ORIGIN OF WATER SIGNATURES WITHIN CLAVIUS AND OTHER IMPACT CRATERS ON THE MOON. P.H. Schultz[1], S. Li[2], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook St., Box 1846, Providence, RI, 02912 (peter_schultz@brown.edu), [2]Hawai'i Institute of Geophysics and Planetology, University of Hawaii.

Introduction: The broad distribution of water and hydrated minerals on [e.g., 1] and below the surface [2,3] has challenged our understanding of the processes responsible. Moreover, there are signatures of water well beyond the polar regions associated with certain central peaks [e.g., 4] and more generally [2; 3; 5]. Early studies dismissed correlations with impact craters and ruled out the role of impact delivery [1, 6]. This contribution presents provides evidence that indicate that recent volatile-rich impacts (primitive asteroids and cometary bodies) indeed have resulted in local concentrations and contribute to the polar and global inventory through gradual recycling of hydrated impact products. The retention of such reservoirs, however, depends on impact angle, speed, target, and conditions of impact.

Background: The Infrared Spectrometer on Chandrayan *Moon Mineralogy Mapper* (M^3) reveals a complex distribution of H-bearing species (OH and H_2O). While many fresh craters create "holes" in the distribution of elevated water concentrations [5], there are also notable concentrations occur within certain craters, Bullialdus [4], Clavius [6; 7], and Copernicus [8]. Haloes with elevated water are also associated with Copernicus, Langrenus, Pythagoris, Bürg, and Le Verrier, along with certain small (10 km) craters [8]. The present study reviews these and other occurrences.

Impact-Associated Elevated Water: Crater-related concentrations of water occur in five distinct areas: central peaks; near-rim ejecta; certain small fresh craters (and clusters); localized regions associated with crater rays (secondary craters); and breached-rim craters. As noted above, examples of elevated water concentrations with the interiors of certain craters and near-rim ejecta have been presented before. Here, we focus on the selected examples of breached-rim craters.

Impacts that overlap the rim of much larger craters result in a breach in the crater rim. This process opens the transient crater during the earliest stages of formation. As a result, portions of the impactor are exposed and spread across the floor of the overlapped crater. This process has been demonstrated experimentally [7-10] and theoretically [11]. Moreover, later ejecta trajectories are disrupted and redirected, thereby exposing the early-stage components that interact (mix) with the floor materials. On the Moon, the early-stage component on the Moon includes significantly elevated water concentrations. Three examples are shown. The first shows an impact on the rim of a larger degraded crater and resulted in a breached-rim, elongate crater about 10 km in diameter (**Fig. 1**). The fork-shaped enhanced water abundance (100-200 ppm) occurs within a water-depleted halo. This shape is consistent with the pattern of a decapitated impactor [12]. Other examples have been found closer to the equator.

The second example is the enhanced water abundance within the crater Clavius (**Fig. 2**). The distribution of water occurs in a band that crosses the crater floor. M^3 data [5] indicate levels that reach 300-600 ppm, subsequently confirmed by later telescopic data from SOFIA [6]. Rays (secondary craters) from the more recent crater Tycho, however, cross the western and eastern floor of Clavius and removed (mixed) pre-existing water trapped in the regolith. Rather than being related to Clavius, however, the enhancement of water correlates to the asymmetric distribution of ejecta from the crater Rutherfurd (~50 km diameter) across southern floor of Clavius. Mapping the grooves and ejecta grooves (**Fig. 2b**) reveal that the first contact of the Rutherfurd impactor occurred near the rim crest of Clavius, thereby spreading ejecta and decapitated projectile material across the floor of Clavius. As illustrated in previous studies [10], the convergence of grooves and secondaries can be used to constrain the initial size of the Rutherfurd impactor to be about 9 km.

Discussion: Figures 1 and 2 illustrate just two examples of craters with breached rims/walls that result in asymmetric ejecta coincident with enhanced water. The association is consistent with a signature derived from the impacting body, rather than excavated water reservoirs. In a sense, breached craters resemble highly oblique impacts that spread the impactor component (vapor, melt, surviving fragments) downrange [9, 12]. This component from oblique impacts, however, may be lost due to its high speed, unless the impact angle is extremely low where the lateral distribution of ejecta (butterfly pattern) prevents burial (and mixing) by later arriving ejecta [11]. In contrast, breached-rim craters result in directing this component across the adjacent low-lying surface or into the opposite wall.

Impact experiments reveal that hypervelocity impacts into porous targets can result in impact melts and breccias capturing as much as 30% of the water carried in carbonaceous chondrite projectiles [13]. Such results demonstrate that sequestering water can occur, in contrast to general perceptions. For example, Honniball et al [6] questioned this process for the levels observed in the lunar regolith because the experiments predict levels four times higher than those observed. As a result, they dismiss the role of impact-delivered water, including the observations for the levels inside Clavius. Direct application to the lunar regolith, however, requires adjustments for the higher impactor speeds, subsequent mixing during emplacement, and later impact recycling. Ironically, the signature within Clavius actually illustrates the role of impact-delivered volatiles due to the impactor component from the rim-breached crater Rutherfurd.

