Advances in Astrobiology and Biogeophysics

This series aims to report new developments in research and teaching in the interdisciplinary fields of astrobiology and biogeophysics. This encompasses all aspects of research into the origins of life - from the creation of matter to the emergence of complex life forms - and the study of both structure and evolution of planetary ecosystems under a given set of astro- and geophysical parameters. The methods considered can be of theoretical, computational, experimental and observational nature. Preference will be given to proposals where the manuscript puts particular emphasis on the overall readability in view of the broad spectrum of scientific backgrounds involved in astrobiology and biogeophysics. The type of material considered for publication includes: - Topical monographs - Lectures on a new field, or presenting a new angle on a classical field - Suitably edited research reports - Compilations of selected papers from meetings that are devoted to specific topics.

More information about this series at http://www.springer.com/series/5118

Anna Neubeck • Sean McMahon
Editors

Prebiotic Chemistry and the Origin of Life

Springer

Editors
Anna Neubeck
Department of Earth Sciences
Uppsala University
Uppsala, Sweden

Sean McMahon
UK Centre for Astrobiology
University of Edinburgh
Edinburgh, United Kingdom

ISSN 1610-8957 ISSN 1613-1851 (electronic)
Advances in Astrobiology and Biogeophysics
ISBN 978-3-030-81038-2 ISBN 978-3-030-81039-9 (eBook)
https://doi.org/10.1007/978-3-030-81039-9

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This is a book about the beginnings of life on Earth from a geochemical and biochemical standpoint. It has been written by specialists working on the frontiers of several disciplines, and it is intended to provide a readable overview both for trained scientists and for advanced students in geobiology, astrobiology, and related fields. It is by no means a complete or comprehensive introduction to the field, but rather a work-in-progress report from some of its leading protagonists. We have tried to sidestep some well-worn arguments in favour of fresher perspectives and original insights. Nevertheless, the eleven peer-reviewed chapters assembled here outline many of the central questions that drive origins-of-life research today, suggest what the answers may be, and show how future work may settle them.

According to accepted common scientific understanding, life on Earth emerged through the self-organisation of lifeless matter far from thermodynamic equilibrium. Self-catalysing networks of chemical reactions gave rise to protocells: encapsulated, homeostatic units capable of reproducing themselves according to an internal genetic code. How this event or series of events unfolded is deeply unclear; the first half-billion years or so of life's history are missing from the record, and carbonaceous residues in the oldest known rocks have been heavily altered by heat, pressure, and the passage of time, destroying biochemical information. But if the origin of life cannot be observed, perhaps it can be reconstructed through painstaking, interdisciplinary scientific detective work. Clues are found in the chemistry of the elements, in the composition of meteoritic and primordial materials, in the biochemical and genetic makeup of viruses and cellular organisms alive today, in laboratory and computer simulations of prebiotic chemical reaction pathways, and in geochemical evidence from the early Earth. Cellular remains, when they finally appear in the rocks, tell us that life had already become surprisingly diverse, complex, and tolerant of environmental extremes when the fossil record began to be written. Taken together, these clues are beginning to tell a coherent story.

It is a story that begins in space. In **Chap.** 1 of this volume, **Marco Fioroni** describes the synthesis of transition metals in supernovae and their chemical transformations in space and on the young, habitable Earth. He emphasises the importance of transition metals and minerals for organometallic chemistry on the early Earth and also for the origin of life: today, almost 40% of all enzymatic reactions involve metalloenzymes. Several chemical pathways to form simple and complex building blocks and catalysts for life are thoroughly discussed, and the possible contribution of extraterrestrial organometallic/metallorganic compounds is emphasised.

In **Chap.** 2, **Robert M. Hazen and Shaunna M. Morrison** enlarge upon the mineralogical complement of the early Earth and its significance for prebiotic chemistry. They show that many biochemically central elements were supplied not in their rare and exotic mineral forms, but from the more common rock-forming minerals in which they occur as minor and trace elements. Thus, boron, molybdenum, phosphorus, and other elements would have been widely available at reactive surface sites of minerals such as olivine, pyroxene, feldspar, and magnetite, even though borate, molybdate, and phosphate minerals (and so on) were rare. This provides an elegant solution to a long-standing problem in origins-of-life chemistry.

Chapter 3, contributed by **Eva Stueeken and Nicholas Gardiner**, reconstructs the Hadean Earth as a complex, geologically dynamic world. The primordial crust, volcanic and hydrothermal systems, oceans, ice, the atmosphere, and the interfaces and transport pathways between these linked systems may all have played important roles in the operation of prebiotic chemical reaction networks. In this perspective, the major steps leading to the origin of life need not all have occurred in any single environmental setting or "crucible". Rather, we can consider the early Earth as a global chemical reactor for the origin of life.

