Communication of IUGS Geological Standards

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Ratification of the base of the ICS Geological Time Scale: the Global Standard Stratigraphic Age (GSSA) for the Hadean lower boundary

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(Received: December 13, 2023; Revised accepted: January 30, 2024)

https://doi.org/10.18814/epiiugs/2024/024002

The base of the ICS (International Commission on Stratigraphy) Geological Time Scale was ratified in 2022 by defining a new Global Stratigraphic Standard Age (GSSA) for the lower boundary of the Hadean Eon (formerly 4000–3600 Ma); the age of the Solar System based on the oldest solids, calcium-aluminium inclusions (CAIs), generated in the protoplanetary disk. The formal GSSA for the Hadean base is the oldest reliable, weighted mean U-corrected Pb–Pb age of 4567.30 ± 0.16 Ma obtained for CAIs in primitive meteorites Allende and Efremovka. This age is supported by the 4568–4567 Ma U-corrected Pb–Pb ages of chondrules in Northwest African meteorites. The boundary sets an upper lifetime for the protoplanetary disk and timing of planet formation. The Hadean Eon encloses the accretion and differentiation of the Earth and other planets, the Moon-forming Giant Impact, the beginning of the suggested Late Heavy Bombardment, and the formation of the Earth's protocrust. Due to the Moon-forming Giant Impact that occurred after the differentiation of the proto-Earth and the fact that Earth's first crust has been destroyed, the age of the planet Earth itself remains an open question. However, many pieces of astronomical, *chemical, physical, and chronological evidence point to the very fast formation of the Solar System and rapid accretion and differentiation of the proto-Earth in only a few million years. Compared to the half-billion-year duration of the Hadean, it is reasonable to set the age of the Earth at the beginning of the formation of the Solar System. This communication explains and justifies the selection of the GSSA for the Hadean base.*

Introduction

The Hadean Eon spans from the formation of the Solar System to the first reliable U–Pb chronological evidence for the crust on the Earth. In the past, the ICS (International Commission on Stratigraphy) status of the Hadean has been an 'informal' undivided period before the Archean, mainly because of the scarcity of physical evidence. A step was taken forward in 2022, when the Executive Committee of the IUGS (International Union of Geological Sciences) ratified the formal GSSA (Global Stratigraphic Standard Age) for the base of the Hadean. The SPS (Subcommission on Precryogenian Stratigraphy) voting result was 93.75% in favor (15 votes), and 6.25% against (1 vote) of the 16 votes received in total; 38.46% of the members did not vote (10 non-votes). The ICS Voting Committee (consisting of the Executive Committee Officers and all the Subcommission Chairs), votes were 94.44% in favor (17 votes), and 5.56% against (1 vote), with 18 votes received in total (including 2 non-votes).

According to the new definition by the ICS, the Hadean began with the formation of the Solar System at 4,567 Ma and ended at 4,031 ± 3 Ma, when the first reliably dated rocks of the Acasta Complex, Slave Craton, Canada, were formed (Bowring and Williams, 1999; Reimink et al., 2016). The early Hadean was a time of planetary accretion, differentiation, and the formation of the Moon when a giant impact of a protoplanet into Earth occurred. The term 'Hadean' was coined after Hades (the Greek word *Aïdes* means invisible), the Greek God of the underworld (Cloud, 1972).

The challenge in setting Hadean boundaries was that the ICS criteria for stratigraphic boundaries are not easily applied to the formation of the Earth itself. We do not know exactly how old the Earth is, because the planet accretion in the early Solar System took some time. However, our understanding about the Hadean has greatly increased along with methodological developments that allow us new and refined time constraints based on primitive materials in meteorites, zircon grains inherited from the Earth's first crust, and geochemical studies of post-Hadean, mantle-derived rocks utilizing short-lived radionuclides. Astronomical observations on protoplanetary disks surrounding protostars and the structure of the Solar System, geochemical and isotopic studies of meteorites, and physical models of planetary development all provide clues to the early Earth evolution. The lower boundary of the Hadean is based, above all, on chronological information on recognized events in the solar system, acquired by appropriate, high-precision geochronological methods.

