THE AGE OF THE EARTH

John Valley

The "Age of the Earth" is one of the most common titles in the geological literature, and with good reason. The scientific and philosophical implications are immense. This issue of *Elements* is devoted to measuring geologic time on the 100th anniversary of a book with this title (Holmes 1913). The book is a good read—a clear historical account, with groundbreaking science that still stirs controversy today. It's available free online.

Arthur Holmes was the first to use radioactivity to date a range of rocks, and before Dempster discovered ^{235}U in 1935, Holmes estimated Earth's age at 1600–3000 million years (Ma) (Holmes 1927). This estimate was not improved on until 1953, when Clair Patterson, using a more advanced mass spectrometer, published the age of 4510–4560 Ma, soon refined to 4550 ± 70 Ma (Patterson 1953, 1956), in perfect agreement with modern estimates (this issue). In detail, geochronometers using extinct, short-lived isotopes have now shown that Earth accreted over an interval of time, which is within the uncertainty of Patterson's age (e.g. Halliday 2006). There are many excellent accounts of this history (Burchfield 1975; Dalrymple 1991; Lewis 2000; Lewis and Knell 2001).

> "It is perhaps a little indelicate to ask of our Mother Earth her age."
> —Arthur Holmes (1913)

While most readers of *Elements* understand that geochronology is based on observable data, refutable hypotheses, and repeatable tests, the age of the Earth, like evolution, continues to be challenged. Creationist beliefs, which morphed into Intelligent Design, are common. Questions of faith address issues that are outside the realm of science, which deals with what we can observe and test. Nevertheless, some politicians publicly proclaim that no one knows the age of the Earth, with the implication that modern science is wrong, and demands are made to include "scientific creationism" in science courses.

The age of the Earth is not controversial among scientists. Clear rebuttals to young-Earth advocates include those by Dalrymple (1991) and Wiens (2002). The academies of science in 67 nations have formally concluded that "within science courses taught in certain public systems of education, scientific evidence, data, and testable theories about the origins and evolution of life on Earth are being concealed, denied, or confused with theories not testable by science" and that no scientific evidence contradicts the age of 4500 Ma for Earth or the theory of evolution (IAP 2006). If we all agree, why do we need to talk about it?

The question is: how best to explain the age of the Earth to nonscientists? We confront this in many venues, including education at all levels. Each year, at the University of Wisconsin, I ask classes of 200 students, "Have you had a discussion with someone who thinks the Earth is much younger than 4500 million years?", and about 50% say "yes." I then have 50 minutes to talk about how rocks are dated and to compare 4500 Ma with earlier estimates. I explain that geochronology is based on observable data and that the hypotheses are testable, and I encourage students to at least look through the windows of clean-labs to see people running mass spectrometers. The serious students may read this issue of *Elements* and get an appreciation for the depth and complexity of determining age, but no first-year student, and certainly no younger student, is in the position to make these observations themselves. The data are observable to specialists running mass spectrometers, but not to most others. The scientific method is less interesting, and far less compelling, when someone can't make the observations themselves.

Thus we also need to explain why the Earth cannot be 6000 years old using evidence that is more easily observed and understood by a layperson, such as tree rings, varves, layers in glacial ice, and rates of weathering, erosion, sediment deposition, and cooling of plutons, just to name a few. If the Pyramids are still standing after 5000 years, how can the Grand Canyon form in 6000? Many arguments made by Hutton and Lyell two centuries ago apply today. This brings me back to Holmes's book, which reviews earlier estimates and was written at the end of the remarkable period before the First World War.

At the end of the 19th century, Lord Kelvin famously concluded that Earth formed 20–40 million years ago based on a simple thermal model (Kelvin 1895, 1899). This was disputed by geologists, who maintained that more time was needed to explain the evolution of Earth or life. Kelvin's (1899) final estimate of 24 Ma old. elicited a strong response from T. C. Chamberlin (1899). The discussion at that time was far-reaching, and included Laplace's solar nebula hypothesis as opposed to the newer idea of planetesimals, hot versus cold accretion of Earth, advective heat transfer in the mantle, the source of heat in the Sun, and the first habitats for life on Earth. Kelvin was confident in his position because the age of the Sun was estimated to be less than 20 Ma, based on the assumption that its energy derived from chemical reactions or gravitational energy during compression. At a time when radioactivity was unknown, it was a stretch to conceive of a hot Sun more than 20 Ma old. Chamberlin questioned nearly all of Kelvin's assumptions, prophetically enquiring:

"Is the present knowledge relative to the behavior of matter under such extraordinary conditions as obtained in the interior of the sun sufficiently

Cont'd on page 4

THIS ISSUE

This issue takes us on a voyage in time, starting with the discovery of radioactivity and carrying us forward to today. We meet the giants the field of geochronology is indebted to. We see the challenges that have been met and those that lie ahead. We are reminded that for a mineral date to have meaning, the context of the mineral analyzed and the rock of which it is a constituent must be thoroughly documented. And this is an overarching theme of all papers in this issue.

It took me a while to understand the "crisis" mentioned in the Schmitz and Kuiper article. After all, 251.2 ±3.4 Ma and 249.98 ±0.2 Ma seemed like dates in pretty good agreement. But as geochronology matures and instruments allow higher precision, scientists set out to answer ever more complex questions.

While checking facts on the Web, I learned that Rutherford did most of the research that led to his Nobel Prize at McGill University in Montréal, and that his collaboration with Soddy also started at McGill—it began as a debate "where we hope to demolish the Chemists," said Rutherford. Read an account of this fascinating encounter at http://publications.mcgill.ca/headway/magazine/turning-points-a-look-back-at-how-a-great-debate-led-to-mcgills-first-nobel-prize.

