4.5 Chronology of the Solar System

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4.5.1 Definitions and principles of age determinations based on radioisotopes

Solar System chronology is based on radiometric dating, i.e. age determinations using radioisotopes. Both long-lived and short-lived – now extinct isotopes – can be used (Table 1).

Table 1. Nuclide systems used for radioisotopic dating – general references in [86Fau, 03McK, 03Wad, 05Dic]

Nuclide	Isotopic abundance [%]	Decay type	Decay product	Half-life [1] [a]	Method
^{238}U	99.28	α	^{206}Pb	4.47×10^9	U-Pb
					U-He
		spontaneous fission	$^{131\text{-}136}$Xe	8.2×10^{15}	U-Xe
					Xe-Xe
			fission tracks		fission tracks
^{235}U	0.72	α	^{207}Pb	7.04×10^8	U-Pb
^{238}U + ^{235}U		α	^{206,207}Pb	above	Pb-Pb
^{232}Th	100	α	^{208}Pb	1.40×10^{10}	Th-Pb
^{40}K	0.0117	β⁻	^{40}Ca	$1.25 \cdot 10^9$	K-Ca
		K-capture	^{40}Ar	$\lambda_K / \lambda_\beta = 0.117$ [3]	K-Ar, ^{40}Ar-^{39}Ar
^{87}Rb	27.83	β⁻	^{87}Sr	4.88×10^{10}	Rb-Sr
					initial Sr
^{147}Sm	15.0	α	^{143}Nd	1.06×10^{11}	Sm-Nd
^{187}Re	62.6	β⁻	^{187}Os	$\sim 5 \times 10^{10}$	Re-Os
^{176}Lu	2.59	β⁻	^{176}Hf	3.78×10^{10}	Lu-Hf
Extinct nuclides [2]					
^{26}Al	-	β⁺	^{26}Mg	7.4×10^5	Al-Mg
^{182}Hf	-	β⁻	^{182}W	8.9×10^6	Hf-W
^{53}Mn	-	β⁻	^{53}Cr		Mn-Cr
^{129}I	-	β⁻	^{129}Xe	1.7×10^7	I-Xe
^{244}Pu	-	(α) sp. fission	$^{131\text{-}136}$Xe	8.2×10^7	Pu-Xe
^{107}Pd	-	β⁻	^{107}Ag	6.5×10^6	Pd-Ag
^{146}Sm	-	α	^{142}Nd	1.03×10^8	
^{205}Pb	-	K-capture	^{205}Tl	2×10^7	

[1]) Accuracy and the intercalibration of radioisotopic ages of different decay systems seriously depends on uncertainties in the respective decay constants [01Beg]. Short-lived nuclide systems need calibration against long-lived chronometers, mostly U-Pb-Pb is used.

[2]) For initial isotope abundances, see Section 4.3.3 "Meteorites" by P. Hoppe in this volume or [03McK, 07Sco]

[3]) λ_K and λ_β are partial decay constants for K-capture and β⁻-decay, respectively.

The age of a system (mineral, rock, geochemical reservoir) is usually expressed in million years (Ma) or billion years (Ga) and can be understood as the accumulation time *t* of a daughter isotope D by radioactive decay from a parent nuclide P, and can be calculated using the age equation:

$$t = \frac{1}{\lambda}\ln\left(1+\frac{D}{P}\right), \; (D, P \text{ in number of atoms; } \lambda\text{: decay constant}) \qquad (3)$$

A system to be dated – a mineral, a rock, a major geologic unit or even a planet – must meet the following conditions in order that the mass-spectrometrically measured quantities (element and isotope abundances) correspond to geologically meaningful ages [86Fau, 03McK, 03Wad, 05Dic]:

1) over the accumulation time *t*, no loss or gain – except radioactive decay – of *P* or *D* should occur, unless such changes can systematically be corrected for (closed system).

2) During formation of the system, parent and daughter elements were completely or partially fractionated (due to their different geochemical behaviour) and the daughter element isotopes were equilibrated (i.e. homogenized) which allows the determination of the initial abundance of daughter atoms.

Then radioisotope ages date the event of fractionation of parent from daughter element. This may be caused by the crystallization of cogenetic minerals, yielding the crystallization age of a rock. Strictly speaking these ages are cooling ages, as the radiometric clock only starts below the so called closure temperature when diffusion of daughter element isotopes becomes ineffective. Particularly, this has to be taken into account for daughter isotopes with high diffusion coefficients. For example, ages determined by systems involving radiogenic noble gases are so-called "gas retention ages".

In addition to formation or cooling of individual rocks and minerals, large scale processes may also be dated, e.g. planetary differentiation and the accompanying separation of siderophile elements (partitioning into core forming metal) and lithophile elements (partitioning into a silicate mantle), yielding a core formation age [e.g., 02Kle, 02Yin, 08All, 08Hal].

4.5.2 The age of the Solar System: from dust to planets

4.5.2.1 The formation process of planetary systems

It is commonly accepted that the Sun and the planets in our Solar System formed by collapse of an interstellar cloud of gas and dust, as suggested by more than 200 years ago by Kepler and Laplace. The presence of numerous protoplanetary discs in star formation regions is proof of this concept. The existence of > 270 extrasolar planets demonstrates that planet formation processes are quite effective. It is to be noted that compared to our solar system most of the discovered extrasolar planets have generally small semi major axis and high masses, which, however probably is due to observational bias.

A major process in the initial stage of planet formation is hierarchical growth from sub micrometer sized dust grains to mm and cm sized aggregates by hit and stick collisions. Once further growth to km – sized planetesimals is completed, gravitation acts as additional force to proceed to formation of asteroid sized planetesimals and Mars-sized protoplanets. Final growth to full sized planets needs dynamical excitation, i.e. close encounters, and needs probably several tens of millions of years for the terrestrial planets. Gas and ice giants in the outer Solar System formed beyond the snow line, where ices cause a higher surface mass density and faster accretion time scales. For example, Jupiter is thought to have formed a ten Earth mass core and subsequent gravitational attraction of its gaseous envelope within 3 - 10 million years [e.g. 03Lun]. Other mechanisms may also have supported fast Jupiter formation, such as concentration of material across evaporation fronts [04Cuz].

The initial stages of planet formation are limited by the lifetime of protoplanetary discs in star formation regions since disks of fine grained dust apparently disappear on time scales of 3 - 6 Ma [01Hai]. Gas seems to dissipate on similar time scales, although the uncertainties are large. Simultaneous planetary accretion and disk dissipation can be monitored via irradiation effects, e.g. implantation of solar wind ions during an early epoch of planet formation [e.g. 00Tri].

A specific astrophysical constraint on the absolute age of our Solar System is provided by helioseismology that yields an age of the Sun of 4.57 ± 0.11 billion years [02Bon]. All other constraints are derived from radio-isotope dating of rocks − mostly meteorites −, using either long-lived or short-lived nuclide systems. The presence of short-lived nuclides in the early Solar System provides fundamental evidence that star formation occurred very shortly before our Solar system was born in a cluster, in which stars of both low and high mass form simultaneously. Massive stars develop rapidly into their final stages emitting stellar outflows with freshly synthesized isotopes, including short-lived isotopes, see, e.g., the Orion nebula stellar environment. The presence of ^{60}Fe in meteorites recording early Solar System history suggests a nearby Supernova [03Tac, 07Biz, 08Dau]. Stellar winds and shock waves from rapidly evolving massive stars may additionally help to trigger star formation or dissipate the Molecular Cloud material.