The age 4,567 Ma ratified as the base of the ICS Geological Time Chart is obtained from the absolute dates of calcium-aluminium-rich inclusions in chondritic meteorites (earlier adopted by Strachan et al., 2020), which are the first solids known to have formed in the Solar System. This definition follows the ICS procedures by setting the Hadean lower boundary according to the absolute ages of actual planetary materials (although likely recording events before Solar System planets assembled) that can be tied to the currently accepted models for the Solar System formation. In this communication, we provide rationale for the selection of the Hadean lower boundary.

Formation of the Solar System

The astronomical observations on protoplanetary discs around protostars (Figs. 1 and 2), such as HL Tauri (e.g., Yen et al., 2019), new chronological data obtained for meteorites and advanced computa-

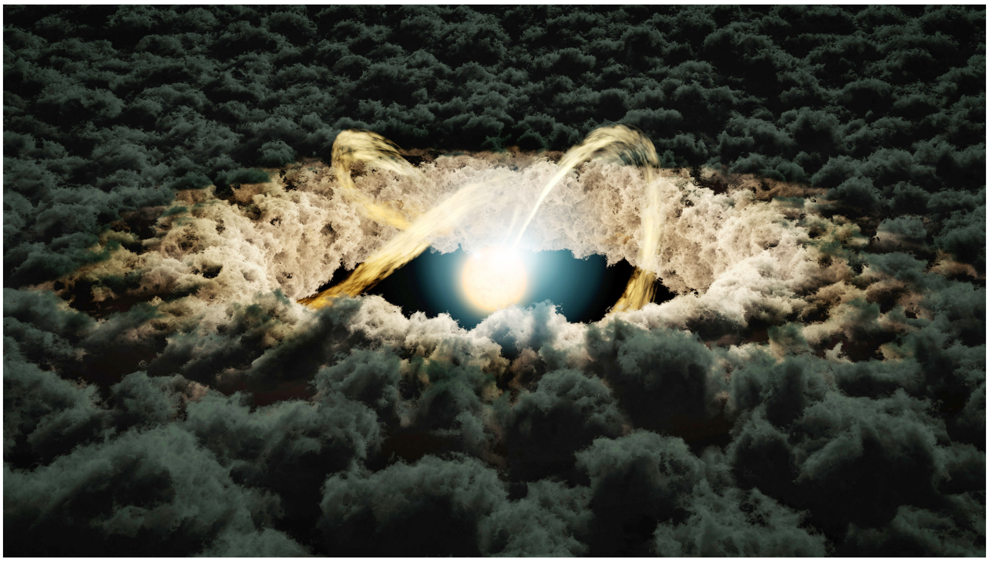

Figure 1. Artistic illustration showing a protostar surrounded by a protoplanetary disk. Material from the thick disk flows along magnetic field lines and deposits onto the surface of the star. When material hits the star, it lights up brightly. CAIs and chondrules found in meteorites fallen to Earth are the first condensates of the protoplanetary disk around the young Sun. Image credit: NASA/JPL-Caltech.

tional modeling have provided critical constraints on the formation of the Solar System. The latter is thought to have formed about 4.6 billion years ago from an interstellar cloud of gas and dust (protosolar molecular cloud). The cloud collapsed, perhaps because of a shock wave from a nearby supernova, and subsequently flattened into a swirling disk of material (Kumssa and Tessema, 2023). Gravity pulled material into the centre, and the sun was born when hydrogen atoms combined to form helium under extreme pressure in the core (Fig. 1).

Within the protoplanetary disk that surrounded the proto-Sun (Fig. 2), small calcium-aluminium particles condensed from high-temperature solar gas and clumped together with droplets of melted dust aggregates. These particles, formed nearly at the same time as the Sun, are the first physical evidence on the formation of the Solar System. Today, they are found in primitive meteorites as **calcium-aluminium-rich inclusions (CAIs)** and spherical grains known as **chondrules**. The chondrules within the protoplanetary disk continued to clump together forming larger and larger rocky bodies, which accreted into **planetesimals** (<100 km in diameter), planetary **embryos** (>1,000 km in diameter) and protoplanets (Johansen et al., 2021). When the size of the bodies grew large enough, they melted and differentiated due to radioactive heat and impacts, and their gravity shaped them into spheres (Fig. 3). The formation of the Earth was accompanied by a giant collision that generated the Moon (Barboni et al., 2017). Not all the material in the protoplanetary disk came together to form planets, the residual materials form asteroids, comets, and meteoroids, many of which have hit the Earth since its formation.