Conclusions: A survey of breached-rim craters and other crater-related with hydrous signatures reveal that impacts by volatile-bearing asteroids are making significant contributions to the lunar volatile budget, consistent with observations of water and other volatiles from the LCROSS mission. This is consistent with the expected flux of cometary bodies based on dynamical models and wind-streak craters on Mars indicating that there should be about 38 lunar craters >10 km and 10 craters >20 km over the last 1 Ga [14].

References:

[1] Milliken, R. & Li, S. (2017); Nat. Geosci. 10, 561; [2] Colaprete, A. *et al* (2010), *Science* 330, no. 6003, 468; [3] Schultz, P. H. *et al*. (2010), *Science* 330, no. 6003, 463; [4] Klima, R. et al. (2013), Nat. Geosci. 19, 561; [5] Li, S. & Milliken, R. *Sci. Adv.* (2017); [6] Honniball, C. I. et al. (2020), *Nature Astronomy* 5, pages121–127; [7] Feoktistova, E. A. et al. (2021), LPSC 52, 1411; [8] Schultz, P. H. et al. (2020), LPSC 51, #2688; [9] Schultz, P.H. & Eberhardy, C.A. (2015), Icarus 248, 448; [10] Schultz, P.H. & Crawford, D.A. (2016), *Nature* 535, 391–394; [11] Schultz, P. H. and Wrobel, K. (2012), *Jour. Geophys.* 117, E04001, doi:10.1029/2011JE003843; [12] Schultz, P.H. & Gault, D.E. (1990), *GSA Sp. Paper* 247, 239; [13] Daly, R.T. & Schultz, P.H. (2018), *Sci. Adv.,*4:eaar2632; [14] Quintana, S.N. & Schultz, P.H. (2019), Icarus 326, 175.

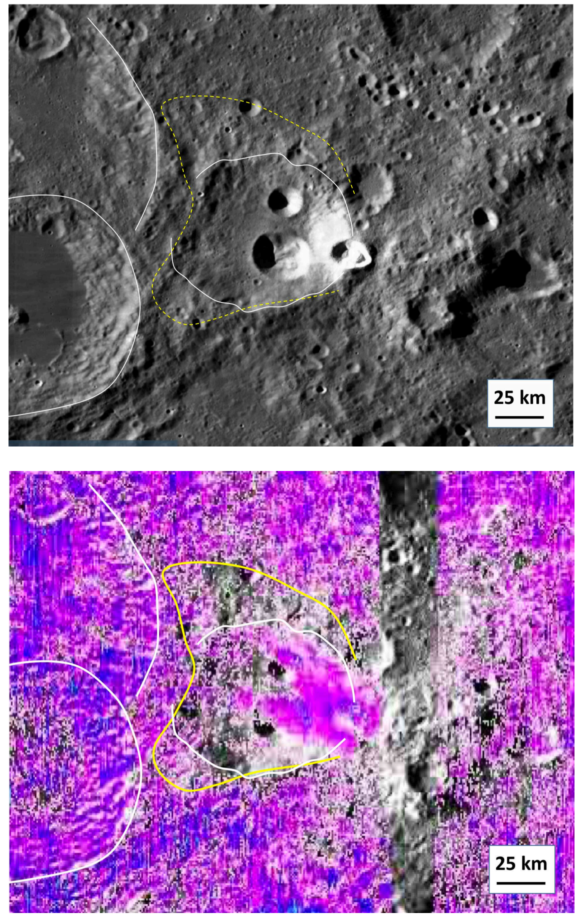

Fig. 1: Elevated water concentrations associated with a fresh10km-diameter crater (-42.54; 143.9) that formed on the rim of a larger, older crater (white outline). A broad water-depleted halo (yellow outline) corresponds to removable by scouring by ejecta and the vapor component. The elevated water (100-200 ppm) extending from the breached crater rim is attributed to a projectile component.

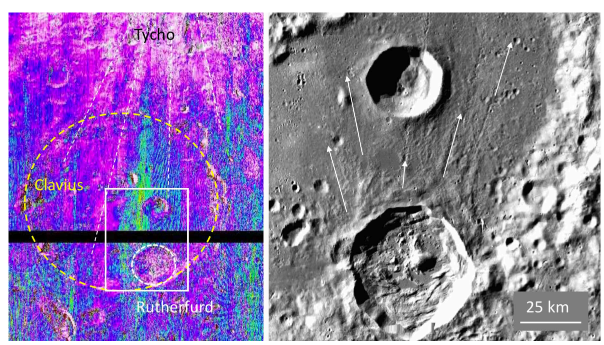

Fig. 2: Elevated OH (left) up to 400 ppm correlate with debris (arrows) from the crater Rutherfurd, which was produced by an oblique (SSW-NNE) impact on the rim of the large flat-floored crater Clavius (dashed outline at left). Small secondary craters from Tycho to the north (dashed lines) suppress OH levels on either side of the hydrous melt/ejecta deposit.