IMPACT GARDENING ON EUROPA. Cynthia B. Phillips[1] and Lisa Grossman[1,2], [1]Carl Sagan Center for the Study of Life in the Universe, SETI Institute, 515 N. Whisman Rd, Mountain View CA 94043; phillips@seti.org [2]Department of Astronomy, Cornell University, Ithaca, NY.

Introduction: Remote sensing measurements of Europa and other airless icy bodies are sensitive only to a thin surface veneer of material. Spectroscopic measurements are assumed to apply to the bulk subsurface composition, but in addition to endogenic geological activity, the surface layer is subject to exogenic processes such as sputtering and impact gardening.

Charged-particle interactions with materials at Europa's surface can produce oxidants and simple organics [1-4]. These oxidants and organics, if transported downward through the ice shell to a liquid water layer, could provide a significant amount of energy to sustain a biosphere. However, irradiation also destroys such materials if they remain exposed on Europa's surface [5,6]. Sputtering erosion and surface mixing through impact gardening act to change the preservation depth.

Impact gardening, i.e. mixing of the surface by micrometeorite impacts, can serve to bury surface irradiation products and preserve them from future destruction. It also serves as a physical mixing of the surface remote sensing layer, transporting surface materials to the subsurface as well as subsurface materials to the surface. An investigation of the gardening depth on Europa is relevant to understanding the physical processes at Europa's surface, as well as the physical and chemical state of the remote sensing layer.

Previous Work: An initial survey of gardening vs. sputtering by Chyba [2,3] used an estimate of sputtering at the Europan surface [7] of 0.2 μm yr^{-1}, and a gardening estimate [6], based on a lunar analogy, of 1-10 cm over a mean Europan surface age of ~10 Myr [8,9]. For this case, Chyba [2,3] took the relevant radiation-processed depth at Europa's surface to be ~1 mm, the stopping depth of incident electrons [10,11,4].

However, subsequent estimates [4] suggested that the sputtering rate at Europa was more than an order of magnitude lower, ~0.02 μm yr^{-1}, and that the gardening depth over 10^7 yr was ~1.3 m, rather than 1-10 cm. In this case, oxidants and organics created by irradiation of Europa's surface would be efficiently buried by gardening, and therefore protected. A later estimate by Phillips and Chyba [5] found a gardening depth of 0.67 m. All of these initial estimates depended on extrapolations down from many orders of magnitude.

New Gardening Estimate: We are currently updating the gardening rate for Europa using observations of small craters on Europa by Bierhaus *et al.* [19] combined with the lunar regolith growth studies of Shoemaker *et al.* [14,15] and Gault [16] as summarized in Melosh [17]. This method has the advantage of using actual observations from the Europa system and also requires less extrapolation.

Cumulative crater distributions for Europa and elsewhere in the solar system have a typical form: $N_{cum}(>D) = c\ D^{-b}$, where N_{cum} is the cumulative number area density of craters of diameter equal to or greater than D, c is a constant, and b is the exponent in the power law. Using this distribution, we can calculate the fraction f_c of the total area covered by craters with diameters between some value D and the maximum value (we actually integrate up to infinity). Paralleling the Melosh [17] treatment of Shoemaker [14], we can say that:

$$f_c(D,\infty) = -\frac{\pi}{4}\int_D^\infty D^2 \frac{dN_{cum}}{dD}\,dD = \frac{\pi bc}{4(b-2)}\left(\frac{1}{D^{b-2}}\right)$$

At the point where F_c=2, according to Melosh's [17] treatment of Shoemaker [14], the surface is covered twice over with craters in a particular size bin. This is the minimum crater coverage, according to Shoemaker, at which the bottoms of all the craters of this diameter or less are interconnected and therefore form a broken layer [14]. The minimum regolith thickness can therefore be taken to be the depth of a crater whose diameter D_{min} produces a value of F_c=2.

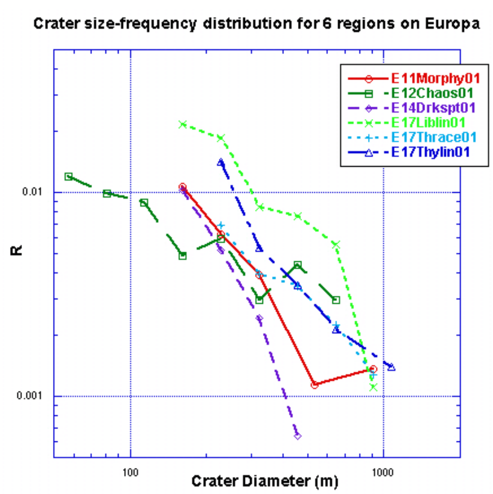

Figure 1: Size-frequency distribution for 6 regions on Europa. Data from Bierhaus et al. [19].

