

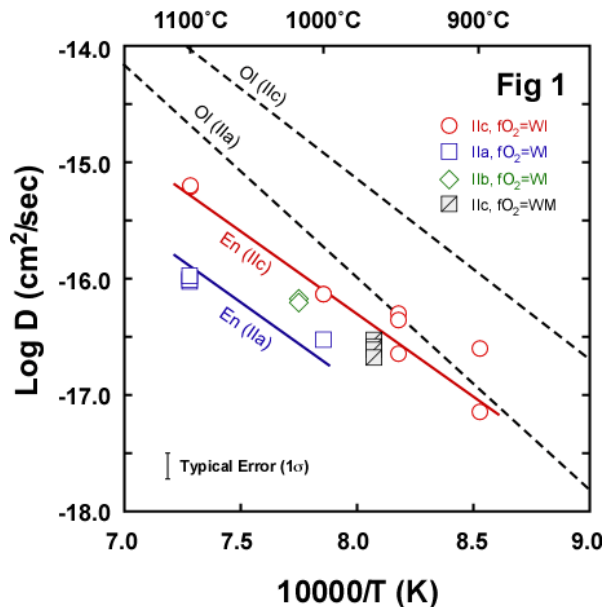
Mn-Cr THERMOCHRONOLOGY OF EARLY SOLAR SYSTEM PROCESSES. J. Ganguly¹, M. Ito² and X. Zhang¹, ¹ Department of Geosciences, University of Arizona (ganguly@geo.arizona.edu), ²RI Center, University of Tokyo (motoo@ric.u-tokyo.ac.jp).

Introduction: The ⁵³Mn-⁵³Cr decay system, with a half-life of 3.7 Myr, has emerged as an important chronometric tool to study the time scales of events in the early solar system when ⁵³Mn was still extant. Using recent developments in closure temperature theory [1,2], which will be referred to as Dodson-Ganguly-Tirone or DGT formulation, the extent of resetting of Mn-Cr mineral age can also be used to extract important constraints on the high temperature cooling rate if diffusion data for Cr in the commonly used isochron minerals, such as olivine and pyroxene, are available. We have, thus, undertaken a systematic experimental study of the required diffusion kinetic properties, used these data to develop thermochronological formulations and applied the latter to extract information on cooling rate and burial depths of meteorite samples in their parent planetary bodies.

Experimental: Gem quality natural crystals of forsterite (Fo₉₁) and enstatite (En₉₆) were oriented by single crystal X-ray diffraction, cut normal to a-, b- and c- crystallographic directions, and polished to mirror-finish. The samples were pre-annealed at 1 bar and T-fO₂ conditions at or close to those of diffusion experiments. A thin layer of Cr was deposited on the polished surface of a pre-annealed crystal by thermal evaporation of Cr₂O₃ under high vacuum condition. Tracer diffusion profile of Cr was induced by annealing a sample with Cr surface layer at a temperature between 900-1100°C. The fO₂ was controlled by a computer regulated flowing mixture of CO and CO₂, and monitored by a zirconia sensor. After diffusion anneal, the sample was analyzed by depth profiling in an ion microprobe by secondary ion mass spectrometry (SIMS), as described in [3].

Results: The diffusion data were modeled by appropriate solution of the diffusion equation, and a numerical optimization program [3]. Fig. 1 shows a composite Arrhenian plot of Cr diffusion in olivine [3] and enstatite, along with the experimental data for the latter. As in the case for olivine, there is no significant fO₂ dependence of D(Cr) in orthopyroxene between those of wüstite-iron (WI) and hematite-magnetite (HM) buffers. The diffusion is anisotropic in both minerals, with the fastest and slowest diffusion directions being parallel to the c-axis and a-axis, respectively. The activation energy of Cr diffusion in Ol and Opx //c-axis are ~300 and 287 kJ/mol, respectively.

