Using oxygen isotope "stratigraphy" to define the onset of the Archaean in the absence of a rock record

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There is a growing body of opinion in favour of determining Precambrian boundaries using chronostratigraphic principles (placing them at events or transitions in preserved rock sequences of known geological age) rather than the generally accepted use of chronometric methods (defined in years based on geochronology and without specific reference to the rock record). This is despite the fact that applying the former would preclude the first 500 million years of Earth's history, for which there is no known rock record. This has fundamental implications for placing the onset of the Archaean, which is currently undefined. Proposals to define this boundary based on the extant rock record are flawed since, (i) they would force it to be located at a time younger or equal to the oldest known rocks (currently the 4.03 Ga Acasta Gneiss) and (ii) the rock record is merely a series of 'snapshot' occurrences through geological time, that becomes more fragmentary with age. Furthermore, whether or not individual rock outcrops record the beginning or ending of any fundamental process or event (i.e. boundary conditions) on the early Earth cannot be evaluated – but seems extremely unlikely.

It is against this backdrop that we propose an innovative chemostratigraphic method for defining the beginning of the Archean. It is based on the condensation of the early steam atmosphere, an event of unquestionable importance and world-wide synchroneity, which resulted in a chemical signature recorded in the ancient zircon record.

The oxygen isotope ratio (δ18O) of magmatic zircon is a robust recorder of the oxygen isotope composition of the parental magma. As no significant reservoir higher in δ18O than peridotite (e.g. whole rock = ~5.5‰) is known in the Earth's mantle, magmas in equilibrium with the mantle crystallize zircons that have a narrow range of δ18O = 5.3±0.3‰. Significant deviation from 'mantle zircon' values towards higher δ18O in magmatic zircon can only result if the parental magma incorporates higher δ18O material (e.g. supracrustal rocks) through melting or assimilation. Hence, a high δ18O value in zircon (e.g. above ~6.0‰) is a clear signature of melting crustal rocks that have experienced low-temperature alteration by liquid water. Our data obtained from the oldest known crystals on Earth at Jack Hills, Western Australia, indicate that from 4400 to 4325 Ma, zircons record mantle δ18O values of 5.4±0.4‰ (n=2), and from 4325 Ma to 4200 Ma zircons preserve mildly elevated δ18O values from 6.3 to 6.5±0.4‰ (n=3). After 4200 Ma, many zircons with δ18O values as high as 7.3±0.3‰ occur, identical to the maximum value of 7.5‰ measured in zircons from >120 known Archaean igneous rocks. The oxygen isotope ratio of detrital igneous zircons from Jack Hills thus record a fundamental change in the chemistry of terrestrial magmas at ~4200 Ma.

We therefore propose that the lower boundary of the Archean be provisionally set at 4200 Ma, based on the δ18O changes of igneous zircons, and hence magma compositions, as a consequence of interaction with liquid water on the Earth's surface. The dramatic rise in the range of δ18O to 7.3 ‰ for igneous zircons at 4200 Ma signifies the recycling of supracrustal rocks into magma, and the unambiguous presence of water on Earth by this time. A boundary at 4200 Ma not only reflects a change in igneous processes but may also signify stabilization of the Earth's continental crust, as evidenced by its weathering, alteration and erosion. The δ18O chemostratigraphy recorded in ancient igneous zircons is the only record of early surface cooling, and highlights the potential of using global chemostratigraphic changes to identify other significant Precambrian events for defining important time boundaries.

Applying the features identified above, the Archaean would be defined as the first eon characterized by surface waters, supracrustal rocks, crustal recycling, and incorporation of crustal rocks in igneous magmas on a grand scale. This change also marks the earliest period when Earth was hospitable to life, and its onset is considered one of the most profound events in early Earth history.