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^{26}Al as a heat source for early melting of planetesimals: Results from isotopic studies of meteorites

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Abstract. Ion microprobe studies of magnesium isotopic composition in igneous components from several chondritic meteorites have been carried out to look for ^{26}Mg excess that may be attributed to the presence of the now-extinct radionuclide ^{26}Al($\tau \sim 1$ Ma) at the time of formation of these objects. A positive evidence for the presence of ^{26}Al in the analysed objects will strengthen its case as the primary heat source for the early thermal metamorphism/melting of meteorite parent bodies. Based on calculated temperature profiles inside chondritic objects of different sizes and initial ^{26}Al/^{27}Al ratios, we have estimated the initial abundances of ^{26}Al needed to provide the heat necessary for the wide range of thermal processing seen in various types of meteorites. The magnesium isotopic data obtained by us do not provide definitive evidence for the presence of ^{26}Al at the time of formation of the analysed igneous phases in different chondritic meteorites. Experimental evidence for a planetary scale distribution of ^{26}Al in the early solar system to serve as a significant heat source for the thermal metamorphism and melting of meteorite parent bodies (planetesimals) remains elusive.

Keywords. Early solar system; meteorites; igneous inclusions; isotopes; ion microprobe.

1. Introduction

The parent bodies of meteorites have experienced varying degrees of physical and chemical processing as inferred from studies of the different types of meteorites. For example, there is abundant petrographic evidence for large scale aqueous alteration in the parent bodies of primitive carbonaceous chondrites very early in their evolutionary history. The parent bodies of the ordinary and enstatite chondrites have suffered varying degrees of thermal metamorphism, whereas those of the achondrites, stony iron and iron meteorites have undergone extensive differentiation following complete or partial melting. These processes have been reviewed by Hewins and Newsom (1988); McSween *et al* (1988) and Zolensky and McSween (1988). The thermal metamorphism in chondritic parent bodies suggests temperatures of 400–950 °C, whereas melting of the parent bodies of differentiated meteorites requires temperature in excess of 1000 °C. The formation of meteorite parent bodies of a few tens to a few hundreds kilometers in size, and their subsequent thermal processing took place very early in the history of the solar system, perhaps within the first few tens of million years (Ma). This inference is based on the formation ages of Ca–Al-rich refractory inclusions (CAIs) found in primitive carbonaceous chondrites, that are believed to be some of the earliest solar system solids, and of thermally metamorphosed chondrites and differentiated meteorites (Chen and Wasserburg 1981; Manhès *et al* 1987; Göpel *et al* 1989; Tera *et al* 1989; Lugmair and Galer 1992). Based on the studies of extinct nuclide (^{60}Fe, ^{53}Mn) records in two differentiated meteorites, Lugmair *et al* (1995) have recently suggested that this time interval could be less than 6 Ma. Although several mechanisms have been proposed for heat generation during the early history of meteorite parent bodies (see for e.g. review by Wood and Pellas 1991), the most favored one is heating due to the radioactive decay of the now-extinct short-lived radionuclides, ^{26}Al($\tau \sim 1$Myr) and ^{60}Fe($\tau \sim 2$ Myr), initially incorporated in these objects. The basic criterion to be satisfied by any radionuclide to be an effective heat source within a meteorite parent body is that its mean-life should be small or comparable to the conductive heat transfer time scale of the body. This time scale is of the order of 10^6 to 10^8 years for 10–100 km size meteorite parent body of chondritic composition (Scott *et al* 1989). Another constraint is the relatively short time interval (less than a few tens of million years) within which thermal processing of the meteorite parent bodies took place.

Urey (1955) first proposed that the short-lived radionuclide ^{26}Al($\tau \sim 1$ Ma) could be an effective heat source for heating and early melting of meteorite parent bodies. If ^{26}Al was still extant at the time of formation of such bodies it will act as a heat source. However, evidence for the planetary scale presence of live ^{26}Al in the early solar system is yet to be established conclusively even though its presence in CAIs has been well established (Lee *et al* 1976; see also Wasserburg 1985; Cameron 1993). The measured values of initial ^{26}Al/^{27}Al in CAIs vary over a wide range (0 to $\sim 5 \times 10^{-5}$). This variation most probably reflects post-formation secondary processes affecting the CAIs, as the initial ^{26}Al/^{27}Al in the solar nebula at the time of formation of the CAIs is believed to be rather uniform with a value of $\sim 5 \times 10^{-5}$ (Podosek *et al* 1991; Goswami *et al* 1994; MacPherson *et al* 1992, 1995). This abundance of ^{26}Al/^{27}Al, if present in meteorite parent bodies as well, will be enough to raise the temperature to melting. But, the CAIs are nebular products formed within less than a million years following the isolation of the solar nebula (Srinivasan *et al* 1994), and they are present only in the least altered carbonaceous chondrites where they constitute less than 5% of the total meteorite mass. In order to establish ^{26}Al as a planetary (meteorite parent body) heat source, one must obtain evidence for the presence of residual ^{26}Al in meteoritic phases that are definite products of large scale melting or thermal metamorphism.

