The Cool Early Earth

John Valley and William Peck published a paper in the prestigious journal *Nature* (Jan. 11, 2001). Their research was reported on the front page of the *N.Y. Times*, and in *Time* magazine. John was a guest on National Public Radio's *Whad'Ya Know* with Michael Feldman and he was interviewed on *Science Friday* with Ira Flatow. (See the front cover.)

John W. Valley
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The earliest history of the Earth is veiled in mystery because there are no preserved rocks. With so little information, an Early Hot Earth has generally been assumed that was unlike the modern Earth and more like Venus where lead melts on the surface, there is no liquid water and acid steam forms a heavy atmosphere. The Early Hot Earth was heated by radioactive decay of both long-lived and now extinct, short-lived isotopes; energy released by heavy meteorite bombardment, possibly including a Mars-size body to form the Moon; and release of potential energy during gravitational settling of iron to form the Earth's core (1). The exact timing of these events and the rates of cooling are uncertain.

The age of the Earth is estimated to be 4.56 Ga from the U-Pb age of the oldest meteorites. No known rocks from the Earth are older than 4 billion years and very few rocks exist from the first billion years. "The older the rock, the greater the chance that it no longer exists" (fig. 1, ref 2). In 1986, Compston and Pidgeon (3) analyzed sample W74 that was collected from the Jack Hills of Western Australia by Simon Wilde of Curtin University (Perth Australia) and discovered single crystals of detrital zircon as old as 4.2 Ga, but rocks of this age have never been identified.

In July 1998, John Valley met Simon Wilde at a conference in Beijing. John inquired about the ancient detrital zircons. William Peck, then a graduate student, and John wanted to analyze the oxygen isotope ratios of these zircons using new ion microprobe techniques. This request led to Simon's survey of hundreds of zircons and his discovery in May, 1999 of a tiny crystal (150 x 200 mm) that he dated at 4.404 ±4 Ga, 130 million years older than any other known piece of the Earth. When this sample was analyzed on the electron microprobe at UW-Madison with assistance from John Fournelle, it was found to have fine concentric banding and inclusions of SiO_2 which prove that the zircon grew in a quartz-saturated magma.

William and John then took this crystal to Edinburgh, Scotland where they worked with Colin Graham and John Craven to analyze the oxygen isotope ratio and the concentration of rare earth elements by ion microprobe. The ion probe is capable of analyzing nanogram size samples, one million times smaller than is possible by other techniques. John spent his 1989-90 sabbatical in Edinburgh where he and Colin succeeded in making the first oxygen isotope analyses by ion probe at better than one permil, the precision required for analysis of terrestrial samples (4). John and William operated the Edinburgh ion probe around the clock for 11 days, working overlapping 14-hour shifts; John got the nights when it is quiet and the instrument is most stable. After eight days of testing and analyzing standards, the 4.4 Ga zircon was put in the high vacuum chamber leading to the biggest surprise of all. Instead of giving the expected oxygen isotope ratio of the

