Publications of the Institute of Geophysics, Polish Academy of Sciences
Geophysical Data Bases, Processing and Instrumentation
vol. 452 (P-4), 2025, pp. 85–88
DOI: 10.25171/InstGeoph_PAS_Publs-2025-014
SVALGEOBASE II: Tectono-thermal evolution of Svalbard, geological workshop, Svalbard 2024

The Hadean: Was It Really Hell-like?

Simon A. WILDE

School of Earth & Planetary Sciences, Curtin University, Perth, Australia

✉ S.Wilde@curtin.edu.au

Keywords: Hadean, early Earth, Plate Tectonics, uniformitarianism.

1. INTRODUCTION

The term “Hadean” was first introduced by Preston Cloud (1972) for the earliest eon in Earth history. It was derived from the Greek word meaning “God of the Underworld”, but was frequently interpreted to mean that the early Earth was hell-like (cf. Wilde 2022a). This was supported by the view that it was a hot and turbulent place at this time. Implicit in the definition was that it defined the time before preservation of the earliest known rocks. With the discovery of the oldest known magmatic zircon at 4.03 Ga in the Acasta gneiss in the Northwest Territories of Canada (Bowring and Williams 1999), consensus was reached that the Hadean commenced at 4000 Ma (4 Ga), as originally proposed by Plumb and James (1986), although it remained “informal” until its recommendation and adoption in 2012 by the International Subcommission on Precambrian Stratigraphy and the International Union of Geological Sciences (IUGS) (Van Kranendonk et al. 2012).

So, was the early Earth really hell-like? It is generally agreed that the Earth underwent complete melting following its accretion, resulting in its differentiation into a core, mantle, and primordial crust. But how do we know what it was like at the Earth’s surface if there are no rocks preserved from the Hadean? The answer lies with the discovery of detrital zircon crystals older than 4 Ga in the Narryer Terrane of the Yilgarn Craton in Western Australia (Froude et al. 1983; Compston and Pidgeon 1986). Subsequent work here and elsewhere has led to the discovery of more zircon crystals older than 4 Ga (see Fig. 1 for global distribution), with the oldest being a single site on a Hadean grain recording an age of 4404±8 Ma (2σ) from Jack Hills in the Narryer Terrane (Wilde et al. 2001). Aided by the concurrent development over the past two decades of evermore precise analytical techniques at the micro- and nano-scales, and for a growing range of elements and isotopes, it has been possible to make what appear to be reasonable deductions as to what conditions might have been like at the surface during the Hadean.

