

# Heterogeneous distribution of presolar grains in the early solar system

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Meteorites possess presolar grains that originated as condensates within other stellar environments. Recent high-precision Sr and Nd isotopic analyses of bulk meteorites provide evidence that a heterogeneous distribution of presolar grains existed in the early solar system.

**KEYWORDS:** Presolar grains, Nucleosynthesis, Solar system

## 1. Introduction

Meteorites that did not experience planetary differentiation are termed as “chondrites.” Some unequilibrated chondrites incorporated micrometer-scale primitive dusts, called presolar grains, which possess dramatically different isotopic compositions from other solar materials (compiled in [1]). Therefore, it has been considered that presolar grains originated as condensates within other stellar environments such as asymptotic giant-blanch i.e., AGB stars, supernovae, and novae. Hence, presolar grains offer a record of the individual nucleosynthesis of various elements existing in the solar system.

Despite the discovery of presolar grains in chondrites, the distribution of these grains and the corresponding information about the conditions in the early solar system are still obscure. Owing to their extremely anomalous isotopic compositions, a heterogeneous distribution of presolar grains in the early solar system would be reflected in the isotopic variety of bulk-scale meteorites. The isotopic deviation of meteorites from terrestrial rocks is termed “nucleosynthetic isotopic anomalies.” To focus on the distribution of solid materials in the early solar system, refractory trans-iron elements are suitable to measure the isotopic compositions of bulk-scale meteorites. Notably, trans-iron elements are predominantly synthesized through either a slow (s-process) or rapid (r-process) neutron-capture reaction in neutron-rich stellar sites; some proton-rich nuclides are synthesized via photodissociation and proton-capture reaction (p-process). In this study, nucleosynthetic isotopic anomalies of Sr and Nd are investigated to track the physicochemical process of presolar grains.

## 2. Experimental procedure

We investigated 16 types of bulk-scale chondrites. Measured samples were listed in Table I. Chondrites are divided into CCs (carbonaceous chondrites) and NCs (non-carbonaceous meteorites) based on isotopic systems [2]. As the evidence from the similarity to C-type asteroids and abundant organics and hydrous minerals, CCs are considered to form in the outer region of solar system compared to NCs. NCs contain enstatite chondrites (EC), ordinary chondrites (OC), and minor types of chondrites (e.g., Rumuruti chondrites; RC). CCs are classified into eight subgroups (CI, CM, CO, CV, CK, CR, CH, and CB) based on the O isotopic compositions, chemical compositions, and textural information.

Because bulk chondrites include acid-resistant presolar grains, complete sample digestion must be performed to conduct high-precision isotopic analysis. Recently, a complete digestion method has been developed to apply the isotopic analysis for bulk chondrites (e.g., as described in [3]). In this study, the powdered meteorite samples were digested by HF, HNO<sub>3</sub>, and H<sub>2</sub>SO<sub>4</sub> with high-pressure digestion system. After the digestion of samples, Sr and Nd were separated from the aliquots via cation-exchange and extraction chromatographic resin [4]. Finally, we measured Sr and Nd isotopic compositions with TIMS (Thermal Ionization Mass Spectrometer) [5].

**Table I.** Sr and Nd isotopic compositions of chondrites. The isotope ratios for meteorite samples are reported in  $\mu$  notation, which represents parts per 10<sup>6</sup> deviations from the mean values of terrestrial rocks ( $\mu^iM = (R_{\text{meteorites}}/R_{\text{terrestrial rocks}} - 1) \times 10^6$ ,  $R = {}^iM/{}^jM$ ).

