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The age of the Solar System redefined by the oldest Pb–Pb age of a meteoritic inclusion

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The age of the Solar System can be defined as the time of formation of the first solid grains in the nebular disc surrounding the proto-Sun. This age is estimated by dating calcium–aluminium-rich inclusions in meteorites. These inclusions are considered as the earliest formed solids in the solar nebula. Their formation marks the beginning for several long- and short-lived radiogenic clocks that are used to precisely define the timescales of Solar System events, such as the formation and evolution of planetary bodies[1-3]. Here we present the ^{207}Pb–^{206}Pb isotope systematics in a calcium–aluminium-rich inclusion from the Northwest Africa 2364 CV3-group chondritic meteorite, which indicate that the inclusion formed 4,568.2 million years ago. This age is between 0.3 (refs 4, 5) and 1.9 (refs 1,6) million years older than previous estimates and is the oldest age obtained for any Solar System object so far. We also determined the ^{26}Al–^{26}Mg model age of this inclusion, and find that it is identical to its absolute Pb–Pb age, implying that the short-lived radionuclide ^{26}Al was homogeneously distributed in the nebular disc surrounding the proto-Sun. From the consistently old ages in the studied inclusion, we conclude that the proto-Sun and the nebular disc formed earlier than previously thought.

High-resolution timescales of early Solar System processes such as planetary accretion and differentiation rely on precise, accurate and consistent ages obtained with the absolute long-lived ^{207}Pb–^{206}Pb chronometer, based on the decay of ^{235}U–^{207}Pb (half-life of ∼704 Myr) and ^{238}U–^{206}Pb (half-life of ∼4.47 Gyr), and relatively short-lived (now extinct) chronometers such as ^{26}Al–^{26}Mg (half-life ∼0.73 Myr), ^{53}Mn–^{53}Cr (half-life ∼3.7 Myr) and ^{182}Hf–^{182}W (half-life ∼8.9 Myr). In recent years, advances in analytical techniques, particularly improvements in the precision of mass spectrometric analyses, have enabled sub-Myr precision on the ages obtained from these high-resolution chronometers, but have also revealed inconsistencies between these ages[2,7]. In particular, there are inconsistencies in the ages of calcium–aluminium-rich inclusions (CAIs) as determined by different high-resolution absolute and relative chronometers[6]. These submillimetre-to-centimetre-sized inclusions are believed to have formed by condensation at high temperature in the protoplanetary disc (that is, unmelted CAIs), and some later experienced one or more brief episodes of partial or complete melting (for example igneous type B CAIs; ref. 8). As such, CAIs are among the earliest solids to form in the solar nebula[8], and therefore their absolute ages can be used to define the time of formation of the Solar System. Current estimates of the high-precision Pb–Pb ages for type B CAIs from the CV3 chondrites Allende and Efremovka range from 4,567.11 ± 0.16 Myr (refs 1,6) to 4,568.5 ± 0.5 Myr (ref. 9), with internal isochrons for individual CAIs from these meteorites defining ages strictly in the range of 4,567.1–4,567.6 Myr (refs 1,4–6). This range of CAI ages is inconsistent with the short time interval of less than a few tens of thousands of years for CAI formation estimated from ^{26}Al–^{26}Mg isotope systematics[5,10,11]. Analytical methodologies involved in Pb–Pb dating (in particular, differences in the types of mass spectrometer and in the chemical treatments) are unlikely to be the source of the apparent range in the Pb–Pb ages reported for CAIs because (1) Pb isotope analyses using double-spike and Tl-doping methods measured by multicollector inductively coupled plasma mass spectrometer in various institutions, including our instrument at Arizona State University (ASU), are comparable in precision and accuracy to those obtained by thermo-ionization mass spectrometer[12] and (2) we have previously tested various leaching protocols on different fractions of an Allende type-B CAI and have excluded the possibility of leaching-induced Pb isotope fractionations[4].

