THE COOLING RATE OF SEVERAL OLIVINE-PHYRIC SHERGOTTITES ON THE BASIS OF FE-MG ZONING IN OLIVINE.

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Introduction: We have developed a model to calculate the cooling rate (or burial depth) by using the Fe-Mg chemical zoning profile of olivine considering diffusional modification during crystal growth, because chemical zoning provides information on thermal history of minerals [e.g., 1]. We have applied the model to calculating cooling rates of olivines in type II porphyritic olivine chondrules in the Semarkona (LL3.00) chondrite and found that porphyritic olivine chondrules in Semarkona show a wide range of the cooling rate. Since the cooling rate obtained by dynamic crystallization experiments only shows the possibility of the cooling rate, we need to calculate the cooling rate for actual olivines. In this abstract, we have calculated the cooling rate and burial depth of several martian meteorites.

Y 980459, DaG 476, Dho 019, LAR 06319 and NWA 1068 are olivine-phyric shergottites that contain olivine megacryst and minor amounts of orthopyroxene in a fine-grained groundmass of olivine, pyroxene and maskelynite [e.g., 2-4]. Olivines in these shergottites are considered to be phenocryst that is a large and conspicuous crystal of the earliest generation.

EET 79001 contains two distinct igneous lithologies (A and B). Lithology A contains large olivine and orthopyroxene [e.g., 5]. Their chemical compositions are clearly out of equilibrium with the surrounding melt and considered to be xenocrysts that are foreign to the body of rock as their huge sizes suggest.

Model and Calculation Procedures: Crystallization of olivine starts at temperature T_S and ends at temperature T_E as temperature decreases (Fig. 1). We assume that the olivine crystal is a sphere, and that olivine crystal growth is parabolic [6], that is, dR/dt is proportional to $1/R$, where R is the radius of crystal and t is time.

Fe-Mg zoning in olivine primarily formed by fractional crystallization. We calculated an Fe-Mg zoning profile (primary zoning profile) by using the Rayleigh equation for closed-system fractional crystallization. The equation is $C_L/C_0 = F^{KD-1}$, where C_0 and C_L are the initial concentration in the bulk liquid and the concentration in the observed liquid, respectively. K_D is the distribution coefficient, and F is the fraction of liquid remaining. We used the distribution coefficient for Fe/Mg of 0.30 [e.g., 7].

For the cooling rate calculation, we assume that cooling is single and linear (continuous) from starting temperature (T_S) to closure temperature (T_F) at which Fe-Mg interdiffusion essentially ceases considering the cooling rate. T_F is lower than ending temperature (T_E). Diffusional modification calculated by numerically solving the diffusion equation also starts at T_S and ends at closure temperature (T_F) and takes place during ongoing olivine crystal growth

We determined three unknown parameters, cooling rate (or burial depth), initial concentration for fractional crystallization (C_0), and fraction of liquid remaining (F) by employing the non-linear least squares method (Simplex method) to fit the computed zoning profile to the observed zoning. The detailed calculation procedures are given in Miyamoto et al. [1].

Estimation of T_S and T_E: We estimated T_S and T_E by using MELTS under the option of "equilibrium" [8] for the bulk chemical composition of each shergottite. We estimated T_S as the temperature at which olivine having the core Fa component (=Fe/(Mg+Fe). mol%) crystallizes and T_E at which olivine having the rim Fa component crystallizes. We used a closure temperature (T_F) of 700 °C.

The T_S and T_E vary with the core and rim Fa components, because the Fa component increases as the temperature decreases. This may partly relieve the cutting effect of thin section and difference in the time of nucleation, because olivine having more Fe-rich core compositions may crystallize at a lower temperature.

Because the core Fa component now observed for olivine shows the result of diffusional modification, actual Fa component when olivine starts to crystallize is usually lower than that now observed. This is related to the value of T_S, because T_S is determined by the core Fa component by using MELTS. We performed the iteration process, until T_S converges to the consistent value with the initial Fa component (C_0).

Diffusion Coefficient: Because we assume that the compositional gradient of the Fa component of olivine is controlled by Fe-Mg interatomic diffusion, the result is strongly dependent on the value of the Fe-Mg interdiffusion coefficient used in the calculation. We used the Fe-Mg diffusion coefficient in olivine reported by Misener [9], with consideration of the effect of oxygen-fugacity included [10]. The oxygen fugacity used in this study is $\log fO_2 = \text{IW}+1$ or QFM-2.