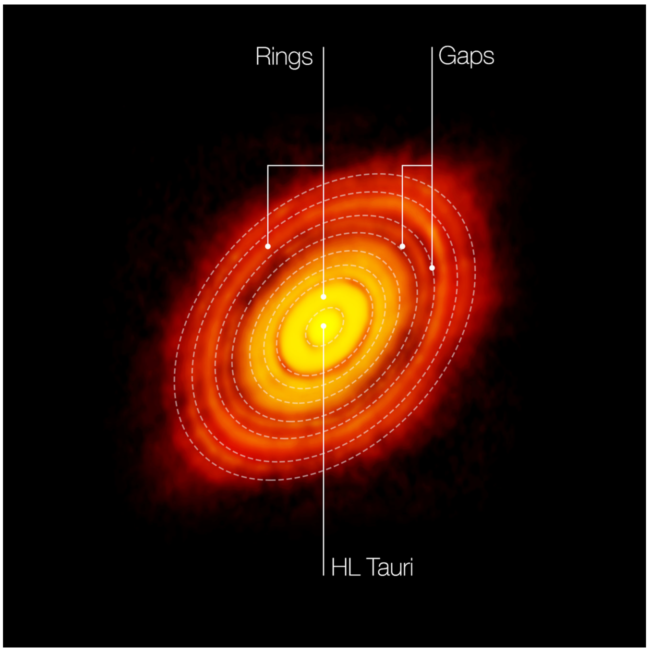

Figure 2. The ALMA (Atacama Large Millimeter/submillimeter Array) image (2014) of the protoplanetary disk around the young star HL Tauri showing concentric bright rings separated by gaps in the system. Planets are possibly forming in the dark patches. Image credit: ALMA (ESO/NAOJ/NRAO).

Relative and Absolute Dating of the Early Solar System

The age of the Solar System is constrained by geochronological analyses of CAIs and chondrules from primitive meteorites, which represent the oldest solids originated within the protoplanetary disk and have remained essentially unchanged since their accretion. Among primitive meteorites, carbonaceous chondrites are the least evolved. They did not remelt since their formation and may therefore contain the oldest particles that first condensed from gas and dust within the protoplanetary disk, and even particles generated in the presolar dust of interstellar space.

Short-lived ^{26}Al-radionuclides: Timers of the early Solar System

^{26}Al is a radionuclide that decays into its stable daughter isotope ^{26}Mg, with a short half-life of 0.73 million years. The presence of now

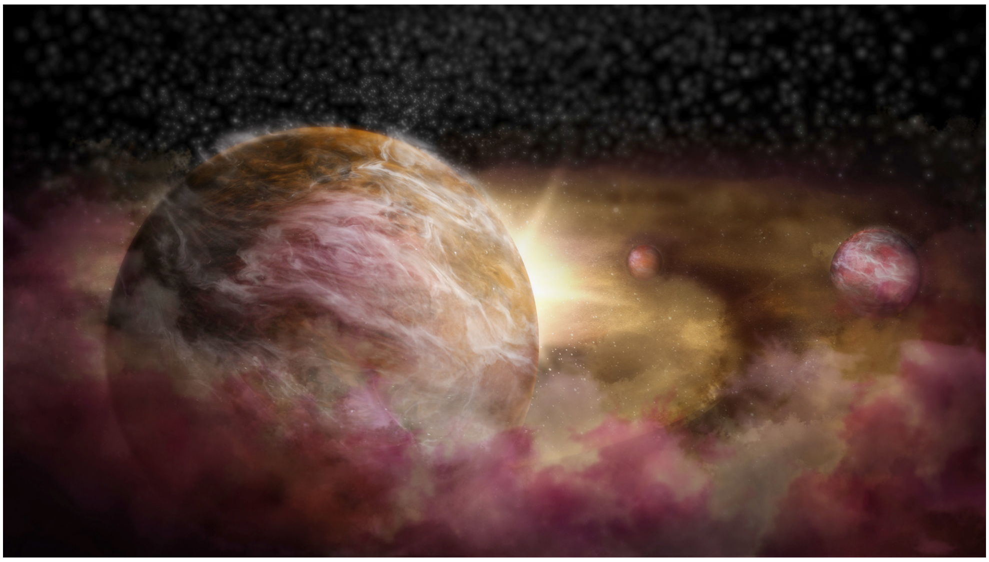

Figure 3. An artist's rendition of protoplanets forming around a young star. Image credit: NRAO/AUI/NSF; S. DAGNELLO.