The case of ^{60}Fe being a plausible planetary heat source was strengthened by the recent discovery of its one-time presence in two differentiated meteorites, Chevorny Kut and Juvinas (Shukolyukov and Lugmair 1993a, b). These authors inferred a solar system initial ^{60}Fe/^{56}Fe of $1{\cdot}6 \times 10^{-6}$ which could provide the total heat needed for melting and differentiation of meteorite parent bodies with as much as 26 weight per cent of iron. However, recent studies of the extinct nuclide ^{53}Mn by Lugmair *et al* (1995) in the same meteorites indicate a much lower initial ^{60}Fe/^{56}Fe at the time of formation of the parent body(ies) of these meteorites. Thus, even though the planetary scale presence of ^{60}Fe in the early solar system is well established, its role in early melting of planetesimals is unclear.

Several attempts have been made to obtain evidence in meteorites for ^{26}Al as an effective heat source for thermal processing in meteorite parent bodies (Schramm *et al* 1970; Hutcheon and Hutchison 1989; Bernius *et al* 1991; Kennedy *et al* 1992;

Zinner and Göpel 1992; Hutcheon *et al* 1994; Sahijpal *et al* 1994; Hutcheon and Jones 1995). But only two cases of excess ^{26}Mg, attributable to *in situ* decay of ^{26}Al have been reported. The first observation of ^{26}Mg excess was reported by Hutcheon and Hutchison (1989), from an anorthite grain in an igneous chondrule-like clast of the unequilibrated ordinary chondrite Semarkona. A $^{26}Al/^{27}Al$ ratio of $(7{\cdot}7 \pm 2{\cdot}1) \times 10^{-6}$ at the time of formation of this clast was inferred from the data obtained in this study. If this is assumed to be representative of initial $^{26}Al/^{27}Al$ ratio in bulk chondritic parent bodies, it is sufficient to cause incipient melting of well-insulated bodies. The second observation of ^{26}Mg excess was reported by Zinner and Göpel (1992) who analysed anorthositic feldspars from the H4 chondrite Ste. Marguerite and inferred an initial $^{26}Al/^{27}Al$ of $(2{\cdot}0 \pm 0{\cdot}6) \times 10^{-7}$, that is much below the value necessary for initiating thermal metamorphism. The uniqueness of the analysed objects as products of large scale melting or thermal metamorphism and their pristine nature are two important questions that must be addressed in such studies and some ambiguity has remained in the case of the Semarkona sample in this regard. It is therefore important to analyse well-documented igneous meteoritic phases to look for the presence of ^{26}Al at the time of their formation. In the present study, we have studied Al-rich phases in a number of carefully selected igneous components found in different chondritic meteorite for evidence of ^{26}Al at the time of their formation. Initial results from this work were presented in the XXV Lunar and Planetary Science Conference (Sahijpal *et al* 1994).

2. Sample details and experimental procedures

We have analysed plagioclase phases of igneous inclusions from two unequilibrated chondrites, Dengli and Severnyi Kolchim, both belonging to the H3 group, and from the Tsarev meteorite belonging to the L5 group of chondrites. In addition, Al-rich phases in chromite chondrules and inclusion from the unequilibrated H-chondrite, Raguli and anorthite grains separated from the multi-component meteorite breccia Kaidun were also chosen for analysis.

The basaltic inclusion in the Tsarev meteorite consists of Ca-rich pyroxene and minor orthopyroxene grains embedded in a glassy plagioclase matrix and is characterized by a fine-grained magmatic texture (Migdisova *et al* 1992; 1994). The chemical composition of Ca-rich pyroxene and plagioclase in the inclusion are similar to that of the host chondrite. However, the phase proportion in the former is similar to that of the eutectic (basaltic) mixture. The similarity in the chemical compositions suggests that the basaltic inclusion and the host chondrite are genetically related. Partial melting of host chondritic material by which plagioclase-pyroxene fraction was melted and separated from residual olivine and orthopyroxene has been proposed as the mode of formation of this inclusion. The basaltic inclusion most probably formed by rapid solidification of melt without equilibration with residual solid.

