

STRONTIUM ISOTOPE ANOMALIES IN CA-AL-RICH INCLUSIONS AND THE RB-SR CHRONOLOGY OF VOLATILE DEPLETION REVISITED. U. Hans¹, T. Kleine², B. Bourdon¹. ¹Institute of Geochemistry and Petrology ETH Zürich, Clausiusstrasse 25, 8092 Zürich, Switzerland (ulrik.hans@erdw.ethz.ch), ²Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster.

Introduction: Many planetary objects are depleted in moderately volatile elements but the exact mechanisms involved remain unclear [1]. Constraining the timing of volatile depletion is key for understanding its causes. Such age constraints can be obtained from ⁸⁷Rb-⁸⁷Sr chronometry because Rb is volatile whereas Sr is refractory. Consequently, the initial ⁸⁷Sr/⁸⁶Sr of a volatile-depleted planetesimal records the time at which this planetesimal separated from the solar nebula or any other gas-rich reservoir.

Basaltic achondrites (eucrites, angrites) are ideally suited for the application of Rb-Sr chronometry because their parent bodies are examples of early, volatile-poor protoplanets. Previous studies used the initial Sr isotopic compositions of angrites and eucrites to infer that their parent bodies accreted late, more than 2 and 3 Myr after CAI formation, respectively [1,2,3]. This interpretation is based on the observation that angrites and eucrites have initial ⁸⁷Sr/⁸⁶Sr slightly higher than that of Ca-Al-rich inclusions (CAI) [5,6]. Such late losses of volatile elements are unlikely to be related to processes within the solar nebula but more likely would reflect volatile losses associated with energetic collisions between planetesimals and some other larger bodies [1].

Here we present high precision Sr isotope data for basaltic achondrites and CAI that lead to timescales of accretion and volatile depletion significantly different from those calculated previously [1,2,3].

Analytical techniques: Pieces of angrites, eucrites and CAI were gently crushed in an agate mortar, separated in different grain size fractions. The separates were cleaned by ultrasonication in ethanol, washed in cold 2 M HCl and then ultrasonicated in 1 M HCl for ten minutes. All samples were dissolved in closed Savillex vials in HF-HNO₃. Rb and Sr concentrations were determined by isotope dilution on ~10 % aliquots of the digestion solution. For all aliquots, Rb and Sr were purified for mass spectrometry analyses using standard cation exchange techniques.

High precision Sr isotope measurements were performed in multi-dynamic mode using the Thermo-Finnigan Triton thermal ionization mass spectrometer at ETH Zurich. All runs were normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194 and measured with ~20 V on ⁸⁸Sr. For each run, 600 ratios were obtained, resulting in within-run precisions of ± 2-4 ppm for ⁸⁷Sr/⁸⁶Sr. Repeated analyses of NBS 987 during the course of this study yielded ⁸⁷Sr/⁸⁶Sr = 0.710250±0.000003 (2 SD). The external precision of our measurements thus is ±4 ppm (2 SD),

which is a factor of 4-5 more precise than the reproducibility that could be obtained using older generations of TIMS. Rubidium isotope dilution measurements were performed on a Nu Plasma MC-ICPMS at ETH Zurich using admixed Zr for mass bias correction. Sr isotope dilution measurements were performed using TIMS.

Results: Rb-Sr data for angrites obtained in this study are shown in Fig. 1 along with previously published data for angrites. The data plot along two distinct trends, one which is the 4.56 Ga reference line calculated using an initial ⁸⁷Sr/⁸⁶Sr measured for a D'Orbigny plagioclase with ⁸⁷Rb/⁸⁶Sr~0. The Sr isotope composition of these samples most likely reflects accumulation of radiogenic ⁸⁷Sr from ⁸⁷Rb decay since their crystallization. The other trend is defined by samples of Angra dos Reis and D'Orbigny, which have indistinguishable ⁸⁷Sr/⁸⁶Sr but variable ⁸⁷Rb/⁸⁶Sr, indicating a recent addition of Rb to these angrites. Thus, using the measured ⁸⁷Rb/⁸⁶Sr to correct for ⁸⁷Rb-decay results in spuriously low initial ⁸⁷Sr/⁸⁶Sr for these samples. The initial ⁸⁷Sr/⁸⁶Sr determined in this study is higher than those obtained in previous studies [2,3] but is indistinguishable from that of eucrites.