Meteorites	Types	Find or fall	$\mu^{84}\text{Sr}$ [6]	$\mu^{150}\text{Nd}$	References ( $\mu^{150}\text{Nd}$ )
<i>Non-carbonaceous meteorites (NCs)</i>					
Y-691	EC	Find (Antarctica)	$4.9 \pm 15$	$11 \pm 12$	[6]
Y-980223	EC	Find (Antarctica)	$3.9 \pm 19$	$15 \pm 11$	[6]
Forest City	OC	Fall	$19 \pm 14$	$17 \pm 19$	[7]
Saratov	OC	Fall	$25 \pm 14$	$20 \pm 7.8$	[7]
Modoc (1905)	OC	Fall	$25 \pm 14$	$6.0 \pm 7.8$	[7]
Tuxtuac	OC	Fall	$23 \pm 16$	$13 \pm 7.8$	[7]
Saint-Séverin	OC	Fall	$21 \pm 16$	$23 \pm 12$	[7]
SAH 98072	EC	Find (Desert)	$24 \pm 14$	$-0.7 \pm 12$	This study
NWA 4814	RC	Find (Desert)	$12 \pm 14$	$11 \pm 11$	This study
<i>Carbonaceous chondrites (CCs)</i>					
Allende	CV	Fall	$83 \pm 12$	$27 \pm 13$	[7]
Kainsaz	CO	Fall	$58 \pm 16$	$26 \pm 7.1$	[6]
Murchison	CM	Fall	$57 \pm 8.3$	$24 \pm 12$	[7]
DaG 412	CK	Find (Desert)	$57 \pm 14$	$0.1 \pm 8.9$	This study
DaG 190	CO	Find (Desert)	$46 \pm 12$	$27 \pm 7.4$	[7]
Dho 1432	CR	Find (Desert)	$5.4 \pm 14$	$26 \pm 9.5$	[7]
SaU 290	CH	Find (Desert)	$12 \pm 17$	$9.3 \pm 9.5$	This study

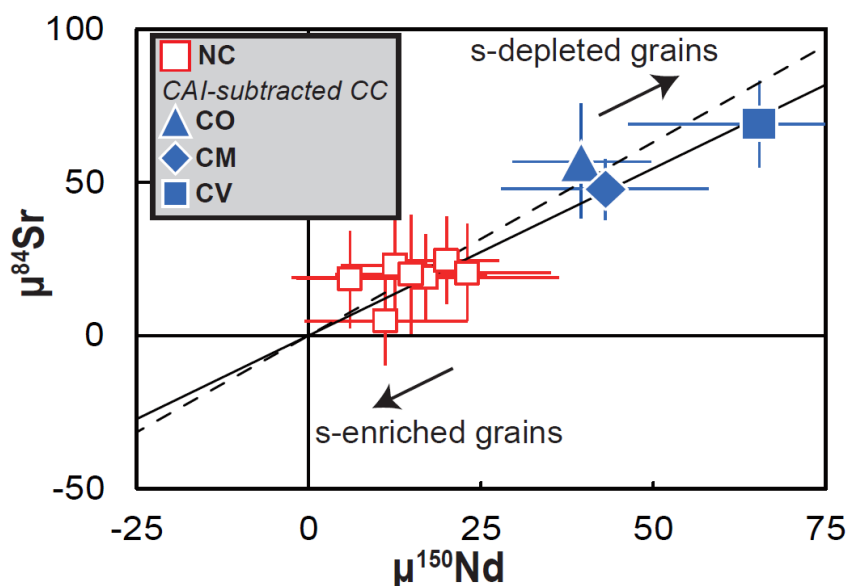
### 3. Strontium and neodymium isotopic anomalies

The Sr isotopic compositions of meteorites found in the “desert” have been modified due to the terrestrial alteration. Therefore, meteorites observed when they fell to the Earth (“fall” meteorites) and found in “Antarctica” were exclusively used to discuss.

CCs contain the isotopically anomalous inclusions condensed in the early solar system, called “CAI” (calcium-aluminum-rich inclusion). To focus the distribution of presolar grains in the early solar system, the Sr and Nd isotopic compositions of CAI were subtracted from bulk CCs by mass-balance calculation (Fig. 1; CAI-subtracted CC).

Results revealed a linear isotopic correlation between Sr and Nd isotopic anomalies ( ${}^{84}\text{Sr}/{}^{86}\text{Sr}$  versus  ${}^{150}\text{Nd}/{}^{144}\text{Nd}$ ) in terrestrial rocks and chondrites after the correction of CAI (Fig. 1). The bold line represents the mixing line of the Earth and s-process enriched (s-enriched) grains. It should be noted that s-enriched grains possess extremely low  ${}^{84}\text{Sr}/{}^{86}\text{Sr}$  and  ${}^{150}\text{Nd}/{}^{144}\text{Nd}$  ratios, because  ${}^{84}\text{Sr}$  and  ${}^{150}\text{Nd}$  are not synthesized by s-process. The data of chondrites were plotted on the s-process mixing lines and CCs (CV, CO, and CM) showed

deficit of s-process nuclides compared to NCs and the Earth. This finding suggests that Sr and Nd isotopic variations were induced by a heterogeneous distribution of s-enriched and/or depleted grains.