Short-lived radioisotopes are an important tool to elucidate early Solar System history, as they provide a better time resolution (i.e. smaller uncertainties) for the first few million years of the Solar System. However, as the respective parent nuclides are extinct today, the calculation of radioisotope ages from isotope anomalies of the decay products implies the assumption that short-lived nuclides were homogeneously distributed in the solar nebula (which was probably the case for most nuclides) and requires calibration to a long-lived isotope system (e.g. ^{26}Al-^{26}Mg versus U-Pb-Pb). For calibration of different short-lived chronometers, several approaches using a variety of calibrations are used [01Gil, 07Mar, 07Sco, 06Tri].

4.5.2.2 Formation and age of first Solar System solids

Various stages of planetary growth in the early Solar System can be evaluated using meteorites (for definition, nomenclature and types see Section 4.3.3 "Meteorites" by P. Hoppe in this volume). Most meteorites stem from the small asteroids between Mars and Jupiter, estimates of the number of asteroids sampled by meteorites are on the order of 100. The asteroid belt represents a swarm of small planetesimals that never managed to completely grow to a full sized planet. Some asteroids (or parts of them) were never heated significantly (e.g. to form metallic cores and silicate mantles like all the terrestrial planets), and preserve micrometer- to cm-sized relicts of the hierarchical growth process: For example, chondrites are composed of micrometer sized dust (matrix) and mm-sized rounded silicate droplets (called chondrules) that formed by (principally unknown) energetic flash heating processes as individual objects in dust enriched regions of the solar nebula. Another class of cm-sized objects that experienced high temperature processing in the solar nebula are Calcium Aluminum rich Inclusions (CAIs) with mineral assemblages expected for high temperature condensates.

The radioisotopic clocks of chondrules and CAIs yield their formation age, if they had been stored in relatively cold locations (e.g. surface near layers) of their parent asteroids, or if the asteroids as a whole have not been heated too severely. CAIs are commonly considered as oldest objects in the Solar System, based on their high absolute U-Pb-Pb age and their high initial ^{26}Al/^{27}Al ratio of ~5 × 10^{-5} [76Lee]. A frequently quoted U-Pb-Pb age is 4567.2 ± 0.6 Ma obtained on Efremovka CAIs [02Ame] which is in agreement with previous values of 4566 ± 2 Ma [81Che, 95All], while a more recent value of 4568.5 ± 0.5 Ma for Allende CAIs is marginally higher [07Bou] and appears more consistent with short-lived nuclide chronologies [07Mar, 08Bur].

The CAI initial ^{26}Al/^{27}Al ratio of ~ 5 × 10^{-5} [76Lee] appears quite homogeneous ("canonical") in many CAIs and indicates that their formation processes were active only during a limited time interval, and that secondary processing in the nebula was not severe. Some reported "supracanonical" ^{26}Al/^{27}Al values [e.g., 05You, 06Thr] were not confirmed recently [08Jac]. In general, CAI formation is considered to have occurred during the earliest stages of the protosolar accretion disk.

Most chondrules from chondrites appear 1 - 3 Ma younger than CAIs (Table 2; ^{26}Al-^{26}Mg ages in Fig. 1), indicating that the solar nebula contained fine dust for at least 3 Ma, along with energetic processes responsible for chondrule flash heating.

Table 2. Age of the Solar System and age of first solids

Object	Age [Ma]	Method[1]	$^{26}Al/^{27}Al$ [$\times 10^{-6}$]	Reference
Sun	4570 ± 110	Helioseismology		02Bon
CAIs				
CV All	4566 ± 2	U-Pb-Pb		81Che, 95All
CV Efr	4567.2 ± 0.6	U-Pb-Pb	46.3 ± 4.4	02Ame
CV All/Efr	4568.5 ± 0.5	U-Pb-Pb		07Bou
CV All/	4568.0 ± 1.7	^{182}Hf-^{182}W		05Kle1
NWA2364	4568.3 ± 0.7			08Bur
CV All	**≡ 0**	**^{26}Al-^{26}Mg**	50	76Lee
CV All, Leo, Efr, Gro			45 - 70	05You
CV[2]			58.5 ± 0.5	06Thr
CV All			49 ± 2.8	08Jac
CV All			52.5 ± 1.0	04Biz
Chondrules				
CR Acf059	4564.7 ± 0.6	U-Pb-Pb		02Ame
CV All	4566.6 ± 1.0	U-Pb-Pb		08Ame3
	4565.5 ± 0.5			08Con2
CV All			13.6 - 56.6 [5]	04Biz
LL Sem	1.7 - 2.3	^{26}Al-^{26}Mg	5.7 - 9.2	00Kit
	1.93 ± 0.23		7.9 ± 1.0	
LL Bis	0.8 - 2.5	^{26}Al-^{26}Mg	4.5 - 23	99Mos,00McK,
	1.80 ± 0.49		7.0 ± 1.1	02Mos
L[3]	1.0 - 2.2	^{26}Al-^{26}Mg	6.5 - 16	07Rud
	1.82 ± 0.36		7.9 ± 1.0	
CO Y81020	1.3 - 2.9	^{26}Al-^{26}Mg	3.1 - 14.1	04Kur
	1.90 ± 0.48		8.6 ± 0.5	
CO Y81020	2.2 - 3.2	^{26}Al-^{26}Mg	2.4 - 6.5	04Kun
	2.67 ± 0.37		3.8 ± 0.7	
CR[4]	2.2 - 4.2	^{26}Al-^{26}Mg	1.0 - 6.2	07Nag, 08Kur,
	3.00 ± 0.68		1.9 ± 0.3	08Nag

Meteorite name abbreviations: CV chondrites: All: Allende; Efr: Efremovka; Gro: Grosnaja; Leo: Leoville; Vig: Vigarano; LL3 chondrites: Bis: Bishunpur; Sem: Semarkona; Desert regions: Acf: Acfer; NWA: North West Africa; Sah: Sahara; Antarctic regions: ALH: Allan Hills; EET: Elephant Moraine; GRA: Graves Nunataks; LEW: Lewis Cliff; QUE: Queen Alexandra Range; Y: Yamato

[1]) U-Pb-Pb ages are given in Ma before present, ^{26}Al-^{26}Mg ages as Ma after CAIs

[2]) CV chondrites studied: All, Vig, Sah98044 NWA779

[3]) L chondrites studied: LEW86134, LEW86018, QUE97008, Adrar003, ALH77176

[4]) CR chondrites studied: EET92042, EET92147, GRA95229, NWA721

[5]) ^{26}Al excess is calculated from bulk ^{26}Mg excess, and could date older precursor material, not necessarily the chondrule formation event

4.5.2.3 Formation and age of asteroid sized planetesimals

Growth to km and 100 km sized planetesimals (meteorite parent bodies) was associated with heating, resulting in thermal metamorphism (producing ordinary chondrite parent bodies: H, LL, L) and/or the action of hydrous fluids and aqueous alteration (producing some carbonaceous chondrite parent bodies: CM, CI), or even separation of metallic cores and silicate mantles on some asteroids (producing parent bodies of iron meteorites and basaltic achondrites).

Lacking effectiveness of other heat sources (heating by impacts, decay heat of long-lived nuclides ^{40}K, U, Th), heating almost certainly was caused by decay heat of short-lived nuclides [99Sri, 03Tri], for the most part ^{26}Al, and probably ^{60}Fe [03Tac]. Within the first 2 Ma after CAI formation, all planetesimals > 40 km are expected to be partially molten and differentiated [05Biz, 06Tri, 06Hev, Fig. 2]. Hf-W dating of iron meteorites [05Kle1, 06Sch] confirms such a scenario (Table 3). Further evidence is provided by U-Pb-Pb ages of the basaltic achondrites, i.e. pieces of rapidly cooled asteroidal crusts (Table 3): Asuka 881394 aged 4566.5 ± 0.3 Ma (Eucrite) [06Ame] and the angrite SAH99555 that was dated to 4566.2 ± 0.1 [05Bak] and later revised to 4564.58 ± 0.14 [08Con1] and 4564.86 ± 0.38 Ma [08Ame1] or the angrite D'Orbigny with 4564.42 ± 0.12 Ma [08Ame2]. Such data indicate that differentiated planetesimals formed and evolved within a few Ma after CAIs (Table 3).