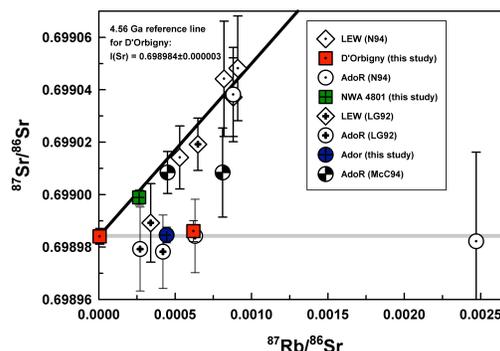


Figure 1: Rb-Sr data for angrites obtained for this study compared to previously reported data. LG92 = [2], N94 = [3], McC = [3]

Fig. 2 shows Rb-Sr data for Allende CAI obtained in this study along with data from previous studies [5,6]. All the CAI analyzed here plot along a 4.56 Ga reference line and are consistent with Rb-Sr data obtained for CAI previously. However, the ⁸⁷Rb/⁸⁶Sr ratios of the CAI samples investigated in this study are too high to determine a meaningful initial ⁸⁷Sr/⁸⁶Sr of CAI. Nevertheless, Fig. 2 shows that the initial ⁸⁷Sr/⁸⁶Sr of the CAI analyzed here is similar to that of the CAI investigated in previous studies [5,6]. The lowest

$^{87}\text{Rb}/^{86}\text{Sr}$ ratio was obtained here for ALL#1-6 and its calculated initial $^{87}\text{Sr}/^{86}\text{Sr}$ is in agreement with values obtained from CAI 3529-Z [5] and D7 [6].

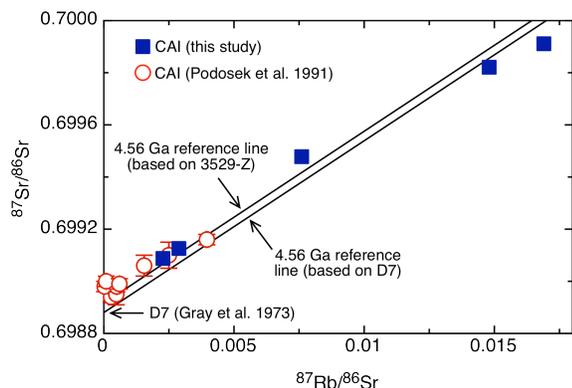


Figure 1: Rb-Sr data for Allende CAI obtained in this study. CAI data from [5] and [6] are shown for comparison. Solid lines represent 4.56 Ga reference lines, calculated using the initial Sr isotope composition reported for Allende CAI 3529-Z and D7.

Fig. 3 shows the $^{84}\text{Sr}/^{86}\text{Sr}$ ratios determined for basaltic achondrites and CAI. While angrites and eucrites have $^{84}\text{Sr}/^{86}\text{Sr}$ ratios that are indistinguishable from that of the Earth, all the investigated CAI are characterized by ^{84}Sr excesses of between 75 and 150 ppm relative to terrestrial Sr.

Discussion: The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of angrites as obtained from data for D'Orbigny, Angra dos Reis and NWA 4801 (Fig. 1) is ~ 100 -150 ppm higher than the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of CAI 3529-Z [5] and D7 [6] (Fig. 2). This difference may be used to determine the timing of volatile loss from the angrite parent body, which requires an assumption regarding the Rb/Sr ratio of the material from which the angrite parent body accreted. For instance, if this material had a solar Rb/Sr, then Rb-loss occurred at ~ 3 Myr after CAI formation (relative to CAI 3529-Z [5]). This interpretation is consistent with those of previous studies [1,2,3] and would require that these planetary bodies started off as relatively volatile-rich objects that catastrophically lost their volatiles late [1].

