^{26}Al in Eucrite Piplia Kalan: Plausible Heat Source and Formation Chronology

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Aluminum-magnesium isotopic analysis of plagioclase in the eucrite Piplia Kalan, with $^{27}Al/^{24}Mg$ ratio between 2000 to 7000, reveals the presence of excess magnesium-26 resulting from in situ decay of the short-lived nuclide aluminum-26. This observation confirms aluminum-26 as a plausible heat source for melting and differentiation of the eucrite parent body in particular and for planetesimals in general. The inferred initial abundance of $^{26}Al/^{27}Al$ of $(7.5 \pm 0.9) \times 10^{-7}$ indicates that melting, differentiation, and crust formation in the parent body of Piplia Kalan was complete within 5 million years of the formation of the solar system.

Radiometric ages of differentiated meteorites obtained with Sm-Nd, Rb-Sr, U-Pb, and Pb-Pb isotopic systematics cluster around (4.4 to 4.6) $\times 10^9$ years ago (Ga) (*1*), indicating that they evolved as a result of melting and differentiation of their parent bodies within 20 million years (My) of the formation of the solar system. The antiquity of the differentiated meteorites is also confirmed by the presence of short-lived radionuclides such as ^{60}Fe [half-life ($t_{1/2}$) ~ 1.5 My], ^{53}Mn ($t_{1/2}$ ~ 3.7 My), ^{107}Pd ($t_{1/2}$ ~ 6.5 My), and ^{182}Hf ($t_{1/2}$ ~ 9 My) at the time of their formation (*2*). Decay of the short-lived radionuclide ^{26}Al to ^{26}Mg with a half-life of 0.73 My was postulated (*3*) to provide the heat required for early melting of planetesimals representing the parent bodies of differentiated meteorites. Electromagnetic heating of planetesimals in the early solar system has been proposed as another possibility (*4*).

The presence of ^{26}Mg excess resulting from decay of ^{26}Al was demonstrated in calcium-aluminum inclusions (CAIs) from the Allende meteorite, and the initial $^{26}Al/^{27}Al$ abundance was determined to be 5×10^{-5} (*5*). Subsequent work on CAIs from a large number of primitive chondrites has provided evidence for the presence of ^{26}Al with similar abundance (*6*, *7*). Therefore, it is plausible that the distribution of ^{26}Al in the solar nebula was widespread at the time of formation of CAIs (*7*). However, several attempts to detect ^{26}Al in differentiated meteorites such as eucrites, angrites, and mesosiderites have been unsuccessful (*8*). The presence of well-resolved ^{26}Mg excess was reported in an igneous clast from the unequilibrated chondrite Semarkona corresponding to an initial $^{26}Al/^{27}Al$ ratio of $\sim 8 \times 10^{-6}$ (*9*). This clast has a chondrule-like morphology and texture similar to eucrites, and the inferred ^{26}Al abundance is sufficient to produce incipient melting of solid bodies of chondritic composition (*9*). An upper limit for the initial $^{26}Al/^{27}Al$ ratio of 4×10^{-6} was obtained from a search of ^{26}Mg excess in another igneous clast in the Parnallee chondrite (*10*). However, it is not clear how differentiated meteorites are related to such igneous clasts in chondritic meteorites. Absence of any evidence for ^{26}Al in differentiated meteorites has been considered as an argument against the role of ^{26}Al as a heat source for differentiation of the parent bodies of these meteorites (*11*, *12*).

The absence of ^{26}Mg excess in differentiated meteorites is in itself not a sufficient reason to exclude ^{26}Al from being a plausible heat source. For example, if the time required for parent bodies to cool below the closure temperatures of Al-Mg system is too long, then ^{26}Al would decay below detectable limits. Alternatively, thermal metamorphism or impact events affecting the parent bodies at later times could lead to redistribution of Mg isotopes that can obliterate any excess that may have been present initially in these objects. The low Al/Mg values in the analyzed phases can also make the detection of ^{26}Mg excess difficult because of the limitation of instrument sensitivity. However, any measurable excess of ^{26}Mg detected in differentiated meteorites would support ^{26}Al as a heat source.