Table 3. Ages of differentiated meteorites (irons, basaltic achondrites) provide lower limit for asteroid formation and differentiation

Rock	Parent body	U-Pb-Pb age[1] [Ma]	^{26}Al-^{26}Mg age[1] [Ma]	^{182}Hf-^{182}W age[1] [Ma]	Ref.
Basaltic achondrites	**(crustal cooling or differentiation of silicate portion)**				
Asuka 881394	Eucrite (HED)	4566.5±0.3[4]			06Ame
SAH99555	Angrite	4564.86±0.384			08Ame1
		5664.58±0.14[5]			08Con1
		(4566.2±0.1)[5]			05Bak
				5.1±1.3	07Mar
D'Orbigny	Angrite	4564.42±0.12			08Ame2
				4.7±1.3	07Mar
AdoR	Angrite	4557.65±0.13			08Ame2
Angrites[2]	Angrite		3.1 - 3.4 [6]		05Bak
Eucrites[3]	Eucrite (HED)		3.05 - 4.04 [6]		05Biz
Vaca Muerta	Mesosiderite		2.6 - 3.6 [6]		05Biz
Irons	**(separation of metallic core from silicate portion)**				
Magmatic irons IIAB, IC, IIIAB, IVA, IVB				1.5 [7] $\varepsilon_W = -3.9 - -3.1$ $\varepsilon_W = -3.51_{-0.19}^{+0.1}$	05Kle1 06Sch

Meteorite name abbreviations as in Table 2; AdoR: Angra dos Reis (angrite)

[1]) U-Pb-Pb ages are given in Ma before present, ^{26}Al-^{26}Mg and ^{182}Hf-^{182}W ages in Ma after CAIs

[2]) Angrites studied: Camel Donga, Ibitira, Juvinas, Stannern, Dhofar 007, Talampaya, Bilanga

[3]) Eucrites studied: AdoR, D'Orbigny, NWA1296, SAH99555

[4]) Interpreted to date preaccretional Pb loss by 07San

[5]) 08Con1 revised value of 05Bak

[6]) Model ages derived from initial ^{26}Al/^{27}Al calculated from ε_{Mg} ($\varepsilon = 1$ corresponds to 1/10000 deviation from a standard ^{26}Mg/^{24}Mg ratio, see e.g. [05Dic]). These model ages date formation of silicate source.

[7]) Model ages derived from initial ^{182}Hf/^{180}Hf calculated from ε_W ($\varepsilon = 1$ corresponds to 1/10000 deviation from a standard ^{182}W /^{184}W ratio, see e.g. [05Dic])

Thermally metamorphosed planetesimals can be expected for formation times 2 - 4 Ma after CAIs [05Biz, 06Tri, 06Hev, Fig. 2], when the abundance of short-lived isotopes and the associated degree of decay heat had sufficiently ceased. Metamorphic heating of ordinary chondrites (maximum temperatures of ~ 1220 K) indicates that they probably accreted about 1 Ma before the less intensely heated CO and 2 Ma before CR carbonaceous chondrites. This is largely consistent with the formation of the youngest chondrules of these chondrite types, which should – of course – precede the formation of the corresponding parent body (Figs. 1, 2). Chronological data suggest that a specific parent body could have incorporated chondrule populations that formed up to ~ 1 Ma earlier, but age uncertainties prevent firm conclusions. Another constraint on chondrite formation time scales is derived from the age of metamorphic chondritic minerals which must postdate chondrite parent body accretion (Table 4). For example, oldest phosphates and feldspars in H chondrites are only 5 Ma younger than CAIs. The age of these minerals represents cooling through closure temperatures of the respective minerals and radioisotopic systems. Hence, in case the rocks cooled slowly through temperature intervals set by closure temperatures of different radiochronometers, different values are obtained for cooling ages, with the oldest value approximating closest the formation age. Note that rocks in Table 2 and 3 for which different chronometers were applied (chondrules and basaltic achondrites) are rapidly cooled so that age differences due to slow cooling need not to be taken into account.

For H chondrites in Table 4, low petrologic types (i.e. metamorphic grade 4,5 mildly heated) are older than high petrologic types (metamorphic grade 6, severely heated) which is a consequence of slower (longer) cooling of H6 types that resided in more interior regions of their parent asteroid.

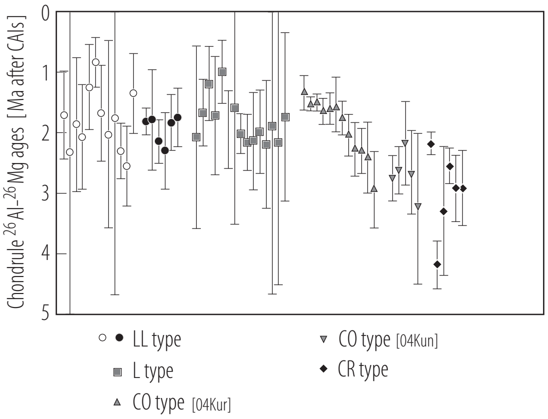

Fig. 1. ^{26}Al-^{26}Mg ages of individual chondrules (Ma after CAIs) for LL, L, CO and CR chondrite parent bodies (references see Table 2). CO type chondrules studied by [04Kun] were more Al-rich than by [04Kur].

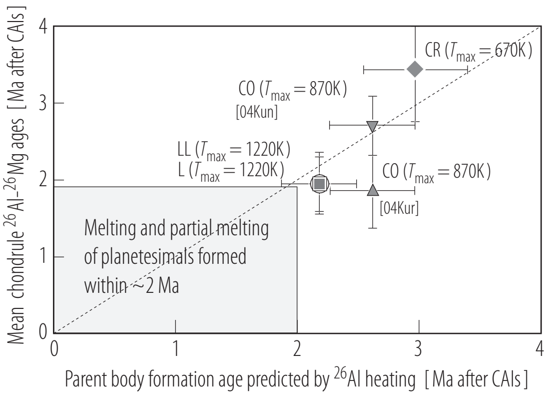

Fig. 2. Mean Al-Mg ages of chondrules from individual chondrite parent bodies are largely consistent with respective chondrite parent body formation ages derived from ^{26}Al heating based on parent body modelling [06Tri, 05Biz, 06Hev]. This indicates that chondrule formation shortly preceded planetesimal formation, with planetesimals forming during 4 Ma.

Other long-lived isotopes systems like ^{87}Rb-^{87}Sr, ^{176}Lu-^{176}Hf, ^{147}Sm-^{143}Nd, ^{40}K-^{40}Ar or ^{40}Ar-^{39}Ar generally confirm a Solar System age of 4568 Ma, however, they are only rarely capable to resolve the time interval of planetesimal formation and metamorphism 0 - 10 Ma after CAIs [e.g. 94Nyq], as they suffer from insufficient precision (at least a few Ma) and accuracy due to a bias in the respective decay constants [01Beg]. These systems are, however, useful in elucidating the post formation history characterized by large scale planetary differentiation processes, collisional evolution and impact metamorphism.

