PRIMARY, SECONDARY, AND SESQUINARY CRATERS ON EUROPA. K. Zahnle[1], J. Alvarellos[2], A. Dobrovolskis[3], P. Hamill[4], [1]NASA Ames Research Center (kzahnle@mail.arc.nasa.gov), [2]Loral Space Systems, [2]University California Santa Cruz, [4]San Jose State University.

Introduction: Small impact craters are abundant on Europa [1-3]. Few of these craters represent primary impacts by errant comets [2,3]; rather, most are secondary craters or sesquinary[1] craters made by ejecta from impacts by relatively large comets. Here we report on a concise model of secondary and sesquinary cratering that takes into account primary comet impacts both on Europa and also on the neighboring Galilean satellites [6]. We focus is on impact ejecta from Io, because (i) these ejecta provide rock to Europa's ice and (ii) being made of rock they are likely to be relatively big compared to ice ejecta and thus better suited to making big sesquinary craters.

We first discuss primary impact cratering on Io and Europa. Taking volcanic resurfacing into account we find that, for our nominal comet impact rate, there should be 1.3 impact craters on Io. Io's impact crater is equally likely to be of any diameter between 100 m or 20 km. The parallel model for impact craters on Europa predicts an average global surface age between 60 and 100 Ma.

We next address the mass of material transferred from Io to Europa by impact and celestial mechanics. Test particle simulations indicate that 8% of the impact ejecta reaching orbit about Jupiter following a comet impact on Io hits Europa [6]. The amount of Ionian basalt that reaches Europa is considerable. Most of it crosses over in a relatively small number of brief events. We use a Monte Carlo model to quantify the probability distribution of events.

As an example consider a million time window. In such a short interval the amount of material transferred to Europa is usually modest, because the biggest comet to hit Io in a typical million year window is usually not very big. The median is 4e14 g of basalt transferred. Half the trials give between 8e13 and 2e15 g. Thus, in a typical million year time window, basalt ships to Europa at a rate of 2.5-60 g/s. The median of 13 g/s is somewhat smaller than the estimated 45 g/s micrometeoroid flux [7]. By contrast the mean—4e16g, or 1300 g/s—is very big, much bigger than the micrometeoroid flux. The mean is dominated by impacts that have only a small chance of actually taking place during the life of the solar system at current impact rates. On longer time scales the mass of basalt transferred from Io to Europa exceeds the micrometeoroid flux. The median over any 10 Myr window is 90 g/s, and over 100 Myr the median rises to 250 g/s.

We then develop a general description of secondary and sesquinary craters based on theoretical ideas proposed by Melosh [8]. Melosh split impact ejecta into two kinds: "Grady-Kipp fragments" to describe rocks from below the surface that are associated with the main excavation flow, and "spalls" that originate where the excavation flow breaches the surface. Our model predicts the number and sizes of ejecta in each category. At this level of description the model has no free parameters. However, there is an ambiguity in the size of spalls that relates to their originating as thin plates of rock. Vickery [9] found that the bigger secondary craters were made by flocks of boulders that had originated as a single spall plate but had not had time enough to separate. Spall plates are expected to break up into fragments of a scale comparable to the thickness of the plates. We found it necessary to introduce a free parameter to describe the partitioning between "tabular" spalls and "equant" spalls.

Discussion: Our model's chief successes are that it correctly predicts the size of the largest secondary crater, it correctly predicts the steep size-number distribution of small craters on Europa, and it predicts the right number of small secondary craters. The model also predicts the size of the crater where the size-frequency distribution of secondary craters changes slope, but this prediction has bnot been tested.

Our model's successes indicate that Melosh's overall picture—of an excavation flow made up of Grady-Kipp fragments, topped by a thin spall layer that gives rise to the biggest and fastest ejecta—has, at minimum, the merit of being quantitatively useful.

Our model's failures are interesting as well. Our model predicts that many if not most of the 0.1-1 km diameter craters on Europa have their origin in spalls ejected from Io. Put another way, the model predicts that the number of sesquinary and secondary craters on

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[1] "Sesquinary" stems from the latin root ``sesqui-" meaning one-and-a-half; its most familiar use in English is in ``sesquicentennial." We use sesquinary to describe craters by impact ejecta that went into orbit about the central planet. In previous papers [4,5] we used "poltorary," which has a slavic root, for the same concept. Sesquinary craters have a character intermediate between primary craters and conventional secondary craters.