extinct ^{26}Al at the beginning of the Solar System has been confirmed by the discovery of ^{26}Mg excess in primitive Solar System objects. This ^{26}Mg excess correlates with the Al/Mg ratio, which indicates that it is the decay product of the now extinct radioactive isotope ^{26}Al. The present excess of ^{26}Mg relative to the stable isotope ^{27}Al yields the original ^{26}Al/^{27}Al ratio. The first objects of the Solar System can be dated relative to the formation of the Solar System by measuring the Al and Mg isotopes, presuming that ^{26}Al was distributed uniformly in the solar system, although this view has been recently challenged by several studies (Krestianinov, 2023 and references therein). Nevertheless, the Al–Mg method is widely used to constrain the early Solar System evolution (e.g., Bollard et al., 2017; MacPherson et al., 2020).

U-corrected Pb–Pb ages: The clock of the Solar System

The short-lived radionuclide systems provide only relative ages with respect to when the Solar System was formed, therefore, a method based on long-lived isotope systems yielding a high-precision absolute age for the Solar System is essential. Of all the isotopic dating methods in use today, the uranium-lead method is the most established and the most reliable. This method is based on the long decay chains of ^{238}U and ^{235}U to ^{206}Pb and ^{207}Pb, with the half-lives of 4.47 billion and 703.8 million years, respectively. The resulting ^{207}Pb/^{206}Pb ratio depends on initial ^{238}U/^{235}U and Pb isotope ratios, and the time elapsed since the closure of the system. The present-day ^{238}U/^{235}U ratio required for the age calculations has earlier been assumed to be 137.88 in all solar system materials. However, this ratio seems to vary significantly in CAIs and chondrules compared to Earth's materials (Brennecka et al., 2010; Connelly et al., 2012). Therefore, the latest age calculations use measured ^{238}U/^{235}U ratios. Extrapolation from an array of measured present-day Pb isotope ratios, representing the combination of the initial and radiogenic Pb, provides the age of the system. Therefore, high-precision U-corrected Pb–Pb dating is a powerful tool for establishing the age of the Solar System (Amelin et al., 2010; Connelly et al., 2012).

Plotting data for acid-leached Pb fractions of a CAI or chondrule in a ^{207}Pb/^{206}Pb vs. ^{204}Pb/^{206}Pb space provides its y-intercept age. The most primitive Pb isotope compositions measured, together with the intersections of individual Pb–Pb isochrons (regression lines in the Pb–Pb space), should provide the initial Pb isotope composition of the Solar System.

Meteorites: Witnesses of Early Events in the Solar System

There are three main types of meteorites. **Stony** meteorites are pieces of chondrule aggregates or outer layers of differentiated planetary bodies, and they consist of silicate minerals and minor metal flakes. **Stony-iron** meteorites have equal amounts of metals and silicates, and they are thought to be derived from the domains at the boundary between the metallic cores or pools and the silica layers of their parent bodies. **Iron** meteorites, recently reviewed by Scott (2020), are almost completely made of metal, and are considered to be fragments of the metallic cores of the differentiated bodies. Absolute and relative dating of different types of meteorites provides chronological information on the evolution of the Solar System.

Stony meteorites fall into two major groups: chondrites and achondrites according to whether they contain chondrules or not. Chondrites are the products of chondrule accretion within the protoplanetary disk, and they have not melted since their formation. Therefore, they represent the most primitive meteorites in the Solar System and are the building blocks of larger planetary bodies known as planetesimals. Achondrites, on the other hand, are the igneous pieces of large, differentiated parent bodies. Both chondrites and achondrites have many subgroups based on their compositions, structures, and minerals they contain.

Chondrites (C), stony meteorites consisting mostly of silicate minerals, are divided into carbonaceous chondrites, enstatite chondrites, and ordinary chondrites. The most chemically primitive group (with their composition thus being closest to that of the Solar System) of the carbonaceous chondrites is CI (named after the Ivuna meteorite). Another group, CV3 (named after the Vigarano meteorite, petrological type 3), that includes meteorites dated by the U-corrected Pb–Pb method (e.g., Allende, Efremovka, and Gujba) is interpreted to be the oldest material of the Solar System. The Murchison meteorite that belongs to the CM2 group (named after Murchison, petrological type 2) may even contain some remnants of interstellar dust much older than the Solar System.