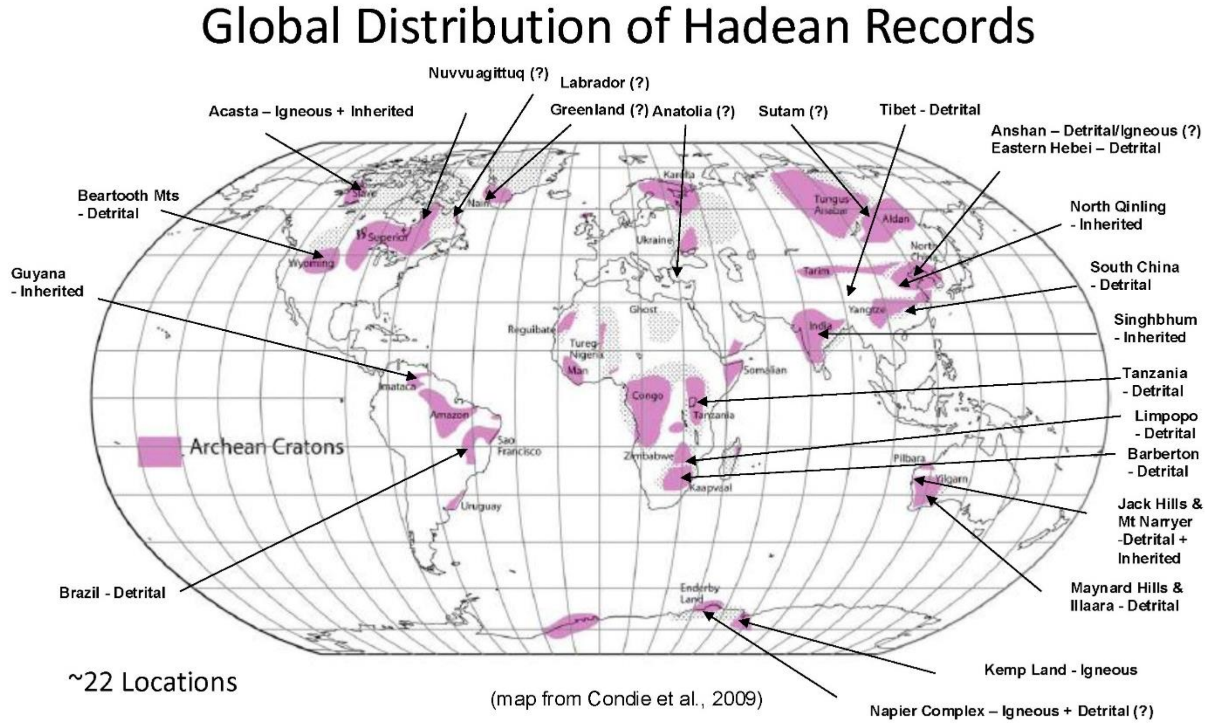

Fig. 1. The currently known global distribution of Hadean zircon. Abundant Hadean grains are only found at Jack Hills and Mt Narryer in the Yilgarn Craton of Western Australia, with any of the localities only recording single detrital grains. Note that when followed by (?), this means that the age is questioned due to reverse discordance or has not been substantiated by additional studies. Nuvvuaqittuq in NE Canada is where Nd isochrons record Hadean ages, but where zircon only records Eoarchean ages.

2. THE EVIDENCE

Early work at Jack Hills identified elevated $\delta^{18}O$ in several Hadean zircon grains, including the oldest (Wilde et al. 2001; Mojzsis et al. 2001), leading to the interpretation that these crystals formed in a magma at least partially derived through the incorporation of material that had interacted with liquid water at the Earth's surface. Such grains with elevated $\delta^{18}O$ were subsequently referred to as "supracrustal" zircon (Cavosie et al. 2005). Collectively, these data pointed to the early development on Earth of both continents and oceans. This required fairly rapid cooling following accretion, melting, and crystallization of an early magma ocean, leading to the "Cool Early Earth" hypothesis (Valley et al. 2002). However, the precise nature of the host rock(s) in which the zircon formed has been subject to considerable debate, ranging from formation in rocks derived from a crystalline magma ocean to S-type granite (see discussion in Wilde 2022b). Indeed, it was shown by Wang and Wilde (2018), based on extensive Lu-Hf data, that the Hadean grains at Jack Hills were not derived from a single protolith and that mafic, intermediate and felsic sources existed on the early Earth. One of the key features was that the Hf data in this and other studies (Harrison et al. 2005; Kemp et al. 2010), pointed to the parent rocks being derived from precursors formed at ca. 4.5 Ga, close to the age of the Earth itself. In addition, this early crust was not destroyed, but continuously reworked in the Narryer Terrane until at least 2.6 Ga, as recorded by the strongly negative εHf values of the zircon in Neoarchean granites (Kemp et al. 2010).

