

THE ORIGIN AND CHEMICAL EVOLUTION OF THE PARENT BODY TO NORTHWEST AFRICA 6704 PRIMITIVE ACHONDRITE. Y. Hibiya¹, G. J. Archer², R. Tanaka³, T. Iizuka¹, K. Ozawa¹, R. J. Walker², A. Yamaguchi^{4,5}, and A. J. Irving⁶. ¹Department of Earth and Planetary Science, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan (yuki-hibiya@eps.s.u-tokyo.ac.jp). ²Department of Geology, University of Maryland, College Park, MD 20742, USA. ³The Pheasant Memorial Laboratory for Geochemistry and Cosmochemistry, Institute for Planetary Materials (IPM), Okayama University, Misasa, Tottori 682-0193, Japan. ⁴National Institute of Polar Research (NIPR), Tokyo 190-8518, Japan. ⁵Department of Polar Science, School of Multidisciplinary Science, SOKENDAI (The Graduate University for Advanced Studies), Tokyo 190-8518, Japan. ⁶Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA.

Introduction: One of the most fundamental and long-standing issues in planetary science is when, where, and how asteroids formed and differentiated [e.g., 1]. Information regarding this must come from meteorites that record the early histories of their respective asteroidal parent bodies. Primitive achondrites are meteorites that have near-chondritic bulk compositions, but exhibit igneous and/or metamorphic textures [e.g., 2]. Such primitive achondrites record variable stages in the transition from chondrite to differentiated achondrites, providing important insights into the differentiation of asteroids in the early solar system.

Northwest Africa (NWA) 6704 is an ungrouped primitive achondrite found in 2010, with a total known weight of 8.4 kg. It is composed predominantly of low-Ca pyroxene, with less abundant olivine, plagioclase, chromite, awaruite, sulfides and merrillite. The interior exhibits a fresh igneous texture with no diagnostic shock deformation effects [3]. Geochemical and petrological similarities suggest that this meteorite is paired with NWA 6693/6926 [4]. Preliminary U-Pb dating for pyroxene fractions of NWA 6704 has yielded an isochron age of 4562.80 ± 0.46 Ma, under the assumption of a $^{238}\text{U}/^{235}\text{U} = 137.79 \pm 0.02$ [5]. The pristine characteristics of this meteorite, coupled with its early crystallization age, make it ideal for exploring the earliest stages of asteroid evolution.

Here, we present the petrologic observations, highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, Pd) abundances, ^{187}Re – ^{187}Os systematics, and O–Ti isotope systematics for NWA 6704. The results are used to constrain the nature and provenance of its parent body, as well as the early chemical evolution of the parent body.

Methods: *Petrology.* We prepared nine polished thin sections from four specimens of NWA 6704 for petrologic studies. Petrologic analyses were conducted using SEM-EDS-EBSD and EPMA at the University of Tokyo and NIPR, Japan.

Highly siderophile element and Re–Os isotope analyses. Osmium isotope and HSE abundance analyses were conducted at the University of Maryland. Details of methods were described in [6].

Oxygen isotope analysis. We prepared five separated fractions (73–120 μm in diameter) washed in high-purity water. Metal grains were magnetically removed. Oxygen isotope analyses were conducted using fluorination and gas purification methods modified after [7] at IPM, Okayama University.

Titanium isotope analysis. We prepared 300 hand-picked chromite grains (60–350 μm in diameter). Titanium was purified by column chromatographic procedure following [8–10]. Titanium isotope analyses were conducted using MC-ICP-MS at the University of Tokyo.

Results and discussion: The texture is characterized by aggregates of orthopyroxene megacrysts up to 1.7 cm in length ($\text{Fs}_{40-42}\text{En}_{55-57}\text{Wo}_{3-4}$), with finer grains including olivine (Fa_{50-53}), chromite ($\text{Cr}/(\text{Cr}+\text{Al}) \sim 0.94$ molar ratio), awaruite (~ 80 wt% Ni), plagioclase ($\text{Ab}_{91-93}\text{An}_{2-3}\text{Or}_{4-6}$) and merrillite. Plagioclase separates share the same optical extinction angle over up to 1 cm^2 , irrespective of its occurrence as either inclusions of, or interstitial to orthopyroxene megacrysts. Plagioclase grains isolated in the megacrysts have euhedral rectangular morphology, but their shapes are subparallel to the facets of orthopyroxene megacrysts, probably as a result of control on crystal shape of plagioclase by orthopyroxene growth process. These observations can be well explained if orthopyroxene megacrysts were originally “skeletal” megacrysts and plagioclase partially filled the well-connected interstitial pores of the megacrysts. Our EBSD mapping demonstrates that the [001] of orthopyroxene megacrysts coincide well with their elongation. Such relationship may result from a dendrite megacrystal elongated along the c-axis with a branching structure [11]. Hence, it is inferred that each of the orthopyroxene megacrysts is a large single branching crystal elongated along [001]. Dendritic crystals generally form under extreme super saturation [e.g., 12], suggesting that the initial cooling rate of this meteorite was very rapid. Based on the skeletal morphology of orthopyroxene, we estimate that initial crystallization occurred under rapid cooling (*ca.* $1\text{--}10^2$ $^{\circ}\text{C}/\text{hr}$ [e.g., 12]).

On the other hand, later, slow cooling is suggested by the presence of pigeonite partially rimming the orthopyroxene megacrysts and containing relatively thin augite exsolution lamellae, and the relatively homogeneous mineral compositions. Using the geospeedometry based on Mg-Fe exchange between chromite and silicate phases [13], we estimate the cooling rate at 950-850 °C to be 10^{-4} - 10^{-2} °C/hr. The olivine-spinel oxygen geobarometer [14] gives f_{O_2} of FMQ-2.6.