Recently, it was argued that CAI Pb–Pb isochron dates based on the most radiogenic analyses spanned a relatively narrow range from ∼4,567.1 to 4,567.6 Myr, whereas older dates based on less radiogenic data are likely to have been affected by a systematic error[6]. As such, it was suggested that the younger Pb–Pb ages of ∼4,567 Myr reflect the true formation age of CAIs and time of Solar System formation. Nevertheless, all CAIs for which Pb–Pb ages have been obtained thus far have been from the Allende and Efremovka CV3 chondrites. It is well recognized that these two meteorites have undergone extensive secondary processing on their parent bodies[13,14], which may have affected the U–Pb isotope systematics in their CAIs.

With the goal of obtaining better constraints on the age of the Solar System and clarifying the possible causes of the apparent discrepancies between high-resolution absolute and relative chronometers, we have investigated the ^{207}Pb–^{206}Pb and ^{26}Al–^{26}Mg isotope systematics in bulk fragments and mineral separates of a type-B CAI from the CV3 chondrite Northwest Africa (NWA) 2364 (hereafter referred to as CAI 2364-B1; see Supplementary Information for sample description).

The Pb isotopic compositions of the acid washes from seven leaching steps (L_1–L_7) and final residues (R) obtained from two bulk (interior and rim) and two mineral fractions (interior) of CAI 2364-1 were measured by multicollector inductively coupled plasma mass spectrometer at ASU (see Supplementary Information for further analytical details, figures and data tables). The measured ^{206}Pb/^{204}Pb ratios, corrected for blank contributions, range from 48 to 11,061 for the acid washes (called leachates hereafter), and from 1,069 to 5,394 for the residues remaining after the acid-washing protocol (Table 1 and Supplementary Table S1).

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Table 1 | Pb–Pb isotope data and Canyon Diablo Troilite (CDT) model ages of the last leachates (L$_7$) and corresponding residues of the three interior fractions (no.s 1–3) from the 2364-B1 CAI.

Samples	Mass (g)	Total Pb (ng)	^{206}Pb/^{204}Pb mass bias corrected	^{206}Pb/^{204}Pb blank corrected	^{206}Pb/^{204}Pb correlated error (%)	^{207}Pb/^{206}Pb blank corrected	^{207}Pb/^{206}Pb correlated error (%)	Sample/blank ^{206}Pb	Sample/blank ^{204}Pb	CDT model age (Myr)	±Myr
No. 1: Bulk fraction, interior	0.142										
Leachate 7		2.3	5,830.6	9,758.9	16.1	0.625960	0.020	991	2	4,567.92	0.31
Residue	0.043	6.5	6,547.7	7,525.9	9.17	0.626219	0.018	1,337	2	4,568.21	0.30
No. 2: Pyroxene (fassaite)-rich fraction, 63–100 μm	0.033										
Leachate 7		1.5	10,183	11,061	3.47	0.625947	0.011	6,806	9	4,568.02	0.29
Residue	0.026	3.6	5,245.1	5,393.8	1.04	0.626393	0.006	10,229	25	4,568.07	0.29
No. 3: Melilite–anorthite-rich fraction, 63–100 μm	0.048										
Leachate 7		2.3	959.15	966.70	0.42	0.629628	0.014	6,494	86	4,566.75	0.29
Residue	0.019	3.3	1,880.4	1,900.9	0.42	0.627557	0.011	9,557	64	4,567.23	0.29
Procedural blank ($n=2$)				19.3	9.5	0.836	2.86				
Standards				^{206}Pb/^{204}Pb	%2SE	^{207}Pb/^{206}Pb	%2SE	*n*			
NBS SRM 981 (2 ppb Pb–1 ppb Tl; Mass bias corrected by Tl doping and standard bracketing with NBS SRM 981)			Session 1 Session 2 Session 3	16.943 16.939 16.940	0.094 0.089 0.056	0.91476 0.91477 0.91463	0.010 0.020 0.023	13 8 12			
NBS SRM 981 recommended values				16.937	0.063	0.91464	0.036				
NBS SRM 983 (2 ppb Pb–1 ppb Tl; Mass bias corrected by Tl doping and standard bracketing with NBS SRM 981)			Session 1 Session 2 Session 3	2,709 2,711 2,795	1.99 7.57 1.33	0.07139 0.07119 0.07122	0.062 0.040 0.069	6 3 6			
NBS SRM 983 recommended values				2,695	5.39	0.07120	0.056				

