WAS THE MOSCOVIENSE BASIN FORMED BY DOUBLE-IMPACT?.

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Introduction: The Moscoviense basin, which is the most prominent mare basalt filled multi-ring impact basin on the lunar farside highlands, is located at (26ºN, 148ºE) and has a diameter of the main ring of either 445 km [1] or 420 km [2]. Some concentric circular structures of the Moscoviense basin (140, 220, 300, 630 km in diameter) were reported based on photo data [2]. Mare basalt of Mare Moscoviense is divided into four individual basalt flows using nomenclatures, age relationships and surface composition [e.g., 3, 4]. Haruyama et al. reported mare volcanism at the Moscoviense basin until 2.57 Ga [5]. Morota *et al.* determined the thickness and age of individual basalt units of Mare Moscoviense and conclude that the magma production in the upper mantle beneath Mare Moscoviense is 3 – 10 times lower than that of the nearside mantle [6]. Spinel-rich rock was firstly discovered at the Moscoviense region using newly obtained hyper spectral image data by Moon Mineralogy Mapper (M^3) onboard the Chandrayaan-I spacecraft [7]. Moreover, very olivine-rich rocks have discovered at ring structures of the Moscoviense basin [8]. Those olivine rich rocks suggested thet they are probably upper mantle materials excavated by basin forming impacts [8].

Structure of the Moscoviense Basin: Using the 1/16 degree grided Kaguya topography model [9], we can easily identify two distinct ring structures and less-clear ring structure (Fig. 1). The innermost-ring (about 180 km in diameter) is seen only partially. The middle-ring (about 420 km in diameter) is clear and a fully closed. The outermost-ring (about 640 km in diameter) is more obtuse than the middle-ring. These characteristics of the Moscoviense rings are not a common feature of other multi-ring basins. For other multi-ring basins such as the Orientale basin, the most prominent and regular outlined ring is the basin rim-crest and middle-rings have irregular topography. But for the Moscovience basin, the middle-ring is the most prominent and it has regular topography. These three rings are not cocentric but they are located on a single line. In addition, for the Moho undulation, the shallowest part is offset from the center of the Moho uplift (Fig. 1).

Offset and linear arrangment of rings and innermost partial ring suggests that the Moscoviense basin formed by an oblique impact. On the other hand, Kaguya crustal thickness models show that the Moscoviense basin has an extremely large (both in width and height) mantle plug, larger than other basins of the same type [10]. The spatial size of the mantle plug of the Moscoviense basin is almost the same size as that of the Freundlich-Sharonov basin that has a 600 km diameter main ring (Fig. 1). Moreover, height of the mantle plug of the Moscoviense basin is much higher than that of the Freundlich-Sharonov basin [10]. Mantle plug size of the impact basin should be mainly controlled by the size of the excavation cavity at the formation of the crater, and by the pre-impact depth of Moho discontinuity. Pre-impact depths of the crust–mantle interface at both basins were almost the same (~ –65 km) (Fig. 1). So the difference is probably due to the size of the excavation. In addition, olivine exposure around the Moscoviense basin supports a very deep excavation (that reaches upper mantle) of the Moscoviense basin forming impact [8]. However, the excavation depth of an oblique impact is shallower than that of a normal impact [11]. The extremely large mantle plug (i.e. extremely large excavation) is therefore hard to explain by a single oblique impact.

Double Impacts Formation Hypothesis: We propose a new idea for the Moscoviense basin formation, which is a “double-impact formation” hypothesis. The essence of this hypothesis is as follows. The first impact formed the ~640 km size pre-Moscoviense basin that is similar to the Freundlich-Sharonov basin. After this, the second impact occurred on the floor of the pre-Moscoviense basin and this formed the ~420 km size multi-ring basin. The partiality of the innermost-ring and the offset between innermost- and middle-ring center can be interpreted by the influence of the structure of the pre-Moscoviense basin as the pre-existing target structure of the second impact. Furthermore, because of the crustal thinning effect at the first impact, the excavation depth of the second impact could have reached the Moho interface beneath the pre-Moscoviense basin. The resulting structure from two times of the dynamic uplift processes should have a huge mantle plug, an offset in rings, and the exposure of olivine rich rock that originally was located at the upper-mantle [8]. In addition, the difference between the Moscoviense and the Freundlich-Sharonov with respect to the amount of mare volcanism can probably be explained by a double impact origin of the Moscoviense basin. If the total amounts of magma production and magma production rate at the two basins are equal, crustal thickness could control the extrusion volume. Thinner and more cracked crust resulting from the double impacts at the Moscoviense basin is more favorable for magma extrusion than a relatively thicker and relatively rigid crust at the Freundlich-Sharonov basin.

