The earliest Earth was a strange inhospitable world, yet transitions to a more familiar planet occurred within the first billion years. In spite of sparse preservation of an ambiguous rock record, recent studies refine the nature and timing of key events. This issue reviews current knowledge of the age of the Earth, massive early meteorite impacts, the early atmosphere and hydrosphere, the rock record, and the first life.

**KEYWORDS:** Hadean, early Earth, geochronology, meteorites, atmosphere, oceans, zircon, life

The surface of the Earth was cruelly inhospitable at the time of its birth about 4.5 billion years ago. Red-hot oceans of magma, massive meteorite strikes, and a dense atmosphere elicit the name “Hadean” for this earliest time period (Fig. 1). Clearly such extreme conditions had to subside before continents, oceans, and life could survive on Earth (see cover). So when did the Hadean end? Evidence from rocks has been used to place this boundary at 3.8 Ga (billion years before present), the age of the oldest known water-laid sediments. The fossil record of life begins even later at 3.5 Ga, although low carbon isotope ratios ($^{13}$C/$^{12}$C) in carbonaceous matter from Isua, Greenland, suggest that life got its start before 3.8 Ga. Recently, isolated detrital zircons as old as 4.4 Ga from localities in Western Australia have provided evidence that the Hadean was shorter than previously thought. While extreme opinions exist on both sides, a moderate position is that small continent-like land masses existed by 4.4 Ga and oceans hospitable to life existed at 4.2 Ga (Fig. 2). In this interpretation, the Hadean was over by 4.2 Ga and possibly earlier. Life may have emerged quickly in the post-Hadean oceans—there is no direct evidence. If life did exist before 3.8 Ga, it was subjected to intense meteorite bombardment and possibly extinction.

The age of the Earth has been debated for centuries. Accurate estimates based on the radioactive decay of uranium to lead were first made with improved mass spectrometers following the Second World War. In the second article of this issue, “The Origin of the Earth—What’s New?,” Alex Halliday describes the precise chronology of events that has been established from the many isotope systems now available for determining the age of rocks. A traditional type of geochronometer uses parent–daughter isotope pairs with long half-lives for radioactive decay (i.e. $^{238}$U→$^{206}$Pb, half-life of 4468 million years, Myr); this method has established the geological time scale in years before the present. A more recently exploited technique uses isotope pairs with short half-lives (i.e. $^{26}$Al→$^{26}$Mg, half-life of 0.73 Myr), in which the parent isotope is now extinct; ages are measured relative to the formation of the solar system. Thus, we can count forward or backward. This situation leads to the irony that the occurrence of some events is well established during the first 50 million years, but the next 500 Myr period from which no known rocks have been preserved (sometimes called the geological “Dark Ages”) is poorly understood, and the following 4000 Myr of Earth history are increasingly well documented. No single date can be assigned for the formation of the Earth, which accreted over a period of time from swirling dust, rocks, and planetesimals (~1 km diameter bodies) in the solar nebula. However, the age of the solar system is known with extreme precision from studies of meteorites to be 4.567 Ga. The Earth grew rapidly after this start, and calculations show that it attained most of its mass within 10 million years. Other events within the first 50 Myr include the gravitational settling of iron to form the metal core of the Earth and the formation of the Moon. The Earth grew rapidly after this start, and calculations show that it attained most of its mass within 10 million years.
formation of the Moon when a planet struck the Earth—a terrestrial impact so violent that both bodies melted and partly vaporized.

The Earth continues to grow today, with \(10^6-10^7\) kg of meteorites added each year, including thousands that are fist-size or larger. This is a trace contribution to the mass of the Earth and largely goes unnoticed. In “Impact Processes on the Early Earth,” Christian Koeberl portrays a far more violent early history of meteorite impacts and cratering. During accretion, the mass flux of material added to the Earth was extreme, but it dropped five to ten orders of magnitude during the first 100 Myr and has continued to decline ever since, except during a resurgence called the Late Heavy Bombardment at ~3.85 Ga. While no evidence of impacts during the first billion years is preserved on Earth, largely due to tectonic reworking, nearly 200 younger impacts are known, the oldest being the Vredefort Dome (2023 Ma) in South Africa. Only the ancient surfaces of the Moon and Mars have provided evidence of the earlier ravages.

