THERMAL AND SHOCK METAMORPHISM FOR ORDINARY CHONDRITES: A QUANTITATIVE STUDY USING X-RAY DIFFRACTIONS.

N. Imae[1,2], M. Kimura[1], A. Yamaguchi[1,2], and H. Kojima[1], [1]National Institute of Polar Research (10-3 Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan, imae@nipr.ac.jp), [2]SOKENDAI (10-3 Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan, imae@nipr.ac.jp).

Introduction: As well as chemical group, petrologic types of various ordinary chondrites (thermal metamorphism) have been determined according to the scheme by [1]. On the other hand, shock stages (shock metamorphism) for them have been determined according to the scheme by [2]. However, both methods are not quantitative, since they depend on the observation of textures. Thus, we explored the quantitative method using in-plane rotation of polished thin section by broad X-ray beam (~1 cm in width), enabling complementary studies such as the textural observation and the other analyses [3]. This approach is the new technique to characterize bulk mineralogical features of stony meteorites. This method applied for ordinary chondrites in the present study. We then newly established the criteria for charactering ordinary chondrites.

Experiments: Sixty polished thin sections mainly of Antarctic meteorites at National Institute of Polar Research (NIPR) were prepared (23 H, 21 L, 16 LL). An X-ray diffractometer (SmartLab, RIGAKU) was used at NIPR installed in 2014, for obtaining the X-ray diffraction of ordinary chondrites. Analytical conditions were as follows: Cu $K\alpha_1$ with 40 kV and 30 mA was used, slit size was 10 mm, Ni filter was used for excluding Cu $K\beta$, and Cu $K\alpha_2$ was removed on the software (PDXL, RIGAKU). Focused indices were mainly olivine (Ol) 130, low-Ca clinopyroxene (Cpx) $22\bar{1}$, orthopyroxene (Opx) 511, and kamacite 110, since these peaks are not overlapped with the other peaks of main constituent minerals of ordinary chondrites. The optical microscopy (OM) and the electron micro probe analyzers (EPMA, JEOL JXA-8200 and JXA-8800 at NIPR) were used for complementary studies. The EPMA conditions for maskelynite in the NWA 4719 and Tenham L6 chondrites were 4 nA current with 10 μm beam diameter. Peak intensities and the full width of half maximum (FWHM) were obtained from the PDXL software.

Results and discussion: Chemical groups for equilibrated ordinary chondrites were clearly distinguished from Ol 130 because this index is related to the fayalite content [4]. However, in case of unequilibrated ordinary chondrites, the peak of Ol 130 is split or broad, corresponding to heterogeneous olivine compositions in types I and II chondrules, and matrices. The intensity ratios of kamacite was useful for distinguishing the chemical group between H and L-LL, but not definite, mainly due to various terrestrial weathering of kamacite especially in H chondrites. Petrologic type was estimated from the decrease of the peak intensity for Cpx $22\bar{1}$ (space group, $P2_1/c$) and instead increase of Opx 511 (space group, Pbca). Combining relative intensities coexisting Cpx $22\bar{1}$ and Opx 511 with FWHM of Opx 511, it is shown that type 4 is on the way to equilibrium. Then, petrologic types 3, 4, and (5,6) are possible to be distinguished for chondrites of S1. Shock metamorphism clearly correlates with FWHM for Ol 130 and Opx 511. In case of severely shocked chondrites classified into shock stage S6 of the NWA 4719 and Tenham L6 chondrites, the decrease of the intensities for Opx 511 and the increase for Cpx $22\bar{1}$ were clearly detected compared with usual L6 intensities. Two highly shocked chondrites do not show any melting features in hosts and include maskelynites, although the high pressure polymorphs occur in thin shock veins [e.g., 5]. Therefore Cpx in the host inverted from Opx under the solid state condition. Considering the phase diagram of $MgSiO_3$ [6], the low-Ca pyroxenes once inverted to high-pressure type Cpx (space group, C2/c) stable at high temperature (up to ~2200ºC) and high pressure (up to ~16 GPa), then changed to low-pressure type Cpx, since the high-pressure type is unquenchable. On the other hand, shock melted chondrites showed intense Ol 130 coexisting with Cpx $22\bar{1}$. It is suggested that they experienced above solidus temperatures and then rapidly cooled less than ~600 ºC [7]. This is also consistent with the examinations (abundant and homogeneous olivine compositions) under the OM and EPMA.

Summary: The X-ray data of various ordinary chondrites includes three dimensional information on the chemical group, thermal metamorphism, and shock metamorphism. We emphasize that it is newly developed approach for characterizing extraterrestrial materials without any significant damage during the measurements.

References: [1] Van Schmus W. R. and Wood J. A. (1967) *Geochimica et Cosmochimica Acta* 31:747–765. [2] Stöffler D. et al. 1991. *Geochimica et Cosmochimica Acta* 55:3845–3867. [3] Imae N. and Nakamuta Y. 2018. *Meteoritics & Planetary Science*. 53:232–248. [4] Yoder Jr. H. S. and Sahama T. G. 1957. *American Mineralogist* 42:475-491. [5] Tomioka N. and Miyahara M. 2017. *Meteoritics & Planetary Science*. 52:2017–2039. [6] Gasparik T. 1990. *Journal of Geophysical Research* 95:15751-15769. [7] Smyth J. R. 1974. *American Mineralogist* 59:345-352.