NUMERICAL STUDY ON THE THERMAL EVOLUTION AND BIRTHPLACE OF GRA 06128 and 06129.

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Introduction: Chronological studies of primitive and differentiated meteorites have proposed two stages in the formation of solid materials in the early solar system [e.g., 1]. The first is the formation stage of parent bodies of differentiated meteorites which occurred within 1 myr after CAI formation. In this stage short-lived radio-isotopes such as ^{26}Al and ^{60}Fe worked as an internal heat source and induced differentiation. The second is the formation stage of parent bodies of chondrites. Since chondrites include chondrules, the parent body of chondrites should have formed after chondrule formation ages, which correspond to later than 1.7 myr after CAI formation. Then, the next question is what happened between two stages. The partially molten meteorites Graves Nunatak 06128 and 06129 (GRAs) would give us keys to understand the interval.

GRAs are paired Antarctic achondrites representing unique asteroidal magmatic processes; they are interpreted to originate from a low-degree partial melt from a volatile-rich oxidized asteroid [2,3]. Thanks to the curiosity, they are still under many comprehensive geochemical and petrologic studies to reveal their origin and evolutional history: e.g., spectroscopic properties, melting condition, metamorphism condition, and magnetic properties [3 and references therein]. Among them, especially, chronological studies have provided critical constraints on the thermal evolution of GRAs and their parent body. Thus, in this study, we try to constrain the physical condition and thermal evolution of GRAs' parent body by carrying out numerical simulations with a wide range of conditions.

Constraints: We employ the following physical and chronological parameters as boundary conditions for our numerical simulations, although these parameters are still in debate. First of all, a parent melt of GRAs represent a low-degree melt of chondritic material (~10-15 %) [e.g., 3]. Melting experiments of chondrite compositions suggest that the melting temperature should not exceed ~1200 °C to keep degree of melting lower than 20% [4, 5]. Secondly, abundance of siderophile elements suggest GRAs experienced only limited silicate-metal separation [2], that means significant vertical mass movement did not take place in the GRAs' parent body. Thirdly, the melting occurred 1.3±0.3 myr and ceased 3.23 myr after CAI formation [2]. Fourth, the temperature fell below 500 °C by the time of 50±60 myr after CAI formation [1]. Successful numerical results that account for the thermal evolution of GRAs must satisfy all of these constraints.

The initial composition of GRA parent body is constrained by melting experiments. Usui et al. successfully reconstructed the mineral assemblage of GRAs by partial melting experiments using a synthesized H chondrite composition [6]. Thus in this study we adopt H-chondritic component as an initial composition of the parent body. The normative mineralogy is calculated to make mg# of olivine and pyroxene into 65 and 70, respectively. The resulting parent body component is compiled in table 1.

Table 1. Composition of GRA parent body

Oxide(wt%)	
SiO_2	36.5
FeO	35.6
MgO	23.7
Al_2O_3	2.08
CaO	1.72
Na_2O	0.89
NiO	2.1
Normative mineralogy (wt%)	
Ab ($NaAlSiO_3O_8$)	7.2
An ($CaAl_2Si_2O_8$)	1.6
Di ($CaMgSi_2O_6$)	5.1
En ($MgSiO_3$)	4.7
Fs ($FeSiO_3$)	5.3
Fo (Mg_2SiO_4)	36.3
Fa (Fe_2SiO_4)	28.3
metal (Fe, Ni)	11.4

Numerical model: We carried out numerical simulation on the thermal evolution of a celestial body (hereafter referred to as a parent body) with various mass from 10^{16} to 10^{20} kg (corresponding to the radius from 8 to 200 km, depending on the porosity). A parent body is divided into 100 grids depending on the cumulative mass from the center of the parent body. Thermal diffusion equations were solved as taking into account the heat generation due to short-lived radioisotopes, ^{26}Al and ^{60}Fe. The abundance ratios of $^{26}Al/^{27}Al$ and $^{60}Fe/^{56}Fe$ are assumed to be $5x10^{-5}$ [8, 9] and $2x10^{-6}$ [8, 10] at the time of CAI-formation (4567.2 Ma[7]), respectively. The bulk density and heat capacity are calculated by harmonic and arithmetic mean of minerals shown in Table 1, respectively. The porosity is varied as a free parameter from 0 to 0.4. The grain size is assumed to be a uniform value of 10^{-5}m. Since the thermal conductivity of complicated mixture is not straightforward, we adopt measured value for consolidated chondrite [11, 12]. Shrinkage of pores due to sintering is also taken into account [12]. The initiation time of thermal evolution, or accretion time, of the parent body is varied as a parameter from 0.5 to 2.0 myr after CAI formation. The earlier the parent body accreted, the larger amount of heat source the parent body acquired in it. The surface temperature is fixed to be 200K throughout the numerical simulation.

For simplicity, we assume that advection of melt do not occur. Instead, we use relaxation method [13] to express the enhanced thermal conductivity for melted region (temperature higher than 1000°C).

Numerical results: Free parameters in this study are: initiation time of the parent body (τ_{ini}), total mass of the parent body (M_p), and the porosity (ϕ). We have already shown that the accretion time of the parent body barely affects the birthplace of GRAs for a non-porous parent body as long as τ_{ini} is between 0.7myr and 1.2myr [14].

For initially porous parent body, wider melt region forms and keeps longer duration since the porous media works as a thermal insulator. As a result, to satisfy the constraints given above, the birthplace becomes shallower for the high porous parent body. The predicted birthplace of GRAs is shown in Fig. 1.

Conclusions: We carried out numerical simulation of celestial bodies under wide variety of initiation time, size, and porosity. According to our numerical result, the birthplace of GRAs should be shallower than 12km. If the parent body is highly porous initially, the birthplace should be shallower.

The initiation time of GRAs' parent body is estimated from 0.7myr and 1.2myr, which is distinctly older than the timing of the accretion of typical chondrite parent bodies. The radius of predicted parent body is between 18km and 50km, which is slightly smaller than the typical size of planetesimals. Although the formation process of parent body could not be constrained by this study, it is clearly shown that the formation process of celestial bodies in the early solar system had proceeded in the first 1myr.

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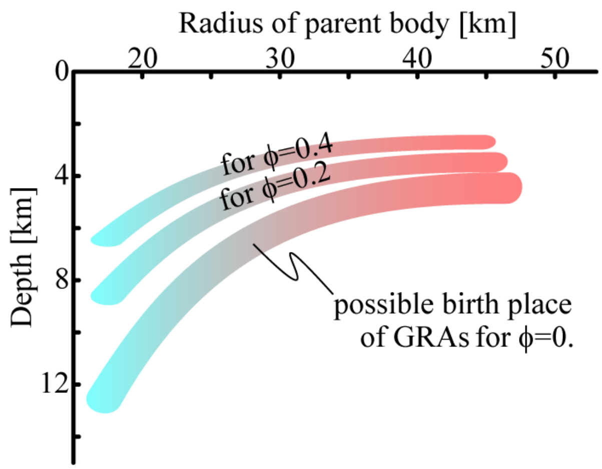

Figure 1: The possible birthplace of GRAs as a function of the radius of the parent body and the depth from the surface. Initiation time of the parent body hardly affects this figure. Birthplace become shallower for higher initial porosity of the parent body. See text for more detail.