Probability Test by Monte-Carlo Simulation: Double-impacts hypothesis can explain both the center offset and the huge mantle plug of the Moscoviense basin. However, are such close double impacts possible statistically? From analysis of current topography (ring structures), the distance between the first and the second impact is about 80 km. To evaluate the probability of a close double impact, we carried out a simple probability test using Monte-Carlo simulation. We assume that basin forming impacts occurr uniformly at the lunar surface. At present day, 50 to 60 impact basins were reported and proposed by researchers [e.g., 1, 2, 12]. So, first we compute 50 impact locations (spatially random-generated impacts) as one set and then we examine the closest distance (minimum value of the nearest neighbor distances for all impacts) for each set. After we generated 100,000 sets, we estimate the probability of close double impacts. The possibility of existence of at least one basin pair with 80 km separation distance (center location distance between fist and third ring structures of the Moscoviense basin) is about 50 %. This probability is not small and thus we infer that a basin-forming double impact with an 80 km offset could have occurred on the Moon.

Conclusions: We measured centers and diameters of ring structures of the Moscoviense basin using newly obtained Kaguya topographic data. Ring structures are not concentric but show a linear offset. Traditional interpretation of this characteristic is an oblique impact formation of the Moscoviense basin. However, an oblique impact cannot account for the extremely large mantle plug of the Moscoviense basin as estimated from gravity. We thus propose a double impact formation hypothesis for the Moscoviense basin. This hypothesis easily explains the mantle plug size, the exposure of olivine rich material probably excavated from upper mantle by basin forming impact and other features of the Moscoviense basin. The probability of occurrence of double impact basin, as inferred from a Monte-Carlo simulation of impact locations, is about 50 % for the Moscoviense basin case (impact location distance between first and second impacts of ~80 km). This probability is not so small as to reject a double impact origin of the Moscoviense basin.

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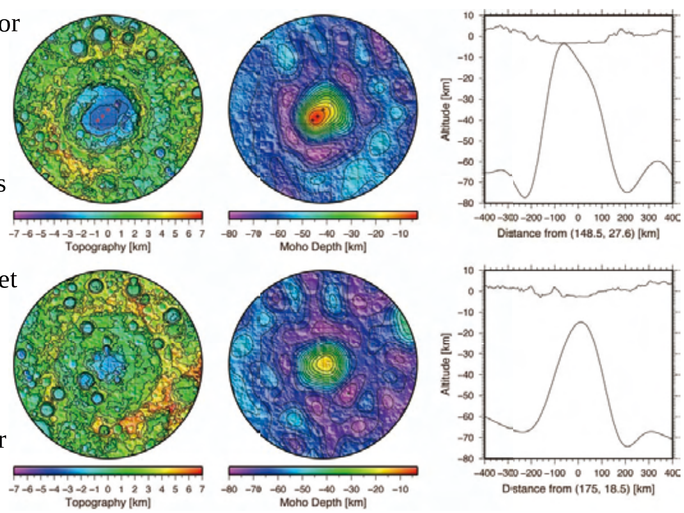

Figure 1. Surface topographic features (left), subsurface structure (Moho discontinuity) map (center), profiles (right) of the Moscoviense basin (upper pannels) and the Freundlich-Sharonov basin (lower pannels) based on Kaguya selenodetic data. Projections of both maps are orthographic projection centered on (148.5 ºE, 27.6 ºN) for the Moscoviense, on (175 ºE, 18.5 ºN) for the Freundlich-Sharonov and horizons are 17 degrees from center. Topography and Moho depth are referenced from 1737.4 km radius standard sphere centered on the center of mass of the Moon. Contour intervals of topography and Moho are 1 km and 5 km, respectively. Crosses indicate center locations of each ring structure. Great circles of azimuth of 45 º at each reference point were employed as track lines of profiles.