The early atmosphere was thick, hot, and poisonous. Carbonic “greenhouse” gases prevailed, and before 2.3 Ga, levels of oxygen were too low to sustain aerobic life. In “Earth’s Earliest Atmosphere,” Kevin Zahnle traces the evolution from a Hadean atmosphere to more clement conditions that could nourish life. In “Earth’s Earliest Atmosphere,” Kevin Zahnle traces the evolution from a Hadean atmosphere to more clement conditions that could nourish life. Early on, not only were the oceans vaporized by energetic impacts, so was the silicate surface of the Earth, followed by magmatic “rain” and “hailstones” of rock! However, the faint young Sun was 30% weaker than today, and cooling of Earth’s surface was surprisingly rapid. Calculations suggest that post-Hadean temperatures subsided enough to precipitate steam as ocean water and, depending on poorly known levels of atmospheric insulation, to freeze water. Zahnle argues that the cool early Earth was actually a snowball with pools of water localized around geothermal vents or at impact sites. These changing conditions could have spurred the emergence of life.

Rocks at least 2.5 billion years old are found on every continent and are relatively common (Fig. 3). However, most of the more ancient rocks have been destroyed or reworked beyond recognition by the Earth’s tectonic processes. Only a handful of small localities are known to be older than 3.6 Ga. In “Antiquity of the Oceans and Continents,” Allen Nutman reviews studies of these key areas, with emphasis on Isua, Greenland, the most diverse early terrane. In spite of moderate metamorphism, ~3.8 Ga rocks from Isua preserve evidence of plate tectonics, oceans, and perhaps life. The only known older rocks are gneisses from Acasta, Canada, at 4.0 Ga. The only record of rocks older than this comes from isolated crystals of the mineral zircon from Western Australia that are as old as 4.4 Ga.

Zircons are exceptionally robust and retentive. The most ancient grains were removed from unknown parent rocks, transported as wind-blown dust and river mud, and deposited as detrital grains in sedimentary rocks. They carry chemical clues to their origin in the form of mineral inclusions, trace elements, growth zoning, and isotopes of uranium, lead, oxygen, and hafnium (see “Zircons Are Forever”: www.geology.wisc.edu/zircon/zircon_home.html). The study of these tiny time capsules requires the use of advanced instruments, including large secondary-ion mass spectrometers called ion microprobes, which measure the age (U–Pb) and oxygen isotope ratio in 10–20 µm domains. These characteristics can be correlated with other features in the 100–300 µm crystals (Fig. 4). The existence of zircons as old as 4.4 Ga indicates that small amounts of granitic (sensu lato) proto-continent existed at that time. Without such buoyant crust, the zircon-bearing rocks would have
sunk into the mantle and been destroyed. High oxygen isotope ratios in some early zircons suggest that liquid water oceans existed at 4.2 Ga (Fig. 2). Evidence from Ti and Hf has been interpreted as indicating even earlier granites (sensu stricto) and that plate tectonics was operating, but the uniqueness of these interpretations is debated (Harrison et al. 2006; Valley et al. 2006).

The oldest-known fossil evidence for life, along with appropriate geochemical signatures, is found in ~3.5 Ga rocks, but this does not necessarily date the emergence of life. If the first life was at 3.5 Ga, that would suggest that it was delayed by 700 million years after the end of the Hadean. In “The First Billion Years: When Did Life Emerge?” William Schopf discusses the evidence for life found in rocks from the oldest localities. It appears that one-celled organisms were diversified, flourishing, and relatively common by ~3.5 Ga, indicating that the first life came much earlier. If the carbon isotope record in metamorphic rocks is correct, then the emergence of life was before 3.8 Ga. In fact, all of the essential ingredients for life were assembled on Earth as soon as near-surface waters cooled enough for DNA to be stable (~4.2 Ga). If life emerged on Earth or was delivered from space at this time, its main challenge would have been possible annihilation during the Late Heavy Bombardment (~3.85 Ga). Survival chances would have been enhanced if primitive microbes, like archaea, were...
capable of subsisting underground in the absence of sunlight. Alternatively, the earliest life on Earth may have evolved and become extinct many times before 3.85 Ga, and the present inhabitants of Earth may be descended from the first continuously successful life, but not the first life.

