IMPACT IMPACTS ON EUROPA'S UPPERMOST METERS. E. S. Costello[1,2], C.B. Phillips[3], R. R. Ghent[4], P. G. Lucey[1] [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI, USA , ecostello@higp.hawaii.edu; [2]Dept. of Geology and Geophysics, University of Hawaii, Honolulu, HI, USA; [3]NASA Jet Propulsion Laboratory, Pasadena, CA, [4]Planetary Science Institute, Tucson, AZ, USA.

Introduction: The surfaces of airless bodies such as Earth's Moon and Jupiter's moon Europa are modified by crater-forming impacts. Over time, impacts produce a well-mixed surface layer of pulverized rock at the Moon's surface called regolith. To describe Europa's icy surface layer, we introduce an etymological sister to regolith: "**regopag**" from the Greek "rhegos-" meaning "blanket" and "pagos-" meaning ice or salt evaporite deposit. This new term highlights the conceptual similarity between the two, but distinguishes the dominantly water ice impact-generated fragmental material that likely blankets Europa and other airless icy worlds from rocky lunar regolith. The regopag has also previously been called "icy regolith;" however, as we learn more about the ice-bearing poles of the Moon and Mercury and ice-rock transitional bodies such as Ceres, "icy regolith" may also imply ice particles mixed into silicate regolith. In addition, regopag is uniquely shaped by thermal and radiolytic processes [e.g. 1,2,3] in ways that silicate regolith and regolith-ice mixtures are not. Despite the differences, the regopag on Europa, like the Moon's regolith, will have formed through years of energetic impacts and acts as a fluffy blanket over the surface.

Models of the thickness and evolution of the impact-generated lunar regolith have been used and developed since the Apollo era. One such model is the impact mixing model published by Gault et al. [4], which quantifies the frequency with which impacts excavate material to a certain depth as a function of time. The original Gault et al. model under-predicted the impact gardening that produced the observed depth-distribution of space weathering products (which darkened regolith that has been exposed to the surface) observed in Apollo cores [e.g. 5]; however, a revival of the Gault model by Costello et al. [6] included the gardening driven by secondary impacts and provided an excellent fit that could quantitatively describe the impact processing of the upper few meters of regolith for timescales greater than 100 thousand years. We adapt the Costello et al. [6] model of impact processing of the Moon to quantitatively investigate the impact processing of the surface of young, icy Europa, to determine the effects of impacts in time and space on Europa's hidden meters and the thickness of its impact generated regopag.

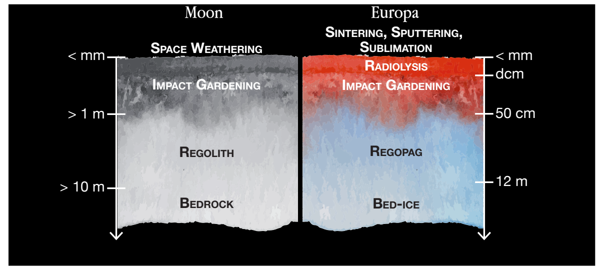

Figure 1: An illustration comparing the surfaces and depth extent of processes affecting the Moon and Europa.

Models & Results: We model regopag depth by calculating the thickness of a thin spherical shell of inner radius equal to the radius of Europa and with volume equal to the volume ejected by impacts into a hard ice target. We integrate over a maximum crater diameter of 45 km and a minimum crater size of 1 m, assuming that craters smaller than 1 m mostly eject material that is already regopag. Our results show that the contribution of primary impactors is negligibly small. Despite lower energy, secondary impacts are so frequent given the relative lack of small primary impacts that their ejecta is the dominant contributor to the regopag. We predict on the order of 10 m of regopag accumulates on a 10 Myr old surface (Fig. 2a).

Once regopag is formed, it is churned by frequent smaller impacts. We calculate the depth of impact gardening using the model by Costello et al. [6] adapted to the special case of Europa using parameters to scale impactor diameter to crater diameter for cratering in an icy target and the cratering rate implied by small crater counts [7,8] and modeled from the primary impact rate [9]. Just like on the Moon, impact gardening is shallower than the regopag depth. We calculate that the top 10 cm to 1 m of Europa globally is thoroughly mixed. Some regions have been more thoroughly gardened. We plot the depth-distribution of impact gardening depth with probability in Fig. 2b.

Discussion & Future Work: In previous work the impact gardened mixing depth has been called the "in situ reworking zone", implying that material in this zone is so frequently overturned by impacts that it might as well be on the surface [5,6]. The top 20 to 30 cm of regopag on Europa is likely saturated with radiolytic products and any material in this gardening zone spends a significant amount of calendar time at the uppermost surface. We should expect spatial heterogeneity in the depth distribution of surface correlated products, just as there is spatial heterogeneity in the depth distribution observed in the Apollo cores; however, if we are searching for biomolecules that have never been irradiated at the surface, we conclude that we must look deeper than 50 cm.