The Dengli (H3) meteorite is a complex chondritic breccia containing several angular clasts and inclusions (Ivanova *et al* 1992, 1993). The plagioclase phases from a silica-bearing inclusion, an angular clast (clast number 2 of Ivanova *et al* 1992) and a chondrule were analysed by us. The silica-bearing inclusion has a round shape and consists of orthopyroxene, clinopyroxene, feldspar and silica (probably crystobalite). The angular clast is composed of olivine, Al-rich clinopyroxene and feldspar. The presence of clinopyroxene and Ca-rich feldspar indicates its similarity with achondrites, and suggests an igneous origin.

The igneous component in Severnyi Kolchim consists of olivine grains surrounded by Ca-rich pyroxene and Ca-rich feldspar (Nazarov *et al* 1993). The presence of Ca-rich feldspar and pyroxene with the absence of metal grains suggests that the clast was formed by an igneous process on a differentiated parent body. However, the mineral chemistry, particularly the higher Fe/Mg ratio in olivine grains relative to that of the late crystallizing phases is difficult to explain in this scenario.

The presence of chromite chondrules and inclusions in the Raguli (H3) meteorite has been reported by Krot and Ivanova (1992) and Krot *et al* (1992). These objects consist of chromite and plagioclase phases with minerals like ilmenite, pyroxene and phosphate as accessory phases. Several models have been proposed to explain the origin of chromite chondrules and inclusions (Ivanova and Krot 1994). These include melting and recrystallization of pre-solar aggregates to form chondrules and inclusions, and secondary alteration of nebular condensate in meteorite parent body or in an oxidizing environment. Although, the presence of live ^{26}Al in these phases does not provide definitive proof of planetary scale thermal processing, it can provide additional clues about the distribution of ^{26}Al during different epochs in the early solar system. In the present study, plagioclase phases from two chromite chondrules and one inclusion were analysed for the presence of ^{26}Al at the time of their formation.

Kaidun meteorite is a heterogeneous multi-component meteorite breccia of carbonaceous and enstatite chondrites (Ivanov 1989). The major constituent of the meteorite has a composition close to type 2 carbonaceous (CM) chondrite. Xenoliths with a composition resembling type 1 carbonaceous chondrite (CI) and two distinct types of enstatite chondrites (EL3 and EH5) are also found within the dominant CM type. This multi-component meteorite breccia perhaps was formed in a series of events causing compaction of these four types of meteorites. The origin of the anorthite grains separated from the carbonaceous matrix by crushing and hand picking is not exactly known.

The isotopic analysis of magnesium in the plagioclase phases from Dengli, Tsarev, Raguli, Severnyi Kolchim and Kaidun was carried out on an ion microprobe (Cameca ims-4f) at a mass resolution of ~ 4000, adequate to resolve hydride and other molecular interferences (Goswami and Srinivasan 1994). As the inclusions in Dengli and Tsarev consist of pyroxene embedded in glassy plagioclase matrix, the analysis of the plagioclase phases with high Al/Mg was often hindered by contributions to the ion signal from the pyroxene grains with low Al/Mg. In order to avoid this problem, the analysis was done using a small diameter primary beam (low primary beam current). This, however, reduced the secondary ion signal resulting in larger statistical errors in the measured isotopic ratios. A similar problem in the case of Raguli was encountered due to contribution from chromite to Mg signal.

Isotopic analyses were carried out in the peak jumping mode by cycling the magnet through the mass sequence 24, 25 and 26 (mass 27 was also included during the analysis of samples from Dengli, Raguli and Tsarev). A typical analysis usually consisted of 25 blocks, with each block representing 5 cycles of data. The deviations in the measured magnesium isotopic ratios (^{26}Mg/^{24}Mg and ^{25}Mg/^{24}Mg) from the reference values were obtained using the relation

$$\Delta^i\mathrm{Mg} = [(^i\mathrm{Mg}/^{24}\mathrm{Mg})_{\mathrm{sample}}/(^i\mathrm{Mg}/^{24}\mathrm{Mg})_{\mathrm{ref.}} - 1] \times 1000 \text{ permil } (i = 25, 26).$$