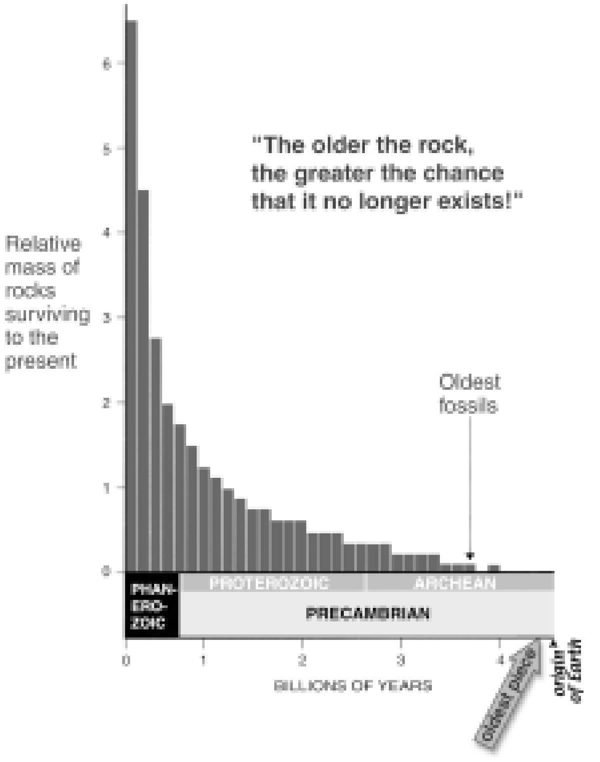

Figure 1

Earth's mantle (5.3‰) the oxygen isotope ratio was significantly higher, 7.4‰ in the crystal core.

High values of oxygen isotope ratio only form at low temperatures on the Earth's surface and are typical of granites derived from melting of sediments. Typical processes involve low temperature hydrothermal alteration, diagenesis and weathering. There are no reservoirs of "heavy" oxygen in the Earth's mantle to match those in the 4.4 Ga zircon. Furthermore, the rare earth chemistry shows that the zircon is not from a meteorite. Taken together, the results of this study show that continental crust started to differentiate on Earth at 4.4 Ga; that liquid water mediated the alteration of the rocks near the surface, and that burial and melting caused recycling of this material and the eventual crystallization of the 4.4 Ga crystal (5). This is the basis of the proposal for a Cool Early Earth.

If liquid water was stable in one area on the surface of the Earth at 4.4 Ga, then the magma oceans envisioned for an Early Hot Earth must have cooled much more rapidly than generally supposed. It is only a small step then to imagine that such temperatures prevailed throughout the Earth's atmosphere and that all steam had condensed to liquid water by that time to form oceans. This is 500 m.y. earlier than previous evidence for the earliest oceans (≥3.85 Ga sediments from SW Greenland). If oceans existed, it is reasonable to speculate whether primitive life could have evolved this early. Previous evidence for the first life includes micro-fossils from the Apex Chert (3.5 Ga), megascopic stromatolites from Australia's Warrawoona Group (3.5 Ga), and low carbon isotope ratios from Isua, Greenland (3.85 Ga). If the late heavy meteorite bombardment recorded on the Moon at 3.9 Ga also impacted the Earth, then any possible life would likely have been extinguished and perhaps life evolved and flourished in periods between large meteor strikes only to be extinguished over and over.

The 4.4 Ga zircon also places constraints on the rate and timing of cooling after the formation of the Moon. The Impact Hypothesis proposes that a Mars-size body struck the Earth at about 4.45 Ga throwing material into Earth orbit which subsequently coalesced to form the Moon. An impact of this magnitude would have melted much if not all of the Earth. The cooling of magma on the Earth's surface is very rapid and an insulating crust would form like the lava lakes in Hawaii. However, the magma ocean at depth would persist and potentially be vented as giant flood basalts by subsequent impacts. Alternate models for the Moon are widely debated, including the Capture Hypothesis which proposes that the Moon is unrelated to the Earth and was brought into Earth orbit by its gravitational field. The implications of temperatures near 100°C at 4.4 Ga for these scenarios are under evaluation. Clearly, if the Moon formed 4.50 rather than 4.45 Ga, or by some process other than impact, the thermal consequences are more easily reconciled with evidence for a Cool Early Earth.

The discovery of the earliest piece of the Earth and the proposal of a Cool Early Earth have been hailed in such disparate sources as *Science* (Dec. 22, 2000), *Nature* (Jan. 11, 2001), the front page of the *N.Y. Times* (Jan. 11, 2001), and National Public Radio's, *Whad'Ya Know* (Jan. 13, 2001). To learn more about this research, see the department's web site, *Zircons are Forever*, www.geology.wisc.edu/zircon.

The authors gratefully acknowledge support from the National Science Foundation and the U.S. Department of Energy. William Peck was the Dean Morgridge Wisconsin Distinguished Graduate Fellow at the time of this research.

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