In more recent studies, a backup to the early oxygen data came from zircon trace element studies (Turner et al. 2020), both indicating no change across the Hadean/Archean boundary. In addition, the trace element data suggested a likely andesitic source, leading to the possibility that plate tectonics may have been operative in the Hadean. This was not a new idea and had previously been suggested by Ichikawa et al. (2017) and Maruyama and Ebisuzaki (2017), with the latter based on theoretically modelling of how and when the Earth had received its volatiles (the ABEL model). This lack of change cross the Hadean/Archean boundary is also a feature of the hafnium data, where time-series analysis of the extensive Lu-Hf database shows that there is periodicity in the extraction from the mantle that has not changed from the Hadean to the Phanerozoic, with the implication this is either an inherent feature of the Earth's mantle since its formation, or that plate tectonics was operative in some form since the Hadean (Mitchell et al. 2022). Finally, a recent paper has reported additional oxygen data that reveals not only elevated "supracrustal" values but also unusually low $\delta^{18}O$ values in ca. 4.0 Ga and 3.4 Ga zircon, interpreted to indicate emergent land by 4 Ga and the onset of the first hydrological cycle on Earth (Gamaleldien et al. 2024).

3. CONCLUSIONS

The evidence presented above indicates a number of interesting aspects with respect to conditions during the Hadean. The favoured interpretation of the zircon oxygen data is that the Earth cooled down relatively quickly and, together with the zircon trace element data, that there was no change across the Hadean/Archean boundary. This was likewise the case with the periodicity revealed by the zircon Hf data. Whether this is a reflection of some form of Hadean plate tectonics remains to be substantiated, but it does indicate a degree of uniformitarianism throughout Earth history. That such information can be gleaned from minute crystals of zircon is testimony to the growing ability to analyse an ever-increasing number of elements and isotopes at the micro- to nano-scales. Collectively, these data provide an insight into conditions on the early Earth that cannot be obtained by other means as no rocks are known to have survived from the Hadean. On balance, conditions during the majority of the Hadean, at least from ca. 4.4 Ga onwards, seem not to have been vastly different to those in the Archean from 3.9 to 2.5 Ga, although the real reason for a lack of rocks prior to 4 Ga remains a mystery. As such, conditions for most of the Hadean – excluding the early accretion and magma ocean events – were evidently not hell-like.

References

Bowring, S.A., and I.S. Williams (1999), Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada, *Contrib. Mineral. Petrol*. **134**, 3–16, DOI: 10.1007/s004100050465.

Cavosie, A.J., J.W. Valley, S.A. Wilde, and EIMF (2005), Magmatic $\delta^{18}O$ in 4400–3900 Ma detrital zircons: A record of the alteration and recycling of crust in the Early Archean, *Earth Planet. Sci. Lett*. **235**, 3–4, 663–681, DOI: 10.1016/j.epsl.2005.04.028.

Cloud, P. (1972), A working model of the primitive earth, *Amer. J. Sci*. **272**, 6, 537–548, DOI: 10.2475/ajs.272.6.537.

Compston, W., and R.T. Pidgeon (1986), Jack Hills, evidence of more very old detrital zircons in Western Australia, *Nature* **321**, 766–769, DOI: 10.1038/321766a0.

Condie, K.C.,. E. Belousova, W.L. Griffin, and K.N. Sircombe (2009), Granitoid events in space and time: Constraints from igneous and detrital zircon age spectra, *Gondwana Res*. **15**, 3–4, 228–242, DOI: 10.1016/j.gr.2008.06.001.

Froude, D.O., T.R. Ireland, P.D. Kinny, I.S. Williams, W. Compston, I.R. Williams, and J.S. Myers (1983), Ion microprobe identification of 4,100–4,200 Myr-old terrestrial zircons, *Nature* **304**, 616–618, DOI: 10.1038/304616a0.

Gamaleldien, H., L.-G. Wu, H.K.H. Olierook, C.L. Kirkland, U. Kirscher, Z.-X. Li, T.E. Johnson, S. Makin, Q.-L. Li, Q. Jiang, S.A. Wilde, and X.-H. Li (2024), Onset of the Earth's hydrological cycle four billion years ago or earlier, *Nat. Geosci*. **17**, 560–565, DOI: 10.1038/s41561-024-01450-0.

