The Hadean Eon and the start of earth history: a point-of-view

Until recently, most geologists would have considered the birth of the solar system, and with it the origins of our home planet, to lie outside the reach of their field. It is true of course that some pioneering geochemical studies established an approximate age for the earth, using ingenious indirect means, some time ago (e.g. Allègre et al., 1995), but a formal name for our planet's early years has been a long time coming. The reason for this oversight is largely because the global body that formalises the subdivision of time and strata, the International Commission on Stratigraphy or ICS, has quite understandably focussed on earth's rock record. Unfortunately, there are no rocks from the first one tenth of our planet's existence, at least not on Earth, with the exception of meteorites.

On October 5th 2022, the International Union of Geological Sciences (IUGS) defined the formal start to earth history by ratifying the onset of the Hadean Eon, "*and by implication the age of the Earth*" (IUGS, 2022). The new Geological Standard Stratigraphic Age (GSSA) has been set at 4567.30 ± 0.16 million years ago (Ma), and replaces the rounded ~4600 Ma age, which has been on the International Chronostratigraphic Chart since 2008. It is good to see this rounded age replaced, but why has this rough estimate not simply been revised as would be done for most other boundaries on the chart? Here we use the eventful history of the Hadean to show that erecting immutable GSSAs to subdivide earth history is both more confusing and less useful than using well-defined events.

What is the Hadean?

According to Greek mythology, Hades was the God of the dead and king of the underworld. His name refers to his place among the sons of Chronus (or Kronos) as the "unseen one", although the exact etymology of his name is disputed. In geology, Hadean refers to a time when Earth history is largely unseen, having to be inferred from geochemistry or extraterrestrial sources. Preston Cloud (Cloud, 1972) envisaged the beginning of the Hadean to represent the "*accumulation of the Earth*", with its end marked by the oldest known terrestrial rocks. As a consequence, the Hadean is not a chronostratigraphic unit, or "eonothem", but a chronometric or time unit only. Unlike the Archean (defined 1977, ratified 1990), Proterozoic (defined 1977, ratified 1990) and Phanerozoic (coined 1930) eons, the Hadean has never been formally defined nor ratified, although it has become widely accepted in recent years to correspond approximately to the same concept initially proposed (Cloud, 1972).

When did the Hadean Eon begin?

As the Hadean has never been formally defined, its starting point has always been moot. The ~4600 Ma age on the International Chronostratigraphic Chart first appeared in 2008, persisting unchanged until October 2022. However, ~4600 Ma seems to have been a rounded placeholder age, awaiting formal definition of the Hadean Eon, in the same way as the Cryogenian Period is shown to begin at ~720 Ma, pending formal ratification of a GSSP. The beginning of the Hadean was initially placed at about 4.56 Ga by Harland et al. (1990) in their book "A geological timescale

1989", in which they referred to it and other ages as "*guesstimated ages*". However, the IUGS decided not to ratify the Hadean, leading to its incorporation into the Archean Eon. The rejection of any formal pre-Archean interval was made clear in the 2004 version of the Geologic Timescale book, in which Robb et al. (2004) stated that "*Descriptive terms such as "Hadean" … are no longer recommended in the present chronometric scheme*".

Despite this statement, in that same year, change was already underway. Wouter Bleeker (Bleeker, 2004), the incoming chair of the International Subcommission on Precambrian Stratigraphy or SPS, recommended formalisation of a Hadean Eon using an approximate age for its onset. Gradstein et al (2008) mention proposals in development for a "*formal Hadean interval, possibly at the Eon level*", and it is from that year that the Hadean appears as an informal eon-level unit on ICS time charts beginning at ~4600 Ma. Harland's guesstimated age of ~4560 Ma was used for the Geologic Timescale book of 2012, but for some reason ICS charts did not adopt the change, retaining instead ~4600 Ma. This renowned reference book is still used as the main source for other boundary ages on the chronostratigraphic chart.