Also presented here are the Pb isotope compositions of the procedural blank (used for correction of the blank contribution), and NBS SRM 981 and 983 Pb standards (used for assessing the accuracy and reproducibility of the measured Pb isotope ratios in the samples) that were analysed during the course of this study; isotope compositions recommended for the NBS SRM 981 and 983 Pb standards are shown for comparison. For the model ages shown here, we assumed the Pb isotope composition of CDT (ref. 30) as the initial composition and ^{238}U/^{235}U = 137.84 (ref. 15). See further details in Supplementary Information.

These extremely high ^{206}Pb/^{204}Pb ratios indicate that our leaching protocol effectively removed any terrestrial Pb that might have contaminated the meteorite during its residence in the Saharan desert (Supplementary Fig. S4). The Pb isotopic compositions of the residue and leachates from the rim fraction are discordant with the compositions of the last leachates and residues of the three interior fractions (Fig. 1a), which is reflected by their younger model ages (Supplementary Table S1). This attests to the presence of a common Pb component in the rim fraction, which may be attributed to a contribution of Pb from the matrix (Supplementary Fig. S1). When we consider only the residues and corresponding last leachates (L$_7$) of the three interior fractions (bulk and two mineral separates), with highly radiogenic ^{206}Pb/^{204}Pb ratios > 950, we obtain an internal Pb–Pb isochron age of 4,568.67 ± 0.17 Myr (2σ, mean square weighted deviation (MSWD) $= 1.4$), assuming the conventionally used value for the ^{238}U/^{235}U ratio for natural U of 137.88. Recently, precise analyses of the ^{238}U/^{235}U ratio of the NBS SRM 950a and 960 standards in multiple laboratories have

