THERMAL HISTORIES OF METAL PHASES IN A CH/CB$_b$ CHONDRITE ISHEYEVO: IMPLICATIONS FROM SIDEROPHILE ELEMENTS. N. Nakanishi[1], T. Yokoyama[1], S. Okabayashi[1], and H. Iwamori[2]. [1]Dept. of Earth & Planetary Sciences, Tokyo Institute of Technology, Tokyo 152-8551, Japan (nakanishi.n.aa@m.titech.ac.jp). [2] Earthquake Research Institute, The University of Tokyo, Tokyo 113-0032, Japan.

Introduction: Isheyevo is a unique meteorite classified as CH/CB$_b$ chondrite that has transitional characteristics between CH and CB$_b$. For instance, the abundance of metal (30–70 vol.%) is akin to CB$_b$, while the existence of type I and II POP chondrules is the nature of CH [1]. The large enrichment of ^{15}N in bulk Isheyevo is similar to those in CR, CH, and CB chondrites [2]. Furthermore, Isheyevo has ^{26}Mg-depleted and ^{54}Cr-enrichment signatures [3]. Therefore, Isheyevo is thought to be least affected by thermal processing and thus accreted presumably in the outer solar system. Based on the short-lived isotope chronology coupled with oxygen isotopes and trace element abundances, Krot et al. [4] concluded that chondrules in Isheyevo have formed in different times and different locations from the other chondrules. Isheyevo contains non-porphyritic chondrules produced during a high energy event such as asteroidal collision [5].

Isheyevo is getting more attention in recent planetary science due to the presence of a sedimentary layer structure that was presumably formed by the sweep-up of materials in an impact plume occurred in the planetesimal collision [6]. Here we present the first comprehensive dataset for the abundances of major elements and highly siderophile elements (HSE) in metal grains from Isheyevo, determined with electron probe micro analysis (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) equipped with a femtosecond laser, respectively. With the new data, we discuss the thermal history of metal phases to better understand the physicochemical conditions in the early outer solar system where the parent body of Isheyevo has formed.

Experimental: The surface of a thick section of Isheyevo was polished with 1 μm diamond paste. The elemental maps in Ni and the concentration profiles of P, S, Cr, Fe, Co, and Ni were obtained by EPMA (JEOL-JXA-8530F). The abundances of HSEs for the multi-spots of these grains (58 spots from 31 grains) were measured with fs-LA-ICP-MS (IFRIT, Cyber Laser + X-series II, Thermo Fisher).

Results and Discussion: The combination of X-ray elemental map and major elements abundances shows the presence of three types of metals in Isheyevo: "zoned metal (ZM)", "unzoned metal (UM)", and "unzoned metal with Ni particles (UM/Ni)". The ZM grains have a Ni- and Co-rich core while UM grains have homogeneous Fe, Ni, and Co abundances across the grain. In contrast, the UM/Ni grains have a nearly homogeneous Co abundance across the grain but have oscillated patterns for Fe and Ni due to the presence of small (< 10 μm) high-Ni particles.

Figure 1 shows the variation of Ru/Fe ratio plotted against Ni/Fe ratio for each metal grain of Isheyevo. Nearly all metal grains including ZM, UM, and UM/Ni have similar compositions and show a positive correlation between Ru/Fe and Ni/Fe ratios. This correlation would be generated by the condensation process during metal formation. Four curves in Fig. 1 are the trajectories of equilibrium condensation for metal grains from a gaseous reservoir calculated by adopting the equation and parameterization (e.g., partition coefficients) described in [7]. The slope of the correlation of Ru/Fe and Ni/Fe for three types of metals suggests that these metal grains have formed from the same initial gas composition at the same pressure with enhanced metal abundances. Such high metal abundances in the initial gas could be produced by impact via planetary collision.

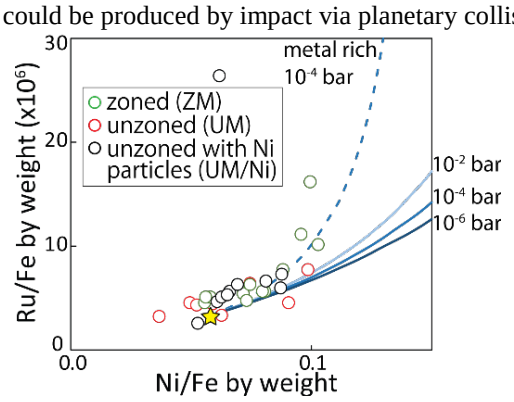

Fig. 1. Plot of Ru/Fe versus Ni/Fe ratios for each grain of ZM, UM, and UM/Ni from Isheyevo. Four curves are calculated equilibrium condensation trajectories of chondritic composition gas (star) with 10^{-2} bar, 10^{-4} bar, 10^{-6} bar, and metal rich composition gas with 10^{-4} bar.

Figure 2 shows the patterns of CI-normalized HSE abundances for each metal grain of Isheyevo. Nearly all grains display significant depletions in Au, which is the most volatile HSE, relative to the other HSEs. However, another volatile HSE, Pd, is not that depleted in the grains compared to refractory HSEs. Additionally, refractory HSE abundances of some grains do not change monotonically in the order of volatility. These observations suggest that Au in all types of the metal grains were preferentially lost by evaporation in a secondary heating process occurred after the initial condensation,

while the compositional change in refractory elements should not have occurred by evaporation or condensation in the secondary heating process.

