COMPACTION CRATERS IN THE KUIPER BELT: IMPLICATIONS FOR KBO SIZE-FREQUENCY DISTRIBUTIONS AND SURFACE COMPOSITION AND STRUCTURE.

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Introduction: The slow spin of cold classical Kuiper belt object (CCKBO) Arrokoth as well as its gravitational surface slope distribution and structural integrity suggest that it is a remarkably low-density body, ~250 to 500 kg m^{-3} [1-6]. Such a density is similar to the lower end of estimates for cometary nuclei (with which Arrokoth likely shares a similar formation history [7,8]), though lower than that of 67P/Churyumov-Gerasimenko, 532 ± 7 kg m^{-3} [9]. For example, comet 9P/Tempel 1 has a preferred density range from 200 to 470 kg m^{-3}, from non-gravitational force (NGF) and *Deep Impact* ejecta plume modeling; from NGF modeling, 19P/Borrelly has a preferred density of 490 kg m^{-3}, whereas for 81P/Wild 2 this value is 300 kg m^{-3} (see Table 1 in [9]). Bulk densities between 250 and 500 kg m^{-3} imply substantial porosities (>70%) for both cometary and Arrokoth's presumed ice+refractory dust compositions [10,11]. This inference is supported by direct porosity estimates from CONSORT microwave sounding of the interior 67P, ≈75-85% [9].

When the porosity of a surface is high enough (above the usual close packing thresholds for granular materials of 30-40%) and when the crushing strength (Y_c) low enough, impact craters can form partially or wholly by compaction as opposed to excavation and displacement [12,13]. Limited experimental evidence shows that the Y_c for cold (77 K), granular ice [14] and porous ice-silicate mixtures [15] are lower than those for silicaceous materials such as pumice at the same porosity (Fig. 1), although no experiments have been carried out on ice-rock(-organic) mixtures at the large porosities ($\gtrsim$70%) likely appropriate to comets, Arrokoth, and other small KBOs. Because the transition to compaction cratering occurs when $\rho g H \gtrsim 0.005 Y_c$, where ρ is density, g is surface gravity, and H is crater depth [13], even Y_c ~25-100 kPa (plausible from Fig. 1) brings the 7-km wide Sky impact (Arrokoth's largest known) to the compaction cratering threshold. If bulk Arrokoth has the crush strength of fresh snow (<few kPa, e.g., Fig. 10 in [16]), then all its identified craters formed by compaction.

The implications of compaction cratering for Arrokoth and other small KBOs are multiple [17]: 1) suppression of impact ejecta leads to momentum "β" values closer to unity; 2) crater scaling depends on both porosity and a strength measure (Y_c); 3) crush up concentrates thermal effects near and below craters, leading to surface devolatilization and armoring; 4) crush up protects small KBOs from catastrophic disruption; and 5) for Arrokoth and other contact binary KBOs, it stabilizes the join between lobes (e.g., we find the formation of Sky likely broke Arrokoth's neck, but it mended). Here we focus on points (2) and (3).

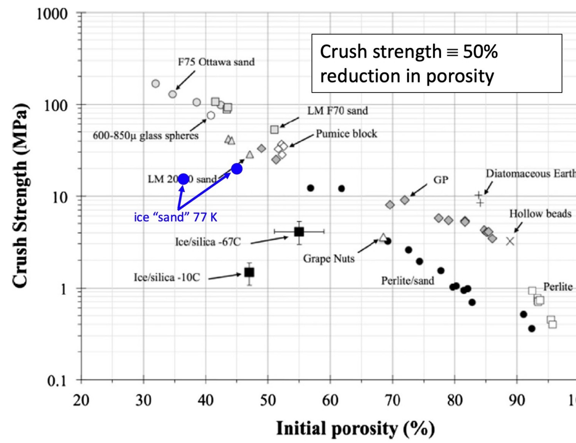

Fig. 1. Crush strength of various granular aggregates as a function of porosity. The crush strength for highly porous, icy KBOs such as Arrokoth is plausibly well under 1 MPa. From [13] with ice "sand" points from [14].

