

EVAPORATION KINETICS OF FORSTERITE-RICH MELTS AND THERMAL HISTORIES OF FUN CAIs. R. A. Mendybaev^{1,2}, F. M. Richter^{1,2}, R. B. Georg³, and A. M. Davis^{1,2}. ¹Chicago Center for Cosmochemistry, ²Department of the Geophysical Sciences, University of Chicago, Chicago, IL (ramendyb@uchicago.edu), ³Department of Earth Sciences, University of Oxford, United Kingdom.

Introduction: Chondrules and CAIs are the most distinctive components of chondrites and provide important constraints on the thermal history of early solar system materials. The texture and chemical composition of the chondrules suggests (e.g., [1]) that these objects have experienced heating at temperatures of 1550°C or more for about a minute or less followed by a rapid cooling with initial cooling rates up to several thousand degrees Celsius per hour. Unlike chondrules, which shows no isotopic anomalies of major elements suggesting that they have formed in dust-rich environments saturated in more volatile components, CAIs are enriched in heavy isotopes of Mg and Si with $\delta^{25}\text{Mg}$ correlating with $\delta^{29}\text{Si}$. This enrichment in heavy isotopes is usually attributed to the evaporation of Mg and Si from molten or partially molten droplets. The mineralogical composition and coarse-grained texture of “normal” Type B CAIs suggest that their precursors must have been rapidly heated to about 1400°C (but not much higher) and then cooled at 1 to 50° C/hr [2].

Fun CAIs are a group of CAIs that are extremely enriched in heavy Mg and Si isotopes, with $\delta^{25}\text{Mg}$ up to ~30‰ and $\delta^{29}\text{Si}$ of 10 to 15‰. Mineralogically they are either forsterite-rich or indistinguishable from “normal” Type B CAIs. The enrichment in ^{25}Mg and ^{29}Si follows the same trend established by “normal” CAIs suggesting that the extremely large Mg and Si fractionations of FUNs are also the result of evaporation. To test this proposition we conducted a set of evaporation experiments in which spherules of different compositions were melted in the high temperature vacuum furnace at the University of Chicago. Here we present the results of these experiments in terms of constraints on thermal histories of FUN CAIs.

Experimental: We used as starting materials FUN1 which is extremely forsterite-rich melt with only 3 wt.% of Al_2O_3 and 2.5wt.% CaO ; and FUN2, a composition close to that of FUN CAI Vigarano 1623-5. Because of the high melting temperatures of forsterite-rich FUN1 composition, the evaporation experiments were conducted in a vacuum furnace ($P \leq 10^{-6}$ torr) at a fixed temperature of 1900°C. Otherwise, the experimental procedure was the same as described in detail in our previous work. (e.g., see [3-5]).

Results and Discussion: Fig. 1 shows evaporation trajectories of residues from FUN1 and FUN2 starting compositions.

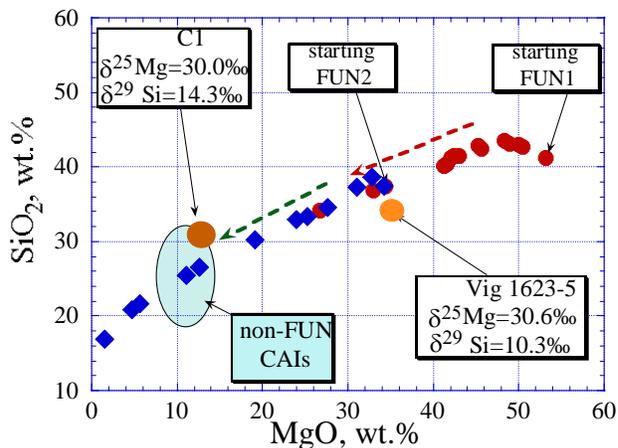


Fig. 1. MgO and SiO₂ concentrations in Vigarano 1623-5 and C1 FUN CAIs, and in evaporation residues from vacuum experiments at 1900°C when FUN1 (red) and FUN2 (blue) starting materials were used. Measured values of $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ in two FUN CAIs are also shown.

The FUN 1 composition was made by adding Mg in the form of forsterite to the composition of Vig1623-5 in such an amount that evaporation of FUN1 would result in $\delta^{25}\text{Mg} \sim 30\%$ when it reaches the composition of Vig1623-5. FUN2 starting composition is close to that of Vig1623-5. The plot shows that the evaporation trajectory for FUN1 melt passes very close to the composition of Vig1623-5 after 30-35 min evaporation at 1900°C. Furthermore, the values of $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ (~31‰ and ~15‰, respectively) in the evaporation residues with bulk composition close to Vig1623-5 are close to those of Vig 1623-5 (31.6‰ and 10.3‰, respectively), which suggest that FUN1 is a reasonable precursor of the Vig1623-5. The evaporation trajectory of FUN2 melt continues the trend established by FUN1 and passes (again after 30-35 minutes of evaporation) through the composition field of non-FUN CAIs. The values of $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ in the evaporation residues close in composition to C1 FUN CAI are ~26‰ and ~11‰, correspondingly, which again are close to the values measured in C1 ($\delta^{25}\text{Mg}=30.0\%$ and $\delta^{29}\text{Si}=14.3\%$).

