SILICA POLYMORPHS IN CUMULATE EUCRITES. H. Ono, A. Takenouchi, T. Mikouchi, Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan, E-mail: o-haruka@eps.s.u-tokyo.ac.jp.

Introduction: Silica minerals are major rock-forming minerals and concentrated in the crust on Earth. They are known to have 23 or more polymorphs under various temperature and pressure conditions. For example, tridymite most commonly occurs as orthorhombic (or hexagonal) crystal system in terrestrial samples, but it is always monoclinic in the extraterrestrial materials [e.g., 1, 2]. There are not so many reports that found silica minerals in extraterrestrial materials [e.g., 3]. Silica minerals are rarely occurred in undifferentiated meteorites (chondrites) mainly because partial melting is needed to crystallize silica minerals. Silica minerals are also rare in differentiated meteorites (achondrites) because most of them are mafic to ultramafic rocks that contain small silica component. The silica minerals in achondrites have been reported as accessory minerals that occurred at the last stage of crystallization of basaltic magma following the crystallization of pyroxene and plagioclase [e.g., 4]. These silica minerals are known to form as several different polymorphs (α-quartz, tridymite, cristobalite etc.) in each meteorite. For example, quartz is found in Serra de Magé (eucrite) and is considered to have been precipitated by a hydrothermal activity [5]. However, in many cases, they are simply reported as "silica minerals" alone and their detailed identifications and discussion using silica polymorphs are not enough. Although silica minerals in extraterrestrial materials have a potential to become one of the good indicators to infer the pressure and temperature history of the meteorite due to occurrence as various polymorphs, they have been rarely been paid attention. Therefore, in this study, we focus on silica minerals in three cumulate eucrites and discuss their formation conditions and inversion rate of tridymite considering their cooling histories.

Samples and Methods: We analyzed thin sections of Moore County, Moama, and Y980433, and observed them by optical microscopy and SEM (the JEOL JSM-7100F at NIPR and Hitachi S4500 at the University of Tokyo). Quantitative chemical analyses and chemical mapping were performed using the JEOL JXA-8530F and JXA-8900L electron microprobe at the University of Tokyo. The condition of quantitative analysis was electron accelerating potential of 15 kV and beam current of 6 nA using broad beam (10 μm in diameter). After locating silica phases by optical microscope and X-ray mapping, their EBSD patterns were obtained using the SEM. Raman spectra of these silica phases are also obtained by the JASCO NRS-1000 and RENISHAW in Via Raman Microscopes at National Institute of Polar Research (NIPR).

Results: *Moore County* is composed of coarse-grained plagioclase and pyroxene. It is estimated by pyroxene lamellae that Moore County was once cooled from 990 ^{o}C to 730 ^{o}C at a rate of 0.00016 ^{o}C/yr and later it was heated up to 930 ^{o}C and then cooled down to 730 ^{o}C at a much faster rate of 0.3 ^{o}C/yr [6]. Silica minerals in Moore County are significantly large (~ 3 mm). Raman spectra show that all of these silica minerals are tridymite (monoclinic) and their EBSD patterns are consistent with the monoclinic structure.

Y980433 consists of coarse-grained plagioclase and pyroxene similar to Moore County. This meteorite is considered to have been cooled very slowly similar to terrestrial layered intrusions because pyroxenes in Y980433 have thin exsolution lamellae within thick exsolution lamellae [e.g., 7]. We found some silica minerals in Y980433, and their EBSD patterns and Raman spectra indicate that there are two kinds of silica polymorphs, tridymite (monoclinic) and quartz. The sizes of tridymite are 0.3~0.5 mm and those of quartz are much smaller (~0.07 mm) (Fig. 1). The thin section studied has many cracks and veins that look like shock melts and quartz grains tend to be found around these veins (Fig. 1). Pyroxene in this meteorite shows wavy extinction, indicating that Y980433 is moderately shocked.

Moama is also composed of coarse grains of plagioclase and pyroxene. Because exsolution size of Moama pyroxene is similar to that in Serra de Magé, it is estimated that this meteorite was slowly cooled at a similar cooling rate (0.0004 ^{o}C/yr) [8]. We found some silica minerals in Moama by optical microscope. EBSD patterns and Raman spectra indicate that all silica minerals in this meteorite are tridymite (monoclinic). Although the maximum size of tridymite is about 0.5 mm, most of them are less than 0.1 mm. Such small tridymite are found between pyroxene and plagioclase, and they sometimes penetrate into pyroxene with curvy boundary (Fig. 2).

Discussion and Conclusion: We found silica minerals in all samples and identified that most of them are monoclinic tridymite. Their EBSD patterns are also consistent with the monoclinic structure and they are not orthorhombic (or hexagonal) which is often found in terrestrial rocks. Quartz was found only in Y980433. Electron microprobe analysis shows that tridymite contains slightly larger amounts of Al_2O_3 and TiO_2 compared to quartz in general (Table 1).

