A 4,565-My-old andesite from an extinct chondritic protoplanet

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Abstract

The age of iron meteorites implies that accretion of protoplanets began during the first millions of years of the solar system. Due to the heat generated by $^{26}$Al decay, many early protoplanets were fully differentiated with an igneous crust produced during the cooling of a magma ocean and the segregation at depth of a metallic core. The formation and nature of the primordial crust generated during the early stages of melting is poorly understood, due in part to the scarcity of available samples. The newly discovered meteorite Erg Chech 002 (EC 002) originates from one such primitive igneous crust and has an andesite bulk composition. It derives from the partial melting of a noncarbonaceous chondritic reservoir, with no depletion in alkalis relative to the Sun. The partial melting began during the first millions of years of the solar system. Due to the scarcity of samples, here, we describe the oldest andesitic magmatism.

Results

Petrography. EC 002 is an unbrecciated greenish rock with a medium-grained groundmass (grain size in the order of 1 to 1.5 mm) with 8 vol% pores. Its texture suggests a crystallization within a thick flow or in a shallow intrusion (Fig. 1). It consists of 45 vol% of lath-shaped albite feldspar (plagioclase and possibly anorthoclase) containing lamellae of K-feldspar, 38 vol% of anhedral pyroxene (ca. 0.6 × 3.7 mm), 5 vol% interstitial silica minerals (cristobalite and tridymite) identified by Raman spectroscopy [SI Appendix, Figs. S1 and S2] with no quartz, and minor spinel, ilmenite, Ca-phosphate, troilite, and FeNi metal. The samples we have examined are rather fresh, with only a few rust patches produced by the alteration of troilite and metal and some carbonate fillings in the fractures, which are typical of Saharan finds (13). Pyroxenes are partly equilibrated and consist of relict augite with fine, closely spaced (~1 μm thick) exsolution lamellae of low-Ca pyroxene, or relict low-Ca pyroxene with fine exsolution lamellae of augite. In addition, EC 002 also contains angular to rounded pyroxene and olivine xenocrysts, irregularly dispersed in the groundmass (Figs. 1 and 2) and reaching several centimeters [up to 9 cm (14)]. They are generally mantled by fine-grained groundmass pyroxenes. EC 002 is slightly shocked. Feldspar and pyroxene show only moderate mottled extinction. Some feldspar grains have fine polysynthetic twinning. Fractures in these minerals are not prominent. The shock stage is M-S2 (15).

Significance

The crusts of the oldest protoplanets are virtually unknown due to the scarcity of samples. Here, we describe the oldest known lava that crystallized ca. 4,565 Ma ago and formed by partial melting of a chondritic parent body. $^{26}$Al-$^{26}$Mg systematics suggest that the elapsed time between melting and crystallization was significant, on the order of several $10^5$ y, probably due to the viscosity of the magma. Although the first protoplanetary crusts were frequently not basaltic, their remnants are not detected in the asteroid belt because their parent bodies served as the building blocks for larger rocky bodies or were nearly totally destroyed.

Author contributions: J.-A.B. designed research; and J.-A.B., M.C., A.Y., P.B., J.V., D.J.B., M.W.B., and B.M. performed research, analyzed data, and wrote the paper. The authors declare no competing interest.

This article is a PNAS Direct Submission.

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Published March 8, 2021.
Phase Compositions. Bulk groundmass pyroxene compositions are generally augitic (Wo27.7-33.0En36.9-38.5Fs30.1-31.0) (SI Appendix, Figs. S3–S7 and Tables S1–S4). Some crystals exhibit remnant zoning from core to rim (Wo22.9En39.4Fs37.7 to Wo35.2En36.3Fs28.5). The crystals are partly equilibrated and are a mixture of augite (Wo38.7-40.9En39.5-41.5Fs18.8-20.7) and fine exsolutions of low-Ca pyroxene (Wo2.4-4.3 En47.1-49.4 Fs47.3-49.3). Feldspars are albitic (Or2.0-7.1Ab75.8-87.4An6.7-21.6) and contain lamellae of K-rich feldspar (Or84.0-84.4 Ab11.3-11.6 An4.3-4.4). Groundmass spinel compositions are Usp18.2-56.5 Sp2.6-6.2 Cm94.2-96.5 and Mg# [100 x Mg/(Mg+Fe)], atomic = 3.51 to 5.83 with no Zn (<0.02 wt%). Silica phases contain detectable amounts of Al, Fe, Ca, and alkalis (Al2O3 = 1.8 to 2.7 wt%; K2O < 0.5 wt%; Na2O = 0.7 to 1.4 wt%; CaO = 0.03 to 0.15 wt%; and FeO < 0.3 wt%).

