Preface

The question of how life first appeared on the Earth continues to fascinate both scientists and lay readers. A scientific database reveals over 31,000 papers related to this topic, and if one uses "origin of life on Earth" as key words to search a well-known online bookseller, perhaps a hundred or so books are available that deal directly with the science related to life's beginning. Why should we add another?

The reason is that the origin of life remains an open question, yet there is a growing optimism in the scientific community that we are getting closer to an answer. A number of new research themes that matured over the last decade have contributed to the burgeoning interest in life's origins, not the least of which is that for the first time in history we are searching for evidence of life on Mars. Results from the rovers show that Mars had liquid water over three billion years ago, at the same time that life began on Earth. A second independent origin would revolutionize our understanding of life as a universal phenomenon, not just confined to our planet.

The advent of systems biology and synthetic biology also changed the way we think about the origin of life. At some point in the pathway leading to life, there must have been a process by which molecular systems were encapsulated in cellular compartments. This understanding is now driving serious efforts to assemble artificial cells using the tools of synthetic biology, in a sense attempting to achieve a second origin of life that will tell us much about the first origin.

The editors wish to thank Richard Sever for initiating the process by which this book came to be, and Barbara Acosta for her tireless work to make it happen. We also thank all of the authors who agreed to contribute chapters. It is not easy to take time away from research to write a book chapter, but the authors agreed with us that this would be a valuable way to share their ideas. The result is a wonderful collection of expert articles that we hope will interest other scientists and guide the next generation of young investigators who are attracted to the problem of life's origin.

Dave Deamer and Jack Szostak
January 2010

Introduction and Overview

The past decade has seen a resurgence of interest, both public and scientific, in the Origin of Life. One of the most dramatic reasons for this is the discovery of hundreds of extrasolar planets, and the eagerly anticipated detection of Earth-like planets orbiting other stars. These ongoing discoveries bring a sense of immediacy to the age old question of whether we are alone in the Universe or live in a cosmos that is teeming with life. The contemporaneous discovery of the extremophiles that populate such surprising environments on our planet strongly suggests that many other planets could, in principle, support life. But how likely is it that there is in fact life on these other planets? The answer to this question depends strongly on whether the emergence of simple biology from prebiotic planetary chemistry is easy or hard, common or rare. This question can be addressed by scientific studies of the origin of life on Earth, studies that encompass the full panoply of events ranging from the formation of the Earth, through its early geochemistry and later prebiotic organic chemistry, to the synthesis of the necessary biomolecular building blocks and finally the self-assembly of primitive replicating cell-like entities that could then use the power of Darwinian evolution to adapt to an ever wider range of environments. It is these studies that are the subject of this volume.

To get some idea of the scope of the question of life's origins, consider for a moment what the Earth's surface was like 4 billion years ago, before life began. There were no genes to tell a living organism what proteins to make. There were no enzymatic catalysts, no photosynthesis, and no metabolism. Instead, on Mars and the Earth, there were sterile mineral crusts, salty oceans containing a dilute solution of thousands of organic compounds, volcanic land masses rising from hot seas, and wet-dry cycles where seas met land. Water continuously evaporated from the interface between sea and atmosphere, condensed as rain and fell on the lava of volcanic islands where it formed small pools containing organic solutes, then evaporated again. From this unpromising chaos of land, sea, and atmosphere, the first life somehow emerged, certainly on the Earth, perhaps on Mars. (See Fig. 1.)

Because life is an emergent phenomenon of chemistry, it has been mostly chemists who are attracted to the question of how life began. When the first microorganisms began to grow and reproduce on the early Earth, chemical reactions associated with growth, metabolism, and replication were among the earliest adaptations to life in a harsh and increasingly competitive environment. But how could the chemistry begin? The answer to this question involves a much larger scope that views life not just from an Earth-centric perspective, but instead as part of a universal process involving the birth and death of stars, planet formation, interfaces between minerals, water, and the atmosphere, as well as the physics and chemistry of carbon compounds. The chemistry of life only becomes possible after physical processes permit life-specific chemical reactions to begin.

The main thrust of this book is to move away from classical scenarios that emphasize the unconstrained synthesis of organic molecules by the treatment of simpler molecules with intense sources of energy. Instead we treat the origin of life as the emergence of molecular systems contained in some form of semipermeable compartment. Containment will be