Table 4. Ages of metamorphic minerals and cooling ages on chondritic parent bodies provide lower limit for formation of undifferentiated asteroids; note extended cooling history of H5 and H6 chondrites resulting in younger Ar-Ar (and partly U-Pb-Pb ages)

Rock	U-Pb-Pb age [94Göp]	^{129}I-^{129}Xe age [99Bra]	^{53}Mn-^{53}Cr age[2] [01Pol, 98Lug]	^{26}Al-^{26}Mg age[3] [02Zin]	^{40}Ar-^{39}Ar age[4] [03Tri]	^{244}Pu fission track cooling time [03Tri]
Mineral	phosphate	feldspar[1]		feldspar	feldspar	Opx/mrl[7]
Closure temperature	720 K				550 K	550 K/390 K
H Chondrites						
St. Marguerite H4	4563 ± 1	4563.0 ± 0.4	4564.9 ± 0.4	5.4 ± 0.1	4564 ± 16	12 ± 11
Forest Vale H4	4561 ± 1		4561.3 ± 0.4	6.1 ± 0.2	4554 ± 8	< 8
Richardton H5	4551 ± 1	4554.1 ± 0.5			4527 ± 11	56 ± 9
Allegan H5	4550 ± 1	4569.3 ± 1.5			4543 ± 11	51 ± 9
Kernouve H6	4522 ± 1	4519.3 ± 6			4501 ± 6	61 ± 8
Guarena H6	4504 ± 1				4486 ± 6	56 ± 9
Estacado[5] H6	4492 ± 15				4467 ± 5	64 ± 8
Acapulco[6]	4557 ± 2	4558.5 ± 1.5			4542 ± 3	104 ± 12

[1]) I-Xe ages recalculated to Shallowater= 4562.3 Ma [01Gil, 04Gil], a more recent value is 4563.5 ± 1 Ma [05Pra]. Errors without absolute calibration error (adds constant systematic uncertainty of ~ 0.7 Ma). For Kernouve, phosphate I-Xe age is given

[2]) Mn-Cr absolute ages calculated using Pb-Pb age of 4557.8 ± 0.5 Ma [92Lug, 98Lug] for LEW86010 ($^{53}Mn/^{55}Mn=1.25\times 10^{-6}$).

[3]) Al-Mg age after CAIs using $^{26}Al/^{27}Al = 5 \times 10^{-5}$ as CAI value

[4]) Ar-Ar ages corrected for +30 Ma due to anticipated revision in K decay constants [01Beg, 01Tri, 07Sch2, 06Mun] and NL25 monitor age of 2657 Ma [07Sch1], errors without absolute calibration errors (adds constant systematic uncertainty of 6 Ma)

[5]) Estacado Pb-Pb age by [07Bli]

[6]) Acapulco Pb-Pb age by [92Göp], Ar-Ar and ^{244}Pu fission track age by [97Pel] and [01Tri]

[7])Represents time needed for cooling between fission track retention in orthopyroxene (opx) at 550 K and in merrillite (mrl) at 390 K – values > 0 indicate slow cooling, resulting in differences of cooling ages of systems with different closure temperature.

4.5.2.4 Formation and age of planets

It is evident that the formation of gas giant planets has to occur within the lifetime of the gaseous solar nebula. Within disk lifetimes inferred from extrasolar protoplanetary disks [01Hai] of 3 - 6 Ma, Jupiter may have formed in situ [07Lis], while for Uranus and Neptune formation at present locations is problematic. The Nice model [05Tsi] solves this problem by assuming core accretion closer to the Sun and subsequent outward migration. A formation time of 3 - 5 Ma after CAIs for Jupiter was derived using indirect lines of evidence from meteorite dating, astrophysical observational constraints on disk lifetimes and celestial dynamics considerations [06Sco and references therein].

For the formation time scales of terrestrial planets, dynamic scenarios suggest fast accretion of Mars-sized protoplanets on nearly circular orbits [00Kok]. The accretion to full sized terrestrial planets needs considerably longer (tens of Ma), as further accretion needs close encounters that can only be achieved by dynamical excitation. In a hierarchical growth process, the final stages are completed by giant impacts such as the collision of a Mars-sized protoplanet and the proto-Earth which produced the moon [87Ben].

One constraint to date the moon forming impact, and – implicitly – the terminal/complete accretion of the Earth are the oldest rocks from the moon. For example, [88Car] measured a Sm-Nd isochron of ferroan anorthosite 60025 of 4.44 ± 0.02 Ga age and suggested “the accumulated body of radiogenic isotope data for lunar rocks permit the moon to be as young as 4.44 - 4.51 Ga”. [99Bor] concluded that “the source of (ferroan anorthosite) 62236 was depleted in light rare earth elements at similar to 4.46 Ga”, while [03Nor] summarised “Sm-147-Nd-143 isotopic compositions of mafic fractions from the 4 ferroan noritic anorthosites for which isotopic data exist (60025, 62236, 67016c, 67215c) define an age of

4.46 ± 0.04 Ga, which may provide a robust estimate for the crystallization age of lunar ferroan anorthosites". These estimates are compatible with ^{40}Ar-^{39}Ar ages of the oldest plagioclase clasts in lunar rocks [74Jes1, 78Dom].

Table 5. Age of the Gas giants, Earth, moon and Mars

Object	Rock/System	Age [Ma]	Process dated	Reference
Jupiter		4564 ± 1 [1]		06Sco
Earth	Planetary differentiation by I-Xe, U-Pb-Pb, Hf-W	4450 4480 ± 20	Core formation, mantle degassing, atmospheric loss	08All 08Hal
	Oldest minerals (Jack Hills zircons)	4404 ± 8		01Wil
	Oldest rocks (Acasta gneiss)	4000 - 4030		99Bow
Moon	Sm-Nd of ferroan noritic anorthosites 60025, 62236, 67016c, 67215c	4460 ± 40	Oldest lunar crustal rock crystallization	03Nor, 99Bor, 88Car
	Hf-W of lunar metals	4506_{-10}^{+90}		07Tou
Mars	ALHA84001	4510 ± 110	Oldest Martian rock crystallization	01Nyq
	Hf-W SNC meteorites	> 4558 [2]	Core formation	07Nim
	Zagami	4048 ± 17 [3]		05Bou
	Shergottites	~ 4100 [3]		08Bou
		170 - 500 [3]		01Nyq

[1]) Using indirect lines of evidence from meteorite, CAI dating, astrophysical observational constraints on disk lifetimes and celestial dynamics considerations [06Sco]
[2]) Assuming simple two-stage model ages, more complex accretionary models also allow core formation ages of 20 Ma after CAIs.
[3]) There is a vivid current debate if shergottites are young (< 1 Ga) or old (> 4 Ga)

Another approach to date the age of the Earth is to determine a core formation age, which is commonly assumed to have not been completed before full accretion of the Earth, because, e.g. the terminal moon forming impact delivered a significant fraction of terrestrial core forming metal. Core formation ages can be obtained by modelling terrestrial Pb isotopes [95All] or in recent years by means of ^{182}Hf-^{182}W dating. While relatively early core formation within 30 Ma after CAIs was considered [02Yi, 02Kle], consistent with a study of lunar metals of 40 ± 10 Ma [05Kle2], a more recently revised value yielded 62_{-10}^{+90} Ma [07Tou]. A considerable source of uncertainty was the question if the metal cores of late impacting material interact (and, hence, equilibrate) with the terrestrial proto mantle. Recent synopses from I-Xe, U-Pb-Pb and Hf-W systems consider the terrestrial major differentiation episode (i.e. a giant impact accompanied by major atmospheric loss and followed by completion of core formation) at 4.45 Ga (120 Ma after CAIs) [08All], or at 4.48 ± 0.02 Ga (70 - 110 Ma after CAIs) [08Hal].