We analyzed two xenocrysts: fragments of a 1-cm-long olivine megacryst and a small pyroxene. The olivine is forsteritic (Fo88, FeO/MnO = 24.2 wt%/wt%), Ca rich (CaO = 1.3 wt%), and poor in Ni (1.3 μg/g) and Co (10.2 μg/g). Its light rare earth element (REE) and alkali abundances are much higher than expected (La = 11.7 ng/g, K = 102 μg/g, Rb = 4.9 μg/g, and Cs = 0.28 μg/g) and could reflect the presence of melt inclusions. The small pyroxene is a low-Ca pyroxene (Fig. 2). It displays a chemically homogeneous core (Wo4.5) with zoned rims, mantled by groundmass pyroxenes.

The cores have relatively high Cr2O3 (~0.5 wt%) and Al2O3 (~0.3 wt%) and low TiO2 contents (~0.1 wt%) compared to low-Ca pyroxene in the groundmass. The FeO/MnO ratios of the xenocryst core (21.1 wt%/wt%) are identical to those of the low-Ca pyroxene in the rims and in groundmass (~20 to 21 wt%/wt%). Pyroxenes surrounding the crystal are more magnesian than those in the groundmass. Spinel grains found inside this xenocryst are more Cr and Al rich than those found in the groundmass (Usp0.9 to 2.8, Sp12.4 to 17.3, Cm84.3 to 88.1 and Mg# = 11.9 to 15.7).

These olivine or pyroxene xenocrysts could be debris from the nascent mantle of the protoplanet (melting residues) or crystals formed from previous magmas. A definitive answer cannot be given with the study of only two crystals. Note that the largest pyroxene xenocrysts reach 9 cm (14) and are certainly not “mantle like.” Similar FeO/MnO ratio and Δ17O (14) suggest they are more likely derived from the crystallization of associated magma(s) more magnesian than EC 002.
**Geochemistry.** We crushed a 1.1-g sample devoid of apparent xenocrysts, representative of the groundmass, and therefore very close to the melt from which EC 002 crystallized. With 58 wt% SiO$_2$ and 4.54 wt% of Na$_2$O+K$_2$O (Fig. 3 and SI Appendix, Table S4), it is andesitic according to the International Union of Geological Sciences criteria (18). The rock is quite rich in MgO and FeO. Its CIW norm indicates proportions of pyroxenes and plagioclase in accordance with modal estimates (53 wt% pyroxene and 40.5 wt% plagioclase [i.e., about 47 vol% pyroxene and 47 vol% plagioclase taking into account the mineral densities]. The calculation also shows some normative quartz (2.5 wt%), indicating a rock slightly oversaturated in SiO$_2$. EC 002 is very poor in P (216 μg/g), Ni (18.5 μg/g), Co (5.85 μg/g), Cu (1.4 μg/g), Pb (90 ng/g), W (22 ng/g), Ga (2.6 μg/g), and Zn (0.44 μg/g). EC 002 displays some excesses in Ba, Sr, and U, which are usual for Saharan finds (e.g., ref. 19) and will not be further discussed. Other incompatible trace element abundances (e.g., REE, Th, etc.) are low and of the order of 5 or 6 times the chondritic reference. Indeed, the CI-normalized trace element pattern of EC 002 is rather flat with no noticeable anomaly, even for high field strength elements and alkalis (Fig. 4). This rock is only slightly light REE depleted (Lan/Smn = 0.973) as noncarbonaceous (NC) chondrites (Tm/Tm* < 1 and typically 0.97 to 0.98) and achondrites and inner solar system planetary bodies [Vesta, Mars, Moon, and Earth, with average Tm/Tm* typically ~0.975 (21)].

The chemical composition of EC 002 is very different from that of other andesitic achondrites. It is, for example, much richer in alkalis than NWA 11119, without reaching the concentrations of ALM-A or GRA 06 (Fig. 3). The smoothness of its trace element pattern (Fig. 4), parallel to that of NC chondrites even for alkalis, also distinguishes it from the other known achondritic lavas.