The reference magnesium isotopic ratios used by us are: $(^{25}Mg/^{24}Mg) = 0{\cdot}12663$ and $(^{26}Mg/^{24}Mg) = 0{\cdot}13932$ (Catanzaro *et al* 1966). Correction for instrumental and intrinsic (sample) isotopic mass fractionation was done using the linear mass fractionation relation, $\Delta^{26}Mg = 2\Delta^{25}Mg$, to calculate any excess ^{26}Mg as:

$$\delta^{26}Mg = \Delta^{26}Mg - 2\Delta^{25}Mg.$$

If $\delta^{26}Mg$ is positive and this excess is attributed to *in situ* decay of ^{26}Al initially present in the object, one can write:

$$\begin{aligned}(^{26}Mg/^{24}Mg)_m &= (^{26}Mg/^{24}Mg)_i + (^{26}Mg^*/^{24}Mg)\\ &= (^{26}Mg/^{24}Mg)_i + (^{26}Al/^{27}Al)_i \quad (^{27}Al/^{24}Mg),\end{aligned}$$

where m and i refer to the measured and the initial values of the isotopic ratios and the * represents the radiogenic addition. This equation is linear between the variables $(^{26}Mg/^{24}Mg)_m$ and $(^{27}Al/^{24}Mg)$. For a well-behaved isotopic system, the slope and the intercept of this correlation line give the initial $^{26}Al/^{27}Al$ and $^{26}Mg/^{24}Mg$ at the time of formation of the analysed phase. In the case of samples from Raguli, Dengli and Tsarev, $^{27}Al/^{24}Mg$ ratio was obtained from the measured $^{27}Al^+/^{24}Mg^+$ ratio using appropriate yield factors (Srinivasan 1994). As mass 27 was not included in the analysis of

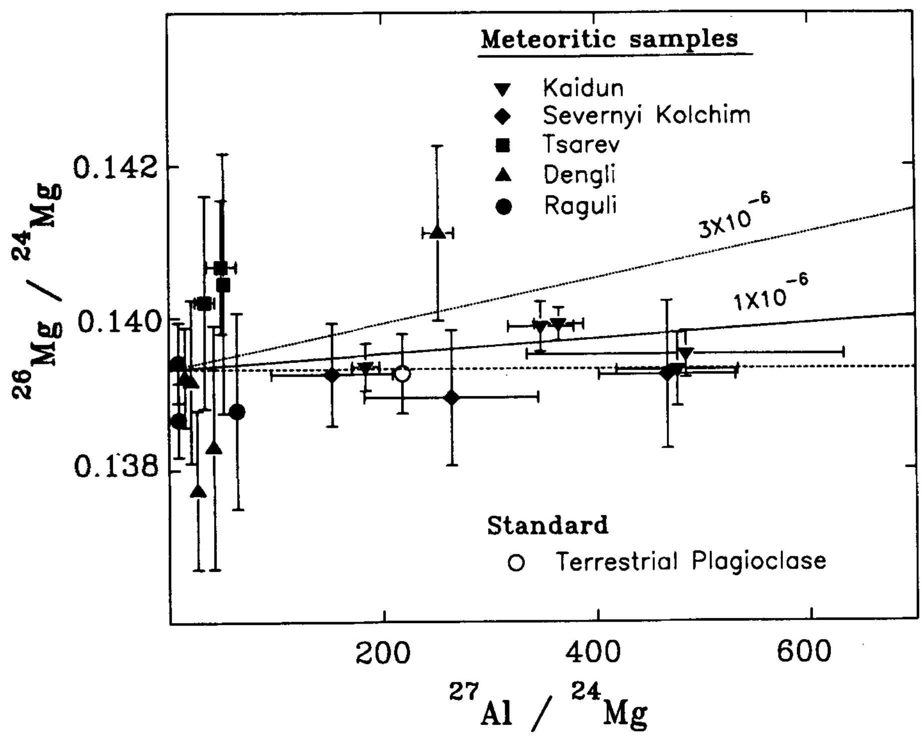

Figure 1. Measured isotopic ratios of $^{26}Mg/^{24}Mg$ in plagioclase phases plotted as a function of their measured $^{27}Al/^{24}Mg$ ratios. The dashed line represents the reference magnesium isotopic ratio ($^{26}Mg/^{24}Mg = 0{\cdot}13932$). The two dotted lines represent expected evolution of a closed Mg–Al isotope system for two values of initial $^{26}Al/^{27}Al$.

Severnyi Kolchim and Kaidun, we estimated this value from the mean of the measured $^{27}Al/^{24}Mg$ ratio before and after each analysis.

