DIFFUSION KINETICS OF Cr IN OLIVINE AND ^{53}Mn-^{53}Cr THERMO-CHRONOLOGY OF EARLY SOLAR SYSTEM OBJECTS.
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Introduction: The short lived ^{53}Mn-^{53}Cr decay system ($t_{1/2}$ = 3.7 Myr) has emerged as an important chronometer for the study of time scales of processes in the early history of the solar system when ^{53}Mn was still extant [1,2,3]. Excess ^{53}Mn relative to the terrestrial values has been detected in olivines from different types of meteorites. The interpretation of Mn-Cr mineral ages of olivine requires quantitative understanding of its closure temperature, which can be calculated from the diffusion kinetic property of Cr. In addition, if the latter is known, the extent of resetting of ^{53}Mn-^{53}Cr age of olivine during cooling can be used to retrieve the cooling rate, thereby providing a new planetary thermo-chronometer that is applicable to the early solar system processes. We have, thus, determined the diffusion coefficient of Cr in olivine as a function of temperature at controlled fO_2 condition, and applied these data to calculate the closure temperature of this decay system in olivine, the closure (Mn-Cr) age profile in single crystals, and cooling rate of pallasite from the available data on the resetting of the Mn-Cr mineral age [1].

Experimental Procedure: Gem quality natural olivine crystals, Fo_{84}, were oriented in a single crystal X-ray diffractometer and cut normal to the c axis. One face of the cut slice was polished to a mirror finish by a combination of chemical and mechanical polishing.

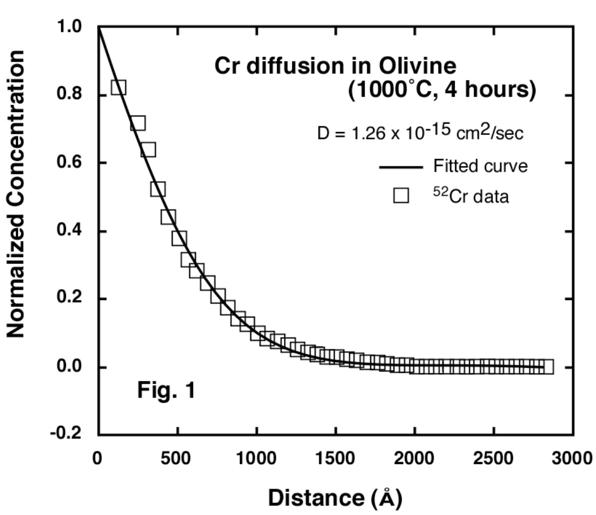

Fig. 1. Typical depth profile of ^{52}Cr diffusion parallel to the *c-axis* in olivine, and model fit according to the appropriate solution of the diffusion equation.

These slices were pre-annealed for 24 hours at 900°C and fO_2 corresponding to that of wüstite-iron (WI) buffer by a flowing gas mixture of CO and CO_2. Thin layers of Cr were deposited on the polished surfaces of the pre-annealed crystals by thermal evaporation of Cr_2O_3 under a high vacuum condition. The crystals with Cr thin films were annealed at temperatures between 900 and 1100°C (P = 1 bar) to induce isothermal Cr diffusion profiles parallel to the c axis. fO_2 was controlled as above and monitored continuously by a zirconia sensor. The experimental diffusion profiles of Cr in olivine were analyzed (as ^{52}Cr) by depth profiling in an ion probe (Cameca, ims-3f SIMS) using a primary beam of mass filtered $^{16}O^-$. The crater depths were measured by a surface profilometer that was calibrated against known standards.

Results: Fig. 1 shows a typical diffusion profile of ^{52}Cr parallel to the c-axis in olivine, and a model fit to the data using the solution to the diffusion equation in a semi-infinite slab with fixed surface concentration of the diffusing species. The experimental data at 900, 1000 and 1100°C (P = 1 bar and fO_2: WI buffer) yield an Arrhenius relation of D = 2.28e-2 x *exp*(-E/RT) cm^2/s with E (activation energy) = 323 kJ/mol.

Closure Temperatures & Age Profiles: Using the above diffusion data, we have calculated the closure temperature of Cr diffusion in olivine according to the extension of Dodson's formulation [4] by Ganguly and Tirone [5] that accounts for the effect of initial temperature (T_o), in addition to those of cooling rate and grain size. The results are illustrated in Fig. 2 for two different spherical grains of 1 and 0.5 mm in radial dimensions, and T_o = 700-1000°C. Within a single grain, the closure temperature is variable and progressively decreases towards the rim, thereby leading to an age profile. The closure temperatures shown in Fig. 2 are weighted average temperatures over an entire grain. In these calculations, the grains were assumed to cool according to the asymptotic relation $1/T(K) = 1/T_o + \eta t$, where η is a constant (with dimension of $K^{-1}t^{-1}$). Accordingly, the cooling rate is a function of temperature and is given by ηT^2. The cooling rates shown in the figure are those at the closure temperatures.

Fig. 3 shows two sets of Mn-Cr age profiles which would develop in olivine grains upon cooling according to the asymptotic relation such that the cooling rates at 650°C are 5 and 50 °C/Myr. The age profiles are presented in terms of the extent of resetting of age (Δt) as a function of the normalized radial distance (r/a) from the center and a dimensionless parameter M. The latter accounts for the effects of diffusion, grain size and cooling rate and are defined within Fig. 3. As an illustration of the use of this dimensionless parameter, let us consider the age profile that developed at a cooling rate of 5 ^oC/Myr at 650^oC ($\eta = 5.8x10^{-6}$ $K^{-1}Myr^{-1}$) and M = 0.2. If $T_o = 800^oC$, then $D(T_o) = 4.2 \times 10^{-18}$ cm^2/s and consequently a (radius) = 1.1 mm. For a specified values of cooling rate (i.e. η) and M, a $\propto$ $\sqrt{D(T_o)}$. The average age for each age profile is shown by a horizontal line.