Scaling: Crater scaling for *highly porous* granular materials (those with porosities n greater than 50%) is given by Eq. (20) in [13]:

$$\pi_V = \left[0.75\left(\frac{Y_c}{\rho U^2}\right)^{-3\mu/2} + 0.023\,\pi_2^{-3\mu/(2+\mu)}\right] \times \mathrm{psf}(n)$$

where $\pi_V \equiv \rho V/m$ is cratering efficiency and $\pi_2 \equiv ga/U^2$ the gravity-scaled size, with a, m, and U the impactor radius, mass, and vertical velocity, respectively, and V the resulting crater volume (equal densities for impactor and target are assumed). The exponent μ in this scaling is 0.54, and psf(n) = 10.4*exp*(-5.07n) is an empirical porosity scale factor derived by [13] from centrifuge impact experiments. We assume n varies linearly from 0.70 to 0.85 for bulk densities between 500 and 250 kg m^{-3}, respectively, and illustrate this scaling in Fig. 2 for a Y_c low enough so that com-

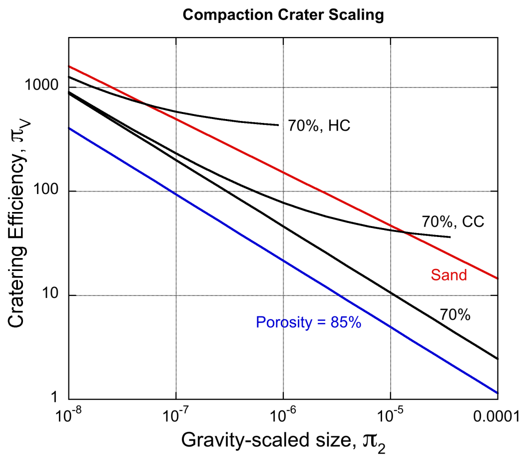

Fig. 2. Cratering efficiency comparison between cohesionless regolith (modeled as dry sand) and highly porous granular materials, based on [13]. High porosity lowers cratering efficiency (reduces mass excavated and displaced). Depending on the value of $Y_c/\rho U^2$, crushing and compaction can contribute to crater volume at larger gravity-scaled sizes, counteracting this trend. Such scaling is illustrated for Y_c = 100 kPa, ρ = 500 kg m^{-3}, and the characteristic impact speeds for cold classical and hot classical Kuiper belt objects onto Arrokoth, 300 and 1400 m s^{-1}, respectively [18]. The transition to compaction cratering is truncated here at its limit of applicability at right (see [13]).

paction scaling is achieved for Sky on Arrokoth, but not out of line with values in Fig. 1. Compaction scaling is a form of strength scaling, but in this case the strength asymptotes occur at large, rather than small, π_2.

SFD Controversies. The size-frequency distribution (SFD) for smaller KBO craters was measured directly on the unsaturated, ideally illuminated Charon cryovolcanic plain, "Vulcan" Planitia (VP). Least-squares fits and maximum likelihood estimates (MLE) in [19] give shallow differential power-law slopes near –1.7 or –1.8; MLE on remapped VP craters gives slightly steeper slopes near –2.0 [20] (both papers quote slope uncertainties of 0.2-0.3). In contrast, [21] present a rather torturous series of arguments based on Arrokoth data that the VP crater differential SFD is actually –2.2-to-2.5, despite its clear incompatibility with the actual VP impact record.

Moreover, for Charon the crater SFD implies an even shallower *impactor* SFD [22]. For a more-or-less solid cryovolcanic surface and gravity scaling [23], the power-law slopes in [19,20] above translate to –1.3(–1.4)/–1.6 for simple craters, –1.5(–1.6)/–1.8 if complex. But for compaction scaling (on Arrokoth) the impactor SFD should be much closer to the crater SFD, i.e., π_V is less dependent on π_2 (Fig. 2), accentuating the disagreement between [19,20] and [21]. We note that [24] find that a differential crater SFD of –1.66±0.3 is *not* incompatible with Arrokoth's cratering record: the formation of a singular, large crater (Sky) may appear improbable, but it can't be statistically rejected. We also note that VP is by definition a resurfaced unit and while ancient [25] may not be quite as old a counting surface as Arrokoth, i.e., may or may not reflect the high, post-instability bombardment advocated by [21]. Or it may simply be that the impact crater population on Arrokoth, which is by no means as well characterized as that on VP [2,26], offers greater latitude in interpretation than argued in [21].

Surface Densification and Heating. Compaction (crush-up) implies that most of a given impactor's kinetic energy is taken up as waste heat below the impact point, with momentum transferred to the rest of the body by elastic waves. For typical cold classical encounter velocities, impactor and near-field target temperatures should reach ~100 K, warm enough to mobilize hypervolatile ices, whereas faster, hot classical or scattered disk objects can melt methanol and water ice. Stratigraphically, compaction craters consist of a densified lens buried by infilled loose surface material [13]. In contrast to a body like the Moon, where a volcanic surface can develop a fragmental surface layer or regolith under prolonged bombardment, a small underdense, granular KBO such as Arrokoth can develop a degree of (subsurface) armoring if sufficiently impacted. Arrokoth's crater density is far from saturated [2], but if [21] is correct, then it and other "pristine" CCKBOs may be saturated by meter-scale impactors, which may partially account for its smooth appearance.

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