Closure Temperatures and Thermochronological Relations: In the classic Dodson formulation [4],



the closure temperature (T_C) of a geochronological system in a mineral depends only on cooling rate and grain size. It was, however, shown by Ganguly and Tirone [1,2] that in a slowly diffusing system, the T_C also depends on the initial temperature, T_0 . Fig. 2 shows the T_C of olivine and orthopyroxene as function cooling rate and grain size at $T_0 = 900^\circ\text{C}$, using the average D values for diffusion parallel to c- and a-axis in each mineral. The diffusion data were used to calculate the relationship between the extent of resetting of Mn-Cr cooling age and cooling rate according to the DGT formulation [1,2] and a non-linear cooling model according to $1/T = 1/T_0 + \eta t$. These results are illustrated in Fig. 3 for grains with spherical geometry. Both T_C and cooling rate-cooling age relationship for olivine are taken from [3]. These graphical formulations or the corresponding computer programs can be used to retrieve cooling rates at high temperatures from the extent of resetting of the Mn-Cr cooling age of olivine and orthopyroxene, if data for T_0 and grain size of crystals used in the mass spectrometric analyses are available.

Applications: We show illustrative applications of the Mn-Cr thermochronologic formulations to meteorite samples using the available data on olivine/orthopyroxene-chromite mineral ages [5].

Pallasite Omolon. Using the data in [5], it was concluded [3] that the age loss (Δt) of the Mn-Cr sys-

tem in olivine in the pallasite Omolon since the parent body formation is ~ 10 -5Myr. With $T_0 = 1100^\circ\text{C}$ and ~ 5 mm diameter average grain size that were used in the mass spectrometric analyses, these results yield average cooling rate between T_0 and T_c (~ 985 - 1000°C) of ~ 20 - 40°C/Myr , which extrapolates to ~ 10 - 17°C/Myr at 500°C , in agreement with the metallographic results [6,7], according to the non-linear cooling law used in the modeling. It is, thus, concluded [3] that the pallasite Omolon experienced a smooth cooling history, instead of a two stage cooling history, as suggested earlier [8]. The inferred cooling rate implies a burial depth of ~ 30 km, which should correspond to the core/mantle boundary, in a parent body of at least ~ 100 km radius.

Cumulate eucrites. Using the Mn-Cr orthopyroxene-chromite ages of the cumulate eucrites Moore County and Serra De Mage, and the time of HED parent body formation [5], we conclude that the age loss (Δt) of orthopyroxene crystals during cooling of the parent body are ≥ 16 Myr for Moore County and 10-16Myr for Serra De Mage. Unfortunately, no data on grain size of OPx that were used in the mass spectrometric analyses are available. We assume the grain diameters were 1-5mm.

The Fe-Mg ordering data in orthopyroxene in Serra De Mage [9] suggest a cooling rate of $\sim 10^3^\circ\text{C/Myr}$. Such rapid cooling rate reflects cooling under near-surface condition after the samples were ejected from their original sites and buried within a regolith blanket. Using a peak temperature of the regolith of 900°C and the above cooling rate, it can be shown that no significant age loss of the Mn-Cr system in OPx was possible when the sample of Serra De Mage was buried within a regolith. Thus, the inferred age loss of orthopyroxenes was essentially due to slow cooling at their original sites.

Phase equilibrium data suggest that orthopyroxene in cumulate eucrites crystallized at $T < 1140^\circ\text{C}$ [10]. Thus, we assume $T_0 = 1000$ - 1100°C . The combination of T_0 , Δt and the assumed value of grain size of the cumulate eucrites yield, according to Fig. 3, cooling rate of ~ 5 - 25°C/Myr for Serra De Mage and $\leq 15^\circ\text{C/Myr}$ for Moore County. Using [12], these cooling rates suggest burial depth (Z) of ~ 15 - 30 km for the Serra De Mage and ≥ 20 km for the Moore County cumulate eucrites, if the parent body, assumed to be Vesta, was completely rocky during cooling to the closure temperatures ($\geq 900^\circ\text{C}$) for Cr diffusion in OPx. Consequently, the eucrite upper crust in the HED parent body extended beyond 20 km depth.

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