ALMAHATA SITTA MS-MU-011 AND MS-MU-012: FORMATION CONDITIONS OF TWO UNUSUAL ROCKS FROM THE UREILITE PARENT BODY. T. Mikouchi[1], A. Takenouchi[1], M. E. Zolensky[2] and V. H. Hoffmann[3,4], [1]Dept. of Earth and Planet. Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, [2]ARES, NASA Johnson Space Center, Houston, TX 77058, USA, [3]Faculty of Geosciences, Dept. of Geo- and Environmental Sciences, University of Munich, Geschwister-Scholl-Platz 1, 80539 München, Germany, [4]Dept. of Geosciences, University of Tübingen, Geschwister-Scholl-Platz, 72074 Tübingen, Germany, E-mail: mikouchi@eps.s.u-tokyo.ac.jp.

Introduction: Almahata Sitta meteorites are unique polymict breccia, comprising of many different meteorite groups as individual fragments dominated by ureilite lithologies and are considered to be recovered fragments of the asteroid 2008TC$_3$ [e.g., 1]. Recently, two unusual Almahata Sitta samples (MS-MU-011 and MS-MU-012) have been reported that show close petrogenetic relationships to ureilites [2,3]. MS-MU-011 is a trachyandesite mainly composed of feldspar (plagioclase and anorthoclase) and pyroxene (pigeonite and augite) having ureilitic oxygen isotopic ratios [2]. MS-MU-012 is the first ureilite example (unbrecciated) containing primary plagioclase crystals [3]. The findings of these two rock types are important to better understand formation conditions of ureilites and the evolution of their parent body(s). In this abstract we discuss formation conditions of these ureilite-related rocks using redox state estimate by Fe valence states of plagioclase and olivine cooling rate calculations.

Samples and Analytical Methods: We prepared polished sections from small fragments of MS-MU-011 and MS-MU-012 that were purchased from a meteorite dealer. The sections were analyzed by field emission gun electron microprobe (JEOL JXA 8530F at Univ. of Tokyo). The Fe valence of feldspar was estimated using synchrotron radiation X-ray Fe-XANES (BL-4A, PF, KEK, Tsukuba, Japan) with the same procedure described in [4].

Results: Followings are mineralogy and petrology of MS-MU-011 and MS-MU-012.

MS-MU-011. The section studied shows a fine-grained texture composed of ~85% feldspar laths and ~15% pyroxene with rounded shapes (Fig. 1) although small amounts of Si-rich feldspathic glass with K-enrichment (up to 4 wt% K_2O) were found at interstitial areas to feldspar and pyroxene. Feldspar grains are up to 1 mm long and show clear chemical zoning from the $An_{35}Or_1$ core to the An_8Or_3 rim although more An-rich plagioclase (An_{53}) is reported in [2]. Pyroxene is a composite grain (~1 mm) of pigeonite ($En_{60-55}Wo_8$, 0.2 wt% Al_2O_3, 0.6 wt% TiO_2, 0.4 wt% Cr_2O_3) and augite ($En_{42-45}Wo_{35-39}$, 0.5 wt% Al_2O_3, 1.2 wt% TiO_2, 0.8 wt% Cr_2O_3) with the roughly estimated abundance of pigeonite:augite=1:3 (Fig. 2). These pyroxene compositions give 1000-1050 ^oC for equilibration temperature [5]. No exsolution lamellae are found for both pyroxenes by the resolution of FEG-EPMA. All of these observations are consistent with [2]. The Fe-XANES analysis was performed for two feldspar grains and the obtained $Fe^{3+}/\Sigma Fe$ ratios are 0.30 ($An_{26}Or_1$) and 0.48 ($An_{13}Or_2$) (Fig. 3). The presence of Fe^{3+} is obvious and $Fe^{3+}/\Sigma Fe$ ratios may be increasing with decreasing An content by progressive crystallization, but it is required to analyze more feldspar grains to clarify its relationship.