^{53}Mn-^{53}Cr Thermochronology: As illustrated in Fig. 2, one can calculate cooling rate (CR) from the extent of resetting (Δt) of Mn-Cr decay system in olivine if the data on the grain size and peak temperature are available. This is done by constructing a curve of T vs. CR that satisfies the specified values of Δt and T_o (thin solid line in Fig. 2) and finding the intersection of the curve defining the T_C vs. CR relation for the given values of T_o and grain size. Using this approach we have tried to constrain the cooling rate of the pallasite Omolon on the basis of the available data on Mn-Cr age defined by an olivine-chromite isochron [1], using reasonable assumptions for some of the unknown parameters. The mineral isochron yields an age of 4558 Ma, which is ~ 10 Myr younger than the age of the solar system. The grains were abraded prior to the mass spectrometric analyses so that their average age should be somewhat younger than this value. We assume $10 \leq \Delta t \leq 15$ Myr. Also since no data on the grain size are available, we assume, somewhat intuitively, that the original radial dimensions of the analyzed grains were, on the average, between 1 and 2 mm in diameter. The cooling rate that we intend to calculate is in the parent body of pallasites. Thus, we need to know the time lapse for the parent body formation since the formation of solar system. We assume this to be 0-5 Myr. Consequently, the age loss (Δt) of the Mn-Cr system in olivine in Omolon since the parent body formation is 5-15 Myr. The peak temperature is assumed to be 800-1000^oC. With these assumptions, we calculate that the cooling rate of the pallasite Omolon should be between 3-45 ^oC/Myr to yield the observed Mn-Cr age of olivine.

We will present graph relating cooling rate to grain size and T_o for a range of probable planetary conditions (analogous to that developed by Ganguly et al. [6] for the Sm-Nd system in garnet) which could be used to retrieve cooling rates from known values Δt, T_o and grain size.

References: [1] Lugmair G. W. and Shukolyukov A. (1998) *GCA*, *62,* 2863-2886. [2] Nyquist L. et al. (2001) *Meteorit. Planet. Sci.*, *36,* 911-938. [3] Hutcheon I. (1998) *SCIENCE*, *282*, 1865-1867. [4] Dodson M. H. (1973) *Contr. Mineral. and Petrol.*, *40*, 259-274. [5] Ganguly J. and Tirone M. (1999) *EPSL*, *170*, 131-140. [6] Ganguly J. et al. (1998) *SCIENCE*, *281*, 805-807.

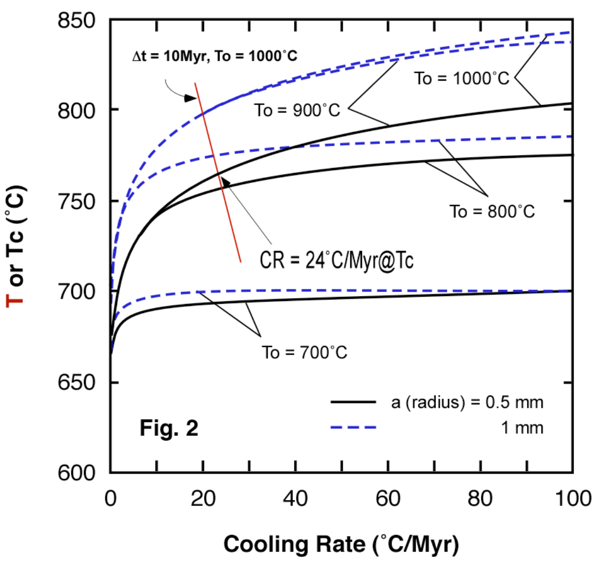

Fig. 2. The closure temperature of ^{53}Mn-^{53}Cr decay system in olivine as a function of cooling rate, grain size and initial temperature, according to Ganguly and Tirone [5].

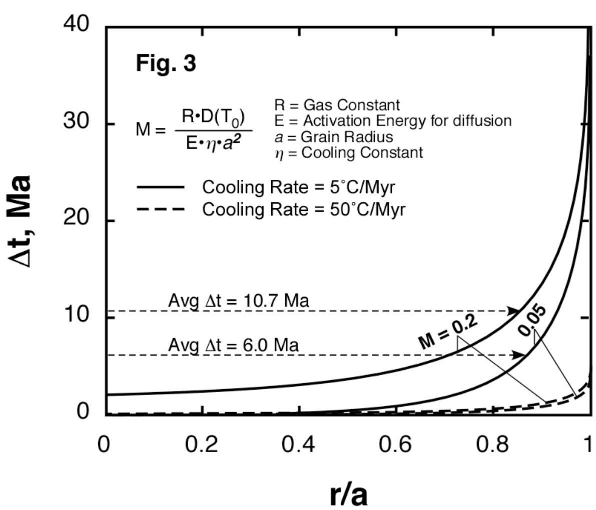

Fig. 3. Resetting of ^{53}Mn- ^{53}Cr age in olivine single crystal as a function of the dimensionless parameter, M, and normalized radial distance, r/a, where is the grain radius. T-t relation: $1/T = 1/T_o + \eta t$.