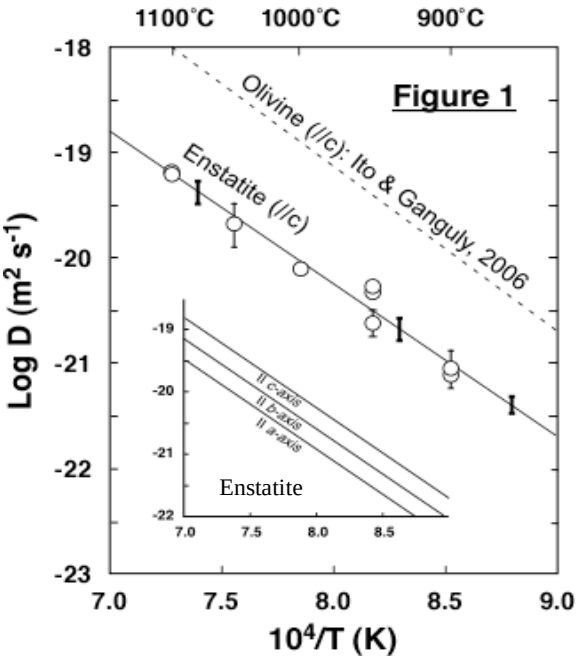
CLOSURE TEMPERATURES OF Mn-Cr AND Pb-Pb DECAY SYSTEMS IN PYROXENES: IMPLICATIONS FOR AGES OF CUMULATE EUCRITE AND ANGRITE. J. Ganguly[1], M. Ito[2] and X. Y. Zhang[1], [1]Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA (ganguly@email.arizona.edu), [2]NASA, Johnson Space Center ARES, Mail code KR, 2101 NASA Parkway, Houston TX, 77058, USA.

Introduction: Interpretation of mineral ages requires proper understanding of diffusion closure temperatures (T_c) of the daughter products. We have determined diffusion kinetic properties of Cr in natural enstatites and used the data to calculate T_c of the short-lived ^{53}Mn-^{53}Cr decay system ($t_{1/2}$ = 3.7 Myr), as function of initial temperature (T_o), cooling rate (CR), grain size and geometry. In addition, we also calculated T_c of Pb-Pb system in augite using available diffusion data [1]. These results are applied to (a) the Mn-Cr orthopyroxne age of a cumulate eucrite to calculate its CR, and thereby to constrain the thickness of eucrite upper crust in the HED parent body (asteroid Vesta), and (b) interpret the apparently discrepant Mn-Cr and Pb-Pb ages of pyroxene in a primitive differentiated basaltic meteorite (angrite) in terms of its thermal history.

Experimental method and results: Gem quality natural enstatite (En_{96}) crystals were cut normal to a-, b- and c- crystallographic axis, and polished to mirror-finish. The samples were pre-annealed at 1 bar and T-fO_2 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 Cr_2O_3. Tracer diffusion profile of Cr was induced by annealing a sample with Cr surface layer at a temperature between 900-1100˚C under controlled $f(O_2)$ conditions. The quenched samples were analyzed by depth profiling in ion microprobe (SIMS).



The main body of Fig. 1 shows Arrhenius plot of the diffusion data retrieved from the experimental diffusion profiles of Cr in enstatite parallel to c-axis (vertical bars: ± 1σ), and comparison with D(Cr//c) in olivine [2].The inset shows the anistropy of Cr diffusion in enstatite. The $f(O_2)$ conditions correspond to those of WI buffer. D(Cr) in enstatite was found to *decrease* by a factor of 2-3 for increase of $f(O_2)$ from WI to 4.5 log unit above WI buffer conditions at 950 and 1050˚C, possibly suggesting significant contribution from interstitial diffusion. The Arrhenian parameters ($D = D_o\exp(-E/RT)$) for D(Cr//c-axis; WI buffer) in enstatite are: $D_o = 2.19(10^{-9})$ m^2/s, E (± 1σ) = 257 (12) kJ /mol.

