EARLY EARTH

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Contents

Summary

The " early Earth" encompasses approximately the first gigayear (Ga, 10^9 y) in the evolution of our planet, from its initial formation in the young Solar System at about 4.55 Ga to sometime in the Archean eon at about 3.5 Ga. This chapter describes the evolution of the early Earth and reviews the evidence that pertains to this interval from both planetary and geological science perspectives. Such a description, even in general terms, can only be given with some background knowledge of the origin and calibration of the geological timescale, modern age-dating techniques, the formation of solar systems, and the accretion of terrestrial planets. These issues are therefore introduced and interwoven with a broadly chronological account of the history of Earth from older to younger eras. From this evolutionary perspective, it can be concluded that we live on a highly dynamic planet that has experienced a long history of evolutionary stages, each of which is or has been unique in some ways. Against this perspective, the present Earth merely represents a "snapshot" in an ongoing evolution to future states.

1. Introduction

Everyday life provides few direct clues as to the antiquity of Earth. Nevertheless, we inhabit an ancient planet that formed about 4.550 Ga ago (Ga, 10^9 y) as an aggregate of rock, dust, and gas swirling around a newly formed star, our Sun. Humans (*Homo sapiens sapiens*), stemming from a long lineage of ancestral primates, populated this planet only recently, with the oldest hominid fossil remains being a mere 5 Ma (Ma, 10^6 y) old or so. In contrast, remains of hard-bodied, invertebrate animals ("shelly fossils") can be traced further back in time and are found in sedimentary rocks as old as 544 Ma, the beginning of the Cambrian period of Earth history. Prior to 544 Ma stretches a vast expanse of time, more than 4 Ga long and accounting for 88% of Earth history. This vast expanse of "deep time" is referred to as the Precambrian.

The present chapter summarizes the early parts of this long history of our planet, which is referred to informally as the era of the "early Earth". Detailed knowledge of the early Earth, including its ultimate origins and subsequent evolution, is important because it provides the necessary evolutionary context to understand the present behavior of the planet. It also provides a logical connection between Earth and the origin and evolution of the Solar System. Hence, early Earth studies represent specialized but important contributions to the science of geology.

Critical themes for the early Earth are the history of accretion, the intense early impact record, the gradual secular cooling of the planet, the onset of crustal growth, and the initiation and evolution of life. Each of these will be discussed in some detail and woven into a broadly chronological account of Earth history.

Sources of information concerning the early Earth are varied. The most important direct source of information is the preserved geological rock record, not only from Earth itself, but also from its satellite the Moon, as well as from meteorites and, in the near future, other planets and asteroids to be visited by sample–return missions. Earth's rock record now stretches back more than 4 Ga, and the oldest preserved and well-dated terrestrial material is a zircon crystal dated ~4.4 Ga, which was recovered from a much younger sandstone in Western Australia. Ultimately, these rare preserved rocks and minerals are the hard data against which theoretical models based on geophysics, geochemistry, and planetary science can be tested (**see *Historical Overview of the Universe: Planets***).

2. Early Earth: Concepts

2.1. Divisions of Geological Time

The study of the history of Earth requires a meaningful subdivision of geological time. The basic reasons for this are two-fold:

- Given the immense span of time represented by 4.55 Ga of Earth history, it is useful to divide this history into smaller eras to allow us to focus in on particular events and processes. Obviously, this effort should aim at finding natural subdivisions in the rock record that can then be calibrated by radiometric dating methods, including events such as the emergence of life or major evolutionary radiations, global volcanic eruptions, or catastrophic meteorite impacts.

- As in any science, there is a need for clear, concise, and precise terminology to facilitate communication of concepts and ideas.

Unfortunately, the geological timescale terminology in use today is the cumulative outcome of a convoluted history of classification and reclassification of mostly stratified (i.e., layered) rocks and their fossil content during the growth of the geological sciences over the last three centuries. Hence, the timescale terminology can only be understood against the background of how it arose. A brief summary of its development is given below and illustrated in Figures 1 and 2.