And if you have only a few minutes to explain the dating of minerals in a Geology 101 class, I suggest you download a video produced by the EARTHTIME community. Noah McLean, a coauthor in this issue, explains his geochronology research in this 4 m 42 s long video, which you can access at http://www.youtube.com/watch?v=k9RbnRDx9ts.

Pierrette Tremblay, Managing Editor

INTRODUCING PATRICIA DOVE, PRINCIPAL EDITOR 2013–2015

With the start of 2013, Patricia M. (Trish) Dove joins the *Elements* team as a principal editor. Trish is the C. P. Miles Professor of Science in the Department of Geosciences at Virginia Tech. She earned her bachelor's and master's degrees at Virginia Tech, then her PhD at Princeton, and she completed a postdoctoral fellowship at Stanford. Trish is one of the outstanding geochemists of her generation. She has made wide-ranging contributions in the biogeochemistry of Earth processes, which includes mineral surface processes at the molecular scale, the kinetics of geochemical processes, mineral–microbe interactions, and biomineralization.

Honors she has received include the Clarke Medal of the Geochemical Society, the US Department of Energy's Best University Research Award (twice), Geochemical Fellow status jointly from the Geochemical Society and the European Association of Geochemistry, and membership in the National Academy of Sciences. She will be awarded the Mineralogical Society of America's Dana Medal in 2014. She has served on the Board of Directors of the Geochemical Society and has a strong interest in education and communication as well as research. We are delighted to have her as a member of the editorial team.

James I. Drever, Principal Editor 2010–2012

EDITORIAL *Cont'd from page 3*

exhaustive to warrant the assertion that no unrecognized sources of heat reside there? What the internal constitution of atoms may be is yet an open question." (Chamberlin 1899, p 12)

One wonders how much Chamberlin, a geologist in Chicago, knew of the implications of Henri Becquerel's physics experiments in Paris that began with a chance observation just three years earlier.

The decade before Holmes's book saw extraordinary advances that overturned Kelvin's age of the Earth. Important milestones were Becquerel rays (Becquerel 1896), the theory of radioactive decay (Rutherford and Soddy 1902), the discovery that radium decay produces heat (Curie and Laborde 1903), and the hypothesis of radioactive heating of the Sun (Rutherford and Soddy 1903). The discovery of radioactivity provided an explanation for an old Sun and is generally credited for the rejection of Kelvin's age. More importantly, however, mantle convection is also at odds with Kelvin's conductive model (Perry 1895; Chamberlin 1899; Richter 1986; England et al. 2007). The real importance of radioactivity, as laid out by Holmes (1913), was to provide better and well-founded techniques of geochronology. This issue of *Elements* describes impressive new capabilities that deserve the attention of Earth scientists, but the earlier writings may help you explain them to others.

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REFERENCES

Becquerel H (1896) Sur les radiations invisibles émises par les corps phosphorescents. Comptes Rendus de l'Académie des Sciences 122: 501-503

Burchfield JD (1975) Lord Kelvin and the Age of the Earth. Science History Publications, New York, 260 pp

Chamberlin TC (1899) Lord Kelvin's address on the age of the earth as an abode fitted for life. Science 9: 889-901; 10: 11-18

Curie P, Laborde A (1903) Sur la chaleur dégagée spontanément par les sels de radium. Comptes Rendus de l'Académie des Sciences 136: 673-675

Dalrymple CB (1991) The Age of the Earth. Stanford Press, Stanford, 474 pp

England PC, Molnar P, Richter FM (2007) Kelvin, Perry and the age of the Earth. American Scientist 95: 342-349

Halliday AN (2006) The origin of the Earth: What's new? Elements 2: 205-210

Holmes A (1913) The Age of the Earth. Harper and Brothers, London, 196 pp, http://archive.org/details/ageofearth00holmuoft

Holmes A (1927) The Age of the Earth. Ernest Benn Ltd., London, 80 pp

IAP (2006) Statement on the teaching of evolution. Interacademy Panel on International Issues, www.interacademies.net

Kelvin WT (1895) On the age of the earth. Nature 51: 438-440

Kelvin WT (1899) The age of the Earth as an abode fitted for life. Science 9: 665-674, 704-711

Lewis C (2000) The Dating Game. Cambridge University Press, New York, 253 pp

Lewis CLE, Knell SJ (eds) (2001) The Age of the Earth: From 4004 BC to AD 2002. Geological Society Special Publication 190, 288 pp

Patterson C (1953) The isotopic composition of meteoritic, basaltic, and oceanic leads, and the age of the Earth. Conference on Nuclear Processes in Geologic Settings: Williams Bay, Wisconsin, September 21–23, 1953, pp 36-40

Patterson C (1956) Age of meteorites and the earth. Geochimica et Cosmochimica Acta 10: 230-237

Perry J (1895) On the age of the earth. Nature 51: 224-227, 341-342, 582-585

Richter FM (1986) Kelvin and the age of the earth. Journal of Geology 94: 395-401

Rutherford E, Soddy F (1902) The cause and nature of radioactivity. The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science 6: 370-396, 569-585

Rutherford E, Soddy F (1903) Radioactive change. Philosophical Magazine 5: 576-591

Wiens RC (2002) Radiometric Dating: A Christian Perspective. American Scientific Affiliation, www.asa3.org/ASA/resources/Wiens2002.pdf