The weight loss of FUN1 and FUN2 as a function of time is shown in Fig. 2. The evaporation rate is 0.027 ± 0.005 mg/mm²/min, which is much the same as for Type B CAI-like melt (0.022 ± 0.004 mg/mm²/min

at 1900°C). Assuming that the activation energy of evaporation of FUN melt in vacuum is close to ~595 KJ/mole measured by us for CAIB melt, which is also close to ~580 KJ/mole for molten forsterite (Hashimoto, 1990), we obtained the following evaporation rates as a function of temperature: 0.11 mg/mm²/min at 2000°C, 0.0057 mg/mm²/min at 1800°C and 0.0011 mg/mm²/min at 1700°C.

Fig. 3 shows estimated timescales required to evaporate FUN melts with typical sizes of 2.5, 5.0 and 10 mm in vacuum to a degree such that $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ values will be close to those measured in Vig1623-5 and C1 FUN CAIs. The estimated timescales for 5 mm droplets would be only about 10 min at 2000°C, 1 hr at 1900°C, 4 hrs at 1800°C, and 20 hrs at 1700°C. For 2.5 mm and 10 mm samples the timescales will be two times shorter or longer, respectively. In a hydrogen-rich gas the evaporation rates will be significantly higher than in vacuum and thus the timescales considerably shorter [3].

Taking into account petrological observations and the results of the evaporation kinetics we can place constraints on the temperature range experienced by FUN CAIs. We expect that the temperature must have been at least 1750°C based on the melting temperatures of FUN2-like compositions (FUN1 compositions would require even higher temperatures). If the precursor of the FUN CAIs were flash heated to temperatures of 2000°C or higher then in order to survive such high temperatures and have $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ values of 30 and 10 per mil, respectively, the droplets have to cool at the rate of several thousands degree per hour, which seems highly unlikely because of coarse-grained textures of FUN CAIs. Therefore, we would expect that the precursors of FUN CAIs were not heated to temperatures much higher than 1900°C. The duration of the heating is limited by several minutes which is required to produce significant enrichment in heavy Mg and Si isotopes at ~1900°C. We expect that the upper bound of the timescale will be around a day or so constrained by the lifetimes of the droplets (complete evaporation).

Conclusions: 1) Evaporation kinetics of forsterite-rich (FUN) melts at 1900°C is the same as that of Type B CAI-like composition. 2) Timescale for 5 mm FUN-droplets to establish $\delta^{25}\text{Mg}$ and $\delta^{29}\text{Si}$ values of 30‰ by evaporation in vacuum are ~10 min at 2000°, 1 hr at 1900°, 4 hrs at 1800°, and 20 hrs at 1700°C, and several times shorter if evaporated in hydrogen-rich gas. 3) Extremely short timescales at $T \geq 2000^\circ\text{C}$ would require very fast cooling (several thousand degrees per hour) which seems unlikely due to coarse-grained texture of FUN CAIs.

References: [1] Yu Y. et al. (1996) In: *Chondrules and the protoplanetary disk* (Eds. Hewing R. H., Jones R. H., and Scott E. R. D.), 213-219. [2] Stolper E. and Paque J. M. (1986) *GCA*, 506, 1785-1806. [3] Richter F. M. et al. (2002) *GCA*, 66, 521-540. [4] Richter F. M. et al. (2007) *GCA*, 71, 5544-5564. [5] Mendybaev R. A. et al. (2008) *LPS XXXIX*, Abstract #2345. [6] Hashimoto A. (1990) *Nature*, 347, 53-55.

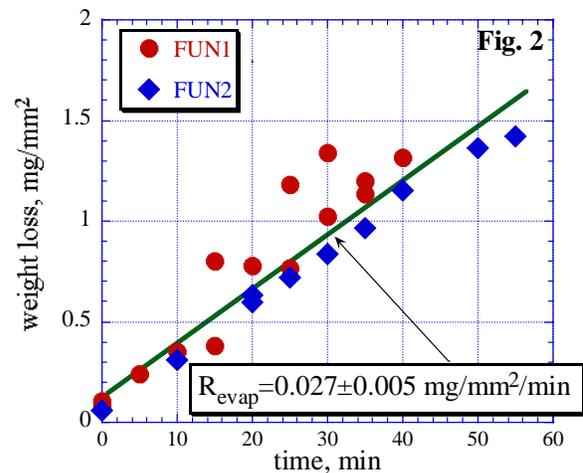


Fig. 2. Evaporation kinetics of forsterite-rich melts at 1900°C in vacuum.

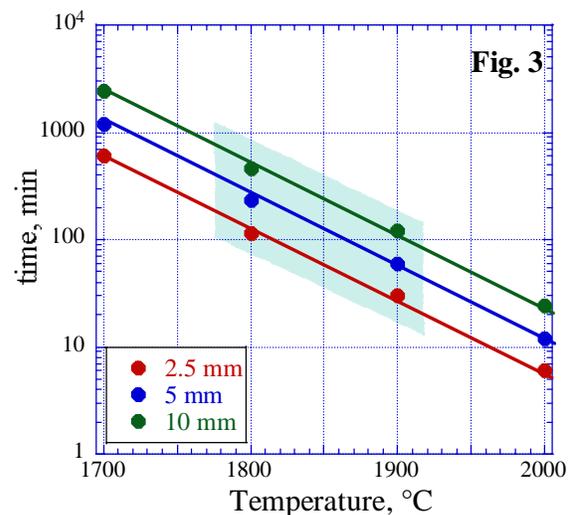


Fig. 3. Estimated timescales required to evaporate molten droplets of FUN compositions of 2.5, 5 and 10 mm in diameter into a vacuum. The box represent the the range of temperatures that would allow sufficient isotopic fractionation and cooling rates to produce FUN-like textures.