Radioisotopic age estimates of planet Mars crucially rely on Martian origin of SNC meteorites [94McS, 06Mey]. These meteorite groups resemble lithospheric rocks (basaltic shergottites, pyroxenitic nakhlites, dunitic chassignites) and are characterized by melt inclusions with gases similar to the Martian atmosphere [83Bog, 94McS], and generally young igneous ages lower than ~ 2 Ga [86Che, 86Jag, 82Shi]. A study recently vividly disputed reinterprets U-Pb-Pb systematics of shergottites indicating an old ~ 4.1 Ga age [08Bou], while many other studies prefer a young age of 170-500 Ma [01Nyq]. Among SNC meteorites, the orthopyroxenite ALHA84001 has an undisputed old crystallization age of ~ 4.5 Ga. Hf-W systematics of Martian meteorites currently do not allow to constrain the core formation (or terminal accretion) age better than < 10 Ma after CAIs, more complex models allow values as high as 20 Ma .

In the context of terrestrial planet formation, it should be kept in mind that the age or "birth" of a planet is not a point-like event, but a formation process that occurs over an extended time interval. In summary, present data (Table 5) suggest that the protoplanet-sized Mars could have accreted and differentiated as early as a few Ma after CAIs, while the Earth-Moon system needed about 100 Ma after CAIs for full differentiation, most probably terminated by the giant impact forming the moon.

4.5.3 Secondary history: collisions, impact cratering, and magmatic activity on large bodies

The post formation history of solid planetary surfaces is dominated by large scale planetary differentiation processes, collisional evolution and impact cratering (Table 6). As a prominent feature, the lunar surface is characterised by "Mare", large impact basins (Orientale, Crisium, Imbrium, Nectaris, Humorum, Serenitatis) that formed in a limited time interval 4.0 - 3.7 Ga ago [74Ter, 77Tur, 74Jes2]. This process is called the "Late Heavy Bombardment" (LHB). Lunar volcanism leading to mare filling was active until 3.0 Ga ago [77Tur]. Possible evidence of the LHB is also inferred from HED meteorites [95Bog1, 80Bog, 95Kun, 03Bog] and the Martian meteorite ALHA84001 [96Ash, 97Tur], although not undisputed [99Bog]. Moreover, meteorite ages also provide evidence for very early impact events (> 4 Ga) in the Solar System [05Kro, 97Kun].

After 3.5 Ga, the impact cratering rate in the inner Solar System is believed to have decreased to a roughly constant level, i.e. within a factor of 4. This can be inferred, for example from crater counting statistics of planetary surfaces or dating of randomly sampled lunar soil impact ejecta [97McE, 01Neu, 99Har, 00Har, 00Cul].

However, the collision rates of small bodies impacting on terrestrial planetary surfaces was occasionally increased, probably by collisions in the asteroid belt. For example, a major collision occurred in the asteroid belt 470 ± 6 Ma ago [07Kor], when a ~km-sized projectile disrupted the L chondrite parent asteroid [90Nak, 95Bog2, 01Sch, 04Hec, 07Kor]. This collision induced high pressure and high temperature metamorphism in many L chondrites [91Stö] and reset their gas retention ages. It caused a swarm of meter sized L chondritic material leading to an increase of normal meteorite fall frequencies by a factor of ~100, preserved as fossil meteorites in middle Ordovician sediments [97Sch, 01Sch] and possible to an increase of km sized asteroids impacting on Earth for the following 30 Ma [01Sch]. Today, more than one third of all meteorite falls are L chondrites.

Late stage evolution of meter-sized meteorites before their fall onto Earth can be traced by cosmic ray exposure ages [Table 6, 03Eug, 03Her]. Cosmic rays penetrate rocky material in the uppermost ~meter, hence the ages date the residence time of meter-sized meteorites in space, excavated by low energetic collisions among small – likely already prefragmented – asteroids. Cosmic ray exposure ages are determined by measuring isotopes produced by interaction with cosmic rays, e.g. stable isotopes like ^{3}He, ^{21}Ne, or radioactive isotopes like ^{10}Be or ^{26}Al. The latter isotopes can also be used to determine terrestrial residence times of meteorites.

As most meteorites stem from small asteroids that could not preserve internal heat and geologic activity longer than a few 100 Ma, the post-formational history is dominated by collisions and impact metamorphism. Impact cratering is also of fundamental importance for Mars and the Moon, and crater counting statistics are valuable tools to elucidate planetary surface chronologies [99Har, 00Har]. Late stage magmatic activity is nevertheless documented as well, e.g. Mare filling on the Moon until 3 Ga ago [77Tur] or Martian meteorites that display evidence for late stage magmatic activity, e.g., the nakhlites or shergottites [01Nyq, 91Jag, 06Mey].

In contrast to Mars or the Moon, the Earth is a much more geologically and tectonically active planet and has an atmosphere and hydrosphere supporting intense erosion and weathering. The record of impact cratering on Earth is comparably low, but nevertheless, presently ~ 175 impact craters [06Ear] are identified, among which preferably young and large impact craters are preserved. The two largest craters are the 2.02 Ga old Vredefort and 1.85 Ga old Sudbury impact structures [94Tri, 96Kam, 96Cor].

As a matter of fact, abundant terrestrial rocks record a variety of tectonic and geologic processes in Earth. For example, major markers in terrestrial history are the oldest zircon mineral grains (4.4 Ga), implying the presence of an early crust, atmosphere and hydrosphere including liquid water [01Wil], the oldest rocks (e.g., Acasta, Isua), earliest evidence for life, and subsequent orogenic cycles leading to major crustal formation episodes, as described in extensive reviews [03Hal, 03Hol].

Table 6. Age of selected secondary (i.e., post formational) events affecting meteorite parent bodies and planets

Object	Process	Age [Ma]	Method	Reference
Moon	Late Heavy Bombardment	4000 - 3700	Rb-Sr, Ar-Ar, U-Pb-Pb, Sm-Nd	74Ter, 77Tur 74Jes2
	Mare filling / volcanism	4000 - 3000		77Tur
HED meteorites	Collisions	4100 - 3400	Ar-Ar	95Bog1, 95Kun
L chondrites	Major asteroid collision	470 ± 6	Ar-Ar, Rb-Sr	07Kor, 90Nak
Martian meteorites	Igneous activity	~ 1300	U-Pb-Pb, Sm-Nd, Rb-Sr, Ar-Ar	01Nyq, 91Jag, 06Mey
Cosmic ray exposure ages [Ma], corresponding to small asteroid collisions excavating m-sized bodies to space				
Iron meteorites		< 1500		03Eug
Chondrites H, L, LL, E, CK, CV, CO		< 70 / 7, 15, 20 - 30		92Mar, 94Gra, 95Gra, 00Sch, 03Eug
H chondrites		7, 24, 33		92Mar, 95Gra, 03Eug
L, LL chondrites		6, 15, 27, 39		92Mar, 94Gra, 03Eug
Carbonaceous chondrites CI, CM		< 7 / 0.05 - 2		93Nis, 03Eug
HED meteorites		22 ± 3, 36 ± 3, 12 ± 3[1]		95Eug, 03Eug
A-L [2] chondrites		6 ± 1.5		03Eug
Martian meteorites		0.7 - 20		01Nyq, 03Eug
Shergottites		0.73 ± 0.15, 1.2 ± 0.3, 2.7 ± 0.3, 19.8 ± 2.3		01Nyq, 03Eug
Lherzolites		4.3 ± 0.5		01Nyq, 03Eug
Nakhlites, Chassigny		11.1 ± 1.6		01Nyq, 03Eug
ALH84001		14.7 ± 0.9		01Nyq, 03Eug

[1]) Eucrites only
[2]) Acapuloites-Lodranites

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4.5.4 References for 4.5

74Jes1 Jessberger, E.K., Huneke, J.C., Wasserburg G. J.: Nature **248** (1974) 199.
74Jes2 Jessberger, E.K., Huneke, J.C., Podosek, F.A., Wasserburg G. J.: Proc. 5th Lunar Sci. Conf. (1974) 1419.
74Ter Tera, F., Papanastassiou, D.A., Wasserburg, G.J.: Earth Planet. Sci. Lett. **10** (1974) 1.
76Lee Lee, T., Papanastassiou, D.A., Wasserburg, G.J.: Geophys. Res. Lett. **3** (1976) 109.