Verification of Model: The model was successfully verified by reproducing the Fe-Mg zoning profiles obtained in dynamic crystallization experiments on

analogs for martian and lunar meteorite compositions [11].

Results and Discussion: Fig. 2 shows the representative result of cooling rates calculated for olivines in several olivine-phyric shergottites. Table 1 summarizes the best-fit cooling rates and burial depths calculated by our model.

Olivines in Y 980459 and DaG 476 are considered to be phenocrysts. The calculated cooling rate for an olivine in Y 980459 is larger than that of DaG 476 and is also consistent with the fact that Y 980459 contains glassy mesostasis that includes quench crystals of olivine and pyroxene unlike DaG 476 [e.g., 12].

Although it has been pointed out that LAR 06319 shows close affinity in mineral and whole rock chemistry to NWA 1068 [2], the cooling rate of LAR 06319 is smaller than that of NWA 1068. The difference in the burial depth between them is several meters.

Olivines in EET 79001 are considered to be xenocrysts. The calculated cooling rates for olivines in EET 79001 show 0.77 - 7.3 $^{\circ}$C/day (Table 1). These results imply that each olivine may form in different environmental condition and assembled in EET 79001 after the formation, and that olivines in EET 79001 may be xenocrysts.

The calculated cooling rates for several olivine-phyric shergottites correspond to the burial depth of 1 – 10 m, assuming the rock-like thermal diffusivity (0.004 cm^2/s). This result suggests shallow intrusions or lava flows in the surface layer of Mars for the origin of olivine-phyric shergottites.

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Table 1. The cooling rate and burial depth of olivine-phyric shergottites.

Olivine-phyric shergottite	Ol No.	Cooling rate ($^{\circ}$C/day)	Burial depth (m)*
Yamato 980459	OL1	4.7	3
DaG 476	OL1	2.1	4
EET 79001 Lithol. A	OL1	0.77	7
	OL2	1.9	4
	OL3	7.3	2
Dhofar 019	OL1	0.012	10
LAR 06319	OL1	0.027	8
	OL4	0.060	4
NWA 1068**	OL1	0.80	2
	OL4	15	1
	OL6	0.46	2

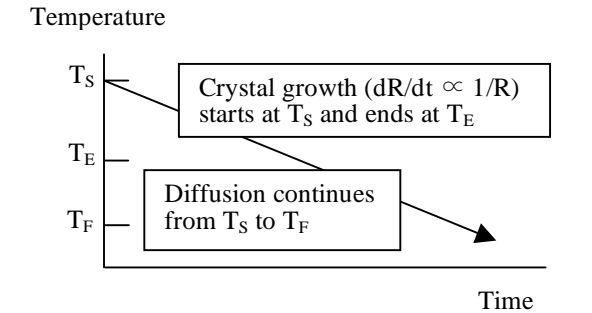∗ κ =0.004 cm^2/s ∗∗ Satake (2009) unpublished data

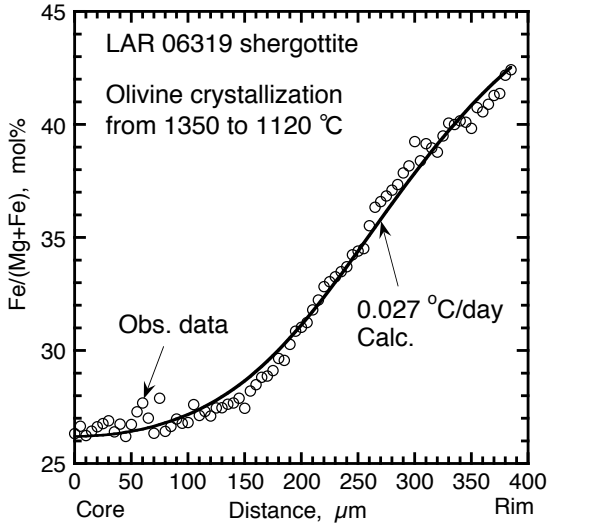Fig.1. Schematic diagram of cooling history

Fig. 2. Calculated zoning profile (solid curve) and observed zoning profile (open circles) for an olivine in LAR 06319 olivine-phyric shergottite. Open circles show zoning profile measured by electron microprobe. Solid curve shows the best fit to the observed profile and the number on curve shows the best-fit cooling rate calculated by our model. T_S is 1350 $^{\circ}$C and T_E is 1120 $^{\circ}$C.