Impact Gardening on Cryospheres: The Depth to Ice and Organics on Europa and Ceres E. S. Costello[1,2], R. R. Ghent[3,4], 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]University of Toronto Dept. of Earth Science, Toronto, ON, Canada; [4]PSI, Tucson, AZ, USA.

Introduction: We apply an analytic model to describe the rate and magnitude of impact gardening on Europa and Ceres. The model is based on the pioneering Apollo-era lunar regolith mixing model presented by Gault et al. (1974) [1], with updated inputs and an expanded parameter space that allows for exploration of the rate of mixing as it is driven by a variety of impactor types into a variety of target materials. We take advantage of the expanded parameter space in this work, as we broaden the scope of the model beyond the Moon to calculate the rate of impact gardening on Europa and Ceres.

We apply the model to Europa to understand the impact portion of Europa's regolith evolution and provide insight into the sampling zone intended for a future Europa lander [2]. Using a drill or other depth sampling device, a Europa mission will search for direct evidence of raw materials for biosynthesis in physicochemical conditions that allow for the assembly, stability, and function or interaction of complex structures and molecules [3]. A critical constraint on the abundance of biomolecules is radiation, and impact gardening exposes any present organics to Europa's destructively irradiated surface environment [4, 5, 6, 7, 8].

We also apply the model to Ceres to explore the rate of impact gardening, seeking to constrain the role of gardening in the processing of Ceres' polar ice and global cryosphere. Ceres is a transitional body between the rocky inner solar system and the icy satellites of the outer solar system with actively replenished high albedo ice deposits in permanently shadowed regions at its poles [e.g. 9, 10]. Thermal diffusion and impact gardening control the rate of vapor production and degradation of ice on Ceres [11, 12].

In each case, the model describes the maximum depth influenced by impact gardening as a function of time. Much as Gault et al. (1974) did, we assume the following: 1) the cumulative flux of objects onto the surface is a power-law function of diameter, and 2) the production of craters follows a Poisson distribution, and 3) the size and shape of craters follow efficiency laws based on target material properties. We update the cratering efficiency laws and implement those presented by Holsapple (1993) [13].

Another important update to the Gault model is the inclusion of secondary cratering, which has been shown to have a significant impact on the rate of gardening on the Moon [14, 15, 16]. In our treatment of both Ceres and Europa we implement the same treatment of secondary impacts, where secondary impactors strike the planetary surface slower than hypervelocity and have size distributions based on the McEwen et al. (2005) study of Zunil crater [17, 18].

Ceres: The modern flux of **o**bjects that impact Ceres are both slower and fewer than those impacting the Moon [19]. Below, we present the gardening rate we calculate for Ceres.

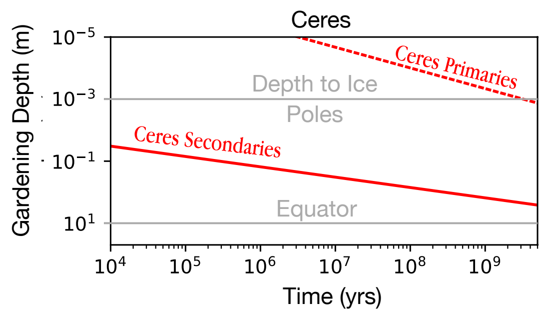

Figure 1 This figure shows the probability that material at the depths indicated on the y-axis have are 50% likely to have been gardened at least one time. Depth to ice is approximated from the Schrorgofer et al (2016) [11] thermal model. Gardening due to primaries is included here because of uncertainty with respect to the flux of secondaries onto Ceres. We are likely overestimating the number of secondaries due to Ceres' relatively low gravity and the escape of otherwise secondary-forming impact ejecta.

Gardening is independent of latitude, but the subsurface thermal gradient is not. Near the equator, ice-destroying thermal gradients are predicted to exist deeper than 10 m in 4.5 Gyr [11]. Even with secondaries included, impact gardening would not interact with ice buried this deeply. There is a 50% certainty that gardening has occurred at little more than half a meter deep in 4.5 Gyr. At high latitudes, the thermal model by [11] suggests that ice is buried only millimeters below the surface. From our gardening calculations we predict that near the poles, impact gardening is a dominant process in controlling the presence and distribution of ice. In ongoing work we investigate the latitude and depth where gardening takes over from subsurface temperature and the implications for the evolution of Ceres' cryosphere and polar surface ice deposits [9, 10].

Europa: Radiolysis on Europa is essentially surficial, with most energetic particles penetrating only the first few microns of regolith [5]. Thermal segregation and sublimation upsets the top microns to millimeters depending on ice albedo [4]. Impacts interact with regolith buried much deeper.

In this work we use the flux at Europa presented by Hueso et al. (2013) [21] compiled from recent observations of Jupiter impact flashes, and input target material properties consistent with an icy target [13] to calculate the gardening rate on Europa.

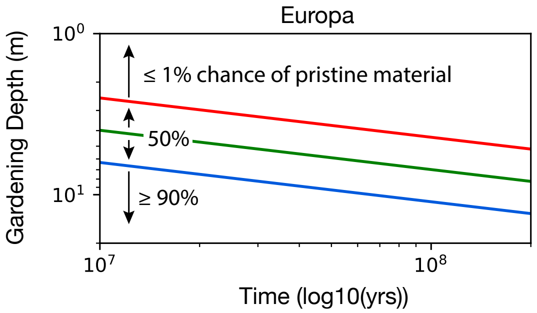

Figure 2 The gardening rate on Europa. This figure shows the probability that material at the depths indicated on the y-axis have *never* been influenced by gardening.

Based on estimates from crater counting, the surface of Europa is 20 - 180 Myrs old [22, 23]. Over this timescale, the model results presented in Figure 2 suggest that the top 2-3 m of regolith on Europa has a high chance of having been gardened. Pristine, un-gardened material is buried at least 7 - 10 m deep.

Discussion: This prediction for a Europa drill is bleak; however, one must remember that the calculations shown here are only representative of gardening depth. A more nuanced treatment of the depth profile of radiolytic dose and the competing rates of degradation and sequester from gardening or replenishment from cryovolcanic activity [24, 25] is ongoing. Further improvement will come from a treatment of the appreciable leading/trailing asymmetries in flux and radiolysis [5, 22, 25]. Our treatment of the sources of impact flux is also a target for fine tuning. We can improve our flux parameter at Europa's orbit by more carefully considering inferences from crater populations on the Galilean satellites [e.g. 22] and analysis of the the origins of impacting material from the Jovian system including basaltic spall fragments from Europa's neighboring satellite Io [e.g. 25, 26].

Secondary cratering is crucial for each of these cases and any future application of the model. The influence of secondary cratering may vary from planet to planet. On Europa, most craters < 1 km in diameter are secondary craters [27]. The volume of material ejected by impacts is 10 to 100 times greater for ice targets than crystalline rocks [28]. On Ceres, relatively low planetary gravity may result in fewer objects falling back onto the surface after a primary impact. Modeling a size and velocity distribution for secondary impactors that is tailored to each planetary case is an important component of ongoing work.

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