Moama would have perhaps experienced relatively simple thermal history because this meteorite was cooled very slowly and no obvious evidence for reheating or shock [e.g., 8]. However, tridymite in

Moama is not transformed to quartz. If the temperature becomes below 870 °C, tridymite is considered to be unstable at ambient pressure and starts inversion to quartz. Such partial inversion of tridymite to quartz is found in Gibeon iron meteorite [9]. Therefore, the presence of tridymite in Moama indicates that tridymite was not transformed to quartz in spite of such a slow cooling rate (~0.0004 °C/yr). In other words, this suggests that tridymite retains primary information of the condition meteorites formed.

Tridymite in Y980433 has many cracks and their EBSD patterns are automatically fitted to two different types of crystal structures, hexagonal and monoclinic although Raman analysis shows that they are all monoclinic. We considered that these two types of EBSD patterns are the result of fitting error by the analysis software, because EBSD patterns at certain directions are similar between hexagonal and monoclinic structures. Otherwise, these tridymites are twin [10] although we found no such textural evidence. It is natural that tridymite has survived without being inverted to quartz in Y980433 during cooling because this meteorite was cooled more rapidly compared to Moama. On the other hand, tridymite has also survived in an impact event because no high-pressure polymorph has been found, indicating that the shock was not over 5 kbar or shock temperature was not enough to cause transformation. Moore County that cooled a little more quickly compared to Moama and reheated during cooling to high temperature has much larger tridymite crystals than other meteorites. This indicates that Moore County was initially cooled at a slower rate than Moama and Y980433, and those tridymites crystallized during this initial slow cooling. In fact, pyroxene shows a slower cooling rate than that of Moama [6].

Regarding polymorphs of silica minerals, quartz was found in Moama. Because quartz is found along veins, there are two possibilities. One possibility is that these quartz grains formed by transformation from tridymite by a shock event with melting. The other possibility is that quartz formed by secondary alteration such as hydrothermal activities similar to be found in Serra de Magé [5].

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Table 1. Quantitative chemical analyses of silica minerals from three cumulate eucrites.

Sample	Moore County	Y980433	Y980433	Moama
mineral	tridymite	tridymite	quartz	tridymite
SiO2	98.61	98.47	98.72	99.78
Al2O3	0.23	0.75	0.12	0.08
TiO2	0.19	0.12	0.04	0.14
FeO	0.03	0.34	0.24	0.27
MnO	nd	nd	nd	0.02
MgO	nd	0.06	nd	nd
CaO	0.03	0.02	0.03	0.03
Na2O	0.03	0.04	nd	0.01
K2O	0.13	0.01	0.03	0.09
NiO	nd	nd	nd	0.03
Total	99.24	99.80	99.17	100.47

nd = not detected

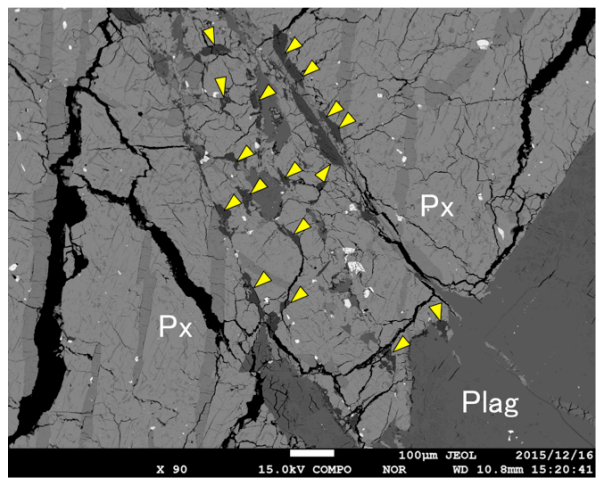

Fig. 1. Back-scattered electron (BSE) image of small quartz grains (dark phases indicated by small yellow triangles) around the vein in Y980433. Px: pyroxene. Plag: plagioclase.

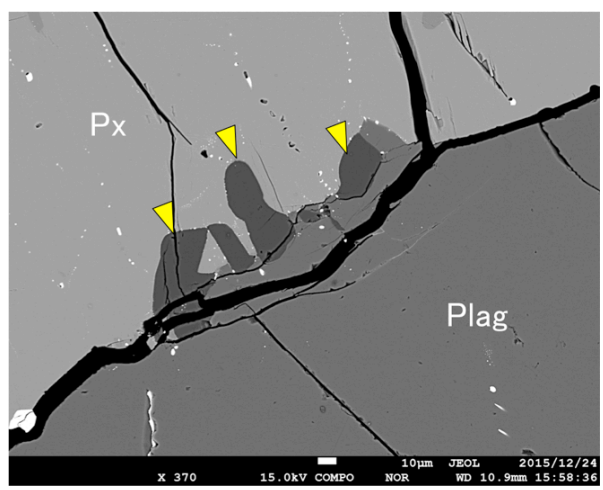

Fig. 2. BSE image of small tridymite grains (dark phases indicated by yellow triangles) penetrate into pyroxene with curvy boundary in Moama.