77Tur Turner, G.: Phys. Chem. Earth **10** (1977) 145.
77Wei Weidenschilling, S. J.: Mon. Not. Roy. Astr. Soc. **180** (1977) 57.
78Dom Dominik, B., Jessberger, E.K.: Earth Planet. Sci. Lett. **38** (1978) 407.
80Bog Bogard, D.D., Hirsch, W.C.: Geochim. Cosmochim. Acta **44** (1980) 1667.
81Che Chen, J.H., Wasserburg, G.J.: Earth Planet. Sci. Lett. **5** (1981) 15.
82Shi Shih, C.-Y., Nyquist, L.E., Bogard, D.D., McKay, G.A., Wooden, J.L., Bansal, B.M., Wiesmann, H.: Geochim. Cosmochim. Acta **46** (1982) 2323.
83Bog Bogard, D.D., Johnson, P.H.: Science **221** (1983) 651-654.
85Woo Wood, J.A.: In: Protostars and Planets II (Black, D. C., Matthews, M. S., eds.) University of Arizona Press, Tucson (1985) 687.
86Che Chen, J.H., Wasserburg, G.J.: Geochim. Cosmochim. Acta **50** (1986) 955.
86Fau Faure, G.: Principles of Isotope Geology. John Wiley & Sons, New York (1986).
86Jag Jagoutz, E., Wänke, H.: Geochim. Cosmochim. Acta **50** (1986) 939.
87Ben Benz, W., Slattery, W.L., Cameron, A.G.W.: Icarus **71** (1987) 30.
88Car Carlson, R. W., Lugmair, G. W.: Earth Planet. Sci. Lett. **90** (1988) 119.
90Nak Nakamura, N., Fujiwara, T., Nohda, S.: Nature **345** (1990) 51.
91Jag Jagoutz, E.: Space Sci. Rev. **56** (1991) 13.
91Stö Stöffler, D., Keil, K., Scott, E.R.D.: Geochim. Cosmochim. Acta **55** (1991) 3845.
92Lug Lugmair, G.W., Galer, S.J.G.: Geochim. Cosmochim. Acta **56** (1992) 1673.
92Göp Göpel, C., Manhès, G., Allègre, C.J.: Meteoritics **27** (1992) 226.
92Mar Marti, K., Graf, T.: Ann. Rev. Earth Planet. Sci. **20** (1992) 221.
93Nis Nishiizumi, K., Arnold, J.R., Caffee, M.W., Finkel, R.C., Southon, J.R., Nagai, H., Honda, M., Imamura, M., Kobayashi, K., Sharma, P.: Lunar Planet. Sci. **XXIV** (1993) 1085.
93Wei Weidenschilling, S.J., Cuzzi, J.N.: In: Protostars and planets III, University of Arizona Press, Tucson (1993) 1031.
94Nyq Nyquist, L.E., Bansal, B., Wiesmann, H., Shih, C.Y.: Meteoritics **29** (1994) 872.
94Göp Göpel, C., Manhès, G., Allègre, C.J.: Earth Planet. Sci. Lett. **121** (1994) 153.
94Gra Graf, T., Marti, K.: Meteoritics **29** (1994) 643.
94McS McSween, H.Y., Jr.: Meteoritics **29** (1994) 757.
94Tri Trieloff, M., Reimold, W.U., Kunz, J., Boer, R.H., Jessberger, E.K.: S. Afr. J. Geol. **97** (1994) 365.
95All Allègre, C.J., Manhès, G., Göpel, C.: Geochim. Cosmochim. Acta **59** (1995) 1445.
95Bog1 Bogard, D.D.: Met. Planet. Sci. 30 (1995) 244.
95Bog2 Bogard, D.D., Garrison, D.H., Norman, M., Scott, E.R.D., Keil, K.: Geochim. Cosmochim. Acta **59** (1995) 1383.
95Eug Eugster, O., Michel, Th.: Geochim. Cosmochim. Acta **59** (1995) 177.
95Gra Graf, T., Marti, K.J.: Geophys Res. **100** (1995) 1247.
95Kun Kunz, J., Trieloff, M., Bobe, K.D., Metzler, K., Stöffler D., Jessberger E.K.: Planet. Space Sci. **43** (1995) 527.
96Ash Ash, R.D., Knott, S.F., Turner, G.: Nature **380** (1996) 57.
96Kam Kamo, S.L., Reimold, W.U., Krogh, T.E., Colliston, W.P.: Earth Planet. Sci. Lett. **144** (1996) 369.
96Cor Corfu, F., Lightfoot, P.C.: Economic Geology **91** (1996) 1263.
97Kun Kunz, J., Falter, M., Jessberger, E.K.: Met. Planet. Sci. **32** (1997) 647.
97McE McEwen, A.S., Moore, J.M., Shoemaker, E.M.: J. Geophys. Res. Planets **102** (1997) 9231.
97Pel Pellas, P., Fieni, C., Trieloff, M., Jessberger, E.K.: Geochim. Cosmochim. Acta **61** (1997) 3477.
97Sch Schmitz, B., Peucker-Ehrenbrink, B., Lindström, M., Tassinari, M.: Science **278** (1997) 88.
97Tur Turner, G., Knott, S.F., Ash, R.D., Gilmour, J.D.: Geochim. Cosmochim. Acta **61** (1997) 3835.
98Lug Lugmair, G.W., Shukolyukov, A.: Geochim. Cosmochim. Acta **62** (1998) 2863.
99Bra Brazzle, R.H., Pravdivtseva, O.V., Meshik, A.P., Hohenberg, C.M.: Geochim. Cosmochim Acta **63** (1999) 739.
99Bog Bogard, D.D., Garrison, D.H.: Met. Planet. Sci. **34** (1999) 451.