Martin Van Kranendonk, subsequent chair of the SPS, again suggested that the Hadean Eon be formalised (ratified) but defined this time by two Global Standard Stratigraphic Ages or GSSAs at 4.568 Ga and 4.030 Ga, respectively, representing solar system formation and the age of the oldest rock, the Acasta Gneiss (Van Kranendonk et al., 2012). The age ~4.568 Ga was given by those authors as the base of the informal Hadean according to "*the current Precambrian time scale, from the International Commission on Stratigraphy*" (their Fig. 16.1), but recommended the replacement of this approximate age with an immutable GSSA (their Fig. 16.34) to delimit gravitational collapse of the solar nebula at ~4.567 Ga. Ogg et al. (2016) considered therefore the Hadean Eon to be an informal term that represents the "*interval with no preserved record from the formation of the Earth at 4.567 to ca. 4 Ga*", and this agrees with the age range given in the latest version of this reference book (Strachan et al., 2020).

Although there appear to be two conflicting interpretations of the base of the Hadean since 2008 with formal ICS charts consistently retaining ~4600 Ma and others favouring first ~4560 Ma and then ~4567 Ma, this is not really a contradiction and is line with other unit boundaries, estimated ages of which are subject to change. In the case of most unit boundaries, it is a precisely defined event that characterises the boundary and not its age. However, the proposal of Van Kranendonk et al (2012) to erect a GSSA at 4568 Ma is a different concept, which had precedents in other Precambrian GSSAs that were already in existence. But what is a GSSA?

What is a GSSA?

In 1977, the International Subcommission on Precambrian Stratigraphy (SPS) recommended acceptance of the subdivision of the Precambrian into Archean and Proterozoic eons, with a mutual boundary defined at precisely 2500 Ma (James, 1978). In their deliberations, the SPS cautioned against using rock-based nomenclature, e.g. systems and eonothems, for the Precambrian, and so defined the boundary between the Archean and Proterozoic eons with a representative, rounded age. James clarified this decision further by writing that "*no plus-and-*

minus figure is attached to the 2500 Ma value. It is assumed that the precision and error limits that accompany actual radiometric ages will give the needed flexibility and opportunity for exercise of geologic judgement in stratigraphic assignments" (James, 1978). This recommendation was the first of several Global Standard Stratigraphic Ages or GSSAs, which subsequently became the standard for Precambrian timescale subdivision (Plumb, 1991). Plumb and James (1986) clarified GSSAs further by writing that "*age boundaries will therefore be chosen so as to delimit or enclose, rather than designate … events*". They suggested further that "*at some future point it may be appropriate to assign an arbitrary value, such as 4000 Ma, and to designate a third unit of Eon rank, to encompass the very early history of the Earth*", but left open the possibility that the Archean could also be defined to cover that early interval, too. Subsequently, GSSAs were proposed for all Precambrian eon, era and period-level boundaries, with the exception of the base of the Archean (Plumb, 1991). However, their definitions have been inadequately justified in the published literature (Bleeker, 2004), and it is anticipated that they will be replaced with event-based GSSPs over time (Shields et al., 2022).

The new Hadean GSSA

The Hadean Eon still awaits formal definition, but now has a GSSA to define its onset, and with it the beginning of earth history. But is a GSSA necessary for this definition, and is this new GSSA genuinely an advance over what has long been in common use, i.e. a revisable estimated age?