Figure 3 shows the relationship between Co/Fe and Ni/Fe ratios in the ZM, UM, and UM/Ni grains. The multiple data obtained from a single metal grain are represented by the same color. The three types of metals clearly have different correlations in the Co/Fe versus Ni/Fe ratios. The ZM and UM/Ni grains have variable Co/Fe and Ni/Fe ratios within a single grain, while the UM grains have relatively unfractionated Co/Fe and Ni/Fe ratios within single grains. The observed variations were evidently not generated by parent body processes and/or terrestrial weathering, because the three types of metals are present in an adjacently small area (1.3 cm × 1.5 cm). Therefore, the variations of Co/Fe and Ni/Fe ratios within and across each individual ZM, UM, and UM/Ni grains are likely formed by the secondary heating process that occurred in a short period from the metal condensation in the initial impact to the accumulation prior to the accretion of Isheyevo parent body. We consider that the secondary heating process was triggered by an additional impact that sequentially occurred shortly after the initial impact at the same parent body.

The positive correlation between Co/Fe and Ni/Fe ratios for each ZM grain cannot be explained by fractional crystallization because of the tendency of compatibility to solid metal (Co > Ni). The curves in Fig. 3a are the trajectories of equilibrium condensation for metal grains. Our data are plotted along the calculated equilibrium condensation curves. Therefore, we conclude that the ZM grains preserve the compositional variation within each grain that formed by the initial condensation process. In contrast, the UM/Ni grains are commonly observed in H chondrites, stony-iron, and iron meteorites, which are recognized as plessite. Plessite is a mixture of kamacite and taenite phases and formed via slow cooling at a low temperature during the secondary heating event [8]. The negative correlation in Fig. 3c can be explained by fractionation between Co-rich kamacite and Co-depleted taenite. On the other hand, UM grains, which have homogeneous siderophile element compositions in a single grain, could be formed by diffusion via slow cooling or remelting in the secondary heating.

Based on the above discussion, we propose a multiple impact model for the formation of Isheyevo metal grains. All metals have condensed as ZM from a common gas reservoir at the same pressure during a heating event at the initial impact, followed by the formation of UM and UM/Ni grains by reheating in the secondary impact event that occurred shortly after the initial impact. Three types of metal grains in Isheyevo experienced different peak temperatures in the reheating event. Although most of the ZM grains avoided the reheating, they should have been heated to a temperature high enough to evaporate Au ($T_{50\%}$ = 1060 K at 10^{-4} bar [9]). The UM grains possibly experienced the highest peak temperature close to the liquidus of Fe–Ni metal (1000–1400 K [10]). We conclude that planetary collision was active in the early outer solar system and the parent body of Isheyevo was composed of the metal grains that were swept up from different temperature regions in the impact plume.

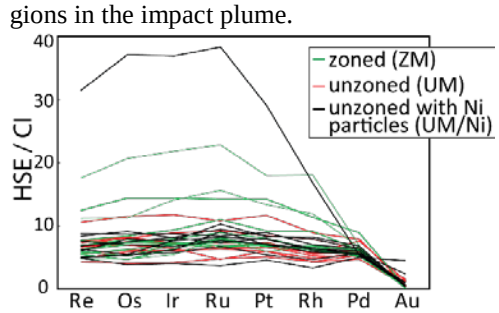

Fig. 2. Patterns of HSE abundances for each grain of ZM, UM, and UM/Ni from Isheyevo. Volatility of HSE increases from left to right [9]. CI data are from [11].

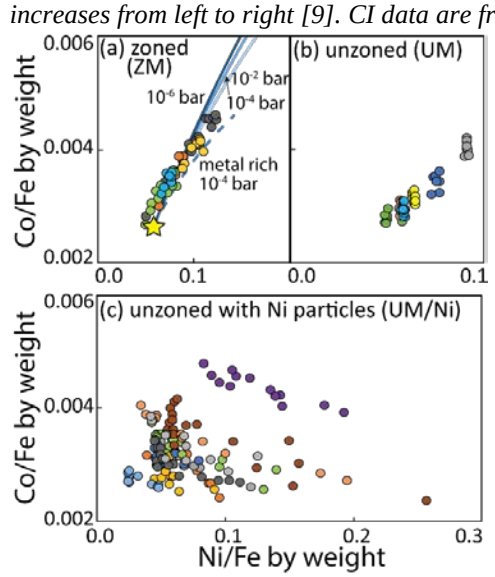

Fig. 3. Plots of Co/Fe vs. Ni/Fe ratios for (a) ZM, (b) UM, and (c) UM/Ni grains. Same colored symbols represent the data collected by line analyses for a single grain. Four curves are calculated equilibrium condensation trajectories as shown in Fig. 1.

References: [1] Ivanova et al. (2008) *MAPS*, **43**, 915. [2] Bonal et al. (2010) *GCA*, **74**, 6590. [3] Kooten et al. (2016) *PNAS*, **113**, 2011. [4] Krot et al. (2007) *Chem. der Erde*, **67**, 283. [5] Krot et al. (2010) *GCA*, **74**, 2190. [6] Morris et al. (2015) *ApJL*, **801**, I22. [7] Campbell et al. (2001) *GCA*, **68**, 3607. [8] Goldstein and Michael (2006) *MAPS*, **41**, 553. [9] Lodders (2003) *ApJ*, **591**, 1220. [10] McCoy et al. (1999) *MAPS*, **34**, 735. [11] Fischer-Gödde et al. (2010) *GCA*, **74**, 356.