Absolute and relative abundances of HSE in bulk fractions are broadly chondritic. Multiple processes, including core formation, igneous processing (partial melting and fractional crystallization), and late accretion established the HSE abundances of different parts of planetary bodies. Immediately following core formation, the HSE concentrations of the silicate portions of planetary bodies were most likely highly depleted and fractionated, relative to bulk chondrites [e.g., 15]. Thus, the broadly chondritic absolute, and relatively unfractionated HSE abundances of bulk fractions are inconsistent with removal of metal/sulfide-bearing partial melts. This suggests a parent body that had not segregated metal on a global scale to form a core by the time this sample formed. Consistent with the interpretation for NWA 6693 [4], we conclude that the precursor lithology of NWA 6704 most likely was characterized by chondritic absolute and relative HSE abundances, and that NWA 6704 crystallized from a melt that underwent only minor HSE fractionation, as compared to other primitive achondrites (e.g., brachinites). The ^{187}Re - ^{187}Os systematics of metal and silicate fractions define an isochron with an imprecise age of 4576 ± 250 Ma [6], indicating comparatively early closure of HSE migration.

These petrological and chemical features can be reconciled if a chondrite-like precursor to NWA 6704 was rapidly heated well above liquidus temperature such that the generated melt retained primitive chemical features. Further, this inference of instantaneous heating is consistent with the presence of Fe-rich vermicular olivine. Vermicular olivine is considered to be the relict decomposition product resulting from abrupt heating to cause incongruent melting (*ca.* >1300 °C; [16]) followed by rapid cooling, which could be realized by impact-induced heating.

The O-Ti isotope compositions of NWA 6704 ($\Delta^{17}\text{O} = -1.052 \pm 0.002$, 1 SD; $\varepsilon^{50}\text{Ti} = +2.28 \pm 0.23$, 2 SD) plot within the range of carbonaceous chondrites (Fig. 1). This suggests that its parent body may have accreted in the same region as the carbonaceous chondrite parent bodies. This inference is supported by the previously reported $\varepsilon^{54}\text{Cr}$ value of $+1.69 \pm 0.07$ for NWA 6704 [17], which is distinct from differentiated meteorites and ordinary and enstatite chondrites.

Overall, these lines of petrological, chemical, and isotope evidence can be best explained by a precipitous thermal phenomenon that occurred on an undifferentiated parent body that accreted in the same region as the carbonaceous chondrite parent bodies. We envision that an impact event induced regional, instantaneous melting up to a super-liquidus temperature, followed by rapid cooling. As a result, coarse orthopyroxene dendrites crystallized from the generated melt having a chondritic composition on the surface. The decrease in cooling rate at a later stage may reflect its burial beneath impact ejecta on the parent body.

References: [1] Weiss B. P. & Elkins-Tanton L. T. (2013) *AREPS*, **41**, 529–560. [2] Prinz M. et al. (1980) *LPS XI*, #902. [3] Irving A. J. et al. (2011) *74th Metsoc*, #5231. [4] Warren P. H. et al. (2013) *GCA*, **107**, 135–154. [5] Iizuka T. et al. (2013) *LPS XLIV*, #1841. [6] Archer G. J. et al. (2016) *LPS XLVII*, #2578. [7] Sharp Z. D. et al. (1990) *GCA*, **54**, 1353–1357. [8] Yamakawa A. et al. (2009) *ACS*, **81**, 9787–9794. [9] Zhang I. J. et al. (2011) *JAAS*, **26**, 2197–2205. [10] Schiller M. E. et al. (2014) *JAAS*, **29**, 1406–1416. [11] Cody A. M. & Cody R. D. (1995) *JCG*, **151**, 369–374. [12] Vetere F. et al. (2015) *ESR*, **150**, 25–44. [13] Ozawa K. (1984) *GCA*, **48**, 2597–2611. [14] Ballhaus C. et al. (1991) *CMP*, **107**, 27–40. [15] Capobianco C. J. et al. (1993) *JGR*, **98**, 5433–5443. [16] Tsuchiyama A. (1986) *JVGR*, **29**, 245–264. [17] Sanborn M. E. et al. (2013) *LPS XLV*, #2032. [18] Warren P. H. et al. (2011) *EPSL*, **311**, 93–100.

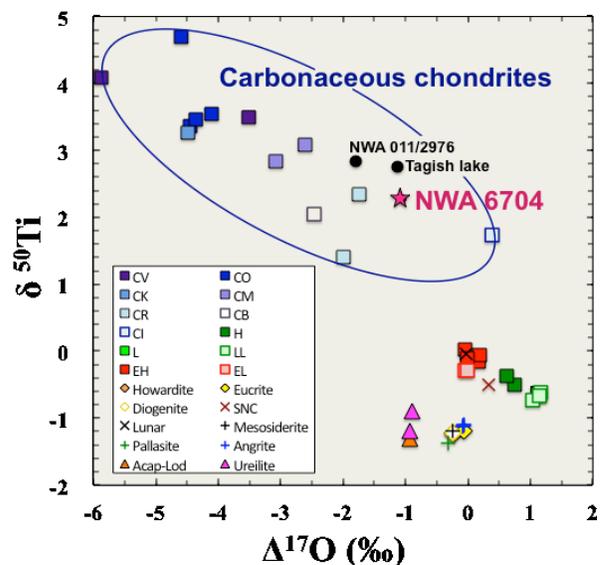


Figure 1. $\Delta^{17}\text{O}$ vs. $\varepsilon^{50}\text{Ti}$ of NWA 6704, as compared with planetary materials. Diagram modified after [18].