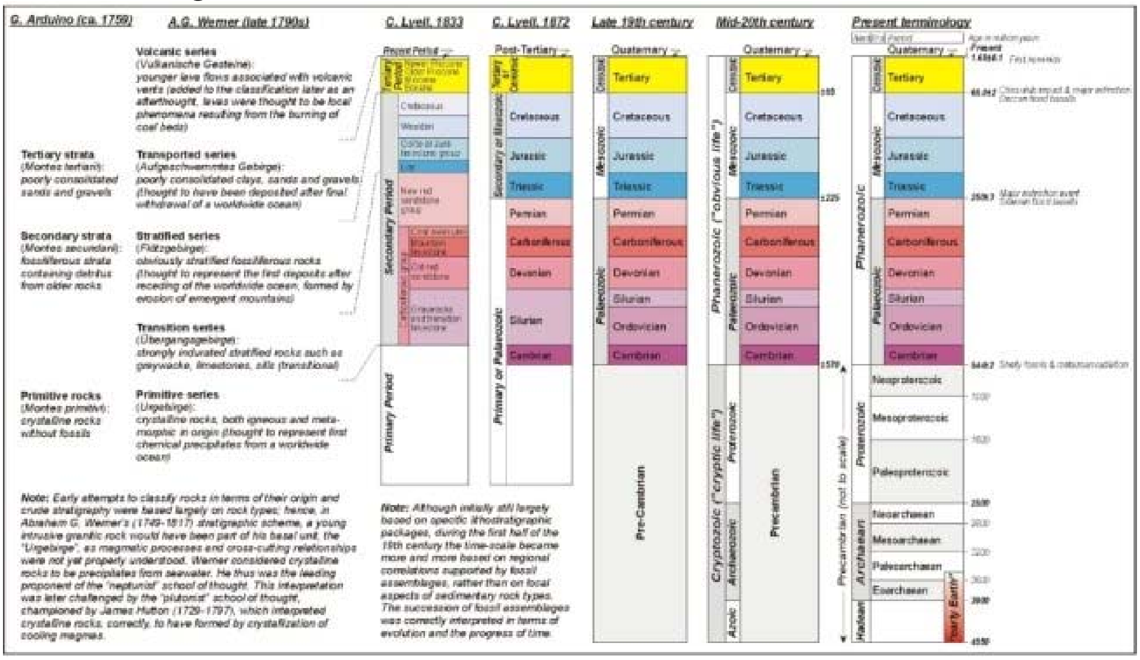

Figure 1. Historical development of the geological timescale, from the birth of geological science in the mid-eighteenth century to its present terminology

The Precambrian part of the timescale is not to scale. The modern timescale is divided into subdivisions of different “rank”: eons, eras, and periods. The “early Earth” is an informal designation of approximately the first gigayear (10^9 y) of Earth’s history.

It has long been recognized that rock sequences represent a progressive superposition of geological processes, and hence preserve a record of prehistoric time with younger rocks lying generally on top of older rocks. This realization, first clearly formulated in 1669 by Nicolaus Steno, later became known as the “law of superposition.” It allows the layers of reasonably preserved stratified rocks, whether deposited on the uplifted bottom of a former sea, on the flanks of a volcano, or within an impact crater on the Moon, to be “read” as the pages of a book on the history of the Earth.

Interestingly, this awareness, together with the first insights into rates of deposition of sedimentary materials and geological strata, and the total thicknesses of stratified rocks, provided some of the first estimates for a minimum age of the Earth—an age that was found to be orders of magnitude greater than the ~6 ka (10^3 y) since the year 4004 BC interpreted from biblical accounts.

A major impetus for subdivision of the geological rock record (and hence geological time) came from the observation that certain fossils are confined to particular layers of sedimentary rocks, and that fossils could therefore be used to date, in a relative sense, the great sequences of sedimentary strata that cover extensive tracts of the continents. From this effort arose the classical subdivision of the younger part of earth history into the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary periods (Figure 1, central columns). Many of these periods were named after a particular type area (e.g., the Jurassic period after the Jura Mountains on the border between France and Switzerland) where rocks of that age were particularly well exposed, whereas others took their name from a particular characteristic, such as, for instance, an abundance of fossil coal layers (Carboniferous period). Also, most periods could be characterized by the dominance of a particular type of fossil or fossil assemblage (e.g., ammonites were particularly prolific in the Cretaceous period and then became extinct at the Cretaceous–Tertiary boundary).