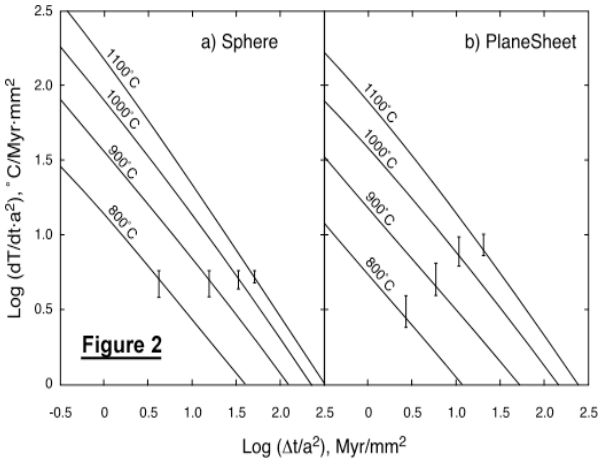
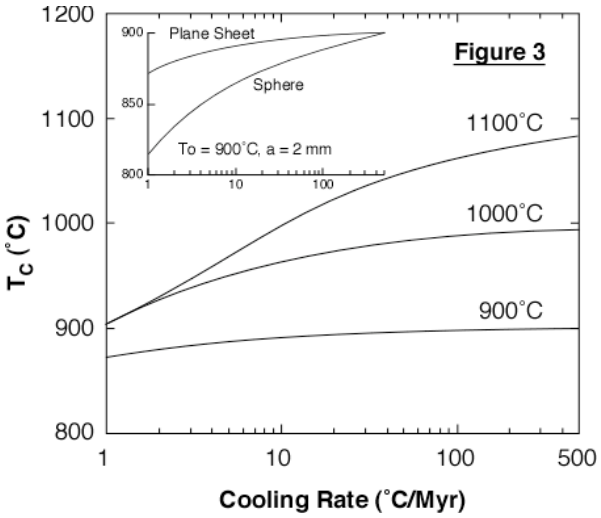
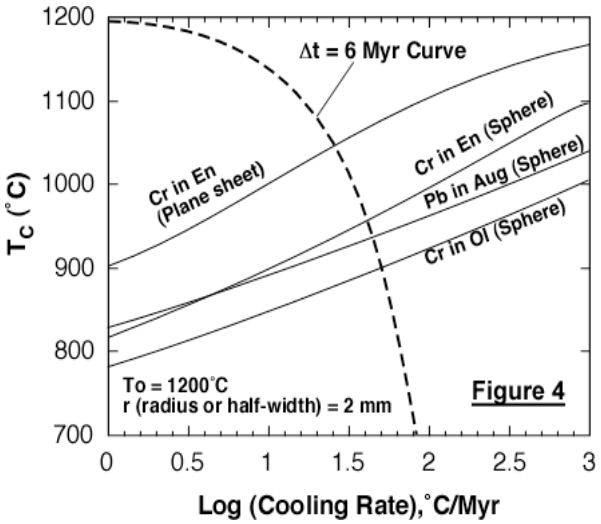
^{53}Mn-^{53}Cr Thermochronology of enstatite:

Formulation. Using the meassured D(Cr) data in enstatite and the formulation of [3], we have calculated the relationship between cooling rate and resetting of age during cooling (Δt) of the Mn-Cr system in enstatite of spherical and plane sheet geometries (Fig. 2). The parameter *a* is a characteristic dimension (radius of a sphere or half-width of a plane sheet). The cooling was assumed to follow an asymptotic relation: $1/T(K) = 1/T_o(K) + \eta t$, where η is a constant ($T^{-1}t^{-1}$). These graphical relations can be used to directly retrieve cooling rate from knowledge of Δt(Mn-Cr) of enstatite, peak temperature (T_o), grain size and geometry.

Application to a cumulate eucrite and parent body model. We have applied the thermochronological relation (Fig. 2) to a cumulate eucrite, Serra de Mage (SDM), using the available Mn-Cr age data of enstatite [4] that suggest a time lapse of 10-16 Myr between the crystallization age and Mn-Cr closure condition of enstatite. It can be shown that no resetting of Mn-Cr age could have been possible under regolith blanket where cooling of SDM took place very rapidly, ~10^3˚C/Myr [5]. Using crystallization age of enstatite in cumulate eucrite of 1000-1100˚C and grain size (radius or half-width) of 0.5-5.0 mm, we obtain cooling rate of 2-27˚C/Myr at T_c (830-890˚C) of Cr diffusion in Opx in SED at its original site within the HED upper crust. Assuming smooth cooling, these results imply cooling rate of 1-13˚C/Myr at 500˚C, and a corresponding burial depth [6] of ~30 km in the asteroid Vesta Thus, the eucrite upper crust is thicker than 30 km that seems to rule out models of internal lithology

of the asteroid with thiner eucrite crust, but is compatible with a relatively olivine-poor model (19.7 % of total mass), with the core varying between 0-25 % of the total [7].

Closure Temperatures of Mn-Cr and Pb-Pb Systems: We illustrate in Fig. 3 the T_c of Mn-Cr system in enstatite for spherical geometry (main body) as function of T_o, cooling rate and grain size (radius), as calculated according to [8]. The inset shows a comaprison between T_c of spherical and plane sheet geometries for T_o = 900˚C and with characteristic size, *a* (radius or half-width), of 2 mm. Figure 4 shows a comparison of T_c(Mn-Cr) in enstatite with that in olivine [2] and T_c(Pb-Pb) in augite, using T_o = 1200˚C and *a* = 2 mm. Analysis of cation diffusion systematics in pyroxne suggests that D(Cr) is augite should be smaller than that in enstatite and, hence, T_c(Cr: augite) higher than T_c(Cr:enstatite).

Interpretation of discrepant Mn-Cr and Pb-Pb ages of D'Orbigny angrite: Excess $^{53}Cr/^{52}Cr$ in olivine, augite, spinel and glass in D'Orbigny yield an isochron with age of 4562.9 (± 0.6) Ma that is ~ 6 Myr older than the Pb-Pb age of augites. For the Mn-Cr internal isochron of D'Orbigny, the closure of Cr diffusion was controlled by the mineral with slowest diffusion property, presumably augite, since D(Cr) in augite is expected to be smaller than that in enstatite. Thus, Mn-Cr age should be older than Pb-Pb age of augite under condition of slow cooling. The dashed line in Fig. 4 shows T_c vs. cooling rate (CR) for age loss of 6 Myr between 1200˚C and T_c. The intersection of this curve with the T_c vs. CR curve of Pb diffusion in augite yields an upper bound on CR of D'Orbigny, assuming that the average grain size is ~ 2 mm (radius). The CR should be slower than that defined by the intersection of the two curves since T_c(Cr:augite) is likely to be less than 1200˚C. Thus, the angrite D'Orbigny cooled slowly at a rate of ≤ 50˚C/Myr leading to a difference of ~6 Myr between the Mn-Cr and Pb-Pb ages of augites.

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