However, the ^{84}Sr excesses observed in CAI compared to the basaltic achondrites and Earth indicate that the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of CAI is not representative for the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the material that accreted to the angrite and eucrite parent bodies (and other inner solar system objects). The elevated $^{84}\text{Sr}/^{86}\text{Sr}$ of the CAI reflects excesses either in p-process isotopes (which would result in a higher abundance of ^{84}Sr) or in r-process isotopes (which would result in a higher abundance of ^{88}Sr). The Mo isotope compositions of A-ZH-2 and A-ZH-4 reveal that these two CAI, as many other CAI, are enriched in r-process isotopes [7]. The measured elevated $^{84}\text{Sr}/^{86}\text{Sr}$ of at least these CAI thus

reflects their anomalously high $^{88}\text{Sr}/^{86}\text{Sr}$, which was used for mass fractionation correction during the mass spectrometric analyses.

An anomalously high $^{88}\text{Sr}/^{86}\text{Sr}$ in CAI also affects the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and results in measured values that are too low. An important observation from the Sr isotope data is that the magnitude of the ^{84}Sr excess observed for CAI (75-150 ppm) is about the same as the difference in initial $^{87}\text{Sr}/^{86}\text{Sr}$ between angrites and CAI (100-150 ppm). Thus, the different initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the basaltic achondrites and CAI do not result from radiogenic ^{87}Sr ingrowth prior to a late catastrophic volatile loss, they rather reflect nucleosynthetic Sr isotope anomalies in Allende CAI.

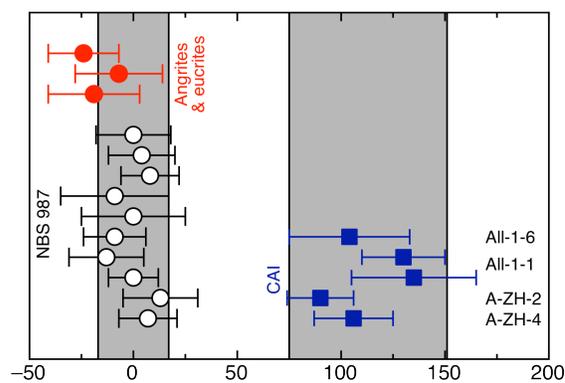


Figure 3: $^{84}\text{Sr}/^{86}\text{Sr}$ ratios for $\mu^{84}\text{Sr}$ basaltic achondrites and Allende CAI. The data are plotted as $\mu^{84}\text{Sr}$, which is the deviation from the terrestrial standard value in parts per 10^6 . The gray shaded bar at $\mu^{84}\text{Sr} = 0$ represents the external reproducibility (2 SD) of the NBS 987 measurements. The gray shaded bar beneath the CAI data represents the average $\mu^{84}\text{Sr}$ of the CAI investigated here.

Once the ^{84}Sr excesses of the CAI are taken into account, their initial $^{87}\text{Sr}/^{86}\text{Sr}$ is indistinguishable from those of the angrites and eucrites. Volatile loss from the basaltic achondrite parent bodies thus occurred very early, about contemporaneously to CAI formation. The volatile-poor nature of these planetary objects thus most probably reflects their early accretion from a solar nebula, whose volatile elements had yet not fully condensed. Finally, the early accretion of the angrite and eucrite parent bodies as inferred here from Rb-Sr chronometry is consistent with Hf-W evidence for very early accretion and differentiation of iron meteorite parent bodies [8].

References: [1] Halliday and Porcelli (2001) *EPSL* 192, 545-559. [2] Lugmair and Galer (1992) *GCA* 56, 1673-1694. [3] Nyquist et al. (1994) *Meteoritics* 29, 872-885. [4] McCulloch (1994) *EPSL* 26, 1-13. [5] Podosek et al. (1991) *GCA* 55, 1083-1110. [6] Gray et al. (1973) *Icarus* 20, 213-219. [7] Burkhardt et al. (2011) *this volume*. [8] Kleine T. et al. (2005) *GCA* 69, 5805-5818.