As the oldest shelly fossils appeared in rocks assigned to the Cambrian period, older nonfossiliferous rocks were designated to be of pre-Cambrian age, a term that subsequently transformed into a more formal usage: the Precambrian (Figure 1, two right-hand columns).

Based on similarities and differences between the characteristics of fossil assemblages from period to period, it was also recognized that the Cambrian to Permian periods had more in common with each other than with later periods, and hence they were collectively referred to as the "Primary" or Paleozoic era (Paleozoic being derived from Greek roots meaning "old life"). Similarly, the Triassic, Jurassic, and Cretaceous periods shared many characteristics and were referred as the "Secondary" or Mesozoic era ("middle life"). The Tertiary and Quaternary periods, following on the older "Primary" and "Secondary" eras, became collectively referred to as the Cenozoic era ("recent life").

It is interesting to note that we now recognize the end of the Paleozoic and Mesozoic eras as two of the largest mass extinction events in the history of life. Although the cause for these mass extinction events remains hotly debated, at least one of them (at the end of the Mesozoic era, at 65 Ma) coincided with a massive impact event in the Yucatan peninsula, Mexico, by a large extraterrestrial body. In addition, both extinction events coincided with, or shortly followed, some of the largest, short-lived, volcanic eruptive events preserved in the geological record—the Siberian flood basalt event at the end of the Permian (~250 Ma), and the Deccan flood basalt event in India at the end of the Cretaceous (67–65 Ma; Figure 1, right-hand column).

During the late nineteenth and early twentieth centuries, further efforts to subdivide geological time into broad eons based on major stages of biotic evolution led to the introduction of the terms Phanerozoic ("obvious life") and Cryptozoic ("cryptic life"). The Phanerozoic eon encompasses the Paleo-, Meso-, and Cenozoic eras, whereas the Cryptozoic was equivalent to the Precambrian. The Cryptozoic was further subdivided into three eons (from old to young): Azoic ("no life"), Archeaozoic ("ancient life"), and

Proterozoic ("first life"). Figure 1 illustrates the relationships between these various terms, not all of which survive in presently used terminology. In North America, the term Archeaozoic was shortened and transformed into Archean.

Efforts to find natural boundaries for these eons in the rock record led to a protracted debate between proponents of particular stratigraphic sections on various continents. In the latter part of the twentieth century, however, radiometric dating methods had evolved sufficiently to indicate that various proposed Archean–Proterozoic boundaries are diachronous (i.e., not time equivalent).

