degassing of Earth's solid interior by magmatic emanation of various gases. He went a bit further by addressing the question of timing of this degassing, concluding that it must have been largely a gradual and continuous process rather than an early, massive discharge. This conclusion was based on both the assumed composition of the volcanic gases (taken to be similar to present volcanic emissions), and the geochemical effects should these be immediately released to the surface in quantities similar to the known excess volatile inventory of sedimentary rocks (which are currently the largest volatile reservoir by a large margin). Rubey's analysis might be faulted because it did not take into account the processes of plate tectonics, unknown at that time, which might have explained the absence of evidence of the effects he described. In addition, much more is now known about ages and amounts of early Archean rocks than was available in the early 1950s. Nevertheless, Rubey's analysis became an important starting point for discussions of Earth's earliest atmosphere and its evolution through the Archean (and later).

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Essentially all subsequent discussions of degassing, the early atmosphere, and atmospheric evolution through time starts with volcanic degassing and the related chemistry of volatiles in magmatic systems, with the major gases thought to be water, carbon dioxide (sometimes monoxide), nitrogen, hydrogen sulfide (later sulfur dioxide), and hydrogen, with the first two dominant. The proportion of hydrogen and relative amounts of carbon dioxide and monoxide have been thought to depend upon whether free iron was present in the source region of the magmas, taken as approximately the upper mantle within a few hundred kilometers of the surface. I will henceforth refer to this as the "standard model".

During the 1970s considerable attention was given to speculation and detailed modeling of planetary accretion. The formation, chemistry, and nebular processing of solids in the pre-planetary solar nebula, including interactions (or lack thereof) with nebular volatiles, was aimed at understanding the compositions and possible histories of the various components of meteorites, usually assumed to be remnants of the earliest accreting material. There is little reason to doubt that the overwhelming bulk of the planets, or at least the non-volatile fraction, was accreted from solid objects resembling meteoritic material in overall composition, perhaps in different proportions depending upon radial distance from the sun. This effort was informed by a large array of elemental and isotopic geochemical data from Earth, meteorites, and eventually other planets. In addition to providing a better understanding of the relationships of various solar system objects and their systematic variations, these efforts provide a theoretical framework for describing, if not understanding in detail, the early history of the solar system. One of the most important, and perhaps well-founded, results was the constraint on the timing of planetary accretion. Establishment of timing constraints on the cratering history of the Moon, and to a somewhat lesser extent Mars and Mercury, helped define the later accretion history, in particular the Late Heavy Bombardment.

Accretion models and the data from planetary missions are largely in agreement that accretion of the terrestrial planets was rather rapid and early, largely completed in the first 100 million years of solar system history (Wetherill and Stewart 1993; Yin et al. 2002; Wood et al. 2006; Halliday 2008). The magnitude of gravitational energy release associated with accreting an Earth-size planet implies substantial heating during accretion, especially later in accretional history. When this is combined with the additional energy that would accompany core formation, it is virtually impossible to escape the conclusion that degassing of Earth must have occurred quite early, and with the release of a large fraction of the volatile inventory from the early accreted material. This conclusion has been largely built into all subsequent treatments of Earth's early atmosphere. Whether accretion was generally chemically homogeneous, that is with the accreting material having a bulk composition similar to that of Earth (or similarly for the other planets with suitable adjustments to match their individual characteristics), or as a sequential non-homogeneous process with refractory components accreting to form a "core", then less refractory material arriving later, and finally with a volatile "veneer" last, can lead to somewhat different results.