Europa should be comparable (Figure 1). This is not what is seen. Bierhaus et al. [2] conclude that no more than 5% of the 0.2-1 km diameter craters on Europa belong to a uniform random background population. Our model predicts that the background population should be rich in sesquinary craters made by spalls from Io. The implication is that our model overpredicts the number of these big iogenic sesquinaries by a factor of several.

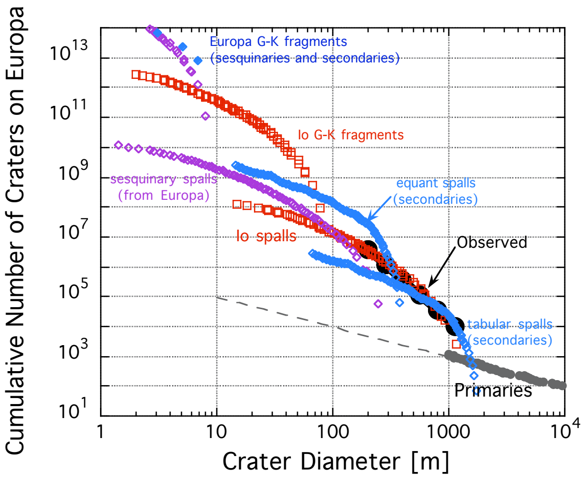

Figure 1. Predicted and observed size-number distributions of small impact craters on Europa, produced by comet impacts on Io and Europa in a typical 60 Ma period. The slight waviness seen in the secondary crater distributions is an artifact of binning. The craters are sorted according to the different categories discussed in the text. In this example 10% of the mass of spalls is in tabular spalls and the balance in equant spalls.

To first approximation Bierhaus et al. [2] sorted craters between secondaries (clustered or with variable steep size-number distributions) and primaries (not clustered and with a shallow size-number distribution). They did not explicitly consider sesquinary craters (not clustered but with variable steep size-number distributions). Thus there may be room in their analysis for a 10-20% contribution from sesquinaries. But there is little doubt that most of the craters they map are clustered and therefore are conventional secondaries. Thus we conclude that a large fraction of the equant spalls from the biggest impacts on Io must themselves break up into fragments that are small compared to the thickness of the spall plate.

There is no inconsistency here with Melosh's arguments—Melosh [8] warned against using his spall-size equation for very high velocity spalls—yet it is something of a disappointment nonetheless. Presumably the actual sizes of these ejecta will range from the spall plate thickness down to the Grady-Kipp fragment size, at least those generated by the 50-100 km crater on Io, and additional information is needed to describe their size-distribution usefully.

Our estimates of the total mass of basalt transferred from Io are relatively robust, as they depend on two independent estimates of the total ejecta mass launched at velocities exceeding Io's escape velocity, and on celestial mechanics. We find that Ionian basalts are probably the leading source of rocky matter to Europa's ice shell, although the lead over other published sources (e.g. micrometeoroids) isn't great. Io's basalts are plausibly the major source of incompatible lithophile elements (e.g. Na and K) to Europa's ice, but they are less likely to be the major source of sulfur (which is abundant in cosmic matter), carbon, or siderophiles.

Ionian basalts could make fine stratigraphic horizons on Europa, given that most of the basalts come in a few very brief events each corresponding to a single significant impact on Io. The scattered basalts might then provide tracers of a former surface. They'd be pushed about by the flow of the ice, perhaps to accumulate where ice converges or to be cleaned away where ice is fresh.

Impact velocities on Europa are generally high enough (the distribution ranges from 1.6 to 9 km/s [6]) that we would expect most basaltic projectiles to disintegrate on impact into gravel, sand, or dust, but there might also be some intact boulders, especially where impacts are oblique or at relatively low velocity. To first approximation the best chances for seeing intact boulders from Io would be on Europa's trailing hemisphere, where impact velocities are lower, but not too near the antapical pole where nothing from Io falls.

Another thing that basalts from Io will make possible is accurate radiometric dating of Europa's surface. The dates would be obtained from the basalts by standard methods. To a good approximation the age of a basalt will equal the length of time it has been on Europa, because no basalt grows old on Io.

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