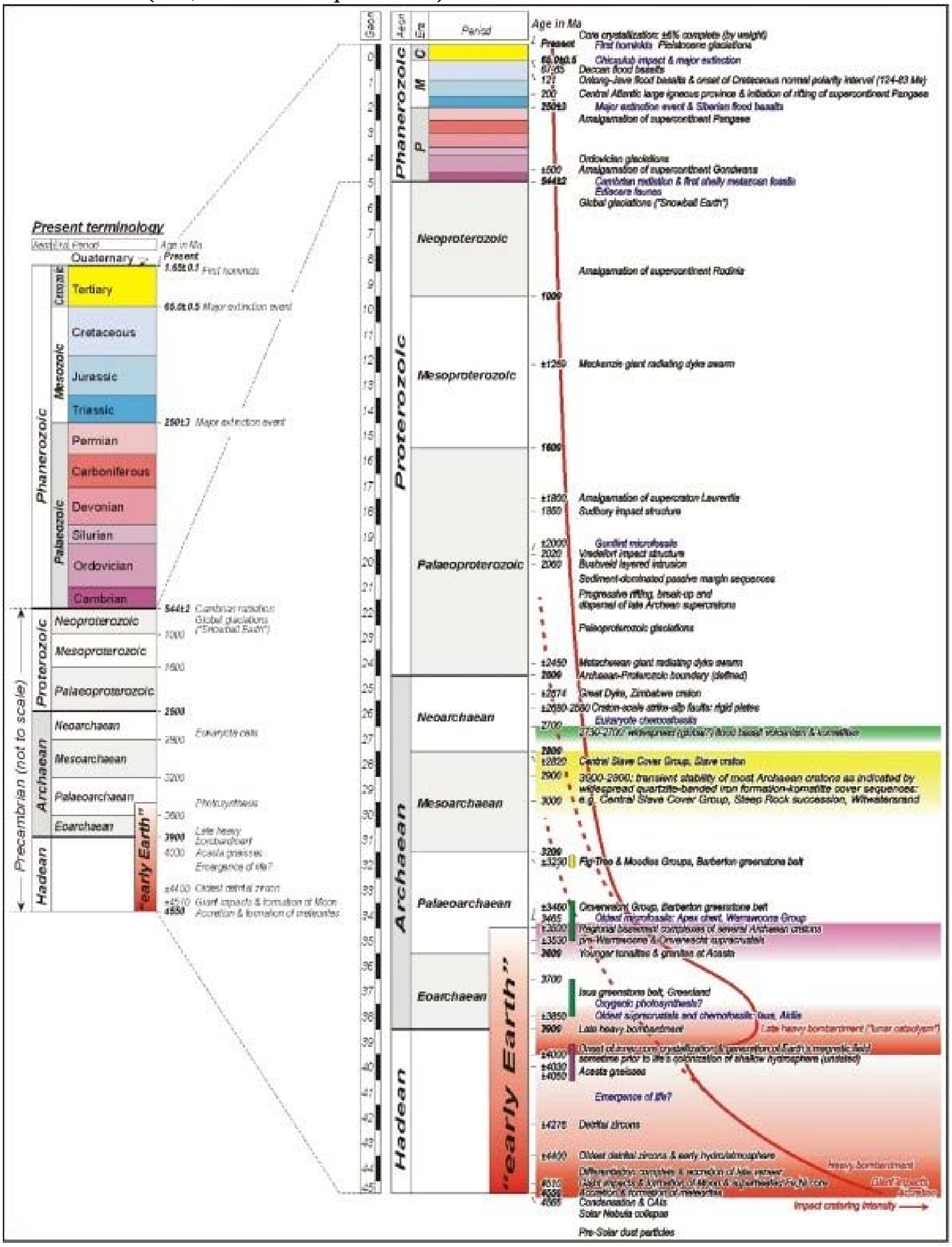

Figure 2. The geological timescale, illustrating present terminology and timing of events relevant to the early Earth

The right-hand column is to scale. The exponentially decaying curve (curves) on the right reflects, schematically, the decreasing impact intensity of extraterrestrial bodies on Earth, from giant impacts toward the end of accretion and the subsequent tail of heavy bombardment, the late heavy bombardment at 3.9 ± 0.1 Ga, to the present reduced (but nonzero!) impact cratering rate. The impact curve probably represents the summation of several different impactor populations and may be much more "spiked" than shown here.

Hence, a decision was made by international committee to place this boundary, arbitrarily, at 2500 Ma, rather than to correlate it with a suitable feature in one specific section of stratigraphy . As a result, the Proterozoic eon now stretches from 2500 Ma to 544 ± 2 Ma, the latter age reflecting precisely dated volcanic ash layers at the beginning of the Cambrian period. The Archean eon stretches back in time from 2500 Ma to the oldest supracrustal rocks known (3.8–3.9 Ga).

Furthermore, to provide a framework of useful time intervals of several hundred million years, the Proterozoic eon has been further subdivided into three eras using the prefixes Paleo-, Meso-, and Neoproterozoic. Such time intervals reflect the typical duration of tectonic cycles, the analysis of which provided the initial impetus for such subdivisions. A similar scheme has recently been introduced for the Archean (Figure 1, right-hand column).

