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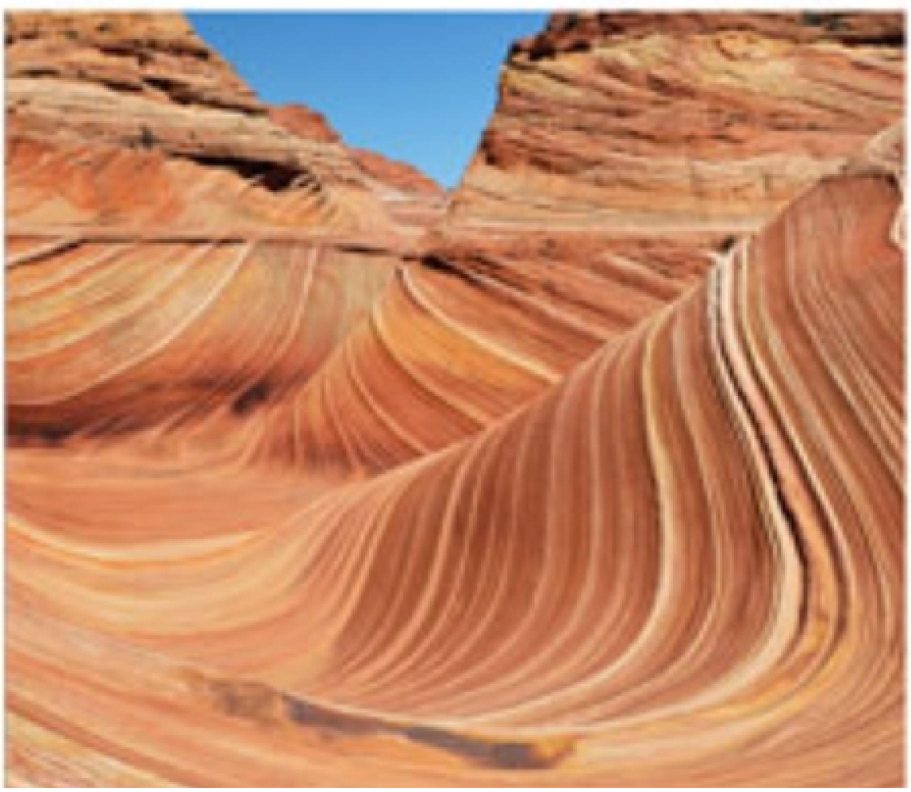
How Science Figured Out the Age of Earth

For centuries scholars sought to determine Earth's age, but the answer had to wait for careful geologic observation, isotopic analyses of the elements and an understanding of radioactive decay

By Paul S. Braterman on October 20, 2013



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Editor's note: The following is the introduction to a special e-publication called Determining the Age of the Earth (click the link to see a table of contents). Published earlier this year, the collection draws articles from the archives of Scientific American. *In the collection, this introduction appears with the title, "Stumbling Toward an Understanding of Geologic Timescales."*

Aristotle thought the earth had existed eternally. Roman poet Lucretius, intellectual heir to the Greek atomists, believed its formation must have been relatively recent, given that there were no records going back beyond the Trojan War. The Talmudic rabbis, Martin Luther and others used the biblical account to extrapolate back from known history and came up with rather similar estimates for when the earth came into being. The most famous came in 1654, when Archbishop James Ussher of Ireland offered the date of 4004 B.C.

Within decades observation began overtaking such thinking. In the 1660s Nicolas Steno formulated our modern concepts of deposition of horizontal strata. He inferred that where the layers are not horizontal, they must have been tilted since their deposition and noted that different strata contain different kinds of fossil. Robert Hooke, not long after, suggested that the fossil record would form the basis for a chronology that would "far antedate ... even the very pyramids." The 18th century saw the spread of canal building, which led to the discovery of strata correlated over great distances, and James Hutton's recognition that unconformities between successive layers implied that deposition had been interrupted by enormously long periods of tilt and erosion. By 1788 Hutton had formulated a theory of cyclic deposition and uplift, with the earth indefinitely old, showing "no vestige of a beginning—no prospect of an end." Hutton considered the present to be the key to the past, with geologic processes driven by the same forces as those we can see at work today. This position came to be known as uniformitarianism, but within it we must distinguish between uniformity of natural law (which nearly all of us would accept) and the increasingly questionable assumptions of uniformity of process, uniformity of rate and uniformity of outcome.

That is the background to the intellectual drama being played out in this series of papers. It is a drama consisting of a prologue and three acts, complex characters, and no clear heroes or villains. We, of course, know the final outcome, but we should not let that influence our appreciation of the story as it unfolds. Even less should we let that knowledge influence our judgment of the players, acting as they did in their own time, constrained by the concepts and data then available.

One outstanding feature of this drama is the role played by those who themselves were not, or not exclusively, geologists. Most notable is William Thomson, ennobled to become Lord Kelvin in 1892, whose theories make up an entire section of this collection. He was one of the dominant physicists of his time, the Age of Steam. His achievements ran from helping formulate the laws of thermodynamics to advising on the first transatlantic telegraph cable. Harlow Shapley, who wrote an article in 1919 on the subject, was an astronomer, responsible for the detection of the redshift in distant nebulae and hence, indirectly, for our present concept of an expanding universe. Florian Cajori, author of the 1908 article “The Age of the Sun and the Earth,” was a historian of science and, especially, of mathematics, and Ray Lankester, whom he quotes, was a zoologist. H. N. Russell, author of the 1921 article on radioactive dating, was familiar to me for his part in developing the Hetzsprung-Russell diagram for stars, but I was surprised to discover that he was also the Russell of Russell-Saunders coupling, important in atomic structure theory. H. S. Shelton was a philosopher of science, critical (as shown in his contribution, the 1915 article “Sea-Salt and Geologic Time”) of loose thinking and a defender of evolution in debates.