99Bor Borg, L.E., et al. : Geochim. Cosmochim. Acta **63** (1999) 2679.
99Bow Bowring, S.A., Williams, I.S.: Contrib. Mineral. Petrol. **134** (1999) 3.
99Har Hartmann, W.K.: Meteorit. Planet. Sci **34** (1999) 167.
99Mos Mostefaoui, S., Kita, N.T., Nagahara, H., Togashi, S., Morishita, Y.: Met. Planet. Sci. **34** (1999) A84.
99Sri Srinivasan, G., Goswami, J.N., Bhandari, N.: Science **284** (1999) 1348.
00Cul Culler, T.S., Becker, T.A., Muller, R.A., Renne, P.R.: Science **287** (2000) 1785.
00Ebe Ebel, D. S., Grossman, L.W.: Geochim. Cosmochim. Acta **64** (2000) 339.
00Har Hartmann, W.K., Neukum, G.: Space Sci. Rev. **96** (2000) 165.
00Kit Kita, N.T., Nagahara, H., Togashi, S., Morishita, Y.: Geochim. Cosmochim. Acta **64** (2000) 3913.
00Kle Klerner, S., Palme, H.: Met. Plan. Sci. **35** (2000) A89.
00Kok Kokubo, E., Ida, S.: Icarus **143** (2000) 15.
00McK McKeegan, K.D., Greenwood, J. P., Leshin, L.A., Cosarinsky, M.: Lun. Planet. Sci. **XXXI** (2000) abstr. no. 2009.
00Sch Scherer, P., Schultz, L.: Meteorit Planet Sci. **35** (2000) 145.
00Tri Trieloff, M., Kunz, J., Clague, D.A., Harrison, D., Allègre, C.J.: Science **288** (2000) 1036.
01Beg Begemann, F., Ludwig, K.R., Lugmair, G.W., Min, K., Nyquist, L.E., Patchett, P.J., Renne, P.R., Shih, C.-Y., Villa, I.M., Walker, R.J.: Geochim. Cosmochim. Acta **65** (2001) 111.
01Gil Gilmour, J.D., Saxton, J.M.: Phil. Trans. R. Soc. Lond. A **359** (2001) 2037.
01Hai Haisch, K.E. Jr., Lada, E.A., Lada, C.J.: Astrophys. J. **553** (2001) L153.
01Hus Huss, G.R., McPherson, G.J., Wasserburg, G.J., Russell, S.S., Srinivasan, G.: Met. Planet. Sci. **36** (2001) 975.
01Neu Neukum, G., Ivanov, B.A., Hartmann, W.K.: Space Sci. Rev. **96** (2001) 55.
01Nyq Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D., Eugster, O.: Space Sci. Rev. **96** (2001) 105.
01Pol Polnau, E., Lugmair, G.W.: Lun. Planet. Sci. **XXXII** (2001) abstr. no #1527.
01Sch Schmitz, B., Tassinari, M., Peucker-Ehrenbrink, B.: Earth Planet. Sci. Lett. **194** (2001) 1.
01Tri Trieloff, M., Jessberger, E.K., Fiéni, C.: Earth Planet. Sci. Lett. **190** (2001) 267.
01Wil Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M.: Nature **409** (2001) 175.
02Ame Amelin, Y., Krot, A.N., Hutcheon, I.D., Ulyanov, A.A.: Science **297** (2002) 1678.
02Bon Bonanno, A., Schlattl, H., Paterno, L.: Astron. Astrophys. **390** (2002) 1115.
02Kle Kleine, T., Münker, C., Mezger, K., Palme, H.: Nature **418** (2002) 952.
02Mos Mostefaoui, S., Kita, N.T., Togashi, S., Tachibana, S., Nagahara, H., Morishita, Y.: Met. Planet. Sci. **37** (2002) 421.
02Yin Yin, Q., Jacobsen, S.B:, Yamashita K., Blichert-Toft, J., Télouk, P., Albaréde F.: Nature **418** (2002) 949.
02Zin Zinner, E., Göpel, C.: Met. Planet. Sci. **37** (2002) 1001.
03Bog Bogard, D.D., Garrison, D.H.: Met. Planet. Sci. **38** (2003) 669.
03Eug Eugster, O.: Chem .d. Erde – Geochemistry **63** (2003) 3.
03Hal Halliday, A.N.: in: Treatise on Geochemistry (Holland, H.D., Turekian, K.K., eds.), Vol. 1, Meteorites, Comets, and Planets (Davis, A. M., ed.), Elsevier, Oxford (2003) 509.
03Hol Holland, H.D., Turekian, K.K.: Treatise on Geochemistry (2003) Elsevier, Oxford.
03Her Herzog, G.F.: in: Treatise on Geochemistry (Holland, H.D., Turekian, K.K., eds.), Vol. 1, Meteorites, Comets, and Planets (Davis, A.M., ed.), Elsevier, Oxford (2003) 347.
03Lun Lunine J.I.: in: Treatise on Geochemistry (Holland, H.D., Turekian, K.K., eds.), Vol. 1, Meteorites, Comets, and Planets (Davis, A.M., ed.), Elsevier, Oxford (2003) 431.
03McK McKeegan, K.D., Davis, A.M.: in: Treatise on Geochemistry (Holland, H.D., Turekian, K.K., eds.), Vol. 1, Meteorites, Comets, and Planets (Davis, A.M., ed.), Elsevier, Oxford (2003) 431.
03Nor Norman, M.D., Borg, L.E., Nyquist, L.E., Bogard, D.D.: Meteorit. Planet. Sci. **38** (2003) 645.
03Tac Tachibana, S., Huss, G.R.: Astrophys. J. **588** (2003) L41.
03Tri Trieloff, M., Jessberger, E.K., Herrwerth, I., Hopp, J., Fieni, C., Ghelis, M., Bourot-Denise, M., Pellas, P.: Nature **422** (2003) 502.

03Wad Wadhwa, M.: in: Treatise on Geochemistry (Holland, H.D., Turekian, K.K., eds.), Vol. 1, Meteorites, Comets, and Planets (Davis, A.M., ed.), Elsevier, Oxford (2003).
04Biz Bizzarro, M., Baker, J.A., Haack, H.: Nature **431** (2004) 275. Erratum Nature **435** (2005) 1280.
04Cie Ciesla, F.J., Lauretta, D.S., Hood, L.L.: Met. Planet. Sci. **39** (2004) 531.
04Cuz Cuzzi, J.N., Zahnle, K.R.: Astrophys. J. **614** (2004) 490.
04Gil Gilmour, J.D., Pravdivtseva, O.V., Busfield, A., Hohenberg, C.M.: Workshop on chondrites and the protoplanetary disk (2004) abstr. no. 9054.
04Hec Heck, P.R., Schmitz, B., Baur, H., Halliday, A.N., Wieler, R.: Nature **430** (2004) 323.
04Kit Kita, N.T., Huss, G.R., Tachibana, S., Amelin, Y., Zinner, E., Nyquist, L.E., Hutcheon, I.D.: Workshop on chondrites and the protoplanetary disk (2004) abstr. no. 9064.
04Kun Kunihiro, T., Rubin, A.E., McKeegan, K.D., Wasson, J.T.: Geochim. Cosmochim. Acta **68** (2004) 2947.
04Kur Kurahashi, E., Kita, N.T., Nagahara, H., Morishita, Y.: Lun. Planet. Sci. **35** (2004) abstr. no. 1476.
05Ame Amelin, Y., Ghosh, A., Rotenberg, E.: Geochim. Cosmochim. Acta **69** (2005) 505.
05Bak Baker, J., Bizzarro, M., Wittig, N., Connelly, J., Haack, H.: Nature **436** (2005) 1127.
05Biz Bizzarro, M., Baker, J.A., Haack, H., Lundgaard, K.L.: Astrophys. J. **632** (2005) L41.
05Bla Bland, P.A., Alard, O., Benedix, G.K., Kearsley, A.T., Menzies, O.N., Watt, L.E., Rogers, N.W.: Proc. Nat. Acad. Sci. **39** (2005) 13755.
05Bou Bouvier, A., Blichert-Toft, J., Vervoort, J.D., Albarède F.: Earth Planet. Sci. Lett. **240** (2005) 221.
05Cuz Cuzzi, J.N, Ciesla, F.J., Petaev, M.I., Krot A.N., Scott E.R.D., Weidenschilling S.: In: Chondrites and the Protoplanetary Disk (Krot, A.N., Scott, E.R.D., Reipurth, B., eds.) Astronomical Society of the Pacific, San Francisco, 2005, Vol. 341
05Dic Dickin A.P., 2005. Radiogenic Isotope Geology. Cambridge University Press, Cambridge.
05Hew Hewins, R.H., Connolly Jr., H.C., Lofgren, G.E., Libourel G.: In: Chondrites and the Protoplanetary Disk (Krot, A.N., Scott, E.R.D., Reipurth, B., eds.) Astronomical Society of the Pacific, San Francisco , 2005, Vol. 341, 286
05Hus Huss, G.R., Alexander, C.M.O'D., Palme, H., Bland, P.A., Wasson, J.T.: In: Chondrites and the Protoplanetary Disk (Krot, A.N., Scott, E.R.D., Reipurth, B., eds.) Astronomical Society of the Pacific, San Francisco, 2005, Vol. 341
05Kle1 Kleine, T., Mezger, K., Palme, H., Scherer, E., Münker, C.: Geochim. Cosmochim. Acta **69** (2005) 5805.
05Kle2 Kleine, T., Palme, H., Mezger, K., Halliday, A.N.: Science **310** (2005) 1671.
05Kro Krot, A.N., Amelin, Y., Cassen, P., Meibom, A.: Nature 436 (2005) 989.
05Pra Pravdivtseva, O.V., Hohenberg, C.M., Meshik, A.P.: Lun. Planet. Sci. **36** (2005) abstr. no. 2354.
05Tsi Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F.: Nature **435** (2005) 459.
05You Young, E., Simon, J.I., Galy, A., Russell, S.S., Tonui, E., Lovera, O.: Science **308** (2005) 223.
06Ame Amelin, Y., Wadhwa, M., Lugmair, G.: Lun. Planet. Sci. **XXXVII** (2006) abstract #1970.
06Cuz Cuzzi, J.N., Alexander, C.O.D.: Nature **441** (2006) 483.
06Ear Earth Impact Database 2006. http://www.unb.ca/passc/ImpactDatabase. Accessed on January 15th, 2009
06Hev Hevey, P.J., Sanders, I.S.: Meteorit. Planet. Sci. 41 (2006) 95.
06Mey Meyer, C.: Mars meteorite compendium (2006). http://curator.jsc.nasa.gov/curator/antmet/mmc/mmc.htm.
06Mun Mundil, R., Renne, P.R., Min, K., Ludwig, K.R.: Eos Trans. AGU 87, fall Meet. Suppl. (2006) Abstract V21A-0543.
06Sch Schersten, A., Elliott, T., Hawkesworth, C., Russell, S., Masarik, J.: Earth Planet. Sci. Lett. **241** (2006) 530.
06Sco Scott, E.R.D.: Icarus **185** *(2006) 72.*
06Thr Thrane, K., Bizzarro, M., Baker, J.A.: Astrophys. J. **646** (2006) L159.