**26Al–26Mg Systematics.** A total of 19 feldspar grains and 11 pyroxenes were analyzed (SI Appendix, Tables S5 and S6). The pyroxenes are characterized by very low $^{26}$Al/$^{24}$Mg ratios ranging from 0.018 to 0.06 and homogeneous (within their typical ±0.15‰)

$$\delta^{26}\text{Mg}^* = \left(\frac{^{26}\text{Mg}^{*}}{^{24}\text{Mg}}\right)_{\text{sample}} / \left(\frac{^{26}\text{Mg}^{*}}{^{24}\text{Mg}}\right)_{\text{CI}} - 1 \times 10^3$$

where $^{26}\text{Mg}^*$ is the radiogenic $^{26}\text{Mg}$ isotopic signature. The data suggest that the parent melt of EC002 was efficiently degassed prior to crystallization. After correction for cosmogenic $^{36}\text{Ar}$, trapped $^{36}\text{Ar}$ isotopes, with concordant $^3\text{He}$ and $^{21}\text{Ne}$ exposure ages of 26.0 ± 1.6 Myr and 25.6 ± 1.0 Myr, respectively. The bulk $^{40}\text{Ar}/^{39}\text{Ar}$ ratio (5.52 ± 0.42) is strongly enriched in radiogenic $^{40}\text{Ar}$ from the decay of $^{40}\text{K}$. The $^{40}\text{Ar}$ abundance corresponds to a K-Ar age of 4534 ± 117 Myr, within uncertainty of the closure age for the $^{26}\text{Al–26}\text{Mg}$ system. This indicates that Ar has been effectively retained within EC 002 since shortly after formation, precluding significant thermal events and implying a relatively early breakup of the parent body. Furthermore, the absence of significant trapped “planetary” noble gas components suggests that the parent melt of EC 002 was efficiently degassed prior to crystallization. After correction for cosmogenic $^{40}\text{Ar}$, trapped $^{36}\text{Ar}$ abundance is only 4.3 × 10^-17 mol · g^-1, which is more than an order of magnitude lower than typical achondrite abundances (25).

**Noble Gas Isotope Composition.** Abundances and isotope ratios of He, Ne, and Ar were analyzed by step heating (SI Appendix, Table S7). Isotope ratios of He and Ne are strongly enriched in cosmogenic isotopes, with concordant $^3\text{He}$ and $^{21}\text{Ne}$ exposure ages of 26.0 ± 1.6 Myr and 25.6 ± 1.0 Myr, respectively. The bulk $^{40}\text{Ar}/^{39}\text{Ar}$ ratio (5.52 ± 0.42) is strongly enriched in radiogenic $^{40}\text{Ar}$ from the decay of $^{40}\text{K}$. The $^{40}\text{Ar}$ abundance corresponds to a K-Ar age of 4534 ± 117 Myr, within uncertainty of the closure age for the $^{26}\text{Al–26}\text{Mg}$ system. This indicates that Ar has been effectively retained within EC 002 since shortly after formation, precluding significant thermal events and implying a relatively early breakup of the parent body. Furthermore, the absence of significant trapped “planetary” noble gas components suggests that the parent melt of EC 002 was efficiently degassed prior to crystallization. After correction for cosmogenic $^{40}\text{Ar}$, trapped $^{36}\text{Ar}$ abundance is only 4.3 × 10^-17 mol · g^-1, which is more than an order of magnitude lower than typical achondrite abundances (25).

**Spectroscopy.** Reflectance spectra of EC 002 reveal the presence of two strong absorptions related to Ca-rich pyroxene. This spectral signature does not correspond to any known asteroid spectral type.
elements. For example, its K/Th ratio (Fig. 4) in the sense that it is not depleted in volatile bodies of iron meteorites (26). The oldest igneous rock previously contemporaneous with the formation of the cores of the parent body of the angrites, which are important additional constraints are brought by silica polymorphs (such as phosphates or plagioclase) would be exhausted in the source after ~17% partial melting (12, 31). Indeed, the trace element pattern of EC 002 fits with an enrichment of andesitic magmas rich in SiO₂ and alkalis (10–12). However, the major element composition of EC 002 lies at the high-melting end of the experimental melting trends defined for ordinary H or LL chondrites (Fig. 3 and SI Appendix, Fig. S8). These trends indicate that melts with the same composition as EC 002 are obtained after plagioclase exhaustion for high degrees of melting (F) of around 25% (SI Appendix, Fig. S9). Such high melting rates would also explain the unfracti onated trace element pattern of EC 002 (Fig. 4) since high crystallization coefficients (such as phosphates or plagioclase) would be exhausted in the source after ~17% partial melting (12, 31). In this way, the trace element pattern of EC 002 fits with an enrich ment by a factor of ~1/F of a typical NC chondrite composition (Fig. 4), in perfect agreement with the experimental data. The thermal history of EC 002 appears quite straightforward. Experimental data allow a precise evaluation of the temperature at which the magma formed (SI Appendix, Fig. S10). The MgO of EC 002 gives an estimated melting temperature of 1,224 ± 20 °C. This high temperature is confirmed by the crystallization temperatures estimated from the bulk compositions of Ca-rich pyroxene (32) in the range of 1,149 to 1,229 °C (average = 1,186 °C [SD =25 °C], slightly lower due to postcrystallization equilibration during cooling). The final equilibration temperature, about 957 °C, is estimated from the highest Ca concentration in pyroxene (32). The MgO of EC 002 is consistent with this interpretation. It is similar to that of some ungrouped basaltic (NC) achondrites such as Bunburra Rockhole, Asuka 881394, and Emmaville, but which are mineralogically and chemically too different to originate from the same parent body as EC 002 (14).