An additional note to the chart revision https://stratigraphy.org/ICSchart/ChangeLog2012-2022-2.txt) clarifies the choice of this specific GSSA. It states that the Hadean GSSA was ratified by IUGS (5/10/2022) as being 4567 +/- 0.16 Ma but that the chart displays it in rounded form: 4,567 Ma. However, this contradicts the original aim of GSSAs, which was to delimit phenomena (Plumb and James, 1986) without the need for error bars. If a GSSA is favoured for the Hadean then it ought to predate the oldest radiometric age. Therefore, the proposal of Van Kranendonk et al (2012) of a GSSA at 4568 Ma still seems valid, as does the widely adopted approximate age at ~4567 Ma. In this regard, it is important to recall that the ~4600 Ma age was never ratified, and so held no validity over any other estimated age. As long as unit concepts are clearly defined, approximate ages can be updated as and when new data become available. Indeed, updates are regularly made for all unit boundaries of the time chart, except for GSSAs.

The Hadean GSSA "*corresponds to the mean U-corrected Pb-Pb age for Ca-Al inclusions in primitive meteorites (from Amelin et al., 2010; Connelly et al., 2012) but should be cited as 4567.30 +/- 0.16 Ma*". Therefore, the new GSSA appears to be little different from all other stratigraphically calibrated ages on the chronostratigraphic chart, which are also shown as a precise radiometric age with an error bar, the difference being of course that unlike GSSAs, other boundary ages can easily be updated. Uncertainties with radioactive decay constants also result in a non-trivial fuzziness when dealing with such old materials (Bleeker, 2004), and so it is questionable whether such a precise GSSA can be justified.

Some final thoughts

How is the Hadean defined? An additional change not mentioned so far is that the chronostratigraphic chart now depicts the Hadean Eon as a formal time unit for the first time and yet no such eon has ever been formally defined. In fact, published updates to the geological time scale have either rejected outright the notion of a Hadean Eon (Robb et al., 2004) or considered it to be an informal term (Ogg et al., 2016; Strachan et al., 2020). The preference for any specific approximate age, say ~4600 Ma, ~4567 Ma, ~4560 Ma or even ~4500 Ma has always depended on whether the Hadean is defined as beginning at the formation of the pre-solar nebula, origin of the solar system, end of the initial accretion and differentiation phase of the Earth, or the planetary collision that led to the Earth-Moon system, respectively. As no agreed definition exists for the Hadean Eon, all these ages have been considered by various authors in the past. Presuming that the accumulation / formation of the Earth (Cloud, 1972 / IUGS, 2022) is the agreed starting point, and the oldest Ca-Al inclusions in meteorites the agreed proxy material for its age, then is a fixed, immutable age necessary?

Hadean GSSA or Golden Spike? Although the precise definition for Earth's origin may be a subjective, even trivial matter, there are important consequences in favouring a rigidly defined age over a rigidly defined event. The Hadean GSSA further cements inconsistency in the current geological time scale, whereby older unit boundaries are treated in a fundamentally different way from more recent ones. A ratified GSSA is immutable except by renewed argumentation and ratification, which is unlike the changeable ages of boundaries defined by GSSPs or of well-defined boundary concepts pending GSSP ratification, for example the ~720 Ma for the base of the Cryogenian Period (Shields-Zhou et al., 2016). A GSSA is thus needlessly inflexible. As soon as a GSSA is established, it is destined to become increasingly out-of-step with the concept behind its establishment, as has occurred repeatedly for other Precambrian subdivisions (Bleeker, 2004; Shields et al., 2022). Moreover, this new definition is not really a GSSA as originally envisaged, but a radiometric age constraint from one specific study, and is thus a novel, third type of boundary definition, causing further inconsistency.

Remove all GSSAs? It seems to us that the arguments put forward by Bleeker (2004) in favour of specific events, equivalent to golden spikes, represent the best way to define not only later subdivision boundaries, but all earth history. Most major geological events, such as the formation of the first rocky bodies in our solar system, formation of the Earth-Moon system, onset of Snowball Earth, Phanerozoic mass extinctions or GSSPs, do not need renewed discussion, redefinition and formal ratification once their defining concepts are firmly established. However, immutable ages require all these stages just to keep up with inevitable improvements in dating or understanding, so we believe it is time to put the GSSA concept to bed once and for all.

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