06Tri Trieloff, M., Palme, H.: In Planet Formation – Theory, Observations, and Experiments (Klahr H., Brandner, W., eds.) Cambridge University Press, Cambridge (2006) 64.
07Biz Bizzarro, M, Ulfbeck, D., Trinquier, A., Thrane, K., Connelly, J.N., Meyer, B.S.: Science **316** (2007) 1178.
07Bli Blinova, A., Amelin, Y., Samson, C.: Meteorit. Planet. Sci. **42** (2007) 1337.
07Bou Bouvier, A., Blichert-Toft, J., Moynier, F., Vervoort, J.D., Albarède, F.: Geochim. Cosmochim. Acta **71** (2007) 1583.
07Joh Johansen, A., Oishi, J.S., Mac Low, M.-M., Klahr, H., Henning, T. Youdin, A.: Nature **448** (2007) 1022.
07Kor Korochantseva, E.V., Trieloff, M., Lorenz, C.A., Buykin, A.I., Ivanova, M., Schwarz, W.H., Hopp, J., Jessberger E.K.: Met. Planet. Sci. **42** (2007) 113.
07Kre Kretke, K.A., Lin, D.N.C.: Astrophys. J. **664** (2007) L55.
07Lis Lissauer, J.J., Stevenson, D.J.: In Protostars and Planets V (Reipurth B., Jewitt, D., Keil, K. eds.) University of Arizona Press, Tucson (2007) 591.
07Mar Markowski, A., Quitte, G., Kleine, T., Halliday, A.N., Bizzarro, M., Irving, A.J.: Earth Planet. Sci. Lett. **262** (2007) 214.
07Nag Nagashima, K., Krot, A.N., Chaussidon, M.: Met.Planet. Sci. **42** (2007) A529.
07Nim Nimmo, F., Kleine, T.: Icarus **191** (2007) 497.
07Rud Rudraswami, N.G., Goswami, J.N.: Earth Planet. Sci. Lett. **257** (2007) 231.
07San Sander, I.S., Scott, E.R.D.: Lun. Planet. Sci. **XXXVIII** (2007) 1910.
07Sch1 Schwarz, W.H., Trieloff, M.: Chem. Geol. **242** (2007) 218.
07Sch2 Schwarz W.H., Trieloff M.: 17th V.M. Goldschmidt Conference, Cologne, Germany. Suppl. Geochim. Cosmochim. Acta 71 (2007), A910.
07Sco *Scott, E.R.D.: Ann. Rev. Earth Planet. Sci.* **35** *(2007) 577.*
07Tou Touboul, M., Kleine, T., Bourdon, B., Palme, H., Wieler, R.: Nature **450** (2007) 1206.
08Ale Alexander, C.M.O'D., Grossman, J.N., Ebel, D.S., Ciesla F.J.: Science **320** (2008) 1617.
08All Allègre, C. J., Manhès, G., Göpel, C.: Earth Planet. Sci. Lett. **267** (2008) 386.
08Ame1 Amelin, Y.: Geochim. Cosmochim. Acta **72** (2008) 4874.
08Ame2 Amelin, Y.: Geochim. Cosmochim. Acta **72** (2008) 221.
08Ame3 Amelin, Y., Krot, A.: Met. Planet. Sci. **42** (2008) 1321.
08Blu Blum, J., Wurm, G.: Ann. Rev. Astron. Astrophys. **46** (2008) 21.
08Bou Bouvier, A., Blichert-Toft, J., Vervoort, J.D., Gillet, P., Albarède, F.: Earth Planet. Sci. Lett. **266** (2008) 105.
08Bur Burkhardt, C., Kleine, T., Bourdon, B., Palme, H., Zipfel, J., Friedrich, J.M., Ebel, D.S.: Geochim. Cosmochim. Acta **72** (2008) 6177.
08Con1 Connelly, J.N., Bizzarro, M., Thrane, K., Baker, J.A.: Geochim. Cosmochim. Acta **72** (2008) 4813.
08Con2 Connelly, J.N., Amelin, Y., Krot, A.N., Bizzarro, M.: Astrophys. J. Lett. **675** (2008) L121.
08Dau Dauphas, N., Cook, D.L., Sacarabany, A., Froehlich, C., Davis, A.M., Wadhwa, M., Pourmand, A., Rauscher, T., Gallino, R.: Astrophys. J. **686** (2008) 560.
08Hal Halliday, A.: Phil. Trans. R. Soc. Lond. A **366** (2008) 4163.
08Jac Jacobsen, B., Yin, Q., Moynier, F., Amelin, Y., Krot, A.N., Nagashima, K., Hutcheon, I.D., Palme, H.: Earth Planet. Sci. Lett. **272** (2008) 353.
08Kur Kurahashi, E., Kita, N.T., Nagahara, H., Morishita, Y.: Geochim. Cosmochim. Acta **72** (2008) A504.
08Nag Nagashima, K., Krot, A.N., Huss, G.R.: Lun. Planet. Sci. **XXXIX** (2008) abstr. no. 1391.
08Tri Trinquier, A., Birck, J.-L., Allegre, C.J., Göpel, C., Ulfbeck, D.: Geochim. Cosmochim. Acta **72** (2008) 5146.