Moganite in a lunar meteorite NWA 2727 as a trace of water ice in the Moon's subsurface

Moganite (monoclinic SiO_2 phase that belongs to the *I2/a* space group) is a mineral of silicon dioxide and has a similar but different crystal structure from quartz [1]. It forms on Earth as a precipitate when alkaline water including SiO_2 is evaporated under high-pressure conditions, as in the formation of sedimentary rocks (e.g., evaporite, chert, and breccia) [1,2]. In contrast, moganite has not at all been expected to be found in extraterrestrial materials since it originates only from recent alkaline water activity. We have discovered moganite in a lunar meteorite named NWA 2727 found in a desert in northwest Africa (Fig. 1) by performing various microanalyses [3]. This is significant because moganite requires alkaline water to form, reinforcing the conclusion of recent remote-sensing spacecraft observations (e.g., LCROSS and Deep Impact) that water exists on the Moon [4,5]. The existence of moganite in NWA 2727 strongly implies that there has been recent water activity on the lunar surface. Here, a new history of lunar water can be interpreted by our discovery of moganite using synchrotron X-ray diffraction (SR-XRD) measurements at SPring-8 **BL10XU**, combined with Raman spectrometry and electron microscopy.

Thirteen different lunar meteorites with various lithologies (gabbro, basalt, anorthositic regolith, troctolite, and their breccias) were investigated in the microanalyses, and moganite coexisting with coesite and stishovite (high-pressure SiO_2 phases formed above 3 and 8 GPa, respectively) was found only in NWA 2727, which may have originated from the local

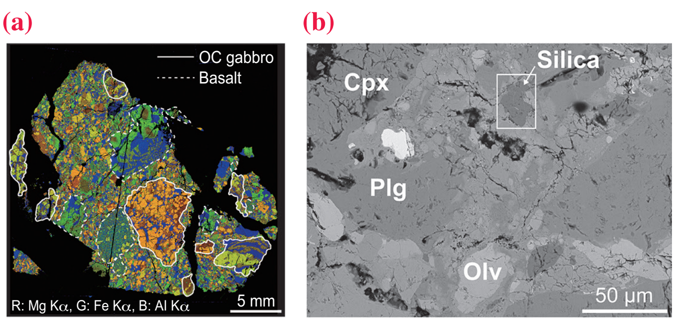

Fig. 1. **(a)** Petrological photographs of NWA 2727. False-color elemental X-ray map of thin section of NWA 2727 with red (R) = Mg Ka, green (G) = Fe Ka, and blue (B) = Al Ka X-rays obtained by the electron probe microanalysis. Areas enclosed by white solid and dashed lines indicate olivine-cumulate (OC) gabbroic clasts and basaltic clasts, respectively. The other areas filling the interstices between these clasts represent the breccia matrix. **(b)** Backscattered electron image of moganite-bearing silica micrograin adjacent to olivine (Olv), clinopyroxene (Cpx), and plagioclase (Plg) in the breccia matrix.

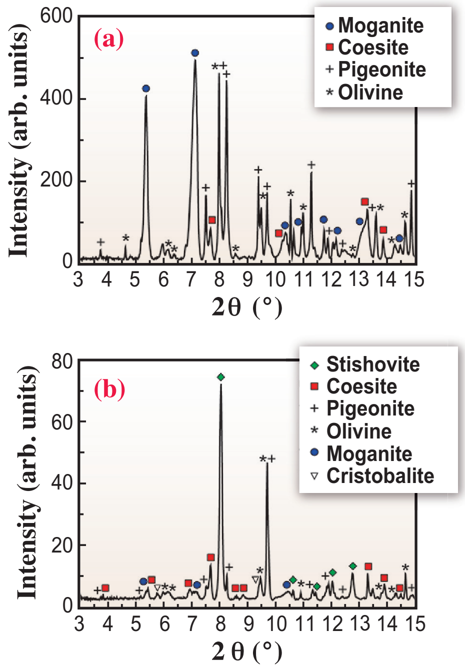

Fig. 2. SR-XRD pattern of the silica micrograins **(a)** with moganite and coesite and **(b)** moganite, coesite, and stishovite in the breccia matrix.

sites within the Procellarum terranes. NWA 2727 was found to be mainly composed of gabbroic and basaltic clasts containing a breccia matrix (Fig. 1), where the breccia matrix contains several silica micrograins (2 to 13 mm in radius) between the constituent minerals (olivine, pyroxene, and plagioclase). The SR-XRD analyses of these silica micrograins in the breccia matrix show characteristics of moganite (Figs. 2(a) and 2(b)) (X-ray wavelength of 0.41569(9) Å). The strong peaks at *d* values of 4.46 and 3.36 Å and weak peaks at 2.31, 2.19, 2.04, 1.97, 1.83, and 1.66 Å can be indexed to a monoclinic lattice with the cell parameters: a = 8.77(1) Å, b = 4.90(1) Å, c = 10.77(3) Å, b = 90.38(3)°, and V = 463.0(6) Å as the space group *I2/a*. This is in good agreement with the structure of moganite. The SR-XRD signatures corresponding to coesite and stishovite can also be obtained from the silica micrograins with moganite. However, we did not discover moganite in the basaltic and gabbroic clasts of NWA 2727 or in the other lunar meteorites examined here. Raman spectrometry and transmission electron microscopy also demonstrated the same tendency as the result of the SR-XRD analyses.