Chiral molecules—those that occur in left- and right-handed forms—are essential in the chemistry of life. In **Chap.** 4**, Axel Brandenburg** asks why biology prefers left-handed amino acids and right-handed carbohydrates, and whether this homochirality was a prerequisite for life or a consequence of it. We learn about biological and abiotic chiral dynamics and what drives the transition from racemic mixtures to homochirality. Brandenburg takes us through the fascinating story of the discovery of chiral molecules and how they might be used to find life on Mars. Homochirality may have emerged as a consequence of autocatalysis in the hypothetical RNA world, and in **Chap.** 5**, Frank Trixler** discusses the importance of mineral surfaces for concentration, selection, homochirality, and the synthesis of nucleotides in such a world. This chapter confronts the complexity of prebiotic nucleic acid synthesis and the multiple paradoxes that inevitably arise from this given the central role of nucleic acids in biology. Another seemingly indispensable feature of life is encapsulation: enclosure within semi-permeable boundaries is a prerequisite for homeostasis. In **Chap.** 6**, Augustin Lopez, Carolina Chieffo, and Michele Fiore** discuss the origins of these boundaries from a chemical perspective, including the synthesis of amphiphilic molecules and their self-assembly into protocellular boundaries on the early Earth. In **Chap.** 7**, Oliver Trapp** discusses the formation and self-modification of organic catalysts and their importance in the origin of chirality, nucleosides, and Darwinian life. Informed by the latest experimental results, he suggests several routes towards nucleic acid-based evolutionary systems and concludes that DNA and RNA may have arisen simultaneously on the early Earth.

The boundary between life and non-life is a debated question closely linked to our understanding of life's chemical and evolutionary origins. Ever since the discovery of bacteriophages in the 1910s, viruses have been central to these debates. **Donald Pan** considers multiple aspects on the role of viruses in the origin and definition of life in **Chap.** 8. Viruses may have played a crucial role in the onset of life and can serve as useful models of prebiotic replicators, although it remains unclear whether they predate the Last Universal Common Ancestor (LUCA) of cellular life. In **Chap.** 9**, Anthony Poole** examines efforts to reconstruct LUCA using the imperfect record of evolutionary history preserved in the genetic sequences of modern organisms. Time has blurred LUCA's traits, and the interpretation of features shared by its descendants is multifaceted. Horizontal gene transfer, gene displacement, and loss all obstruct the prospect of an unambiguous reconstruction of LUCA. Poole describes how these and other constraints limit the resolution at which LUCA can be reconstructed with commonly used methods and finally suggests a feasible procedure to reconstruct LUCA by focusing on general traits.

The first stages of biological evolution are not preserved in the rock record. Nevertheless, the oldest known fossils provide important insights into the nature of early life and its environment. In **Chap.** 10**, Barbara Cavalazzi and her colleagues** describe the cellular remains, fossil bio-sedimentary structures, and other chemical and mineralogical evidence of life present in some of Earth's oldest rocks, showing how these important but controversial materials can be critically interrogated and understood. The fossil record also contains key evidence for the timing of the origin of the eukaryotes. The nucleated cell and its organelles transformed the early biosphere and eventually permitted the emergence of complex, macroscopic, multicellular organisms like ourselves. Thus, in **Chap.** 11, **Heda Agic** concludes our volume by considering this momentous event (or a series of events) from a palaeontological perspective, presenting some recently described, remarkably well-preserved microfossils that record the early evolution of eukaryotes.

This book offers a partial snapshot of origins-of-life research in the early twenty-first century. Many of its chapters were written under strain in the midst of the global COVID-19 pandemic (another testament to the power of viruses), which caused some inevitable delays; we thank our contributors both for their perseverance and for their patience. We are also hugely grateful to the peer reviewers who provided expert critical feedback on the initial drafts of each chapter, and to Ramon Khanna and Christina Fehling at Springer Nature for their support and guidance. Despite all these efforts, we earnestly hope that this volume will *not* stand the test of time: progress in this field is not merely of academic interest but of fundamental importance to humankind. New data will come from many sources: increasingly sophisticated laboratory experiments, new computational approaches to prebiotic reaction pathways, and new discoveries in the rocks of the Earth, Mars, and other planetary bodies. But it will take many more years, much labour, and the skills and ideas of diverse people around the world to understand, finally, where we came from. We hope this book will inspire its readers to take part in this great adventure.

Uppsala, Sweden Anna Neubeck
Edinburgh, UK Sean McMahon

Contents