We report here the results obtained from ion microprobe Al-Mg isotopic studies on plagioclase grains from the eucrite Piplia Kalan. This meteorite fell in 1996 in India and has been characterized elsewhere in terms of its mineral composition and chemistry (*13*, *14*). This eucrite is an equilibrated noncumulate monomict breccia with clasts (~60 to 80 volume %) having diverse texture and grain size. One section, PK-97-1 (Fig. 1), was analyzed for its major- and minor-element chemistry (*15*). The section consists of a coarse-grained and a fine-grained region composed of plagioclase and pyroxenes with minor components of chromite and ilmenite. In the coarse-grained region the plagioclase (~1 mm in size) is lath-shaped to blocky. The pyroxenes (~0.5 to 1 mm) are elongated to equant and are composed of augite exsolution lamellae (~10 μm). In the fine-grained region there are a few laths of plagioclase and pyroxene (200 to 300 μm), fine-grained ground mass, and granular pyroxene and plagioclase. The average mineral compositions

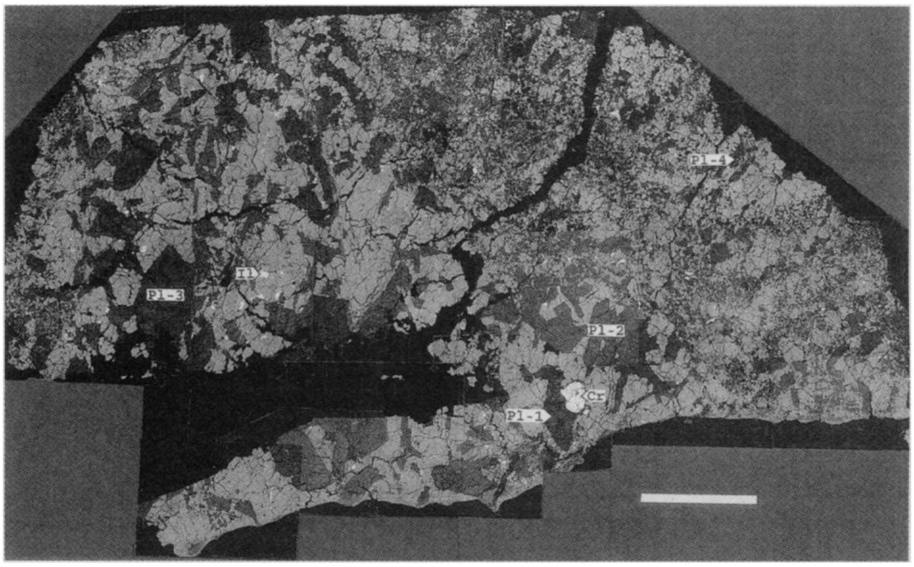

Fig. 1. Piplia Kalan thin section PK-97-1 imaged with back-scattered electrons. The section consists of a coarse-grained and a fine-grained lithology. The plagioclase grains are dark gray, pyroxenes are light gray, and chromite (Cr) and ilmenite (Il) grains are white. The plagioclase grains labeled as Pl-1, Pl-2, Pl-3, and Pl-4 and adjacent pyroxenes were analyzed for their Al-Mg isotopic composition. Scale bar = 2 mm.

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for major and minor phases in this section are given in Table 1.

We carried out a search for a ^{26}Mg excess resulting from the decay of ^{26}Al in Piplia Kalan plagioclase for the following reasons: (i) Sm-Nd age of this meteorite (whole rock and mineral separates) is 4570 ± 23 Ma (*16*), and therefore it is much older compared with some of the other dated noncumulate eucrites like Juvinas and Chervony Kut (*17*); (ii) the Pu-Xe model age of this meteorite (*18*) suggests that its formation age predates one of the oldest basaltic achondrites, Angra dos Reis, for which a precise formation age (4557.8 ± 0.5 Ma) has been determined (*12*); and (iii) the presence of large plagioclase crystals with high Al/Mg values favors the detection of small excesses of ^{26}Mg. We measured Al-Mg isotopic systematics in two lithologies from the section PK-97-1 (Fig. 1) using a Cameca ims-4f ion microprobe (*19*, *20*). Back-scattered electron photomosaic of section PK-97-1 was used during Al-Mg analyses as a guide to avoid inclusions of pyroxene and other minor phases in plagioclase crystals that could contain large amounts of Mg. Three plagioclase grains and pyroxenes adjacent to each plagioclase from the coarse-grained region and a plagioclase grain and adjacent pyroxene from the fine-grained region were analyzed. The results (Table 2 and Fig. 2) show that plagioclase with ^{27}Al/^{24}Mg values ranging from 3000 to 7000 have ^{26}Mg excesses of ~15 to 30 per mil. The pyroxene grains with low Al/Mg ratios have normal Mg isotopic composition within experimental errors. Our data yield an initial ^{26}Al/^{27}Al value of $(7.5 \pm 0.9) \times 10^{-7}$ ($2\sigma_m$) and provide evidence for the presence of ^{26}Al at the time of formation of the eucrite Piplia Kalan. The plausible contribution to the measured ^{26}Mg excess by the decay of cosmogenic ^{26}Al, determined to be 111 dpm/kg in this meteorite, over its cosmic ray exposure age of 23 My (*18*) is estimated to be <1%.