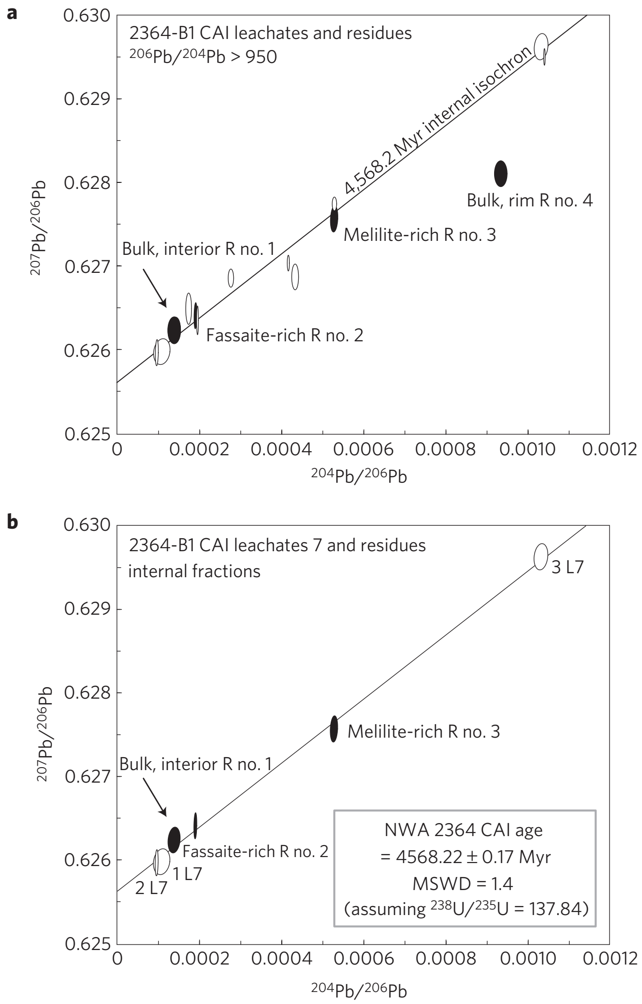

Figure 1 | ^{207}Pb/^{206}Pb versus ^{204}Pb/^{206}Pb in bulk and mineral fractions (residues and leachates with ^{206}Pb/^{204}Pb > 950) of the type-B CAI 2364-B1. a, Residues (R; filled symbols) and the last three leachates (L_5, L_6 and L_7; open symbols) of bulk and mineral fractions of the interior (no.s 1–3) and rim (no. 4) of the CAI 2364-B1. The black line is the Pb–Pb internal isochron shown in Fig. 1b. **b**, The Pb–Pb internal isochron based on R and L_7 from the three interior fractions of 2364-B1 gives an absolute age of $4{,}568.2^{+0.2}_{-0.4}$ Myr (where the uncertainty includes the possibility of deviation of the ^{238}U/^{235}U ratio of this CAI from the value of 137.84 (ref. 15) based on its measured Th/U ratio). Error ellipses are $\pm 2\sigma$. See Supplementary Information for details.

demonstrated that this value for natural U standards is actually somewhat lower at 137.837 ± 0.015 (ref. 15). If the revised value of 137.84 for the natural U isotopic composition is used for the Pb–Pb age calculation as recommended[15], the Pb–Pb isochron age of the 2364-B1 CAI is 4,568.22 ± 0.17 Myr (Fig. 1b; Table 1).

The nine unleached bulk and mineral fractions of the CAI 2364-B1 that were analysed for Al–Mg isotope systematics have a narrow range of ^{27}Al/^{24}Mg ratios (2.30–4.22) (Fig. 2). The radiogenic ^{26}Mg excesses (δ^{26}Mg*) in these fractions range from +0.82‰ to +1.52‰ (Supplementary Table S2). The Al–Mg internal isochron yields an initial ^{26}Al/^{27}Al ratio of 5.03 (±0.26) × 10^{-5}, and an initial δ^{26}Mg* of 0.02 ± 0.06‰ (2σ, MSWD = 1.2) (Fig. 2). This is consistent with the canonical ^{26}Al/^{27}Al value of 5.2 (±0.2) × 10^{-5} found for most CAIs (refs 5,8), and indicates that the duration of the high-temperature event that equilibrated Mg isotopes in the CAI 2364-B1 was at most ~110,000 yr and that the Al–Mg system has subsequently remained undisturbed in this inclusion. We do not find any evidence for supercanonical values such as those reported previously by several workers[10,11,16].

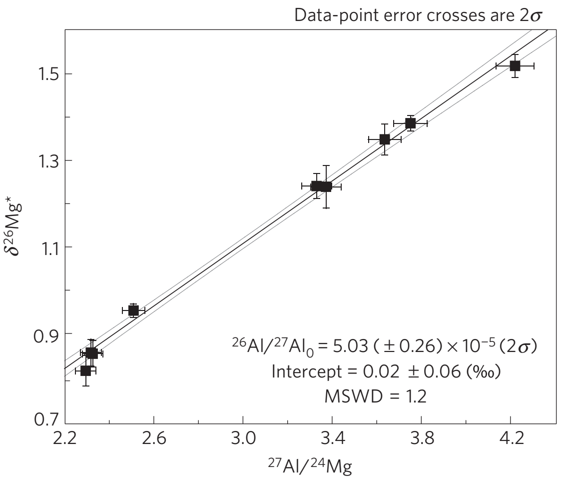

Figure 2 | Al–Mg isotope systematics in bulk and mineral fractions of the type-B CAI 2364-B1. The slope of the best-fit line (black) corresponds to an initial ^{26}Al/^{27}Al ratio of 5.03 (±0.26) × 10^{-5} (MSWD = 1.2). The error envelope on the isochron regression is shown as the grey lines. Errors on the Mg isotope ratios are ±2SE, and errors on the ^{27}Al/^{24}Mg ratios are ±2% (2SD; see Al–Mg isotopic data in Supplementary Information).