Harrison, T.M., J. Blichert-Toft, W. Müller, F. Albarede, P. Holden, and S.J. Mojzsis (2005) Heterogeneous Hadean hafnium: evidence of continental crust at 4.4–4.5 Ga, *Science* **310**, 5756, 1947–1950, DOI: 10.1126/science.1117926.

Ichikawa, H., S. Gréaux, and S. Azuma (2017), Subduction of the primordial crust into the deep mantle, *Geosci. Front*. **8**, 2, 347–354, DOI: 10.1016/j.gsf.2016.08.003.

Kemp, A.I.S., S.A. Wilde, C.J. Hawkesworth, C.D. Coath, A. Nemchin, R.T. Pidgeon, J.D. Vervoort, and S.A. DuFrane (2010), Hadean crustal evolution revisited: New constraints from Pb-Hf isotope systematics of the Jack Hills zircons, *Earth Planet. Sci. Lett*. **296**, 1–2, 45–56, DOI: 10.1016/j.epsl.2010.04.043.

Maruyama, S., and T. Ebisuzaki (2017), Origin of the Earth: A proposal of new model called ABEL, *Geosci. Front*. **8**, 2, 253–274, DOI: 10.1016/j.gsf.2016.10.005.

Mitchell, R.N., C.J. Spencer, U. Kirscher, and S.A. Wilde (2022), Plate tectonic-like cycles since the Hadean: Initiated or inherited? *Geology* **50**, 7, 827–831, DOI: org/10.1130/G49939.1.

Mojzsis, S.J., T.M. Harrison, and R.T. Pidgeon (2001), Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago, *Nature* **409**, 178–181, DOI: 10.1038/35051557.

Plumb, K.A., and H.L. James (1986), Subdivision of Precambrian time: Recommendations and suggestions by the subcommission on Precambrian stratigraphy, *Precambrian Res*. **32**, 1, 65–92, DOI: 10.1016/0301-9268(86)90031-8.

Turner, S., S. Wilde, G. Wörner, B. Schaefer, and Y.-J. Lai (2020), An andesitic source for Jack Hills zircon supports onset of plate tectonics in the Hadean, *Nature Commun*. **11**, 1241, DOI: 10.1038/s41467-020-14857-1.

Valley, J.W., W.H. Peck, E.M. King, and S.A. Wilde (2002), A cool early Earth, *Geology* **30**, 4, 351–354, DOI: 10.1130/0091-7613(2002)030<0351:ACEE>2.0.CO;2.

Van Kranendonk, M.J., W. Altermann, , B.L. Beard, P.F. Hoffman, C.M. Johnson, J.F. Kasting, V.A. Melezhik, A.P. Nutman, D. Papineau, and F. Pirajno (2012), A chronostratigraphic division of the Precambrian: possibilities and challenges. **In:** F.M. Gradstein, J.M. Ogg, M. Schmitz, and G. Ogg (eds.), *The Geologic Time Scale 2012*, Elsevier, 299–392, DOI: 10.1016/B978-0-444-59425-9.00016-0.

Wang, Q., and S.A. Wilde (2018), New constraints on the Hadean to Proterozoic history of the Jack Hills belt, Western Australia, *Gondwana Res*. **55**, 74–91, DOI: 10.1016/j.gr.2017.11.008.

Wilde, S.A., J.W. Valley, W.H. Peck, and C.M. Graham (2001), Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago, *Nature* **409**, 175–178, DOI: 10.1038/35051550.

Wilde, S.A. (2022a), Hadean. **In:** M. Gargaud et al. (eds.), *Encyclopedia of Astrobiology*, Springer-Verlag, Berlin Heidelberg, DOI: 10.1007/978-3-642-27833-4_688-8.

Wilde, S.A. (2022b), Jack Hills (Yilgarn Craton, Western Australia). **In:** M. Gargaud et al. (eds.), *Encyclopedia of Astrobiology*, Springer-Verlag, Berlin Heidelberg, DOI: 10.1007/978-3-642-27833-4_834-5.

Received 4 February 2025
Accepted 18 February 2025