Achondrites are meteorites that do not contain chondrules; they originated from planetesimals that melted due to energy released via radioactive decay and collisions. Consequently, the metals sank into the core and a silicate mantle and crust formed around the core. **Stony achondrites** may represent the fragments of the outer layer of the differentiated planetesimals/planets (silicate mantle or crust), whereas **iron meteorites** represent the metallic core.

Presolar Material

The oldest solids found on Earth are silicon carbide (SiC, mineral name moissanite) grains found in some primitive meteorites. Natural SiC is very rare on Earth, but common in space, where it occurs as dust around carbon-rich stars. Hack et al. (2020) have defined cosmic ray exposure ages for SiC grains of the Murchison carbonaceous CM2 chondrite by using cosmogenic ^{21}Ne isotopes. Their ages range from 3.9 ± 1.6 Ma to c. 3 ± 2 Ga before the formation of the Solar System (c. 4.6 Ga). Although the method provides ages relative to the formation of the Solar System and suffers from large uncertainties, it is still a viable method for obtaining information about the interstellar dust and star-forming events.

Oldest Materials in the Solar System

CAIs and Chondrules in Chondrites

The oldest known objects of the Solar System are millimeter-sized CAIs and chondrules found in primitive meteorites (Fig. 4). Based on the ^{26}Al–^{26}Mg relative ages, the formation of chondrules continued for c. 4 million years after the formation of the Solar System (Connelly et al., 2012; Bollard et al., 2017). CAIs condensed from solar gas during

Figure 4. Samples of carbonaceous chondrites Allende (left) and Efremovka (right). Chondrites contain small, spherical to sub-spherical chondrules and CAIs as light-colored, irregular patches in a fine-grained carbon-rich matrix. Photo: Geological Collections of the Finnish Museum of Natural History/Jaana Halla.

the collapse of a presolar molecule cloud core at high temperatures (> 1,300 K) and pressures (≤ 10–4 bars), whereas chondrules formed by the accretion of dust particles. Chondrules melted and developed igneous texture before they accreted into chondritic bodies. They are composed of ferromagnesian silicate minerals, feldspathic glass, Fe- and Ni-metals, and Fe-rich sulfides. The chondrules likely formed within the protoplanetary disk by the accretion of dust aggregates during transient heating events and under lower temperature and higher water pressure than CAIs (e.g., Connelly et al., 2012).

CAIs and chondrules are found in carbonaceous chondrites, of which the type CV3 is considered to be the most primitive. CAIs and chondrules of the Allende and Efremovka CV3 chondrites (Fig. 4) have been precisely dated using the U-corrected method based on the U–Pb chronometer (e.g., Amelin et al., 2010; Connelly et al., 2012, 2017). Earlier age determinations have not considered the variation in the ^{238}U/^{235}U ratios in CAIs observed by Brennecka et al. (2010).

Connelly et al. (2017) combined the best-accepted ages of four CAIs dated independently at different laboratories: SJ101/Allende (Amelin et al., 2010), 22E, 31E, and 32E/Efremovka (Connelly et al., 2012) as a weighted mean Pb–Pb age of **4567 ± 0.16 Ma** for the Solar System. This age reveals a short period of CAI formation and was assumed as the age of the formation of the proto-Sun and the establishment of the protoplanetary disk (Connelly et al., 2017). A date of 4,567.32 ± 0.42 (Amelin et al., 2010) for the Allende chondrule C30 supports the contemporaneous formation of the CAIs and chondrules.

While CAIs are used to constrain the formation of the Solar System, chondrules are thought to represent building blocks of planetesimals (e.g., Krot et al., 2014; Amelin, 2019; Bollard et al., 2019). Bollard et al. (2017) inferred, based on dating of a statistically significant set of chondrules by Connelly et al. (2012), that the production of chondrules in the early Solar System started contemporaneously with CAIs. Further, the authors inferred that the primary phase of abundant chondrule production lasted for up to a million years subsequent to the short episode of CAI formation and was followed by up to c. 4.5 million years-long production period of chondrules, marked with increasingly evolved Pb isotope compositions with time.

An extraordinary metalliferous chondrite of CBa-type (see Table 1), called **Gujba,** contains large, completely spherical metal and silicate chondrules with a variable amount of troilite and CAIs. These impact-generated chondrules have been precisely dated at **4,562.49 ± 0.21 Ma** (the weighted Pb–Pb mean age of four single chondrules) by Bollard et al. (2015).