3. Results

The results of all the plagioclase analysed are given in table 1 and plotted in figure 1 together with data for terrestrial plagioclase standard. The low $^{27}Al/^{24}Mg$ for two out of the three analyses of Raguli suggests contribution to Mg signal from surrounding chromite. Any radiogenic contribution to ^{26}Mg will increase the $^{26}Mg/^{24}Mg$ ratio above the reference value of 0·13932. The magnesium isotopic composition in all the analysed phases is normal within experimental error except in the case of two anorthite grains from Kaidun. In addition, data from Dengli and Tsarev suggest a marginal excess. However the error limits are too large to rule out normal magnesium isotopic composition at 3σ level. The two anorthite grains from Kaidun show definite excess of

Table 1. Al–Mg data for plagioclase phases in chondritic meteorites.

Sample details	$^{27}Al/^{24}Mg$ $\pm 2\sigma_{mean}$	$\delta\,^{26}Mg$(‰) $\pm 2\sigma_{mean}$
Kaidun		
Anorthite # 1	365 ± 23	$4{\cdot}22 \pm 1{\cdot}57$
Anorthite # 2	184 ± 13	$0{\cdot}19 \pm 2{\cdot}22$
Anorthite # 3	476 ± 57	$-0{\cdot}13 \pm 3{\cdot}47$
Anorthite # 4	484 ± 149	$1{\cdot}35 \pm 2{\cdot}21$
Anorthite # 5	348 ± 31	$3{\cdot}99 \pm 2{\cdot}39$
Severnyi Kolchim		
(Igneous object)		
Analysis # 1	$152{\cdot}3 \pm 57{\cdot}3$	$-0{\cdot}48 \pm 4{\cdot}85$
Analysis # 2	$264{\cdot}2 \pm 81{\cdot}5$	$-2{\cdot}74 \pm 6{\cdot}40$
Analysis # 3	$466{\cdot}7 \pm 64{\cdot}1$	$-0{\cdot}59 \pm 7{\cdot}00$
Tsarev		
(Basaltic inclusion)		
Analysis # 1	$33{\cdot}4 \pm 8{\cdot}9$	$6{\cdot}34 \pm 10{\cdot}05$
Analysis # 2	$48{\cdot}7 \pm 13{\cdot}5$	$9{\cdot}70 \pm 6{\cdot}28$
Analysis # 3	$50{\cdot}9 \pm 5{\cdot}3$	$8{\cdot}14 \pm 12{\cdot}26$
Dengli		
Clast # 2; 1	$26{\cdot}3 \pm 0{\cdot}2$	$-11{\cdot}39 \pm 7{\cdot}46$
Clast # 2; 2	$20{\cdot}7 \pm 1{\cdot}3$	$-1{\cdot}17 \pm 7{\cdot}68$
Clast # 2; 3	$41{\cdot}6 \pm 1{\cdot}6$	$-7{\cdot}35 \pm 11{\cdot}53$
Silica bearing inclusion	$252{\cdot}2 \pm 14{\cdot}1$	$12{\cdot}64 \pm 8{\cdot}28$
Chondrule	$15{\cdot}1 \pm 1{\cdot}4$	$-0{\cdot}76 \pm 4{\cdot}71$
Raguli		
Chromite chondrule # 1	$62{\cdot}96 \pm 5{\cdot}00$	$-3{\cdot}90 \pm 9{\cdot}26$
Chromite chondrule # 2	$8{\cdot}83 \pm 0{\cdot}29$*	$0{\cdot}65 \pm 3{\cdot}78$
Chromite-plagioclase inclusion	$9{\cdot}31 \pm 0{\cdot}06$*	$-4{\cdot}77 \pm 3{\cdot}48$

*The low value suggests contribution to Mg signal from chromite.