Europan crater rays are as charismatic as rays on the Moon, and yet more mysterious in nature and evolution. Europa's second largest crater, Pwyll (45 km diameter), displays extensive rays that are bright against reddened and darkened underlying material. Europan rays like those that surround Pwyll may be conceptually similar to lunar maturity rays, where fresh material is thrown over material that has been chemically and physically altered by exposure to the surface environment. In Europa's case, the surface ice would be radiolyzed and possibly colored over time by endogenic sulfur from Io [e.g. 10,11]. Not all craters on Europa have bright rays. Niamh (5 km in diameter), for example, has dark rayed ejecta - the origin and nature of which is not yet understood. However, despite the persistent mystery of the formation mechanisms and nature of Europa rays, one fact is indisputable: not all craters on Europa have rays of any kind, which implies some form of erasure over time. Phillips et al. [12] showed that rays fade over timescales on the order of 10 Myr.

Over 10 Myr, we calculate impact gardening depth on the order of 10 cm (Fig. 2b). If Europan cratering follows similar laws to cratering on the Moon, then ejecta from Pwyll is ~ 1 m thick 100 km from the rim (10 crater radii away; [13]). If gardening, radiolysis and Iogenic alteration behave together in a similar way that gardening and space weathering erase rays on the Moon, gardening would not be able to erase a 1 m thick ray until more than 100 Myr had passed. Our gardening depth alone is too shallow to account for the erasure rate of rays on Europa.

The regopag is affected by thermal and radiation processes in ways that silicate regolith is not. Impact processes are just one act in a circus of sublimation ablation, thermal segregation, sintering, sputtering, and irradiation. The surface of Europa is extremely active and, as was noted by Phillips et al. [12], sputtering erosion alone may erode the top meter of regopag over only 10 Myr [1], meaning regopag from crater ejecta may be sputtered as quickly as it is produced. If thermal processes or sputtering erosion dominated the erasure of crater rays, then we should observe spatial variation in ray fading that reflects latitudinal variation in temperature [e.g. 14,15] and spatial variation in radiation dose [2]. There is no evidence of a spatial dependence for crater rays or ray fading: Pwyll's rays splay outward with equal brilliance towards and away from the equator; however, exploring the finer scale brightness changes in ray material as a probe of erasure mechanisms is an exciting prospect of the global high resolution images that will be provided by the Europa Clipper mission.

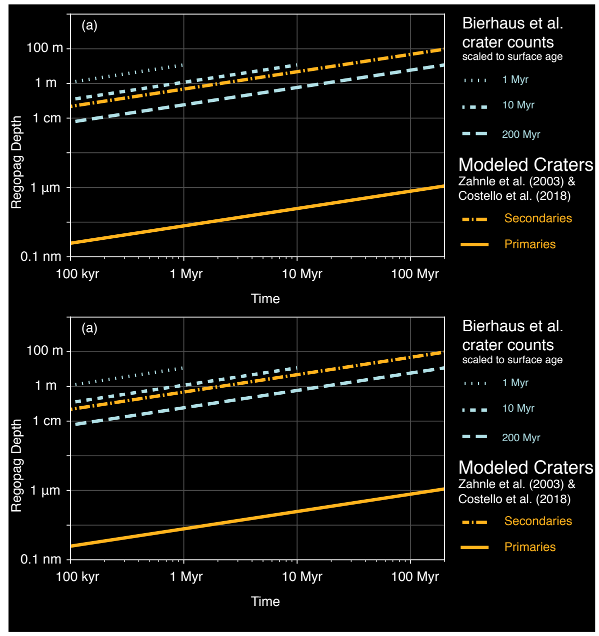

Figure 2: (a) The depth of the impact-generated regopag as a function of time, modeled as the thickness of a thin spherical shell of volume equal to the excavated volume of impact craters. We predict ~10 m thick regopag. (b) The impact gardening depth with time, calculated using the statistical model presented in Costello et al. [6]. The impact gardening zone extends to depths at the decimeter scale.

References: [1] Ip, W. H., et al. (1998). Geophysical research letters, 25(6), 829-832. [2] Nordheim, T. A., et al. (2018). Nature Astronomy, 2(8), 673. [3] Molaro, J. L., et al. (2019). Journal of Geophysical Research: Planets, 124(2), 243-277. [4] Gault, D. E., et al. (1974). In Lunar and Planetary Science Conference Proceedings (Vol. 5, pp. 2365-2386). [5] Morris, R. V. (1978). In Lunar and Planetary Science Conference Proceedings (Vol. 9, pp. 1801-1811). [6] Costello, E. S., et al. (2018). Icarus, 314, 327-344. [7] Bierhaus, E. B., et al. (2005). Nature, 437(7062), 1125. [8] Bierhaus, E. B., et al. (2001). Icarus, 153(2), 264-276. [9] Zahnle, K., et al. (2003). Icarus, 163(2), 263-289. [10] Eviatar, A., et al. (1981). Icarus, 47(1), 75-83. [11] Alvarellos, J. L., et al. (2008). Icarus, 194(2), 636-646. [12] Phillips, C. B., et al. (2000). Journal of Geophysical Research: Planets, 105(E9), 22579-22597. [13] McGetchin, T. R., et al. (1973). Earth and Planetary Science Letters, 20(2), 226-236.[14] Spencer, J. R., Tet al. (1999). Science, 284(5419), 1514-1516. [15] Hobley, D. E. J., et al. Nat. Geosci. 11, 901–904 (2018).