The Pb–Pb internal isochron age of the CAI 2364-B1 is 1.1 ± 0.4 Myr older than those of Allende type-B CAIs (refs 4,5), and 1.6 ± 0.3 Myr older than that of the E60 type-B CAI (refs 1,6) (regardless of whether a value of 137.88 or 137.84 is assumed for the U isotopic composition for the Pb–Pb age calculations) (Fig. 3). This range in Pb–Pb ages is inconsistent with the Al–Mg systematics in these CAIs (refs 1,5,6,10,11), and possible explanations include secondary U–Pb isotopic disturbance and variations in the U isotopic compositions of CAIs. The secondary alteration scenario would require that while the U–Pb systematics in the Allende and Efremovka CAIs underwent disturbance their Al–Mg systematics were variably affected (for example, in the Efremovka CAI E60, ref. 17, or in Allende CAIs, refs 4,5), implying that in CAI phases diffusive equilibration of Pb may have occurred more readily than that of Mg. Considering factors such as grain sizes and cooling rates at the initial temperatures, experimental investigations of the diffusion of Pb in pyroxenes[18] and Mg in melilite and anorthite[19,20] suggest that this could be a feasible explanation.

Recent work has shown that ^{238}U/^{235}U ratios in Allende CAIs vary by as much as −3.5‰ relative to the NBS SRM 950 U standard and correlate with Th/U and Nd/U ratios, indicating the presence of live ^{247}Cm in the early Solar System[21]. The U isotope compositions or trace element (that is, U, Th, Nd) abundances have not been reported for CAIs for which Pb–Pb internal isochron ages have been determined previously[1,4–6]. To assess whether the CAI 2364-B1 may have a ^{238}U/^{235}U ratio that deviates significantly from the assumed value for natural U (previously assumed to be 137.88, but recently revised to 137.84; ref. 15), in which case the Pb–Pb age determined here would require a correction), we have measured the Th/U ratios in aliquots from unleached mineral separates and bulk fractions. The Th/U ratios in these mineral separates and bulk fractions range from 1.1 to 2.8 (±10%, 2SD) (Supplementary Table S2). From the correlation (and including the uncertainties) of the Th/U ratios with the ^{238}U/^{235}U ratios in Allende CAIs (ref. 21), we can infer from the range of Th/U ratios in the CAI 2364-B1 fractions a possible value of ^{238}U/^{235}U of 137.81–137.83 (Supplementary Fig. S5). This implies that the Pb–Pb age of this CAI may be up to 0.3 Myr younger than the isochron date calculated with the assumption of a ^{238}U/^{235}U ratio