The time interval between the initial formation of Earth and the age of the oldest preserved terrestrial rocks has been named the Hadean (after Hades, the god of the "underworld" in Greek mythology). However, when this term was introduced, it was thought that the oldest preserved rocks were only~3.6 Ga in age. Since then, further fieldwork in remote areas, in combination with ever more refined dating techniques, has pushed the limits of the known rock record back to near 4.03–4.05 Ga, and there is no particular reason why even older rocks could not be found in the future. Hence, the Hadean–Archean boundary is sliding back in time, requiring a decision either to maintain the Hadean as presently defined ("no preserved rock record"), or to place its boundary at some specified date (e.g., 3900 Ma; Figure 2).To some extent this debate mirrors the earlier argument about the Archean–Proterozoic boundary. A specified boundary at 3900 Ma seems a logical choice, as this age coincides with what is thought to be a major "cataclysm" in the Earth–Moon system, the so-called "late heavy bombardment." This event, resulting from a renewed and intense influx of large, stray objects into the inner Solar System (comets and/or asteroids), produced some of the major, 1000–2000 km diameter impact basins on Moon (Figure 3). Given the larger size and mass of Earth, and hence a "gravitational cross section" that is ~25 times that of Moon, this influx is almost certain to have caused an even greater disturbance on Earth, perhaps resulting in resurfacing of much of the planet. Hence, it may not be surprising that the oldest preserved volcanic and sedimentary rocks—those of the Isua greenstone belt of southwestern Greenland—are marginally younger than 3900 Ma. Rocks older than those of Isua have been found in northern Canada, but do not include stratified supracrustal rocks.

In summary, the geological timescale as presently used (Figure 2) is a mixed construct of terms, based largely on tradition. Particularly for the Precambrian, some of the divisions and their boundaries only loosely conform with the "natural boundaries" they were designed to reflect. An excellent example is the recent discovery of "chemofossils" (organic macromolecules that can be traced to a certain group of biota) indicating that eukaryote cells were probably in existence at least as early as 2700 Ma, well before the onset of the Proterozoic, the eon to which they were once thought to be restricted. Nevertheless, the present timescale terminology provides a unique set of terms that subdivides geological time into useful intervals. The Hadean–Archean transition, if placed at ~3900 Ma, correlates with a major event in the Earth–Moon system. The Archean–Proterozoic boundary, defined at 2500 Ma, corresponds approximately with a diachronous change in tectonic styles by which continental crust was constructed, and thus reflects a somewhat arbitrary milestone in the thermal cooling history of Earth (**see *Time in the Geological Past of Earth***).