Although our data show excess ^{26}Mg in plagioclase of the Piplia Kalan eucrite, the excess ^{26}Mg shows little variation with ^{27}Al/^{24}Mg ratio (for example, data for grain Pl-1, Table 2), implying that the Al-Mg isochron (Fig. 2) is disturbed. The scatter in excess ^{26}Mg for data points with ^{27}Al/^{24}Mg value of ~3500 also suggests some disturbance in the Al-Mg systematics. However, the measured Mg isotopic composition for the pyroxene grains is normal, suggesting that these disturbances probably reflect low-temperature partial reequilibration of the Al-Mg system, which was confined to plagioclase. A partial reequilibration in Al-Mg systematics, long after ^{26}Al had completely decayed, appears plausible on the basis of the lower Pb-Pb and Rb-Sr age of 4.27 Ga (*16*), which is suggestive of an early low-temperature thermal metamorphism in the parent body of the Piplia Kalan eucrite that did not affect the Sm-Nd and Pu-Xe isotopic systematics. Our data show that the last episode of metamorphism experienced by the parent body of Piplia Kalan eucrite that left its imprint on its

Table 1. Average mineral composition in Piplia Kalan measured in section PK-97-1. The number of analyses is given in parentheses.

Mineral	Plagioclase (7)	Pyroxene		Ilmenite (1)	Chromite (1)
		Fe-poor (6)	Fe-rich (9)		
SiO_2	45.26	50.71	49.24	0.04	0.16
TiO_2	0.01	0.39	0.16	51.92	3.24
Al_2O_3	35.2	0.62	0.15	0	8.45
Cr_2O_3	0	0.28	0.07	0.05	51.54
FeO	0.17	16.52	36.25	44.46	34.75
MnO	0.01	0.5	1.15	0.9	0
MgO	0	9.77	11.43	0.57	0.47
CaO	18.07	20.75	0.92	0.01	0
Na_2O	1.19	0.06	0	0.01	0.01
K_2O	0.07	0	0	0	0
NiO	0.01	0.02	0.01	0	0
Total	100.02	99.65	99.52	97.96	98.51

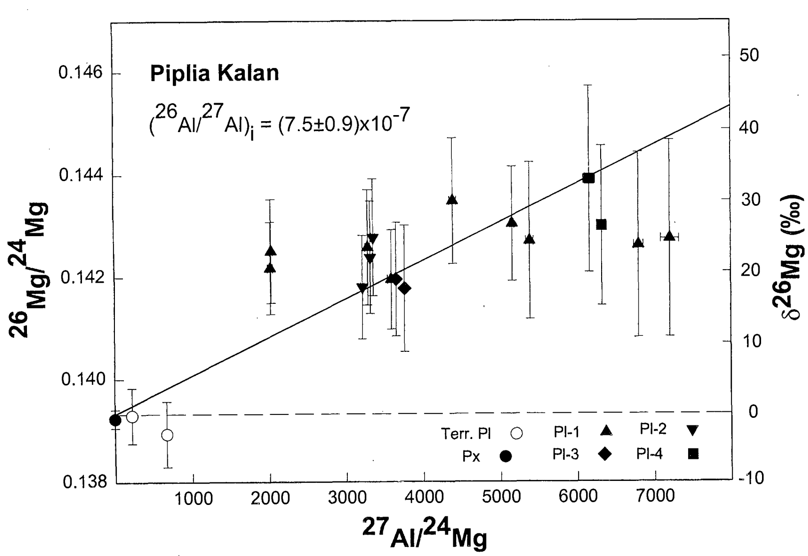

Fig. 2. Al-Mg evolution diagram for Piplia Kalan eucrite measured in the section PK-97-1. The Piplia Kalan plagioclase grains (Pl-1, Pl-2, Pl-3, and Pl-4) and pyroxene (Px) are represented by filled symbols and terrestrial plagioclases (Terr. Pl) by open symbols. The average value for nine pyroxene analyses is plotted to avoid clutter. The slope of the correlation line gives initial $^{26}Al/^{27}Al = (7.5 \pm 0.9) \times 10^{-7}$. The horizontal line represents normal Mg isotopic composition. All errors are $2\sigma_m$.