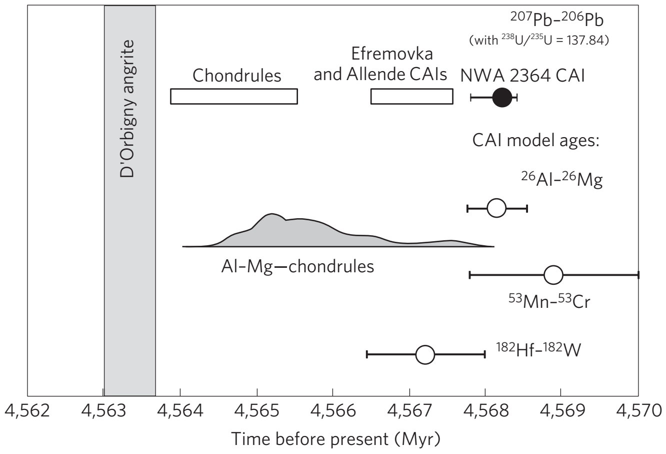

Figure 3 | Comparison of absolute internal Pb–Pb ages of CAIs with the Al–Mg, Hf–W and Mn–Cr model ages for CAIs anchored on the isotope systematics of the D'Orbigny angrite. The Pb–Pb age and Al–Mg model age for CAI 2364-B1 (this study), and Mn–Cr and Hf–W model ages for CAIs (based on previous studies), calculated relative to the D'Orbigny angrite (vertical grey band; see Supplementary Table S3 for parameters used for calculations of the model ages, with their associated errors, and corresponding references). For comparison and consistency, we show the range of Pb–Pb internal isochron ages for CAIs from Allende and Efremovka CV chondrites[1,4–6] and the range of Pb–Pb ages for chondrules from the CR and CV chondrites[1,26] after recalculating the ages assuming ^{238}U/^{235}U = 137.84 (ref. 15). Also shown here is the range and the relative frequency of Al–Mg ages of chondrules from carbonaceous and ordinary chondrites[28].

of 137.84 (ref. 15). Therefore, taking this source of uncertainty into consideration, the age of CAI 2364-B1 is $4{,}568.2^{+0.2}_{-0.4}$ Myr. This age is the oldest high-precision Pb–Pb internal isochron date obtained thus far for any Solar System object and is between 0.3 and 1.9 Myr older (including uncertainties on all the respective Pb–Pb isochron ages) than the internal Pb–Pb isochron ages obtained for other individual CAIs from Efremovka and Allende[1,4–6] (after the latter are also corrected for the recently revised isotopic composition for natural U standards[15], which corresponds to an age adjustment of −0.45 Myr for all of these objects) (Fig. 3). The Pb–Pb age of the CAI 2364-B1 is thus the oldest absolute age yet obtained for any Solar System material and is, therefore, the best estimate for the time of formation of the Solar System, defined here as the formation of the first solid grains in the Solar protoplanetary disc.

Using the Al–Mg and Pb–Pb isotope systematics of the D'Orbigny angrite as an anchor, we can calculate an Al–Mg model age for CAI 2364-B1. With an absolute Pb–Pb age of 4,563.36 ± 0.34 Myr (refs 15,22) (corrected for the measured U isotopic composition in D'Orbigny pyroxenes; see Supplementary Table S3 for further details), and a corresponding initial ^{26}Al/^{27}Al of 5.06 (±0.92) × 10^{-7} (ref. 23) for D'Orbigny, we obtain an Al–Mg model age of 4,568.14 ± 0.38 Myr for CAI 2364-B1 (Fig. 3). The Pb–Pb absolute age reported here for CAI 2364-B1 is thus consistent with its Al–Mg model age, as well as with the ^{53}Mn–^{53}Cr and ^{182}Hf–^{182}W models ages for Solar System formation (Fig. 3, and Supplementary Table S3). In contrast, the absolute Pb–Pb internal isochron ages determined previously for CAIs from Allende and Efremovka[1,4–6] are not concordant with their Al–Mg model ages relative to the D'Orbigny anchor. As discussed earlier, this may reflect disturbance of the isotope systematics in the CAIs from these two meteorites by secondary processing[14,17]. The consistency between absolute and relative chronologies in CAI 2364-B1 indicates that the short-lived parent radionuclides were homogenously distributed in the solar protoplanetary disc, including the CAI formation region. This in turn favours a stellar nucleosynthetic source for these radionuclides rather than local irradiation within the solar nebula.

