論文の内容の要旨

# Mineralogical and geochemical study of brachinite clan meteorites: Implications for early differentiation of planetesimals

# （Brachinite clan 隕石の岩石鉱物・地球化学的研究：微惑星初期分化過程の理解に向けて）

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The study of primitive achondrites is expected to lead to an understanding of the variations of planetary differentiation processes and valuable information about the earliest stages of igneous evolution of planetesimals in our solar system. Previously, primitive achondrites are suggested to have come from the asteroids which was partially differentiated (e.g., Prinz et al., 1983; Nehru et al., 1992; Mittlefehldt et al., 1998). Some researchers recently proposed the inner structures of the parent bodies of primitive achondrites (ureilites, acapulcoites/lodranites and winonaites) and their ages have also been determined (e.g., Wilson et al., 2008; Hunt et al., 2018; Li et al., 2018; Toubol et al., 2008, 2009; Theis et al., 2013; Budde et al., 2015; Worsham et al., 2017). Compared to other primitive achondrites, however, brachinites have been poorly understood and their origin and formation processes have been controversial (e.g., Mittlefehldt et al., 2003; Day et al., 2012; Goodrich et al., 2017). This is because the number of brachinites has rapidly increased in the last fifteen years (10 specimens in 2000, but 44 specimens in 2019), but the study on newly found brachinites has been far from sufficient (Meteoritical Bulletin Database, 2019). Another aspect includes that brachinites are mainly composed of olivine and are hard to apply regular mineralogical and isotopic approaches (e.g., geological thermometers, U-Pb absolute age). Furthermore, the rapid increase of the number of brachinites resulted in the complexities of the grouping of brachinites (e.g., the existence of "brachinite-like meteorites", "ungrouped achondrite related to brachinites" and "brachinite clan"). Therefore, we comprehensively studied twelve olivine-rich achondrites ("brachinite clan meteorites"): Allan Hills (ALH) 84025, Divnoe, Elephant Moraine (EET) 99402, EET 99407, Miller Range (MIL) 090206, MIL 090340, MIL 090405, Northwest Africa (NWA) 4969, NWA 6112, NWA 6308, NWA 10932 and Reid 013, to understand the formation processes and the origin of brachinite clan meteorites. We performed not only conventional petrological and mineralogical study but also chromium isotopic and olivine petrofabric study. Characteristically, we focused on CPO (crystallographic preferred orientation) of olivine. Studying olivine fabrics in rocks is extremely important to obtain the information of the physical environment during and after crystallization. In recent years a lot of observations and experiments of olivine deformation in terrestrial mantle rocks have been performed (e.g., Karato et al., 2008; Ohuchi, 2013). Thus, variation of formation mechanism to produce olivine CPO patterns has been well understood and the olivine CPO patterns observed in natural rocks can be used to estimate the formation condition of the rocks (e.g., Jung et al., 2007; Karato et al., 2008). Brachinite clan meteorites are olivine-rich rocks similar to terrestrial mantle rocks and are expected to exhibit olivine CPO patterns because of the presence of apparent linear structures on the thin sections of some samples. Measuring olivine CPO in brachinite clan meteorites can lead to the better understanding of their formation conditions. However, there are only two olivine fabric studies for four brachinite clan meteorites (Ando et al., 2003; Mittlefehldt et al., 2003), and quantitative evaluation of olivine CPO patterns for brachinite clan meteorites has not been reported. Therefore, a major goal of this study is to obtain the information of formation conditions of brachinite clan meteorites revealed by olivine CPO analysis combining mineralogy and geochemistry for the first time.

In this thesis, we examined the samples from various viewpoints and reconsidered the grouping of brachinites. Chromium stable isotopic compositions in bulk meteorites have been used as a tool to connect meteorites with each other. We measured $^{54}$Cr compositions of nine samples by ICP-MS and found that the obtained $^{54}$Cr compositions are identical within 2SD errors. Combined with reported oxygen isotopic compositions (Greenwood et al., 2012; Goodrich et al., 2017; Hasegawa et al., 2019), the samples studied were found to be well genetically related and are indicated to be treated as one group. Moreover, all the samples of brachinite clan meteorites studied in this thesis display olivine CPO patterns. Olivine fabric is a characteristic property of these meteorites, and we propose that they should be called "brachinites" although different group names were used. We also suggest that "brachinites" should be defined as "olivine-rich achondrites that are relatively close to chondrites in many compositional properties, but showing some olivine CPO patterns" to solve the complexities of the classification of olivine-rich achondrites.

We found the two different types of olivine CPO patterns in brachinites. Olivine grains in Divnoe, NWA 4969 and NWA 6112 are preferentially aligned along [001] (*c* axis), whereas [100] (*a* axis) and [010] (*b* axis) are randomly oriented. Such CPO patterns are suggested to have exposed to magmatic melt flows during their crystallization on their parent body. The other olivine CPO pattern which is preferentially aligned along [010] (*b* axis) was detected in EET 99407, MIL 090206, MIL 090340, MIL 090405, NWA 6308, NWA 10932 and Reid 013. The direction of the *b* axis concentration and the lineation bisect each other at right angles. On the other hand, the dimensions of [100] (*a* axis) and [001] (*c* axis) are arranged on a plane. Such an olivine CPO pattern indicates that these samples may have been sheared in the parent body under the condition of existing melt and/or may be formed by accumulation in magma chambers. The discovery of the two different types of olivine CPO in brachinites showed that there is a need to consider more than two formation processes of brachinites.

We proposed two possibilities of the internal structures of the brachinite parent body by combining olivine fabric data with mineralogy and geochemistry for the first time. These possibilities are: (1) An asteroid had multiple magma chambers with different degrees of partial melting. A magma chamber with small degrees of partial melting generated *b* axis concentration patterns for the residual olivine by deformation. (2) A fully melted asteroid which formed both *b* and *c* axes concentration patterns of olivine as cumulates in magmatic bodies. Because of the oxidative condition not to form large amounts of Fe metal, this asteroid did not generate a metallic core.

Most importantly this study demonstrated that olivine fabric is the common characteristics of brachinites and proposed the inner structure of brachinites parent body, for the first time. This suggestion may give a new variety to the partially differentiated asteroids which were the parent bodies of primitive achondrites. We also showed that studying olivine fabric is extremely important to understand the formation processes and the nature of parent asteroids of differentiated meteorites although such a technique employing EBSD analysis has been rarely employed so far for “primitive achondrites”.