EVIDENCE FOR PARENT-BODY THERMAL-METAMORPHISM OF CO3 CHONDRITE BY ANALYZING FE-MG ZONING OF OLIVINE.

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Introduction: It is known that the CO3 chondrite shows a thermal metamorphic sequence similar to those of ordinary chondrites [e.g., 1] and it is generally thought that thermal metamorphism of CO3 chondrites occurred in its parent body. For this study, we employed Yamato (Y-) 791717 CO3.6 chondrite to study whether thermal metamorphism of CO3 chondrite occurred in the parent body or in the primitive solar nebula by analyzing Fe-Mg zoning in olivine. Y-791717 consists mainly of chondrules, mineral fragments, Ca-Al-rich inclusions, and matrix [e.g., 2] and we used the same Fe-Mg zoning profile of an isolated olivine as that shown in [3].

Many minerals show chemical zoning that provides information on their thermal history such as cooling, reheating and annealing of rocks. Because chemical zoning is mainly controlled by atomic partition and atomic diffusion, it enables us to obtain the cooling rate (or burial depth) by analyzing it on the basis of diffusion calculations under the appropriate boundary conditions.

We have developed two models. One is a model to calculate the cooling rate (or burial depth) in the parent body by using the Fe-Mg zoning profile of olivine and diffusional modification of the primary zoning [4]. The other is a model to calculate the cooling rate in the primitive solar nebula by using the Fe-Mg zoning profile of olivine, considering diffusional modification of zoning profile as crystals grow by fractional crystallization from a melt in high temperatures [5]. Both model calculations are performed by fitting the calculated zoning profile to observed one by solving the diffusion equation. The comparison was made by the residual of least-squares fitting.

Procedures and Results:

Autometamorphism in primitive solar nebula. We studied thermal metamorphism at high temperatures in the primitive solar nebula by applying the model developed by [5] to the Fe-Mg zoning profile of an isolated olivine in the Y-791717 chondrite [3]. The Fe-Mg zoning that formed by closed-system fractional crystallization is modified by Fe-Mg interdiffusion in olivine during the olivine crystal growth (autometamorphism), corresponding thermal metamorphism in the primitive solar nebula at high temperatures. The calculated profile is fitted to the observed one by non-linear least-squares method. The best-fit profile by this model is shown in Fig. 1 and the residual of the least squares is shown in Table 1. Olivine crystallization starts at 1415 ^{o}C and ends at 1233 ^{o}C, which are calculated by using MELTS [6] and the bulk chemical composition of Y-791717. The Fe-Mg interdiffusion continues to the closure temperature (1000 ^{o}C) after olivine crystallization finishes.

Thermal metamorphism in parent body. We applied the diffusional modification model developed by [3] to calculating the zoning profile, corresponding to thermal metamorphism in its parent body. In this model, the primary zoning profile formed by closed-system fractional crystallization (Rayleigh equation) is modified by Fe-Mg interdiffusion after olivine crystal growth finished. Fig. 2 shows the zoning profile calculated by closed-system fractional crystallization. The calculated profile obviously differs from that of the observed one. The solid curve shown in Fig. 2 is modified by Fe-Mg diffusion to fit the observed profile. We calculated the zoning profile for different temperature ranges to obtain the best-fit profile. Fig. 3 compares the the best-fit profiles among different temperature ranges and Table 1 shows the least-squares residuals. The results are different in the curvature of the calculated profile (Fig. 3). The result for the temperature range of 600-100 ^{o}C shows the best fit (Table 1).

Discussion: The results calculated for the parent-body thermal-metamorphism shows a better fit than that in Fig. 1 for thermal metamorphism in the primitive solar nebula (Table 1). This result suggests that thermal metamorphism of Y-791717 CO3.6 chondrite occurred in its parent body. Our result is consistent with those of petrologic and mineralogical study [e.g., 1].

Our study suggests that the detailed analysis of the Fe-Mg zoning profile gives some constraints on thermal metamorphism of meteorites.

Diffusion coefficient. Diffusion coefficient in olivine is a function of the Fe-concentration, oxygen fugacity, and temperature. Oxygen fugacity is also a function of temperature. The curvature of the calculated profiles (Fig. 3) is related to Fe-concentration dependency of the Fe-Mg interdiffusion coefficient of olivine. We used the Fe-Mg diffusion coefficient in olivine reported by [7] with oxygen-fugacity dependence [8] as

$$D_{Fe} = 0.03163 \times 10^{-2} (f_{O2})^{1/6}(0.41+0.0112C_{Fe}) \exp[(-39.27+0.0905C_{Fe})/RT]$$

where D_{Fe} is the Fe-Mg interdiffusion coefficient in cm^2/s, f_{O2} is oxygen fugacity in atm. C_{Fe} is the Fa (= 100x Fe/(Mg+Fe), mole%) component, R is the gas constant in kcal mol^{-1} K^{-1} and T is temperature in K.