Table 2. Al-Mg isotopic data in Piplia Kalan. Plagioclase and pyroxenes are labeled as Pl and Px, respectively. All errors are $2\sigma_m$. The errors in ^{27}Al/^{24}Mg ratio in pyroxene typically range from 2 to 4%. Terrestrial plagioclase with ^{27}Al/^{24}Mg ratios of ~220 and ~670 (USNM 115900) have δ^{26}Mg values of 0.2 ± 3.9 per mil and −2.8 ± 4.6 per mil, respectively.

Phase	^{7}Al/^{24}Mg	δ^{26}Mg
Pl-1-1	7209 ± 117	24.6 ± 13.8
Pl-1-2	6803 ± 60	23.7 ± 13.0
Pl-1-3	4396 ± 45	29.9 ± 8.8
Pl-1-4	5166 ± 24	26.7 ± 8.0
Pl-1-5	5393 ± 49	24.3 ± 11.0
Pl-1-6	3593 ± 46	18.9 ± 7.0
Pl-1-7	3289 ± 34	23.4 ± 8.1
Pl-1-8	2032 ± 19	22.9 ± 7.3
Pl-1-9	2021 ± 34	20.5 ± 6.5
Pl-2-1	3358 ± 25	24.8 ± 8.2
Pl-2-2	3322 ± 26	22.0 ± 7.9
Pl-2-3	3218 ± 22	17.8 ± 7.3
Pl-3-1	3656 ± 22	18.9 ± 8.0
Pl-3-2	3765 ± 24	17.6 ± 8.9
Pl-4-1	6169 ± 76	32.9 ± 13.0
Pl-4-2	6327 ± 35	26.4 ± 11.2
Px-1	0.01	0.2 ± 0.8
Px-2	0.02	−1.8 ± 1.7
Px-3	0.01	1.2 ± 0.9
Px-4	0.01	−2.3 ± 0.8
Px-5	0.01	1.6 ± 0.6
Px-6	0.01	0.2 ± 1.4
Px-7	0.01	−1.8 ± 0.9
Px-8	0.02	−2.5 ± 0.9
Px-9	0.01	1.2 ± 1.1
Px-average	0.01	−0.4 ± 1.0

Al-Mg systematics was not strong enough to equilibrate the Mg isotopic composition in the plagioclase with those in pyroxene.

The results presented here support the suggestion that ^{26}Al was the heat source for melting of planetesimals early in the history of the solar system (*3*). The extent of thermal processing of a planetesimal will depend on its initial ^{26}Al abundance and the size of the body. The ^{26}Al abundance depends on the accretion time of the body relative to CAI formation and its chemical composition. The former determines the extent to which ^{26}Al has decayed from the initial ^{26}Al/^{27}Al value of $\sim 5 \times 10^{-5}$ observed in CAIs (*6*, *7*). It is possible to determine the thermal history of meteorite parent bodies by using the heat conduction equation with ^{26}Al as the exponentially decaying heat source (*3*, *21*, *22*) and temperature-dependent thermal diffusivity and specific heat (*23*). In particular, the time scales for the various stages in the formation of the Asteroid 4 Vesta, presumably the parent body of the HED (howardite, eucrite, and diogenite) group of meteorites (*24*), has been evaluated (*21*). The model calculations predict (relative to CAI formation time) accretion of a body of chondritic composition within 2.85 My, followed by core formation by 4.58 My and crust formation by 6.58 My (*21*). If we assume a uniform distribution of ^{26}Al in the CAI and meteorite-forming zone in the solar nebula (*6*, *7*), the ^{26}Al/^{27}Al value at the time of accretion will be $\sim 3 \times 10^{-6}$ and will decrease to 7×10^{-8} at the time of crust formation. The ^{26}Al/^{27}Al abundance in Piplia Kalan measured by us is an order of magnitude higher than that predicted by the model and suggests that the formation of crust in its parent body was probably complete within 5 My of CAI formation. Our results thus provide evidence for ^{26}Al as an effective heat source for early melting and differentiation of the parent body of eucrites and possibly of other planetesimals as well.