The genesis of EC 002 allows us to understand some aspects of primordial crust formation on bodies of chondritic compositions. Though an andesite can derive from the fractional crystallization of a more primitive melt, this cannot be the case for EC 002. First, EC 002 has low abundance of highly incompatible elements (e.g., REE or Th). If it were an evolved lava, its parental melt would have even lower concentrations, which is difficult to envisage even for a primary basalt. The concentration of MgO (7.06 wt%) and the Mg#-number (= 52.9) of EC 002 are quite high for an andesite and do not support the idea that significant amounts of ultramafic cumulates were extracted. Furthermore, fractional crystallization would have inevitably left its fingerprint in the distribution of trace elements, such as a marked negative Eu anomaly generated by plagioclase crystallization at variance with the composition of EC 002 (Fig. 4). Therefore, it must be considered that EC 002 could be a primitive or even a primary melt. Partial melting of chondrites at low pressure is perfectly capable of generating andesitic magmas rich in SiO₂ and alkalis (10–12). However, the major element composition of EC 002 lies at the high-melting end of the experimental melting trends defined for ordinary H or LL chondrites (Fig. 3 and SI Appendix, Fig. S8). These trends indicate that melts with the same composition as EC 002 are obtained after plagioclase exhaustion for high degrees of melting (F) of around 25% (SI Appendix, Fig. S9). Such high melting rates would also explain the unfracti onated trace element pattern of EC 002 (Fig. 4) since high crystallization coefficients (such as phosphates or plagioclase) would be exhausted in the source after ~17% partial melting (12, 31). Indeed, the trace element pattern of EC 002 fits with an enrich ment by a factor of ~1/F of a typical NC chondrite composition (Fig. 4), in perfect agreement with the experimental data. The thermal history of EC 002 appears quite straightforward. Experimental data allow a precise evaluation of the temperature at which the magma formed (SI Appendix, Fig. S10). The MgO of EC 002 gives an estimated melting temperature of 1,224 ± 20 °C. This high temperature is confirmed by the crystallization temperatures estimated from the bulk compositions of Ca-rich pyroxene (32) in the range of 1,149 to 1,229 °C (average = 1,186 °C [SD =25 °C], slightly lower due to postcrystallization equilibration during cooling). The final equilibration temperature, about 957 °C, is estimated from the highest Ca concentration in pyroxene (32). The cooling of the rock was fast enough to preserve remnant zoning in groundmass pyroxene and the compositions of the core of the small xenocrysts. As a demonstration, we tentatively modeled the zoning profile of Mg# across the small xenocryst exposed in our section (Fig. 2 and SI Appendix). The cooling rate is estimated to be about 5 °Cy between 1,200 and 1,000 °C, a value consistent with a thick lava flow or a shallow intrusion. Important additional constraints are brought by silica polymorphs (SI Appendix). Only cristobalite and tridymite (PO) were detected in EC 002, and quartz is totally lacking. As experimentally shown for eucrites (33, 34), cristobalite crystallized at high temperatures.

Comparison between colors of EC 002 and those from about 10,000 objects from the Sloan Digital Sky Survey database also reveal the rarity if not absence of similar objects within the asteroid population (SI Appendix, section B).