References: [1] Kimura M. et al. (2008) *Meteoritics & Planet. Sci.*, 43, 1161-1177. [2] Kojima H. et al. (1984) *Mem. Natl. Inst. Polar Res., Spec. Issue,* 35, 184-199. [3] Kaiden H. et al. (1997) *Antarct. Meteorite Res.*, 10, 181-190. [4] Miyamoto, M. et al. (1986) *JGR* 91, 12804-12816. [5] Miyamoto M. et al. (2009) *Meteoritics & Planet. Sci.*, 44, 521-530. [6] Ghiorso M. and Sack R. (1995) *Contrib. Mineral. Petrol.*, 119, 197-212. [7] Misener, D. J. (1974) In *Geochemical transport and kinetics,* Carnegie Institute Washington, Publ. 634, pp. 117-129. [8] Miyamoto M. et al. (2002) *Antarct. Meteorite Res.,* 15, 143-151.

Table 1. The result of thermal metamorphism in the parent body for different temperature range.

Temperature range, ^{o}C	Cooling rate, ^{o}C/yr	LSQ Residual
1000 - 500	1100	18.08
800 - 300	12	16.39
700 - 200	0.67	15.81
600 - 100	0.019	15.65
500 - 50	0.00022	16.27
400 - 50	0.73 x 10^{-6}	18.36
Automatamorphism in primitive solar nebula (Fig. 1)	58000	21.69

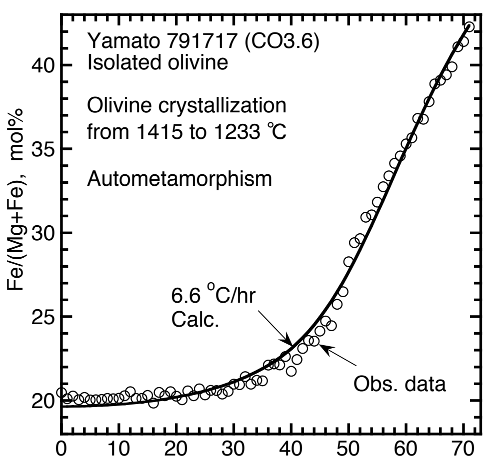

Fig. 1. The best-fit Fe-Mg zoning profile of an isolated olivine in the Yamato 791717 CO3.6 chondrite. Solid curve is the zoning profile calculated in high temperatures considering Fe-Mg interdiffusion during the olivine crystal growth (autometamorphism in the primitive solar nebula). Open circles show the observed Fe-Mg zoning profile measured by an electron microprobe. Olivine crystallization starts at 1415 ^{o}C and ends at 1233 ^{o}C. Fe-Mg interdiffusion continues down to 1000 ^{o}C.

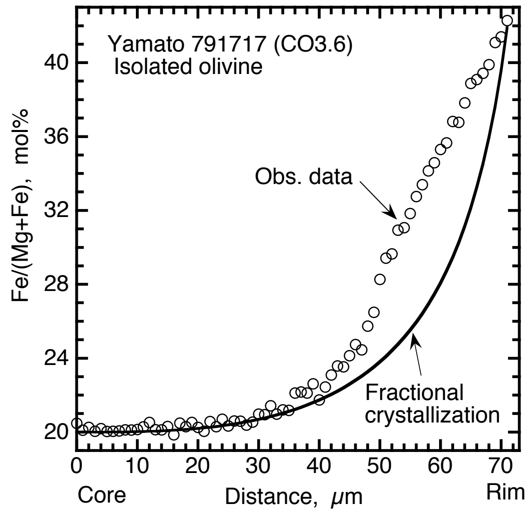

Fig. 2. The zoning profile calculated by closed-system fractional crystallization (solid curve). Liquid remaining is 22%. Open circles are the same as those in Fig.1.

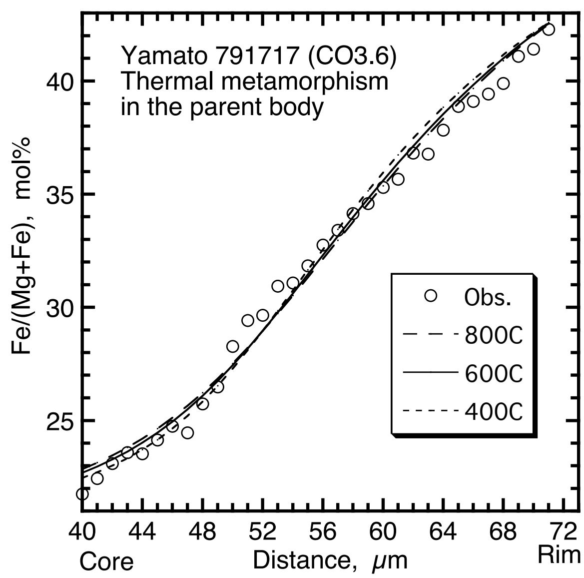

Fig. 3. Comparison of diffusional modification for the primary zoning formed by fractional crystallization (solid cure in Fig. 2) among different temperature ranges. The range of 600- 100 ^{o}C gives the best fit. See Table 1. Open circles are the same as those in Fig.1.