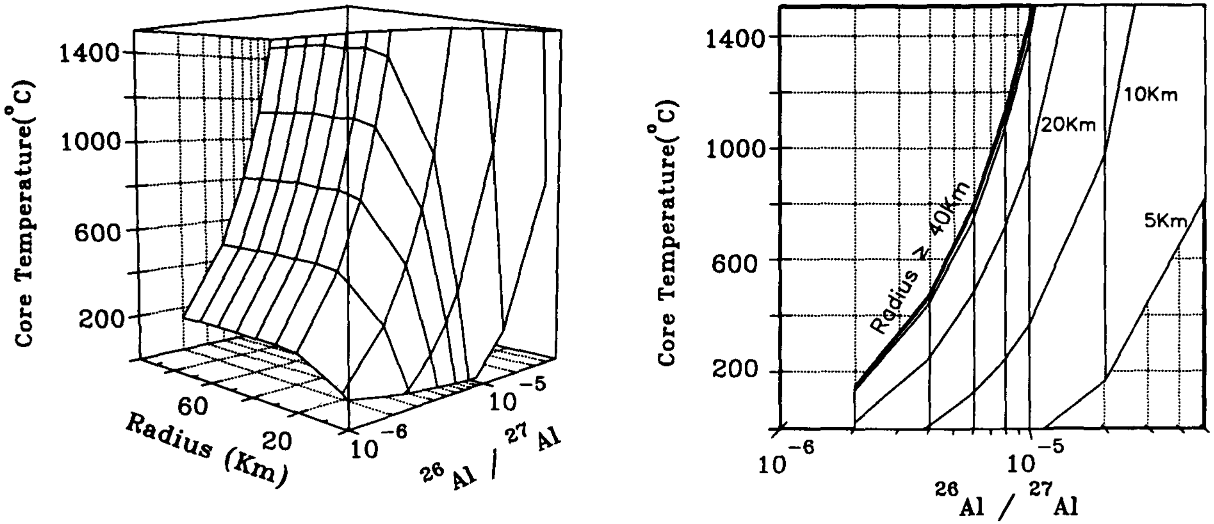

Figure 2. Maximum temperatures attained by chondritic objects of different sizes and initial $^{26}Al/^{27}Al$. A thermal diffusivity of 0·007 cm^2/sec and an initial temperature of 100°K were used in the calculations. The abundance of Al was assumed to be chondritic (1·22 weight per cent).

^{26}Mg with $\delta^{26}Mg = 4{\cdot}2 \pm 1{\cdot}6‰$ and $4{\cdot}0 \pm 2{\cdot}4‰$ (2σ error), whereas other anorthite grains from this meteorite have normal magnesium isotopic composition.

4. Discussion

The magnitude of thermal processing in a meteorite parent body due to radioactive heating by ^{26}Al depends on the initial abundance of ^{26}Al and the size of the object. Before discussing the present results, we first estimate the abundance of initial ^{26}Al (relative to its stable counterpart ^{27}Al) needed to induce thermal metamorphism and/or melting of small planetesimals that acted as meteorite parent bodies. We have used the heat conduction equation (Urey 1955) to calculate the temperature profiles inside meteorite parent bodies of chondritic composition and varying sizes assuming a range of initial $^{26}Al/^{27}Al$ at the time of their formation (figures 2 to 4). Figure 2 shows the maximum temperature attained in a meteorite parent body as a function of its size and initial abundance of ^{26}Al. For radius greater than 40 km, the maximum temperature attained in the body is independent of its size. The minimum value of initial $^{26}Al/^{27}Al$ (assuming chondritic abundance for ^{27}Al) required to induce thermal metamorphism ($T \sim 400°$–$950°C$) near the core region of a chondritic parent body is ~ 4–7×10^{-6}, whereas, an initial value of $\geqslant 8 \times 10^{-6}$ is required to initiate melting ($T \geqslant 1000°C$) if the radius is greater than 40 km. The temperature-time profile for a chondritic body (radius = 100 km) for an initial $^{26}Al/^{27}Al$ of 8×10^{-6} is shown in figure 3(a). As can be noted from the figure, such a body will be heated to temperature greater than 1000°C, except for the outer 20 km layer, that can result in partial melting of the object. However, for lower initial $^{26}Al/^{27}Al$ or for bodies of smaller radius ($\leqslant 40$ km), the temperature may not be sufficient for melting, even though it could be sufficient to initiate thermal metamorphism. For example, only the core region of a 40 km chondritic body with an initial $^{26}Al/^{27}Al$ of 8×10^{-6} (similar to the case just considered) will be heated to a temperature of $\sim$ 1000°C (figure 2) while the outer 20 km