Small Crater Counts: To determine the extent to which the surface was cratered at various crater diameters, we used crater counts from Bierhaus et al. [19,20]. He supplied us with his size-frequency distributions for counts of small craters in six regions on Europa covered by high-resolution Galileo image sequences. The data is shown in R-plot form in Figure 1.

The resolution of the available Galileo images of Europa, which ranged between 10-100 meters per pixel, constrained the minimum measured crater diameter. The smallest crater bin began at 161 meters in diameter for most observations, with only the E12Chaos01 observation going down to 57 meters. Since the surface clearly is not saturated with small craters at these diameters, we had to extrapolate down to smaller craters.

To accomplish this, we took curve fits to the data in Figure 1 and used them to extrapolate down to smaller craters. We continued this extrapolation until we reached a point where cumulative F_c=2, to determine the minimum crater diameter which covered the surface twice over. This crater diameter then gave us the minimum regolith depth. Figure 2 shows our extrapolations. The solid lines are the actual crater counts from Bierhaus et al. [19,20], and the dotted lines are our extrapolation. The horizontal line at the top represents the value F_c=2.

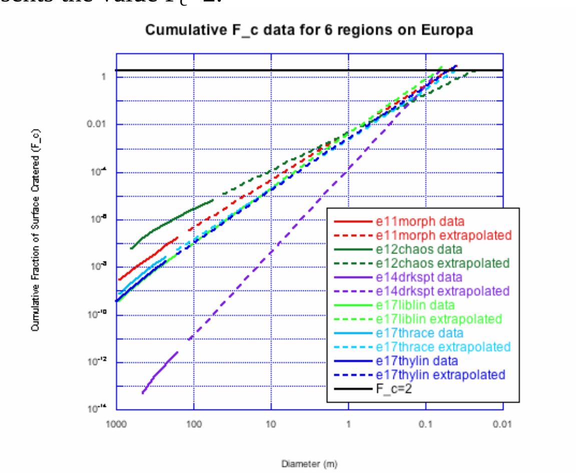

Figure 2: Measured and extrapolated crater data for regions in Figure 1, extrapolated down to a crater diameter at which F_c=2

If we assume a depth/diameter ratio of 1:4, then we can use the intersects of Figure 2 to calculate the regolith thickness for each of the six observed regions. This data is summarized in Table 1.

Observation	Regolith depth (cm)
E11MORPHY01	1.20925
E12CHAOS01	0.55125
E14DRKSPT01	1.598
E17LIBLIN01	1.69425
E17THRACE01	1.00475
E17THYLIN	1.22475

Table 1: Regolith Thicknesses

Our results indicate that the regolith thickness in these six regions varies from a minimum of about 0.5 cm to a maximum of about 1.7 cm, for an average thickness of about 1 cm. We thus suggest that the average regolith thickness on Europa, or the depth to which the surface has been turned over at least once, is about 1 cm. The lowest value of 0.5 cm corresponds to the E12Chaos01 region, which has been suspected of being geologically younger than other parts of Europa [19].

Comparison with Sputtering: For a mean surface age of ~10^7 yr [8,9], Cooper *et al.* [4] suggested that gardening should extend to a depth of 1.3 m. Our new gardening rate suggests that the gardening depth is about 0.01 meters. It thus appears that sputtering may dominate over gardening in most areas of the surface.

Secondary Craters: Bierhaus [19,20] suggests that the majority of the small craters counted in his studies are in fact secondary craters that can be accounted for by the few large primary impact craters on Europa. The presence of secondaries rather than small primary craters does change the process of gardening somewhat. Rather than having a slow, steady accumulation of small impacts spread randomly over the surface, various parts of the surface will instead experience brief showers of small secondary impactors from a particular large impact, interspersed with long periods of very little impact activity.

We believe that the overall mechanics of gardening, in which the surface is mixed once or a number of times down to a particular depth, will remain the same whether the impactor population is made up of small primaries or of secondaries. One possible influence of secondaries may be that their lower impact velocity could result in shallower craters, changing the depth:diameter ratio and therefore the gardening depth estimate. We will be investigating this and other results of secondary craters in the future.

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