MS-MU-012. It is reported that MS-MU-012 contains 14% plagioclase [3], but 2 sections studied (4 x 3.5 mm and 4 x 3 mm) do not contain plagioclase probably because of sample heterogeneity due to small sample size (originally 0.052 g). MS-MU-012 shows a typical texture of augite-bearing ureilite and the modal abundance of minerals is roughly 60% olivine, 25% orthopyroxene and 15% augite. Olivine is homogeneous (Fo_{88}, 0.25 wt% CaO, 0.45 wt% Cr_2O_3, molar Fe/Mn=20) except for the reduction rim. Orthopyroxene is $En_{85}Wo_{4.5}$ with 1.2 wt% Al_2O_3 and 0.9 wt% Cr_2O_3. Augite is $En_{55}Wo_{38}$ with 1.9 wt% Al_2O_3, 1.2 wt% Cr_2O_3 and 0.25 wt% Na_2O. The two pyroxene pair gives equilibration temperature of *ca*. 1200 ^oC [5] (Fig. 2). Fe metal veins are present both at grain boundaries and fractures within olivine and pyroxene. Although no carbon phases are present, Si-Na-rich glass with variable compositions is found along the cracks within olivine and pyroxene associated with Fe metal. Similar observation is found from some ureilites [e.g., 6]. The above mineralogy and petrology are identical to [3]. The olivine reduction rim (chemical zoning of Fe-Mg) of MS-MU-012 can be used to estimate its cooling rate [e.g., 7]. The best fit cooling rate from 1200 ^oC (pyroxene equilibration temperature) to 700 ^oC (typical closure temperature of olivine with fast cooling) is 0.2 ^oC/hr at logfO_2=IW-1 with D_{Fe-Mg} from [8] (Fig. 4). This cooling rate is comparable to fast cooling rates observed for most ureilite olivines [7].

Discussion and Conclusion: It is considered that MS-MU-011 is a crystallization product from a Si-rich magma that is likely to be a partial melting product complimentary to the residue corresponding to ureilites [2]. The result from this study supports this hypothesis, but the interesting result from this study is that crystallization of this melt occurred under relatively oxidizing conditions yielding $Fe^{3+}/\Sigma Fe$ ratio of feldspar reaching ~0.5. Such a high $Fe^{3+}/\Sigma Fe$ ratio of feldspar corresponds to the redox condition above the iron wüstite buffer [9]. Because Almahata Sitta samples were recovered immediately after their fall, it is unlikely to consider that such a high $Fe^{3+}/\Sigma Fe$ ratio is due to terrestrial weathering. Therefore, crystallization of MS-MU-011 was under oxidizing condition, which is not the case for the formation of the ureilite residue. If this was the case, the crystallization of partial melt of the ureilite parent body occurred in a relatively oxidizing region after separation of the melt from the residue.

Unfortunately, plagioclase was not found from our MS-MU-012 sample, but this study shows that its general mineralogy and petrology are similar to augite-bearing ureilites [10] and the obtained fast olivine cooling rate of MS-MU-012 (0.2 °C/hr from 1200 to 700 °C) is consistent with the brake-up of the ureilite parent body while it was still hot (1100-1200 °C) [e.g., 7]. Thus, MS-MU-011 is clearly a ureilite, but somehow retains plagioclase without being removed.

References: [1] Horstmann M. and Bischoff A. (2014) *Chem. Erde*, *74*, 149-183. [2] Bischoff A. et al. (2014) *PNAS*, *111*, 12689-12692. [3] Goodrich C. A. et al. (2016) *79th MetSoc*, Abst., #6105. [4] Takenouchi A. et al. (2017) *Meteoritics & Planet. Sci.*, *52*, 2491-2504. [5] Lindsley D. H. (1983) *Amer. Mineral.*, *68*, 477-493. [6] Chikami J. et al. (1997) *Antarct. Meteorite Res.*, *10*, 389-399. [7] Miyamoto M. et al. (1985) *Proc. 16th LPSC*, *JGR*, *90*, Suppl., D116-D112. [8] Misener D. J. (1974) *Geochem. Transport & Kinetics*, ed. Gilleti B. J. et al., 117-129. [9] Satake W. et al. (2014) *Geochem. Jour.*, *48*, 85-98. [10] Takeda H. et al. (1989) *Meteoritics*, *24*, 83-91.

