Water-rich lunar upper mantle as recorded in lunar meteorites

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Bulk water analyses of the Apollo samples have revealed almost scant water (<1 ppb), which has resulted in the post-Apollo view of a dry Moon. However, with the discoveries of OH species in lunar secondary minerals by mass spectrometry, questions concerning water in the mantle have been revived. Some recent studies of lunar samples proposed a water-rich mantle (9–585 ppm) based on carefully considered assumptions. However, the wet mantle hypothesis has remained inconclusive because the inferences made must be taken with caution as the result of the unreliability of the tentative assumptions used. Recent isotopic analyses of chlorine and oxygen in lunar second minerals predict the dry lunar mantle (<10 ppb), but this hypothesis was build up based on the indirect evidences (not in the direct way using hydrogen mass spectrometry). In this study, we measured water in gabbroic clinopyroxene and olivine of the gabbro lithic lunar meteorites using *in-situ* transmission FTIR heating absorption spectroscopy to determine the actual water content of the upper mantle beneath the Procellarum basin without the unreliable assumptions.

In-situ FTIR heating measurements at 120 °C represent water bands at ~3750, ~3600 and ~3500 cm^{-1} for clinopyroxene and at ~3550, ~3500 and ~3250 cm^{-1} for olivine in the gabbroic lithologies. The *in-situ* FTIR spectra of clinopyroxene and olivine entrained on the shock veins and fusion crusts include similar water bands but with obviously lower absorbances. This behaviour appears to be the result of the dehydration of intrinsic water due to the post-shock annealing in an impact event for the shock vein, and due to aerodynamic heating during the atmospheric entry for fusion crust. Therefore, the abundant water in the gabbroic minerals appears to be derived from the Moon and not the Earth. The *in-situ* FTIR heating measurements of the gabbroic clinopyroxene and olivine at 200–550 °C demonstrated that the absorbances show almost no change up to 300 °C but drastically decrease in temperature from 300 to 550 °C. This result can be attributed to the dehydration of tightly bound molecular water. The other water bands remained after heating to 550 °C, and exhibit anisotropies of the absorbance during rotation of the polarizer. Therefore, the remaining bands can be assigned to structurally oriented OH species.

A conversion using the Beer-Lambert law of the integral absorbance into the water contents revealed that the gabbroic clinopyroxene and olivine contain >339–1363 and >199–1152 ppm water, respectively. Based on these water contents, a mode composition of the constituent minerals determines the mantle water content without the previously proposed assumptions. As a result of our findings, we conclude that there is a water-rich part of the upper mantle that spreads >631 ±498 ppm at depth of >30 to >400 km beneath the Procellarum basin; such water concentrations are as plentiful as that found in the Earth’s mantle. Notably, however, the wet mantle hypothesis requires further consideration because there are some evidence concerning water depletion in the lunar mantle as reported in the previous studies. A tentative theory that explains this discrepancy proposes that the indigenous water is heterogeneously distributed and partly included in the lunar mantle. The heterogeneously and partly water-rich lunar upper mantle proposed here supports recent lunar evolutionary models; accretion and cooling processes of the primary materials in the aftermath of the Giant Impact, differentiation in the lunar magma ocean, the cause of a deep moonquake, and a share of common water sources between proto-Earth and Moon. Our findings also promises new insights into future lunar missions and, particularly into landings on and sample returns from the mantle-originated olivine-bearing sites found by the SELENE mission on the Procellarum basin and South Pole Aitken.

Keywords: Moon, Lunar mantle, Lunar meteorite, Mantle water content, Infrared absorption spectroscopy, Procellarum basin