**Discussion**

As demonstrated by its chemistry and Al-Mg age, EC 002 is a unique fragment of the crust of an ancient, differentiated body, contemporaneous with the formation of the cores of the parent bodies of iron meteorites (26). The oldest igneous rock previously described was NWA 11119 (9), with an age 1.24 Myr younger than EC 002 when calculated with the same canonical compositions. As demonstrated by its chemistry and Al-Mg age, EC 002 is a unique fragment of the crust of an ancient, differentiated body, contemporaneous with the formation of the cores of the parent bodies of iron meteorites (26). The oldest igneous rock previously described was NWA 11119 (9), with an age 1.24 Myr younger than EC 002 when calculated with the same canonical compositions. First, EC 002 has low abundance of highly incompatible elements (e.g., REE or Th). If it were an evolved lava, its parental melt would have even lower concentrations, which is difficult to envisage even for a primary basalt. The concentration of MgO (7.06 wt%) and the Mg#-number (= 52.9) of EC 002 are quite high for an andesite and do not support the idea that significant amounts of ultramafic cumulates were extracted. Furthermore, fractional crystallization would have inevitably left its fingerprint in the distribution of trace elements, such as a marked negative Eu anomaly generated by plagioclase crystallization at variance with the composition of EC 002 (Fig. 4). Therefore, it must be considered that EC 002 could be a primitive or even a primary melt. Partial melting of chondrites at low pressure is perfectly capable of generating andesitic magmas rich in SiO₂ and alkalis (10–12). However, the major element composition of EC 002 lies at the high-melting end of the experimental melting trends defined for ordinary H or LL chondrites (Fig. 3 and SI Appendix, Fig. S8). These trends indicate that melts with the same composition as EC 002 are obtained after plagioclase exhaustion for high degrees of melting (F) of around 25% (SI Appendix, Fig. S9). Such high melting rates would also explain the unfracti onated trace element pattern of EC 002 (Fig. 4) since high crystallization coefficients (such as phosphates or plagioclase) would be exhausted in the source after ~17% partial melting (12, 31). Indeed, the trace element pattern of EC 002 fits with an enrich ment by a factor of ~1/F of a typical NC chondrite composition (Fig. 4), in perfect agreement with the experimental data. The thermal history of EC 002 appears quite straightforward. Experimental data allow a precise evaluation of the temperature at which the magma formed (SI Appendix, Fig. S10). The MgO of EC 002 gives an estimated melting temperature of 1,224 ± 20 °C. This high temperature is confirmed by the crystallization temperatures estimated from the bulk compositions of Ca-rich pyroxene (32) in the range of 1,149 to 1,229 °C (average = 1,186 °C [SD =25 °C], slightly lower due to postcrystallization equilibration during cooling). The final equilibration temperature, about 957 °C, is estimated from the highest Ca concentration in pyroxene (32). The cooling of the rock was fast enough to preserve remnant zoning in groundmass pyroxene and the compositions of the core of the small xenocrysts. As a demonstration, we tentatively modeled the zoning profile of Mg# across the small xenocryst exposed in our section (Fig. 2 and SI Appendix). The cooling rate is estimated to be about 5 °Cy between 1,200 and 1,000 °C, a value consistent with a thick lava flow or a shallow intrusion. Important additional constraints are brought by silica polymorphs (SI Appendix). Only cristobalite and tridymite (PO) were detected in EC 002, and quartz is totally lacking. As experimentally shown for eucrites (33, 34), cristobalite crystallized at high temperatures.

**Fig. 5.** (A) The Al-Mg internal isochron defined by feldspars and pyroxenes of EC 002. The error bars correspond to 2 × SEs on the ratios. (B) Mg isotopic composition of EC 002 compared to the theoretical evolution of the Mg isotopic composition of the solar system [calculated for a chondritic 27Al/24Mg ratio of 0.101, a (26Al/27Al)₀ of 5.23 × 10⁻⁸, and a δ²⁶Mg^* of −0.034‰ (22)].
Subsequently, it partially transformed to tridymite above ~900 °C. Since cristobalite easily transforms to quartz (34), the lack of quartz indicates a very fast cooling rate below 900 °C (>0.1 to 1 °C/d), consistent with the absence of monoclinal tridymite and the possible occurrence of anorthoclase. The most likely explanation for this change in cooling rate is an impact that would have excavated, or more likely ejected, the rock from its parent body, in agreement with the evidence for shock metamorphism (M-S2). The similarity between the K-Ar retention age and the formation age as calculated from Al-Mg indicates that EC 002 was not significantly heated following formation, further supporting the idea that any ejection event occurred rapidly after formation. The cooling history of this meteorite therefore appears to be short, since it would have cooled for only a few decades before it was probably ejected.