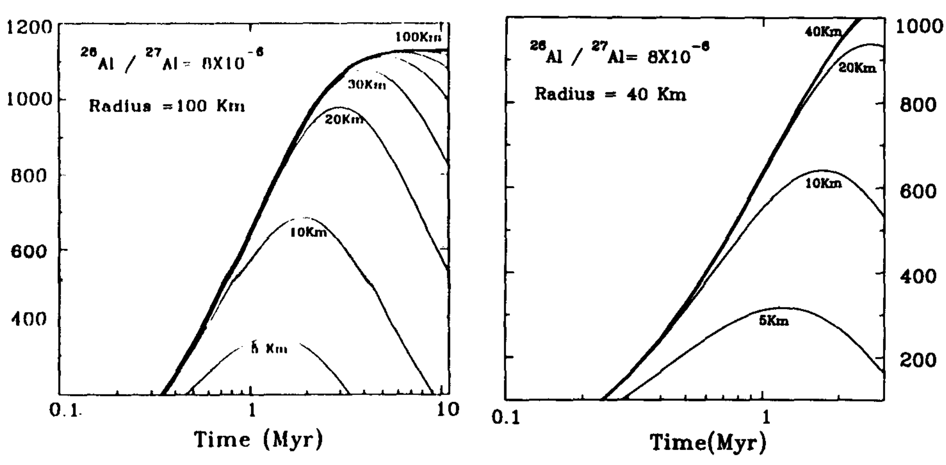

Figure 3. Temperature-time profiles for two chondritic objects of radii 100 and 40 kms for an initial $^{26}Al/^{27}Al$ of 8×10^{-6}. The variation of temperature at different distances from the surface is shown as a function of elapsed time.

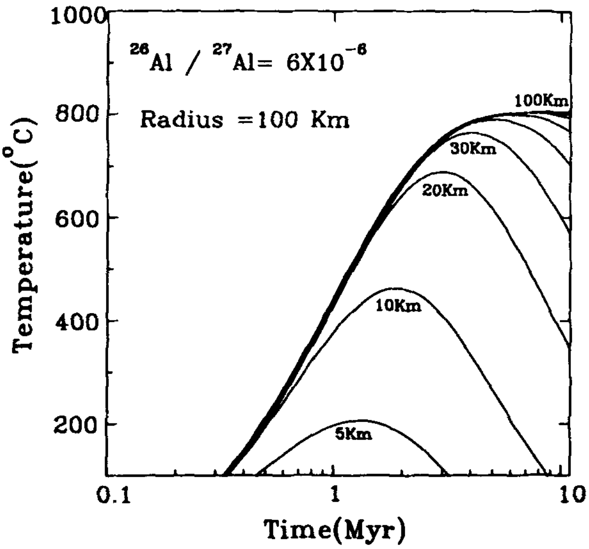

Figure 4. Temperature-time profile for a 100 km chondritic object with an initial $^{26}Al/^{27}Al$ of 6×10^{-6}.

of the object will experience temperature $\leqslant 900°C$ (see figure 3(b)). Even for a large object (radius = 100 km) with low initial $^{26}Al/^{27}Al$ of 6×10^{-6}, only the central region will be heated to temperature greater than 600°C for 2 to 5 Ma (figure 4). Obviously, these temperatures are insufficient for the melting of silicates, but they can cause varying degrees of thermal metamorphism generally observed in chondritic meteorites.

The results obtained in the present study indicate absence of excess ^{26}Mg in most of the analysed phases except for a marginal evidence in a few cases. These include an Al-rich phase in the silica-bearing inclusion from the Dengli chondrite, a plagioclase from Tsarev, and two anorthite grains from the Kaidun meteorite. While the large-error limits in the first two cases do not preclude normal magnesium isotopic composition, the data for Kaidun anorthite clearly show an excess. However, these anorthite grains, hand-picked from this multi-component meteorite, may not be representative products of large scale thermal metamorphism and could be fragments of Ca–Al-rich inclusions (CAIs) present in the CM component of this meteorite. As already noted in the introduction, there is abundant evidence for ^{26}Mg excess in CAIs that are believed to be the first solids to form in the solar system. In addition, not all of the anorthite grains analysed from Kaidun show ^{26}Mg excess. Thus we at best have a few grains with an upper limit of 1×10^{-6} for initial $^{26}Al/^{27}Al$, and the bulk of the analysed grains do not show any detectable ^{26}Al at the time of their formation. Even this upper limit is much below the value of 6×10^{-6} needed for initiating thermal metamorphism in meteorite parent bodies of chondritic composition. Our data therefore do not provide definitive evidence for the presence of residual ^{26}Al at the time of formation of the igneous components from different meteorites analysed by us.

Recent efforts by Hutcheon *et al* (1994) and Hutcheon and Jones (1995) to detect excess ^{26}Mg in Al-rich phases of chondrules and igneous inclusions also yielded negative results. Chondrules are believed to be products of rapid crystallization of melt droplets produced during mutual collisions of solids in a nebular environment and most probably formed after the CAIs, but before the meteorite parent bodies. One would therefore expect ^{26}Mg excess in chondrules if the distribution of ^{26}Al was widespread in the solar nebula. In the following we consider several possible alternatives that may explain the negative results obtained by us and others.