A correlated study of eucrites with extinct radionuclides (for example, ^{26}Al, ^{53}Mn, ^{60}Fe, ^{182}Hf, and ^{146}Sm) and long-lived absolute chronometers (^{147}Sm-^{143}Nd, ^{87}Rb-^{87}Sr, and ^{207}Pb-^{206}Pb) can provide time constraints on the formation and evolution of basaltic crust of the parent body of HED meteorites. The use of extinct radionuclides as relative chronometers is valid under the assumption that they were homogeneously distributed at least in the region of solar system where parent bodies of the differentiated meteorites formed. The ^{26}Al abundance measured in Piplia Kalan can be used to constrain the time scale of formation of its parent body. The observed difference in ^{26}Al abundance between pristine CAIs and the eucrite Piplia Kalan implies a time interval of 4.2 ± 0.1 My between their formation. The ^{147}Sm-^{143}Nd absolute age of Piplia Kalan is 4570 ± 23 Ma (*16*), whereas the absolute age of CAIs obtained from Pb-Pb isotopic system is 4566 ± 2 Ma (*25*). The formation of a differentiated meteorite like Piplia Kalan cannot possibly predate CAIs that are supposed to be the first solids to form in the solar nebula, marking effectively the beginning of the formation of the solar system. Nonetheless, the high Sm-Nd age for Piplia Kalan appears to be consistent with the observation of ^{26}Al therein. The chronology obtained from ^{26}Al abundance in Piplia Kalan is also consistent with the time constraints obtained from ^{53}Mn abundances in another noncumulate eucrite, Juvinas. The presence of ^{53}Mn has been well established in Juvinas (*2*, *26*), and the absolute age of this meteorite was determined to be 4563 ± 1 Ma (*26*), by comparing the ^{53}Mn abundance in Juvinas with those of precisely dated meteorites Lewis Cliff 86010 and Angra dos Reis (*12*). This would imply formation of Juvinas within ~0.5 to 5.5 My after the formation of CAIs, which is in agreement with the time scale inferred from the ^{26}Al data in Piplia Kalan. The abundance of ^{26}Al in Piplia Kalan and of ^{53}Mn in Juvinas and other eucrites suggests that the accretion, heating, melting, differentiation, and subsequent crust formation on the parent body of eucrites took place very rapidly, within 5 My of the formation of the solar system.

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15. The sample was photo-documented with a JEOL scanning electron microscope at Washington University, St. Louis. Back-scattered electron image (BSE) photo-mosaics were created to be used as location maps and guides for ion probe isotopic analyses. Mineral chemistry was determined with a Cameca Camebax electron microprobe at Johnson Space Center, Houston, TX, operating at 15-kV accelerating potential and 40-nA beam current with counting time of 20 s for Al, Ca, Mn, and Fe and 40 s for Si, Ti, V, Cr, and Mg. Natural and synthetic crystalline standards were used for calibration.
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20. Isotopic analyses were carried out with the PRL Cameca ims-4f ion microprobe [see also (*19*)]. Primary beam spot diameter was in the range of 10 μm, and beam currents ranging from 0.4 to 2 nA were used to carry out analyses in pyroxene and plagioclase. ^{26}Mg excesses are reported as δ^{26}Mg, deviation in parts per thousand (per mil) from normal Mg
$$\delta^{26}\text{Mg}=\{[(^{26}\text{Mg}/^{24}\text{Mg})_c/0.13932]-1\} \times 1000$$
where $(^{26}\text{Mg}/^{24}\text{Mg})_c$ is the measured ratio corrected for fractionation by normalizing to $(^{25}\text{Mg}/^{24}\text{Mg}) = 0.12663$ (*27*) using a linear law (*6*) and 0.13932 is taken as the fractionation corrected (^{26}Mg/^{24}Mg) of terrestrial standards (*27*). In plagioclase, we measured the ^{27}Al and ^{24}Mg count rates before and after every isotopic analysis to estimate the average ^{27}Al/^{24}Mg value. This was done to avoid inclusion of ^{27}Al in the measurement cycle because its count rates exceed the dynamic range of electron multiplier under our instrument operating conditions, which maximize the count rates of Mg isotopes. The counting times for individual Mg isotopes 24, 25, and 26 were10, 20, and 20 s, respectively. In each measurement cycle, individual Mg isotopes are scanned and counted; five such cycles constitute a block, and one measurement comprises 10 to 15 blocks. The reported values for Mg isotopic composition are obtained by averaging the values for individual blocks. All errors are $2\sigma_m$.
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