CORE FORMATION AND INTERNAL STRUCTURE OF PLANETESIMALS: THE ROLE OF FORMATION TIME, ACCRETION DURATION, AND TERMINAL SIZE.

T. Suwa[1] and H. Nagahara[1], [1]Department of Earth and Planetary science, The University of Tokyo

Introduction: The core formation process of planetsimals is different from that of Earth-size planets. Because of smaller radii, masses, gravity and accretion energy, the planetsimals don't get adequate thermal energy by accretion to form large scale magma ocean. However, there are evidences for the presence of core in planetesimals: the core in 4-Vesta was found by Dawn mission [1,2] and non-magmatic iron meteorites should have been segregated to form core or metal blebs in bodies that did not experience silicate melting [3,4]. Therefore, differentiated planetesimals had a heat source that provided sufficient thermal energy to balance against heat loss from the surface.

The internal structure of planetesimals has been infered from non-magmatic iron meteorites and chondrites, and two types of the structure (Type A and Type B) have been proposed by [10], where Type A is undifferentiated (Fig. 2a) and Type B has metallic core and unmelted silicate mantle (Fig.2b). The formation time of non-magmatic iron meteorites with the Hf-W isotope systematics is shown to be within 1.5±1 Ma after CAI formation [11,12].

Radioactive decay of short lived nuclides ^{26}Al [5] and ^{60}Fe [6] was a plausible heat source, and the accretion time of planetesimal should affect the energy for internal heating and the degree of differentitation of the bodies. On the other hand, cooling from the surface should be controlled by heat flux from the interior, which is dependent on the thermal conductivity of the interior materials. Thermal conductivity is controlled by the degree of sintering and grain size of interior grains, which are a function of temperature.

Because the eutectic temperature of the Fe-FeS system is much lower than the solidus temperature of silicate, core formation of planetsimals proceeded by percolation of Fe-S melt through unmelted silicate matrix, which is possible when the dihedral angle is smaller than 60^o [7]. It should be mentioned that the surface tension of melt of the Fe-S system dramatically decreses with the sulfur content [8], which affects the possibility of Fe-S melt percolation.

Thus, the interior structure of planetesimal should be considered by taking the accretion, growth, and thermal evolution of the interior simultaneously. Here, we investingate the evolution and differentiation of planetsimals with numerical simulation.

Model: We use a spherical 1D model of a planetsimal, for the numerical simulation, which was originally developed by [13]. We solve a non-stationary heat conduction equation to investigate thermal evolution of an accreting planetesimals, of which interior is heatd by the radioactive decay and which cools from the surface by radiation. Grain-growth and sintering proceed in the interior, resulting in changes of thermal conductivity.

The accreting materials are nebular dusts with H-chondrite composition, which is consisting of silicates, metal and sulfide with the grain size of 1 micron [14-16]. The initial temperature of the accreting body is set to be 290K corresponding to the nebula temperature at 2.36 AU, and the surface temperature is fixed at the temperature through accretion. The porosity change due to sintering is obatined by solving differential equation by [17], which further changes thermal conductivity. The eutectic temperature of the Fe-S system is 1213K and the silicate solidus is 1425K. Fe-S melt migrates in porous media according to Darcy's flow equation [18]. We focus on the temperature range between the Fe-S eutectic and silicate solidus and do not discuss evolution at temperature above the silicate solidus in this study. Percolation of Fe-S melt takes place when the dihedral angle between silicates and the melt is less than 60^o, which corresponds to the temperature of 1390K [8]. If the temperature exceeds this value, the dihedral angle is over 60^o [19,20], that is, Fe-S melt does not percolate in silicate matrix. The surface tension of Fe-S melt is smaller than Fe, and we expect formation of planetesimals with Fe-S core and mantle consisting of silicates and metal (Type C in Fig. 2).

The model contains three free parameters, which are the time of the starting of accretion (formation time, hereafter), accretion duration to grow to the terminal size with a constant accretion rate and terminal size of the planetesimal.

We try to constrain the conditions for the interior structure of planetesimals with Types A, B, and C.

Results: Thermal evolution of a planetesimal with the terminal radius of 50km is shown in Fig. 1, where accretion duration is instantaneous and formation time is 3.0 Ma after CAI. The temperature increases with time and is thermally almost homogeneous in temperature except for the surface region of the body, in particular at the earlier stage. A planetesimal experiences the temperature below the Fe-S eutectic (the black solid line) has the Type A internal structure, that between Fe-S eutectic and FeS melt separation Type B, that between FeS melt separation and silicate solidus Type C. Although we do not discuss in detail, planetesimals experience temperatures above the silicate solidus results in formation of cores, which are apparently classified to Type B, but the mechanism of core formation differes from the previous case in that the core of the previous case was formed by percolation of Fe-S melt through solid silicates and the latter by sink within partically molten silicates.

If the formation duration prolongs for the same final size body, the maximum internal temperature decreases and the body cools more slowly. If the final size of a planetesimal is larger with the same accretion rate, the maximum temperature is higher and the body cools more slowly.