The Mg isotopic composition of EC 002 gives further clues on the timing of differentiation of its parent body. Because of the fast cooling inferred for EC 002, the old 26Al age of 2.255 ± 0.013 Myr after CAIs can be considered to date the crystallization of the parent melt. This age is tightly constrained from the following: 1) the quality of the 26Al isochron (Fig. 5A) that also implies a lack of significant 26Mg redistribution by metamorphism after this fast cooling and 2) the fact that EC 002 is related to inner solar system bodies which are considered to have formed with a canonic level of 26Al even in the hypothesis of heterogeneous distribution of 26Al in the accretion disk (35, 36). The fact that the 26Al isochron intercept gives a δ26Mg0* significantly higher than the canonic initial of the solar system (Fig. 5B) is likely an indication for a protracted history of the parental melt of EC 002 prior to crystallization. In fact, such excesses of 26Mg have not been observed for bulk chondrites (e.g., refs 37 and 38) but are known in two ancient achondrites [NWA 7325: δ26Mg0* = 0.093 ± 0.004‰ (39); Asuka 881394: δ26Mg0* = 0.070 ± 0.002‰ (40)]. They could result from metamorphic perturbations or redistributions (40) or correspond to the protolith isotopic composition in the case of remelting of a crustal reservoir (39, 41). Here, these explanations are not satisfactory due to the short cooling duration of EC 002 and the evidence that the anedetic magma formed directly from a chondritic source. In addition, because the olivine and pyroxene xenocrysts present in EC 002 have a very low Al/Mg ratio (and thus cannot dominate the radiogenic 26Mg signal), their eventual equilibrium with the 26Al by the EC 002 parental melt is also unable to explain the positive δ26Mg0*. Alternatively, since EC 002 has a superchondritic Al/Mg ratio, a high δ26Mg0* value can simply be acquired if the time elapsed between partial melting and crystallization is long enough for 26Mg radiogenic excesses to develop in the melt. In order to investigate this possibility further, the Mg isotopic evolutionary curves of EC 002 and the solar system (equivalent to the evolution of regular chondrites) were compared (Fig. 5B). The two curves intersect between 0.95 Ma and 2.25 Ma (the age of crystallization) after the formation of CAIs. While this range is wide due to the error in the δ26Mg0* value of EC 002, it shows that the transfer of magmas between the melting zones and the surface could have been slow, a duration exceeding a few 107 y being probable. This result confirms and strengthens the inferences made by Collinet and Grove (12), who calculated that the velocity extraction of silica- and alkali-rich magmas in a protoplanet could have been at least three orders of magnitude lower than that of basalts (2.3 to 230 m/Mys versus 1.1 to 1,100 km/Mys, respectively).

Thus, these magmas would have moved slowly, probably only over narrow distances during one half-life of 26Al, rendering the thickening of a primordial crust by the stacking of flows difficult.

The parent body of EC 002 was certainly not unusual, and despite the scarcity of anedetic achondrites identified to date, it is reasonable to assume that many similar chondritic bodies accreted at the same time and were capped by the same type of primordial crust as proposed by Collinet and Grove (12). However, this andesitic crust might have been only temporary. Thermal models of asteroids which undergo partial melting due to the heat generated by 26Al decay (e.g., refs. 26 and 42) show that if accretion starts before 1 Myr after CAIs, the average temperature of the body reaches at least 1,500 °C at 2.2 Myr and can continue to rise after that. This is true whether accretion takes place instantaneously by gravitational instability or at a slower pace by a combination of gravitational instability and pebble accretion. Such temperatures are incompatible with the thermal history reconstructed for EC 002. One solution to this problem would be to consider the following: 1) that the parent body of EC 002 accreted later than 1 Myr (i.e., around 1.5 Myr) and 2) that EC 002 formed at the surface or close to the surface of the parent body (as implied by the texture and cooling history of EC 002). Such a body could escape global melting and have melts generated at ~1,220 °C close to surface migrating over a few 100 kyr to the surface. This would allow the preservation of a primordial crust at the surface of the parent body of EC 002. Such anedetic crusts were perhaps quite common 4,565 Myr ago. Possible parent bodies can be sought among available observations of asteroid surfaces. The spectral data obtained on EC 002 were compared with those obtained on asteroids, taking into account space weathering, the presence of olivine xenocrysts, and residual mantle debris (SI Appendix). EC 002 is clearly distinguishable from all asteroid groups (43, 44), and no object with spectral characteristics similar to EC 002 has been identified to date. Remains of primordial anedetic crust are therefore not only rare in the meteorite record, but they are also rare today in the asteroid belt. This suggests that the earliest differentiated protoplanets that populated the solar system, as well as most of their debris, were certainly destroyed or subsequently accreted to the growing rocky planets, making the discovery of meteorites originating from primordial crusts an exceptional occurrence.