Table 1. List of the oldest material in meteorites found on Earth

Meteorite	Age Ma	Method	Classification	Fell/Find	Status	Reference
Differentiated meteorites						
Gujba impact-generated chondrules	4562.49 ± 0.21 4562.64 ± 0.13		**CBa**, carbonaceous chondrite, Bencubbinite group, large chondrules	Yobe Nigeria 11°29'3N, 11°39'3E Fall 1984	Impact-generated chondrules	Bollard et al. (2015), Connelly et al. (2017)
Erg Check 002 (EC002)	4565.0 (Relative age)	The closure age of the ^{26}Al– ^{26}Mg system (2.255 ± 0.013 Myr after CAIs)	**Achondrite,** ungrouped	Adrar Algeria 60°32'N, 16°11'W Find 2020	'The oldest magmatic rock in the Solar System'	Barrat et al. (2021)
Steinbach	4565.47 ± 0.30	U-corrected Pb–Pb age of late-phase, slowly cooled orthopyroxene	**IVA**, iron meteorite	Germany 50°30'N, 12°30'E Find 1724	'The oldest differentiated achondrite meteorite'	Connelly et al. (2019)
Protoplanetary disk (solar nebula)						
Allende, Efremovka CAIs (Ca-Al rich inclusions in chondrites)	4567.30 ± 0.16	U-corrected Pb–Pb	Allende: CV3 chondrite CAI SJ101 Efremovka: CV3 chondrite CAI 22E, 31E and 32E	Allende: Mexico Efremovk: Kazakhstan (See text)	'The oldest solids of the Solar System', condensed from gas in a protoplanetary disk	Amelin et al. (2010), Connelly et al. (2012, 2017)
Presolar dust (interstellar)						
Murchison, Silicon carbide grains (SiC)	3.9 ± 1.6 Ma to c. 3 Ga before the start of the Solar System	Interstellar cosmic ray exposure based on cosmogenic ^{21}Ne isotope ages	Carbonaceous chondrite, CM2, rich in organic compounds	Victoria Australia 36°37'S ,145°12'E Fall 1969	'Presolar dust, oldest material found on Earth'	Heck et al. (2020)

Differentiated Meteorites

Connelly et al. (2019) reported a U-corrected Pb–Pb age of **4,565.47 ± 0.30 Ma** based on multiple fractions of late-phase, slowly cooled orthopyroxene from a Group IVA **Steinbach** iron meteorite. This is the oldest absolute age for a differentiated meteorite. Together with ^{26}Al–^{26}Mg relative ages of 1.83 ± 0.34 Ma with respect to the CAI formation, this age indicates extremely rapid formation (accretion and differentiation before impact-related breakup and re-accretion) of the original IVA parent body; meaning that the planetary embryos (>1,000 km in diameter) formed within the first million years of the formation of the Solar System.

Erg Chech 002 (EC 002) is a recently discovered meteorite that originated from primitive igneous crust with andesitic bulk composition, derived from a partially melted, chondritic planetary body. With a closure age of the ^{26}Al–^{26}Mg age system of 4,565 Myr, i.e., 2.255 ± 0.013 Ma after the CAI formation, (Barrat et al., 2021), EC 002 is likely the oldest known magmatic rock in the Solar System.

The Age of the Solar System

Considering the available time constraints for the Solar System and planetary formation (see Table 1), we are confident that Earth and other planets accreted from planetesimals and differentiated after the CAI and chondrule formation episode at 4,567 Ma. Four U-corrected Pb–Pb age determinations for CAIs at two different laboratories (Amelin et al., 2010; Connelly et al., 2012) have yielded a weighted mean age of 4,567.30 ± 0.16 Ma (Connelly et al., 2017). This age is currently is the best-constrained older limit for the age of the Solar System.

The current research, although it debates about the mechanisms involved, clearly indicates that the proto-Earth formed shortly after the Solar System. Therefore, we suggest a lower boundary of 4,567 Ma for the Hadean, which corresponds to the beginning of the formation of the Solar System and proto-Earth based on the age of the CAIs in chondritic meteorites. The Hadean lower boundary is thus based on the U-corrected absolute Pb–Pb ages of CAIs and it is supported by the oldest dates for chondrules.