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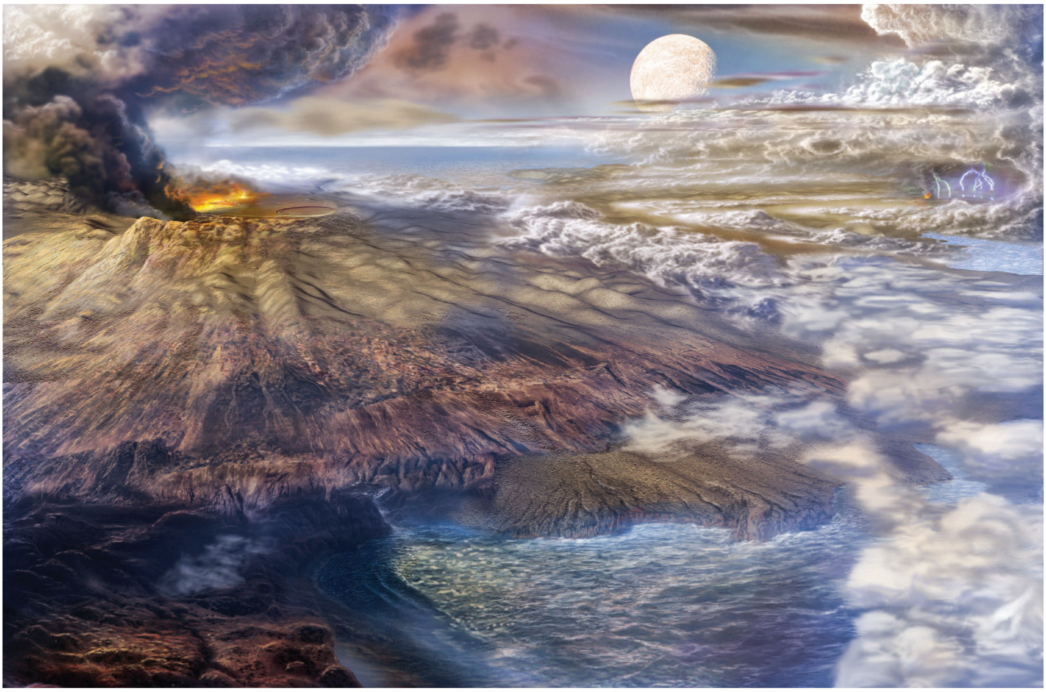

Figure 1. An artist's conception of the early Earth, sometime between 4.4 and 3.8 billion years ago. Oceans had condensed, volcanic land masses resembling Hawaii and Iceland rose out of the seas, and rainstorms produced fresh water ponds on the newly formed land masses. The physical and chemical processes leading to the first forms of life were taking place wherever there were interfaces between minerals, water and the atmosphere. (Figure by Don Dixon, FIAAA © 2005 and reprinted here with express permission from the artist.)

considered not just an afterthought, but instead as essential for life to begin and evolve. On the early Earth, over tens to hundreds of millions of years, vast numbers of microscopic compartments were produced at interfaces of minerals, water, and atmosphere. Within this multitude, some happened to contain genetic molecules that could guide the capture of chemical energy and smaller molecules from the surrounding environment and use this energy to facilitate their own replication. The emergence of compartmented sets of polymers capable of energy-dependent growth, reproduction, and evolution marked the beginning of life as we know it today.

A second theme will be to constrain our guesswork by a serious consideration of what the early Earth was really like, an effort that no matter how difficult is essential to direct realistic and informative laboratory simulations. Questions of impact history, the Hadean/Archaean environment, volcanism, and the establishment of plate tectonics are all critical if we are to understand the chemical and physical environment that prevailed at the time of life's origin.

The invited chapters in this book therefore represent an integrated set of primary concepts that we believe will foster new approaches to the origin of life. Each chapter presents aspects resembling pieces of a puzzle, and they are organized in such a way as to form an approximate chronological narrative. Because science necessarily progresses by filling in gaps with essential knowledge, we have invited authors to make explicit the challenges and future directions they perceive as scientists working on questions related to life's origin. The first chapter introduces the history of the primary ideas that guide research on life's beginning. This is followed by a section entitled Setting the Stage, which describes conditions on the early Earth that can be used to constrain laboratory simulations of the Hadean and Archaean environment. The next section, entitled Components of First Life covers the kinds of molecules that were likely to be available in the prebiotic environment. This is followed by a section called Primitive Systems that discusses the interactions between molecules that are fundamental to our understanding of the origin of living systems. The fourth section is dedicated to polymers that show how the requirements for life can be fulfilled if we treat them as the emergence of systems incorporating a flux of energy and nutrients that drives catalyzed polymerization and replication. The section entitled Transition to a Microbial World describes how the origin and evolution of ribosomes and a genetic code can be understood in terms of the RNA world that preceded it. A chapter on synthetic biology describes how we can use newly developed methods as tools to fabricate artificial cellular systems that show certain properties of the living state, including protein synthesis encoded by encapsulated genes. The book concludes with a final chapter that considers the possibility that life also arose on Mars.

Science is commonly viewed as primarily a body of knowledge, but for those engaged in research it is much more than that. Individual scientists are motivated by questions, not answers. The authors in this volume are each contributing to the progress being made toward answering one of the great questions of biology: How does life begin?

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