In addition to CAIs, chondrules are the other significant chondritic components that were formed in the solar nebula. The formation time interval between CAIs and chondrules is important to constrain because it has implications for the lifetime of the solar protoplanetary disc as well as for the initial abundance of ^{60}Fe in the early Solar System. The latter is significant because ^{60}Fe can only be efficiently produced during stellar nucleosynthesis and has the potential to serve as a prominent heat source for melting and differentiation in the early Solar System; its initial abundance is difficult to assess through direct measurements of Fe–Ni systematics in CAIs owing to complicating factors such as secondary alteration effects and the presence of nucleosynthetic anomalies in the isotopes of the daughter element[24], but may be inferred on the basis of Fe–Ni systematics in chondrules and the formation interval between these objects and CAIs (ref. 25). Thus far, high-precision Pb–Pb ages have been reported for chondrules from the CV chondrite Allende[26], the CR chondrite Acfer 059 (ref. 1) and the CB chondrite Gujba[27]. With the exception of the Gujba chondrules, which were formed relatively late as a result of a giant impact between planetary embryos after the dust in the protoplanetary disc was dissipated[27], these Pb–Pb ages of chondrules are, on average, 2.3 ± 0.9 Myr younger than those of Allende and Efremovka CAIs. The older age for CAI 2364-B1 reported here increases this average time difference between CAI and chondrule formation to 3.2 ± 0.8 Myr (for the sake of consistency, all ages shown in this figure have been recalculated assuming ^{238}U/^{235}U = 137.84; ref. 15; Fig. 3). This is towards the longer end of the time interval of chondrule formation events (that is, ∼1.2 to ∼4 Myr after CAI formation) as recently deduced from high-precision Al–Mg systematics in chondrules from carbonaceous and ordinary chondrites[28]. This raises the question of chondrule storage in the solar nebula over an extended period of ∼3–4 Myr after CAI formation before their accretion into meteorite parent bodies, which may be addressed by turbulence in the solar nebula[29]. Furthermore, this longer time interval yields an initial ^{60}Fe/^{56}Fe ratio that is up to a factor of ∼2 higher than that estimated on the basis of the previously assumed time interval of ∼1.5–2.0 Myr (ref. 25). Therefore, the older age for the Solar System reported here reinforces the likelihood of ^{60}Fe being injected into the solar nebula by a nearby supernova and highlights its significance as a heat source for planetesimal differentiation in the early Solar System.

Methods summary

Fragments of a type-B CAI (∼500 mg), hereafter referred to as 2364-B1 (Supplementary Figs S1 and S2), from the NWA 2364 CV3 chondrite were carefully selected for the Pb–Pb and Al–Mg isotopic investigations. For the Pb–Pb isotope work, two bulk fractions (from the interior and rim portions of the CAI, respectively) were crushed separately in an agate mortar, and two mineral separates from the interior (melilite–anorthite rich and fassaite rich, respectively) were obtained from the 30–63 μm size fraction by density separation (using methylene iodide; $d \sim 3.25$). Bulk and mineral fractions were acid-washed using leaching protocols that are described in detail in Supplementary Information. Leachates were dried down and, along with the residues, were fully dissolved in 29 M HF + 16 M HNO_3 (5:1) at 130 °C in PFA Savillex beakers. The Pb from these solutions was separated using anion exchange column chemistry. For the Al–Mg work, portions from the three interior fractions (one bulk and two mineral separates) on which we also carried out Pb–Pb work were used; six further fractions were prepared by density separation, using methylene iodide and bromoform ($d \sim 2.9$). All fractions were thoroughly rinsed using acetone, following by hand picking under the binocular microscope. Fractions were processed for Al–Mg dating using analytical techniques similar to those described previously[23]. The Al/Mg ratios, and Mg and Pb isotope compositions, were measured using a Thermo-Finnigan Neptune multicollector inductively coupled plasma mass spectrometer at Arizona State University. See Supplementary Information for further details about the chemical procedures, mass spectrometry, blank and mass bias corrections and age calculations.

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Author contributions

A.B. and M.W. planned the project. A.B. carried out the analytical work during her post-doctoral appointment. Both authors discussed the results and contributed to the writing of this manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to A.B.