The Oldest Ages for the Calcium-Aluminium-Rich Inclusions and Chondrules

Allende

Classification: carbonaceous chondrite, CV3
Place of fall: The village of Pueblito de Allende, Chihuahua, Mexico
Coordinates: 26°58'N 105°19'W
Fall: 1969
CAI SJ101, coarse-grained type B1, melted
U-corrected Pb–Pb age: 4,567.18 ± 0.50 Ma
See Fig. 3 in Amelin et al. (2010)
Chondrule C30
U-corrected Pb–Pb age: 4,567.32 ± 0.42 Ma
See Fig. 2B in Connelly et al. (2012)

Efremovka

Classification: carbonaceous chondrite, CV3
Find: Efremovka State Farm, Pavlodar District, Pavlodar Region, Kazakhstan, 1962
Coordinates: 52°30’N 077°0’E
U-corrected Pb–Pb ages of CAIs
22E, unmelted nebular condensate: 4,567.35 ± 0.28 Ma
31E, coarse-grained type B1, melted: 4,567.23 ± 0.29 Ma
32E, coarse-grained type B1, melted: 4,567.38 ± 0.31 Ma
See Table 1 and Fig. 2 in Connelly et al. (2012)

Northwest Africa (NWA) 5697

Classification: ordinary chondrite, L3 (low-iron group, petrological type 3)
Find: Agadir, Morocco, 2008
U-corrected Pb–Pb ages of the oldest chondrules:
5-C1: 4,567.61 ± 0.54 Ma
2-C1: 4,567.57 ± 0.56 Ma
5-C2: 4,567.54 ± 0.52 Ma
5-C10: 4,567.41 ± 0.57 Ma
See Table 1 and Fig. 1A in Bollard et al. (2017)

Table 2. The oldest ages for Hadean events

Event	The oldest age Ma	Method	Reference
Earth’s protocrust	4370	SIMS U–Pb zircon	E.g., Valley et al. (2014), Whitehouse et al. (2017)
The beginning of alleged LHB	>4400 Ma		Bottke et al. (2017)
Moon forming Giant Impact	4510	^{182}Hf–^{182}W	Touboul et al. (2017), Barboni et al. (2017)
Differentiation of the Earth	4530–4510	^{182}Hf–^{182}W (Kleine et al., 2017)	Yin et al. (2002), Kleine et al. (2002)
Differentiation of the primitive planetary objects (iron meteorites)	4565	Pb–Pb ages	Connelly et al. (2019)
Formation of the protoplanetary disk	4567	Pb–Pb ages of CAIs and chondrules	Amelin et al. (2010), Connelly et al. (2012, 2017), Bollard et al. (2017)

Northwest Africa (NWA) 6043

Classification: carbonaceous chondrite, CR3 (Renazzo group, petrological type 3)
Find: Agadir, Morocco, 2009
U-corrected Pb–Pb ages of the oldest chondrules:
1-C2: 4,567.26 ± 0.37 Ma
See Table 1 and Fig. 1A in Bollard et al. (2017)

The Base and Major Events of the Hadean Eon

The new formal base of the Hadean Eon is the age of the Solar System based on the oldest CAIs formed in the protoplanetary disk. The formal GSSA age for the Hadean base is a weighted mean U-corrected Pb–Pb age of 4,567.30 ± 0.16 Ma for CAIs in primitive meteorites (Amelin et al., 2010; Connelly et al., 2012). This age is supported by the 4,568–4,567 Ma U-corrected Pb–Pb ages of chondrules found in Northwest African meteorites (Bollard et al., 2017). These ages set a maximum lifetime for the protoplanetary disk and timing for planet formation. The boundary is based on a high-precision dating method allowing the accuracy of 4 significant digits. This lower boundary encloses the accretion and differentiation of the Earth and other planets, the Moon-forming Giant Impact (GI), the inferred Late Heavy Bombardment (LHB), and the formation of the Earth's protocrust (Table 2).

Discussion

Opinions and Counter-Opinions

In the SPS and the ICS Voting Commission, the proposal received strong support among the voting members, and in both only one member voted against. The opinions of those who did not vote on the proposal (10 members of the SPS and 2 of the ICS Voting Commission) were not expressed and thus are not considered.