Discussions: The calculation results give us two important clues on the core of planetesimals. At first, the core of Type B planetesimals might be the source of non-magmatic iron meteorites, because core was formed by percolation through solid silicates without magmatic elemental partitioning between Fe-S and silicates. The core of Type C planetesimals is rich in sulfur, being close to the Fe-S eutectic composition and the residual metals in the mantle is rich in Fe.

Another important results of the present work is shown in Fig. 3, Another important result of the present work is shown in Fig. 3, where types of planetesimal interior structure are shown as a function of formation time and terminal radius. The boundaries between the types show very weak slope suggesting that the planetesimal interior is strongly controlled by the formation time: planetesimals formed after 3 Ma after CAIs would be undifferentiated (Type A) regardless of the planetary size, whereas most of them formed within 1 Ma are Type D (differentiated bodies with magmatically formed core). Types B and C bodies are preferentially formed between 1 and 3 Ma after CAIs. The figure is specifically for the accretion duration of 1.5Ma, but the very strong dependence of the boundaries on the formation age is also the case for shorter or longer formation duration. If the accretion duration is shorter, Type D are more easily formed, on the other hand, longer accretion duration tends to be resulted in formation of Types A, B and C.

The present work can predict the planetesimal interior structure if we know the formation age with the isotopic measurements of samples and the size of the body, which would be a very powerful tool for future explorations of small bodies except for very small (< ~20 km) bodies.

References: [1] Sanctis et al. (2012) *ApJL* 758. [2] Russell et al. (2012) *Science* 336, 684-686. [3] Horan et al., (1998) *GCA* 62, 545-554. [4] Kracher et al., (1982) *GRL* 9, 412-415. [5] Urey (1955) *PNAS*. 41, 127. [6] Tachibana & Huss (2003) *ApJ* 588, L41 [7] Von Bargen & Waff (1986) *JGR* 91, 9261.

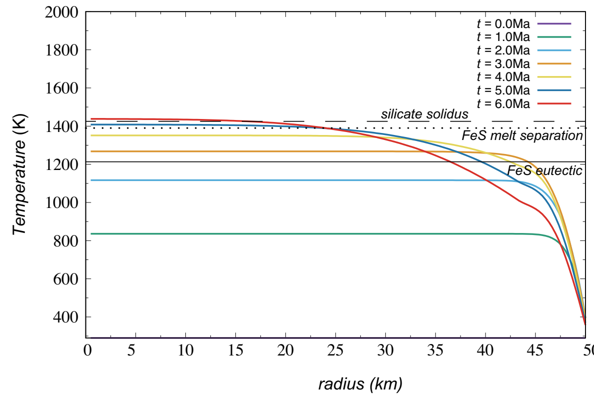

Fig. 1. Evolution of thermal profile of a planetsimal with the radius of 50km accreted instantaneously at 3 Ma after CAI.

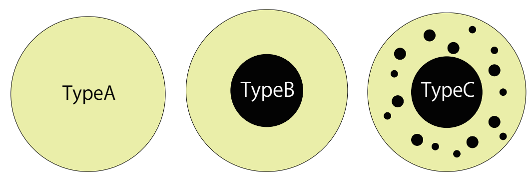

Fig. 2. Three types of planetesimals. Type A: undifferentiated, Type B: differentiated by porous flow, and Type C: partially differentiated with S-rich core and Fe-rich residual metal.

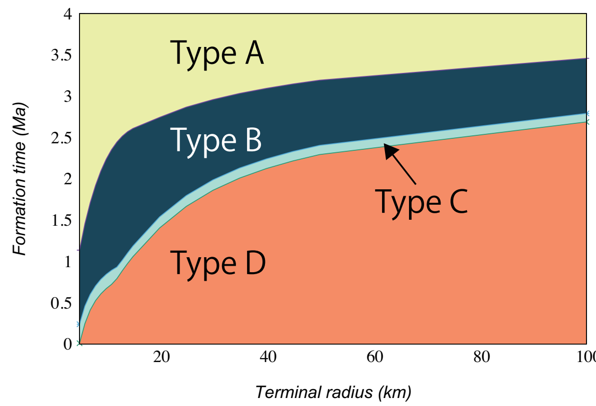

Fig. 3. Conditions for the formation of three types of planetesimal for the accretion time of 1.5Ma after CAIs.

[8] Beere (1975) *Acta Metal*. 23, 131. [9] [10] Trieloff et al. (2003) *Nature*, 422, 502-506. [11] Schersten et al., (2006) *EPSL* 241, 530-542. [12] Qin et al., (2008) *EPSL* 273, 94-104. [13] Neumann et al., (2012) *A&A*, 543 A141. [14] Keil et al. (1962) *JGR* 67, 4055. [15] Byerley & Takebe (1970) *MM*, 2, 1107. [16] Yomogida & Matsui (1983) *JGR*, 88, 9513. [17] Ghosh & McSween Jr. (1998) *Icarus* 134, 187. [18] McKenzie (1985) *EPSL* 74, 81. [19] Lee and Morita (2002) *ISI*, 6, 588-594. [20] Barker et al., (1974) *J. Appl. Phys*. 45, 4872-4887.