Materials and Methods

Petrography and Phase Compositions. We studied two polished sections (~1.5 cm² each), one thick, one thin, and made from the same slab. We examined these sections using an optical microscope equipped with both transmitted and reflected light, an electron microprobe analyzer (EPMA; JEOL JXA-8200), and a field emission scanning electron microscope (JEOL JSM-7100F) equipped with an energy dispersive spectrometer (Oxford AZtec Energy) at the National Institute of Polar Research (NIPR). Pyroxene and spinel were analyzed using a current of 30 nA and a focused beam and plagioclase using 10 nA and a defocused beam (~3 μm in diameter) at 15 keV. For Mn analysis, we used a LIF spectrometer. Count rates using the LIF were increased by a factor of 3 to 4 compared to those of LIF. Bulk compositions of pyroxene are obtained from averaging 10 to 20 points across the grains using a beam diameter of ~30 μm at 15 keV. Data were reduced using a ZAF correction program. Mineral phases were identified with an inVia Raman spectrometer at NIPR.

Geochemistry. Another slice weighing 1.09 g was chosen after a thorough binocular examination of both sides because it contained no apparent pyroxene or olivine xenocrysts. It was crushed using a boron carbide mortar and pestle into a homogeneous fine-grained powder in clean room conditions at Institut Universitaire Européen de la Mer, Plouzané. Clear fragments (45 mg) of a large (~1 cm) olivine crystal were leached in 6 N HCl (120 °C, 30 min), rinsed three times, and dried. Major and trace elements were determined respectively by inductively coupled plasma-atomic emission spectroscopy using a Horiba Jobin Yvon Ultima 2 spectrometer, and by inductively coupled plasma-sector field mass spectrometry using a Thermo Scientific ELEMENT XR spectrometer. We used the same procedures as Cotten et al. (45) for the major elements. The accuracy is better than 5% for Na and P and much better than 3% for the other elements. For trace elements, we used the same procedure as Barrat et al. (20, 21). Based on standards and many sample duplicates, the precisions for abundances are in most cases much better than 5% [two relative SDs (2 × RSD)]. The precisions for Eu/Eu* and Tm/Tm* ratios [X* is the expected X concentration for a smooth CI-normalized RREE pattern, such that Eu0 = (Sm0 × Gd)½ and Tm0* = (Er0 × Yb0)½] are respectively better than 3% and 1.5% (2 × RSD).

26Al-26Mg Dating. A thick slice (~1 cm²) was polished and mounted in a four-window ion probe holder. The Mg isotopic compositions and Al/Mg concentration ratios were measured with the CRPG-CNRS CAMECA IMS 1280-HR2 ion microprobe.
Ion probe settings for feldspar. Because of the low Mg contents (<0.03 wt% of MgO) of the feldspars, the measurements were made in monocollection mode using the central Faraday cup (FC2) for 24Mg+. The samples were sputtered with a 5 nA O primary beam rastered at 15 x 15 μm. The transfer optic magnification was set at 100 μm to ensure an efficient instrumental transmission and to fully fill the field aperture set at 2,000 μm. The mass resolving power (MRP) was set at M/ΔM = 5,000 in order to completely remove the 24MgH+ interference on 25Mg+. One measurement consisted of a 120 s preanalysis sputtering to clean the sample surface and attain stable count rates on detectors followed by automatic secondary beam and energy centering, and 40 cycles with counting times during each cycle of 4, 5, 10, 3, and 3 s at masses 23 (background for EM), 24Mg, 25Mg, 26Mg, and the central Faraday cup (FC2) for 25Al+. The samples were sputtered with a 6 nA O primary beam rastered at 15 x 15 μm. The transfer optic magnification was set at 100 μm to ensure an efficient instrumental transmission and to fully fill the field aperture set at 2,000 μm. The mass resolving power (MRP) was set at M/ΔM = 5,000 in order to completely remove the 24MgH+ interference on 25Mg+. One measurement consisted of a 120 s preanalysis sputtering to clean the sample surface and attain stable count rates on detectors followed by automatic secondary beam and energy centering, and 40 cycles with counting times during each cycle of 4, 5, 10, 3, and 3 s at masses 23 (background for EM), 24Mg, 25Mg, 26Mg, and 27Al, respectively. The Mg isotopic compositions are given in delta notation according to δ25Mg = ln[(25Mg/25Mg)sample/(25Mg/25Mg)standard] × 1,000 (similarly for δ24Mg). The data for the standard 987MgH* were 0.12663 and (25Mg/25Mg)standard = 0.13932 (46). The 25Mg excess due to 24Al decay are noted δ25Mg = 26Mg* − δ25Mg with [β = 0.521 for an equilibrium mass fractionation of Mg isotopes as it is expected for the current object (47)]. The choice of the mass fractionation law is not critical to the current data set since the degree of intrinsic mass fractionation is small and most likely due to uncorrected correlated matrix effects in feldspars (S Appendix, Table S5), and because the Al/Mg ratios of feldspar that control the isochron are high enough for the uncertainty introduced by the choice of fractionation law to be insignificant. Miyake-Jima plagioclase (27Al/28Al = 396.3) was used to calibrate the instrumental isotopic fractionation and the relative Al/Mg ion yield. Two sigma SEs on the mean of ±0.04%, ±0.31%, and ±0.45% for 26Mg, 25Mg, and 24Mg, respectively, were obtained for the standard. The relative Al/Mg ion yield was determined to be 1.00% ± 0.03%. Typical count rates for EC 002 feldspars were 15,000 cps, 2,500 cps, 2,000 cps, and 4.2 × 10^4 cps 26Mg, 25Mg, 24Mg, and 27Al, respectively. The errors reported for the measurements of the samples are two sigma errors calculated by summing in a quadratic way the errors due to counting statistic in each point and the errors due to calibration of instrumental isotopic fractionation and Al/Mg ion yield (S Appendix, Table S5).