The prologue to the drama is the mid-19th century recognition of the relation between heat and other kinds of energy (see the 1857 article “Source of the Sun’s Heat”). The first act consists in a direct attack, led by Lord Kelvin, on the extreme uniformitarianism of those such as Charles Lyell, who regarded the earth as indefinitely old and who, with great foresight (or great naivety, depending on your point of view: see the third installment of the 1900 “The Age of the Earth” article by W. J. Sollas), assumed that physical processes would eventually be discovered to power the great engine of erosion and uplift.

The second act of the drama sees a prolonged attempt by a new generation of geologists to estimate the age of the earth from observational evidence, to come up with an answer that would satisfy the demands of newly dominant evolutionary thinking, and to reconcile this answer with the constraints imposed by thermodynamics. The third act sees the entry of a newly discovered set of physical laws—those governing radioactivity. Radioactivity offered not only a resolution to the puzzle of the earth’s energy supply but also a chronology independent of questionable geologic assumptions and a depth of time more than adequate for the processes of evolution.

Lord Kelvin and his allies used three kinds of argument. The first of these referred to the rate of heat loss from the earth and the length of time it would have taken to form its solid crust. The second referred to such topics as the detailed shape of the earth (bulging slightly at the equator) and the dynamics of the earth-moon system. The third referred to the heat of the sun, particularly the rate at which such heat is being lost, compared with the total amount of energy initially available.

The first argument was completely undermined after taking into account the amount of heat generated by radioactive decay. The second depended on highly dubious theories of formation of the earth and moon and plays relatively little role in this compilation. The third, which by the end was the most acute, presented a problem that outlasted the controversy itself. Thus, when in 1919 Shapley stated that for him the radiometric timescale was fully established, he acknowledged that there was as yet no explanation for the sun’s energy. (He did not need to wait long. In 1920 Sir Arthur Eddington came up with the answer: the fusion of hydrogen into helium.)

In reply to Lord Kelvin’s attacks, the geologists used two principal lines of reasoning. One referred to the depth of the sediments and the time they would have taken to accumulate; the other referred to the salinity of the oceans, compared with the rate at which rivers are supplying them with sodium salts. In hindsight, both theories were deeply misguided, for similar reasons. They assumed that current rates—of sediment deposition and of salt transport by rivers—were the same as historical rates, despite the evidence they had that our own age is one of atypically high geologic activity. Worse, they measured inputs but ignored outputs. The rock cycle, as we now know, is driven by plate tectonics, with sedimentary material vanishing into subduction zones. And the oceans have long since approached something close to a steady state, with chemical sediments removing dissolved minerals as fast as they arrive.

Nevertheless, by the late 19th century the geologists included here had reached a consensus for the age of the earth of around 100 million years. Having come that far, they were initially quite reluctant to accept a further expansion of the geologic timescale by a factor of 10 or more. And we should resist the temptation to blame them for their resistance. Radioactivity was poorly understood. Different methods of measurement (such as the decay of uranium to helium versus its decay to lead) sometimes gave discordant values, and almost a decade passed between the first use of radiometric dating and the discovery of isotopes, let alone the working out of the three separate major decay chains in nature. The constancy of radioactive decay rates was regarded as an independent and questionable assumption because it was not known—and could not be known until the development of modern quantum mechanics—that these rates were fixed by the fundamental constants of physics.

It was not until 1926, when (under the influence of Arthur Holmes, whose name recurs throughout this story) the National Academy of Sciences adopted the radiometric timescale, that we can regard the controversy as finally resolved. Critical to this resolution were improved methods of dating, which incorporated advances in mass spectrometry, sampling and laser heating. The resulting knowledge has led to the current understanding that the earth is 4.55 billion years old.

That takes us to the end of this series of papers but not to the end of the story. As with so many good scientific puzzles, the question of the age of the earth resolves itself on more rigorous examination into distinct components. Do we mean the age of the solar system, or of the earth as a planet within it, or of the earth-moon system, or the time since formation of the earth's metallic core, or the time since formation of the earliest solid crust? Such questions remain under active investigation, using as clues variations in isotopic distribution, or anomalies in mineral composition, that tell the story of the formation and decay of long-vanished short-lived isotopes. Isotopic ratios between stable isotopes both on the earth and in meteorites are coming under increasingly close scrutiny, to see what they can tell us about the ultimate sources of the very atoms that make up our planet. We can look forward to new answers—and new questions. That's how science works.

ABOUT THE AUTHOR(S)

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Glasgow in Scotland, where he now resides, and professor emeritus of chemistry at the University of North Texas. He is author of more than 120 scientific articles and the popular science book From Stars to Stalagmites: How Everything Connects. His present focus is on increasing public understanding of science and scientists, and he serves on the Committee of the British Center for Science Education.