**Fig. 1.** A diagram of the  $\mu^{84}\text{Sr}$  and  $\mu^{150}\text{Nd}$  values of the non-carbonaceous meteorites (NCs) and CAI-subtracted carbonaceous chondrites (CCs). The isotope ratios for meteorite samples are reported in  $\mu$  notation, which represents parts per  $10^6$  deviations from the mean values of terrestrial rocks ( $\mu^i\text{M} = (R_{\text{meteorites}}/R_{\text{terrestrial rocks}} - 1) \times 10^6$ ,  $R = {}^i\text{M}/\text{M}$ ). The lines represent the mixing lines between s-process enriched grains (bold lines: [8]; dashed lines: [9]) and terrestrial rocks.

#### 4. Model for nucleosynthetic isotopic heterogeneity

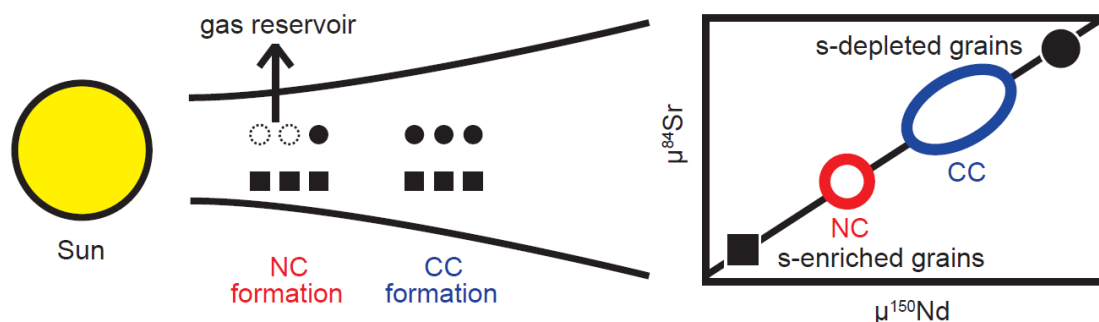
Several models have been proposed to explain the heterogeneity of presolar grains in the early solar system. The traditional model is that the homogenization of the molecular cloud and/or the protoplanetary disk was not complete before the planetesimal formation (e.g., as described in [10]). However, this model does not fully explain the variability in the nucleosynthetic isotope anomalies among trans-iron elements [11].

Alternatively, one of the most plausible scenarios accounting for the isotopic heterogeneity is the assumption that the solar system was initially homogeneous [11–12]. Based on this assumption, we also assume the existence of two endmember grains, s-enriched and depleted grains in the protoplanetary disk (Fig. 2). The thermodynamics simulation [13] suggests that s-enriched grains (likely SiC and graphite) has more refractory characteristics, compared to the s-depleted grains (likely silicate).

These grains would be homogeneously distributed in the initial phase of the formation of solar system. Subsequently, s-depleted grains present in the NCs formation region would be evaporated by thermal processing then incorporated into the gas reservoir (Fig. 2). This process was proposed by the observed depletion of several volatile elements in the Earth compared to CCs [14]. The plausible heat sources in the early solar system is radiation heating from Sun including some outburst events [15]. In contrast to NCs, CCs would not be affected by any thermal processing due to the long distance from Sun. Hence, a thermal gradient in the protoplanetary disk could feasibly cause the observed isotopic heterogeneities between NCs and CCs.

In contrast to Sr and Nd isotopic heterogeneity among chondrites, this heterogeneity has not been observed in some trans-iron elements. This inconsistency would be caused by the

volatility of elements, because the isotopic heterogeneity is absent both in volatile elements (e.g., Te [16]) and ultra-refractory elements (e.g., Os [17]). The thermal processing model likely explain this variability because these volatile and ultra-refractory elements could totally remain in the gas and solid phases respectively, during heating.



**Fig. 2.** Schematic image of the disk evolution model associated with thermal processing. Under thermal processing in the inner solar system, isotopic heterogeneities emerged among NC parent bodies and CC parent bodies.

## 5. Conclusion

Nucleosynthetic isotopic anomalies in bulk meteorites provide evidence that there was a heterogeneous distribution of presolar grains in the early solar system. The observed Sr and Nd isotopic anomalies could be induced by the heterogeneous distribution of s-depleted grains. This heterogeneous distribution of presolar grains may be explained by the thermal processing in the early solar system.

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