- The duration of thermal metamorphism/differentiation was much longer (several Ma) and magnesium isotopic exchange between the analysed Mg-poor(Al-rich) phases and co-existing Mg-rich phases was pervasive during this protracted period. Thus the closure of Al–Mg isotopic system in the analysed objects took place at a time when residual ^{26}Al was extremely small, leading to a barely detectable ^{26}Mg excess. For example, a solar system (CAI) initial $^{26}Al/^{27}Al$ of 5×10^{-5} would decrease to less than $2{\cdot}5 \times 10^{-6}$ within 3 Ma. However, the near surface zone ($\sim$ 10 km) of meteorite parent bodies, from which the chondritic meteorites were excavated and transported to earth during recent impacts, can effectively cool to low temperatures ($\leqslant 600°C$) within a much smaller time scale. In addition, most of the analysed samples in the present study are from chondritic meteorites of low metamorphic grades whose parent bodies did not experience long duration heating at elevated temperatures. Thus effective Mg isotopic exchange and re-equilibration prior to a late closure of Al–Mg isotopic system does not seem to be a plausible hypothesis to explain the absence of ^{26}Mg excess. Further, the observed initial $^{26}Al/^{27}Al$ of 2×10^{-7} in anorthite grains from the H4 chondrite Ste. Marguerite (Zinner and Göpel 1992), that has suffered a very low degree of thermal metamorphism, would require such a process to continue for an unreasonably long time interval of more than 5 Ma before the closure of the Al–Mg isotopic system. Finally, the absence of ^{26}Mg excess in Al-rich phases in chondrules (Hutcheon *et al* 1994; Hutcheon and Jones 1995) also cannot be explained in this scenario as the formation of chondrules is expected to precede the formation of meteorite parent bodies. Since theoretical modelling of the evolution of the early solar system suggests an extremely small time interval ($\ll 3$ Ma) between the formation of the CAIs and chondrules in carbonaceous chondrites (Cameron 1995), much later formation of chondrules in other chondritic meteorite types is difficult to explain.
- Another possible alternative that may explain the negative results is that the analysed phases experienced Mg isotopic redistribution and/or exchange with a reservoir of normal isotopic composition at a later time. In fact, this is believed to be the primary reason for the lower $^{26}Al/^{27}Al$ found in many of the CAIs compared to the generally accepted solar system initial value of 5×10^{-5}, characteristic of petrographically unaltered CAIs (e.g. Podosek *et al* 1992; Goswami *et al* 1994; MacPherson *et al* 1992, 1995). It is also known that most of the CAIs with lower initial $^{26}Al/^{27}Al$ show distinct evidence of secondary low-temperature alteration. So it is possible that the Al-rich silicate phases analysed by us have undergone secondary alterations following their formation resulting in Mg-isotopic re-equilibration to the observed normal values. Such an exchange/redistribution is possible if the analysed phases were derived via recrystallization of Al-rich glassy material during a late stage thermal event in a meteorite parent body (e.g. McSween and Grimm 1994).
- One can also postulate that ^{26}Al was not the primary heat source for early melting of planetesimals. Since radioactive heating is currently considered to be the most plausible cause for early melting of planetesimals, it is difficult to accept this proposition, particularly after ^{60}Fe has been ruled out as an effective heat source. However, absence of strong experimental evidence for residual ^{26}Al in samples from thermally metamorphosed/

differentiated meteorites points towards the need for a closure scrutiny of other physical processes e.g. electromagnetic induction by protosolar wind (Herbert *et al* 1991) suggested for early heating of planetesimals.

In summary, no definite evidence for the presence of residual ^{26}Al at the time of formation of igneous components from several chondritic meteorites has been found to support the case of this short-lived nuclide as the primary heat source for the early melting of planetesimals. Although the absence of ^{26}Mg excess in most of the analysed objects may be attributed to an extended period ($\geqslant 3$ Ma) of thermal processing of meteorite parent bodies resulting in a late re-equilibration of Mg isotopes, the negative results in samples from chondritic meteorites of lower metamorphic groups and the temperature profiles in meteorite parent bodies for different values of initial ^{26}Al/^{27}Al argue against this proposition. It is however difficult to rule out possible magnesium isotopic re-equilibration to normal values at a later time during the residence of the analysed phases in their parent bodies. But this has to happen in a widespread manner so as to affect samples of all the meteorite types analysed so far. Conclusive experimental evidence for the planetary scale presence of live ^{26}Al in the early solar system that will confirm this short-lived nuclide as the primary heat source for early melting of planetesimals is yet to be found.

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