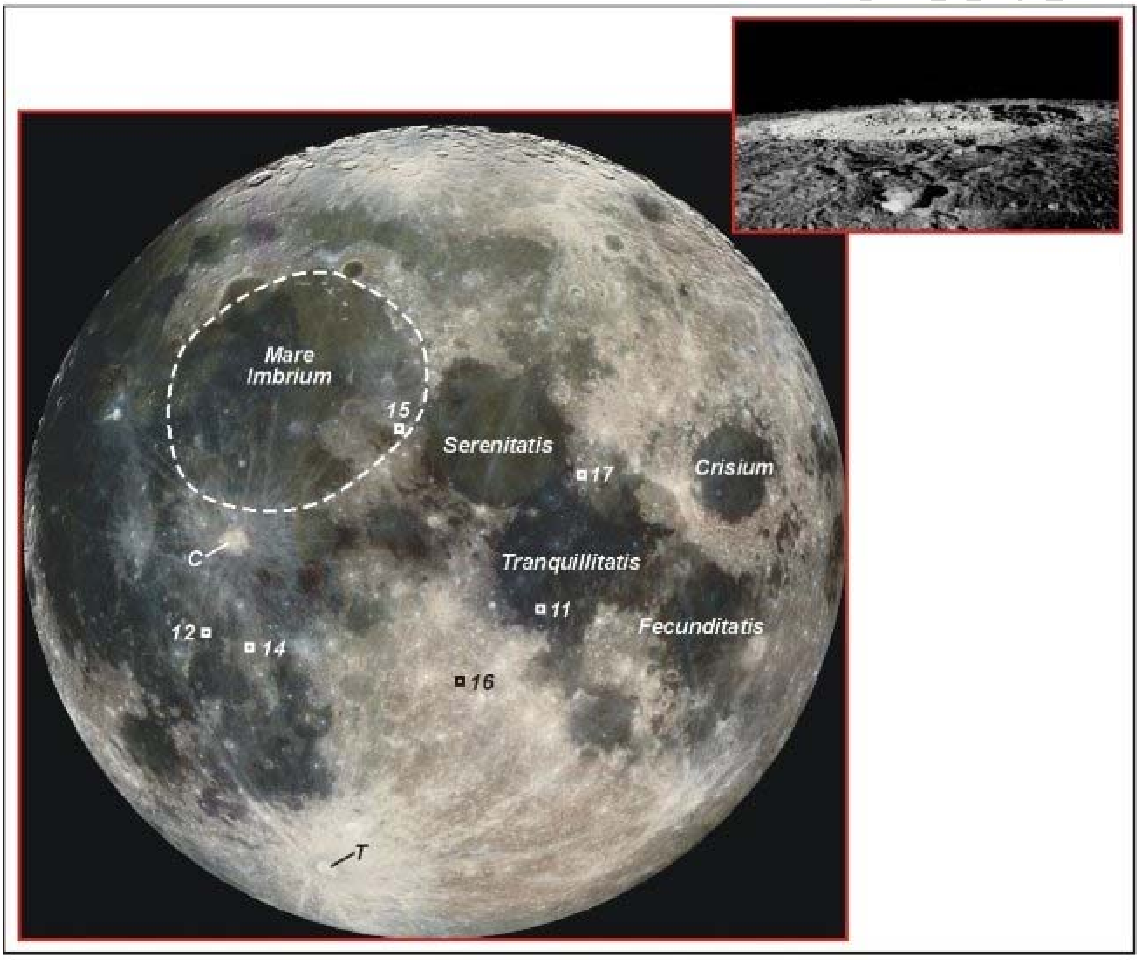

Figure 3. Near side of Moon showing the large, dark, lava-filled impact basins, such as Mare Imbrium (~1000 km in diameter)
Many of the large impact basins are thought to have formed during the late heavy bombardment (3.9 ± 0.1 Ga). Prominent younger impact craters Tycho (T) and Copernicus (C) are also indicated, as are the approximate landing sites of the various

Apollo missions. The inset shows a low-angle view of the ~100 km diameter impact crater Copernicus. (Sources: NASA.)

2.2. Definition of the"Early Earth"

As explained in the previous section, the geological timescale for the Precambrian, divided into the Hadean (older than 3900 Ma), Archean (3900–2500 Ma), and Proterozoic (2500–544 Ma) eons, correlates only loosely with major "natural boundaries" in Earth evolution. The informal term "early Earth" is therefore commonly used to capture, approximately, the first gigayear (10^9 y) of Earth history, from its early accretion phase at 4.55 Ga to well into the Archean, including the time during which some of the oldest preserved supracrustal sequences were deposited and, by inference, oceans not unlike those of today must have been present. The term "early Earth" is therefore nearly synonymous with the combined eons of the Hadean and older parts of the Archean. The younger age limit of the "early Earth" is not clearly defined and will depend on the context and the preferences of individual authors.

The term "early Earth" is perhaps particularly appealing from a planetary science perspective that is interested in understanding Earth evolution, in a direction of "positive time," from its initial birth in a young solar system. This differs from the historical geological perspective that tends to look back into the rock record, in a direction of "negative time." The "early Earth" concept thus reflects the growing emphasis on a coherent model for Earth's first gigayear from both a modern planetary science and a traditional geoscience perspective.

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Biographical Sketch

Wouter Bleeker is a research scientist with the Continental Geoscience Division of the Geological Survey of Canada (GSC), in Ottawa. A graduate from the Free University of Amsterdam, The Netherlands, he obtained his Doctorate in 1990 from the University of New Brunswick, Canada, with a dissertation on the stratigraphy, structural geology, and nickel ore deposits of the early Proterozoic Thompson Nickel Belt, Canada. His research has focused on the structure, stratigraphy, and geochronology of complex Precambrian terrains across various cratons and he is currently leading research efforts by the GSC on the Slave craton of the northwestern Canadian Shield. As part of this research, the age of the oldest terrestrial rocks has been redefined to more than 4000 million years old. Dr. Bleeker's research interests focus on Earth's secular evolution, the Hadean and Archean Earth, the nature of Archean tectonics, and the correlation of Archean cratons.