Noble Gas Isotope Analysis. An 8.2-mg piece of the sample was loaded into a filament furnace consisting of three alumina-coated tungsten evaporation baskets. The sample was extracted directly into one of the baskets while two empty baskets served to calculate the blank contribution. The full analytical procedure has been previously documented in Broadley et al. (49). In brief, the furnace was pumped while baking at 150 °C for 4 h to remove adsorbed atmospheric gases from the walls of the furnace and the sample. The furnace was then pumped for a further 48 h to ensure low blank levels. Gases were extracted from the sample over five temperature steps at 600 °C, 800 °C, 1,000 °C, 1,200 °C, and 1,400 °C. The majority of the He (90%) was released at the 800 °C extraction step. For both Ne (84%) and Ar (91%), the majority was released at 1,200 °C. Negligible amounts of gas were released at 1,400 °C, and inspection of the sample after analysis confirmed it had been completely vaporized. The extracted He, Ne, and Ar were purified, cryo-separated, and analyzed using a Helix-MC mass spectrometer (49). Blanks were analyzed following exactly the same protocol as samples, and for the major extraction step, the He, Ne, and Ar blanks represent 0.01%, 0.01%, and 0.14% of the sample, respectively. Blank contributions for 36Ar were significantly higher given the very low concentration of 36Ar in the sample, with blank contribution reaching a maximum of 50% at 1,000 °C temperature step. Noble gas abundances and isotope ratios are reported in S Appendix, Table S7.

Reflectance Spectra. Reflectance spectra of Erg Chech 002 were measured at Institut de Planetologie et d’Astrophysique de Grenoble using the Shadows instrument (53). We used the standard mode of the instrument (around 7-mm diameter illumination spot), and spectra were measured under nadir illumination and using an observation angle of 30°. One spectrum was obtained for a powdered sample, and three spectra were obtained on distinct location of a raw slab of the meteorite.

Data Availability. All study data are included in the article and in S Appendix.

ACKNOWLEDGMENTS. We thank Mark Thiemann for the editorial handling. David Meitshoeldt and an anonymous reviewer for their detailed comments. We thank Addi Bischoff for showing us the probable occurrence of anorthoclast in EC 002. Analyses in Brest were obtained with the assistance of Bleuenn Gueguen, Céline Liorzou, and Marie-Laure Rouget. This work was supported by JSPS KAKENHI (Grant Number 19H01959), NIPR Research Project KP307, ANR-12-CE31-0004-1 (ANR CRADLE), the UnivEarthS Labex program at Sorbonne Paris Cité (ANR-10-LABX-0023), the European Research Council under the H2020 framework program/ERC Grant Agreement No. 771691 (Solayrs), the European Research Council (PHOTONIS project, Grant Agreement No. 695618), and by the “Laboratoire d’Excellence” LabexMER (ANR-10-LABX-19) and funded by grants from the French Government under the program “Investissements d’Avenir.”

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