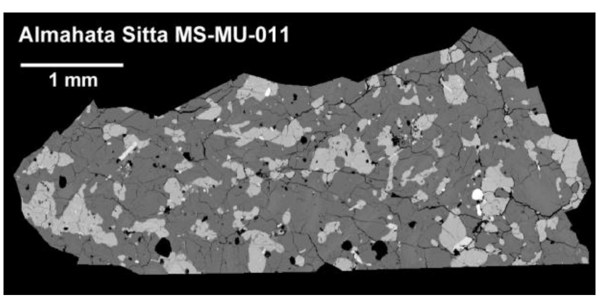

Fig. 1. Back-scattered electron image of the Almahata Sitta MS-MU-011 section studied. The most abundant phase (darker area in this image) is feldspar.

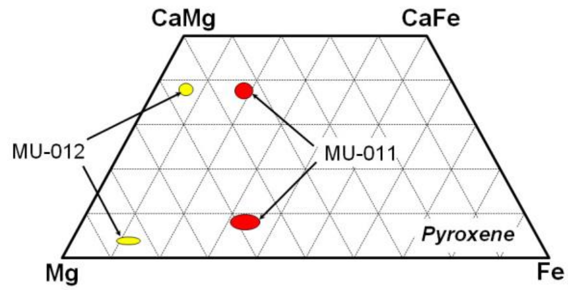

Fig. 2. Pyroxene quadrilateral showing the compositional ranges of pyroxene in Almahata Sitta MS-MU-011 and MS-MU-012.

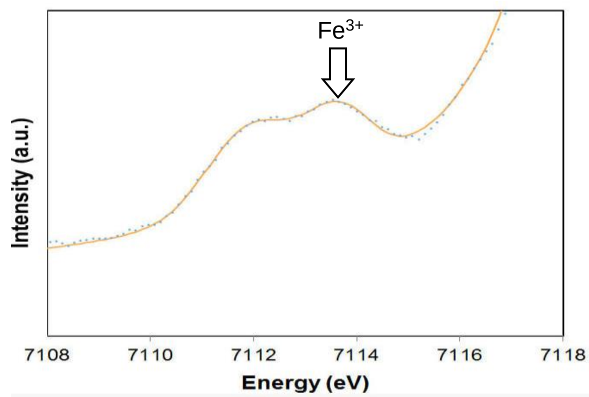

Fig. 3. Pre-edge Fe K absorption XANES of feldspar ($An_{13}Or_3$) from Almahata Sitta MS-MU-012, showing clear presence of Fe^{3+}.

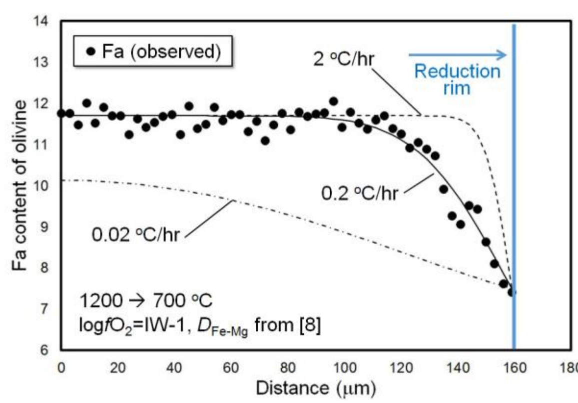

Fig. 4. Calculation of cooling rate of olivine using the Fe-Mg profile at the reduction rim of Almahata Sitta MS-MU-012.