Taken together, these articles summarize a new understanding of the first one billion years of history of our planet and portray its evolution from highly energetic to clement. This is a rapidly emerging field of study that will aid interpretation of other planets and the origin of life, inside the solar system and possibly beyond.

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REFERENCES


GLOSSARY

Archaean – A recently recognized domain of prokaryotic life. Single-celled organisms, similar in structure to bacteria, but different in metabolism and genotype. They include methanogens and hyperthermophiles that may be similar to the first life.

Archean – Precambrian Eon older than 2.5 Ga and younger than the Hadean

Banded iron formation (BIF) – Layered rock composed of centimeter-scale bands of quartz and iron oxide precipitated from ocean water. The earliest known BIFs formed at 3.8 Ga, whereas the largest BIFs formed between 2.5 and 1.8 Ga, at the same time as the rise of atmospheric oxygen.

Carbon isotopes – The ratios of the stable isotopes of carbon (¹³C/¹²C) are normalized to a marine carbonate standard and expressed as δ¹³C in per mil (%). Low ¹³C/¹²C results from metabolism and is commonly cited as evidence for biogenicity. Questions arise in ancient rocks regarding the source of carbon, its preservation, and abioticogenic reactions.

Cathodoluminescence (CL) – Light emitted by minerals during electron bombardment. Commonly viewed with an electron microscope. CL imaging of zircons can detect growth zoning, inherited cores, and damaged domains.

Hadean – Geological time before the Archean Eon, ~4.5 to 4.2 Ga

Ga – Billions of years before the present

Giant Impact Theory – Widely accepted hypothesis that the Moon was formed when the Earth was struck by a Mars-size planet at ~4.5 Ga

Late Heavy Bombardment (LHB) – Event characterized by a sharp increase in the size and number of meteorites striking the Earth and other bodies in the inner solar system; proposed to have occurred at ~3.85 Ga

Lithophile – Refers to elements that concentrate in silicate minerals and melts and are more abundant in the Earth’s crust than in its mantle and core

Ma – Billions of years before the present

Magma ocean – Worldwide ocean of molten rock, initially at the Earth’s surface during accretion but later covered by newly formed crust; may have been hundreds of kilometers deep in the Hadean

Oxygen isotopes – The ratios of the most common stable isotopes of oxygen (¹⁸O/¹⁶O) are normalized to an ocean water standard and expressed as δ¹⁸O in per mil (%). Fractionations are generally mass dependent and used to determine the temperature of geological events. The ratios of ¹⁸O/¹⁶O are measured in rocks from extraterrestrial bodies and sometimes Earth to study mass-independent processes.

Planetesimal – Small kilometer-scale rock bodies orbiting the young Sun

Radioisotopes – Isotopes that undergo radioactive decay. The parent–daughter isotope ratio and half-life can be used to determine the age of a rock.

Siderophile – Refers to elements that concentrate in metal and are more abundant in the Earth’s core than in its outer parts

SIMS, secondary-ion mass-spectrometer – Also called the ion microprobe, an analytical instrument capable of dating zircons and measuring isotope ratios from microscopic spots (typically 10–20 µm) in individual crystals using a highly focused ion beam

Stromatolite – Typically, a finely laminated sedimentary feature formed in shallow water by photosynthetic microbial communities

TIMS, thermal-ionization mass-spectrometer – An analytical instrument most often used for U–Pb geochronology of single zircons and larger samples. Since precision increases with sample size, ages may be more precise than those obtained with the ion microprobe; however, the ability to analyze zoned or heterogeneous zircons is lost.

Tonalite – Granitic plutonic rock with dominant quartz (>20%) and plagioclase [Plagioclase/(Alkali feldspar + Plagioclase)>90%]

Zircon – Common trace mineral (ZrSiO₄) that is highly resistant to mechanical and chemical alteration. It yields the most reliable estimates of the U–Pb age and oxygen isotope ratio for ancient rocks. In situ analysis by ion microprobe can resolve the ages of inherited cores and younger overgrowths.