Opposing views on the base of the Hadean have been presented. Because of the Moon-forming Giant Impact that occurred after the differentiation of the proto-Earth, and the fact that Earth's first crust has been destroyed, the age of planet Earth itself remains an open question. It was pointed out that the Hadean is a term used only for Earth's history, and not as a reference to the age of materials (CAIs and chondrules) in the Solar System that formed when Earth did not yet accrete. Therefore, in this case, the age based on the time when the Solar System formed would seem inappropriate for the base of the Hadean that refers to the Earth's history that does not extend so far back. However, the age of Earth is a complicated subject, requiring in part one to define what is meant by 'the age of the Earth'. How much mass does a planet need to be called 'Earth'? There are several age estimates for the Earth's core segregation, all of them imply that Earth existed, and its core segregated within 10 to 30 million years after CIAs were formed (Kleine et al., 2002, 2017).

When these intriguing questions were discussed, SPS concluded that it is also important to consider the following relevant points:

1. The aim of the SPS is to move away from previous, arbitrary-set boundaries and anchor the boundaries to geological events that can be reliably dated.
2. Setting the boundary at a certain, inferred stage in the growth of Earth would be arbitrary because we lack both applicable absolute dating methods to constrain this stage and a unanimous agreement on when the Earth came into existence, which could lead to endless discussions and arguments.
3. The Earth itself consists of the materials of the Solar System. Its accretion began from CAIs and chondrules, so they were also constituents of Earth; therefore, it is natural to include Earth's formation in the realm of Earth's history.
4. Multiple astronomical, chemical, physical, and chronological evidence (e.g., Schiller et al., 2020) point to rapid evolution of the early Solar System with accretion and differentiation of the proto-Earth in only a few million years, which is a very short time interval compared with the half a billion-year duration of the Hadean.
5. It is natural to include the process of Earth's formation into the realm of the Earth's history; the history and age of the universe began with a hot dense point that was not yet a universe.

Based on these arguments, it was agreed to set the age of Earth at the beginning of the formation of the Solar System. This revised the concept of the Hadean Eon to include the Earth's accretion and differentiation, the Moon-forming Giant Impact, inferred Late Heavy Bombardment, and the formation of the Earth's protocrust.

Future Prospects

Following recent and ongoing attempts to improve the methodology to acquire more accurate U-corrected Pb–Pb ages for extraterrestrial materials (Connelly et al., 2021), further analyses of CAIs and chondrules are expected to refine the age of the Solar System.

Higher precision for the age of the Solar System requires analysis of multiple CAIs and chondrules from several chondrites with a combination of U-corrected Pb–Pb and short-lived isotope geochronology. An increasing number of new types of analyses is expected to commence following recent advancement in absolute chronology of CAIs and chondrules, including the development of methods for the precise analysis of small amounts of Pb and U by TIMS (thermal-ionisation mass-spectrometry) and high-resolution ICP-MS (inductively-coupled mass-spectrometry) as suggested by Connelly et al. (2021).

Towards Hadean Subdivision

Future work will focus on the further division of the Hadean into two eras: Paleohadean and Neohadean. The Paleohadean would be the period of the Earth's accretion, differentiation, and the Moon-forming Giant Impact. The lower and upper boundaries of the Paleohadean will be set based on the high-precision geochronology of meteorites and oldest zircons found on Earth, respectively. The herein suggested Hadean lower boundary would also define the base of the Paleohadean, which would cover the time span for which no physical evidence on Earth itself exists. The lower boundary of the Neohadean could be placed at 4,370 Ma according to the oldest high-precision U–Pb ages for detrital zircon from the Jacks Hills Quartzite of the Narryer Terrane, western Australia (e.g., Valley et al., 2014; Whitehouse et al., 2017), which are, so far, the oldest Earth's materials directly dated by the U–Pb method. These ages prove the existence of the Earth's oldest protocrust, which has not survived up to the present day.

Acknowledgements

PH and SJ publish with the permission of the Executive Director of the Geological Survey of Western Australia.

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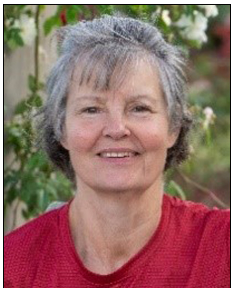

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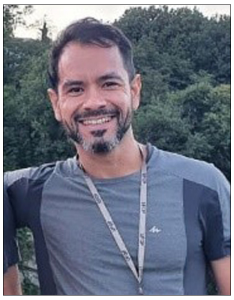

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