Moganite was found in only one of the 13 samples. If terrestrial weathering had produced moganite in the lunar meteorites, there would have been moganite present in all the samples that fell to Earth around the same time, but this was not the case. Furthermore, many previous publications on natural occurrences and laboratory experiments concluded that moganite can only be formed by precipitating from alkaline water under high-pressure consolidation at >100 MPa [1,2], which is a distinctly different environment from the desert. Part of the moganite had changed into coesite and stishovite, indicating their formation through heavy impact collisions on the Moon. These facts confirm our theory that it could not have formed in the African desert.

We interpreted the results as follows (Fig. 3) [3]. Alkaline water-bearing carbonaceous chondrite collisions delivered abundant alkaline water to the lunar surface <2.67 billion years ago. After the collisions, the delivered water was captured as fluid inside the breccia during the shock-induced consolidation. On the sunlit surface, lunar moganite precipitated from this captured alkaline water. Simultaneously, such captured water became cold-trapped in the subsurface and still remains as ice underneath the Procellarum terranes. Lunar moganite coexists with coesite and stishovite, thereby implying that a trace of the subsurface water ice was brought from the Moon by the recent impact <1–30 million years ago. Our moganite-precipitation simulation modeling concluded that a subsurface H_2O concentration higher than the estimated bulk content of 0.6 wt% (18.8 L/m^3 H_2O in a rock) is expected to still remain as ice. This value is in excellent agreement with the concentrations of H_2O ice (5.6±2.9% by mass) excavated from the Cabeus crater in the South Pole observed by LCROSS [4] and those of OH and H_2O molecules (~0.3 wt%) on the North Pole observed by Deep Impact [5]. Thus, the subsurface is expected to be an abundant and available water resource for future lunar explorations (e.g., water for drinking, oxygen for breathing, and hydrogen for fuel). Furthermore, moganite can serve as an excellent marker of the existence of water in the Moon's subsurface, which can be used for astronomy and spacecraft searching for water in Earth's satellite.

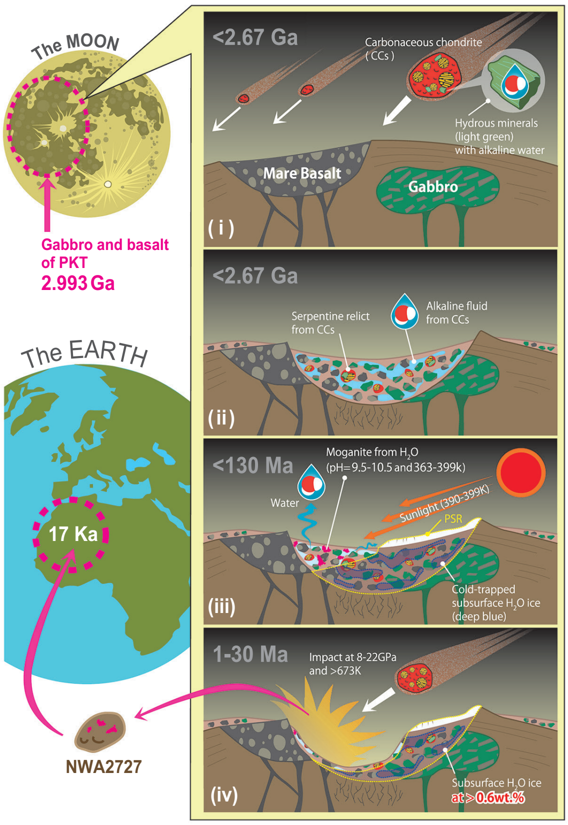

Fig. 3. Schematic of the history of subsurface H_2O in the Moon and the formation of moganite. About 3 billion years ago, mare basalt solidified on the lunar surface, and a gabbroic intrusive chamber crystallized in the anorthositic crust of the Procellarum terrane. (i) Carbonaceous chondrite (CCs) collisions are considered to have occurred <2.67 billion years ago, which led to the delivery of alkaline water to the Procellarum terrane. (ii) After these collisions, constituent rocks of the Procellarum terrane and CCs fragments are considered to have been ejected and brecciated in the impact basin. During breccia consolidation, water delivered by the CCs was captured as fluid inside the breccia. (iii) On the sunlit surface, the captured H_2O is likely to have become a silicic acid fluid, part of which migrated to space and the colder regions. Then, moganite should have precipitated under high consolidation pressure after (ii) the first collisions <2.67 billion years ago and before (iv) the most recent impact 1 to 30 million years ago as expressed below. Below its freezing point, it should have been simultaneously cold-trapped in the subsurface down to the depth of the impact basin. (iv) A subsequent heavy impact event may have launched NWA 2727 from the Moon. NWA 2727 eventually may have fallen to Earth 17±1 thousand years ago. A subsurface H_2O concentration higher than the estimated bulk content of 0.6 wt% is expected to still remain as ice.

Masahiro Kayama[a,b,*], Naotaka Tomioka[c] and Eiji Ohtani[b]

[a] Frontier Research Institute for Interdisciplinary Sciences, Tohoku University
[b] Department of Earth and Planetary Materials Science, Tohoku University
[c] Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology

*Email: masahiro.kayama.a3@tohoku.ac.jp

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