COMPACT CRATERS IN THE KUIPER BELT: IMPLICATIONS FOR KBO SIZE-FREQUENCY DISTRIBUTIONS AND SURFACE COMPOSITION AND STRUCTURE. William B. McKinnon\textsuperscript{1}, K.N. Singer\textsuperscript{2}, S.J. Robbins\textsuperscript{2}, X. Mao\textsuperscript{1}, P.M. Schenk\textsuperscript{3}, O.L. White\textsuperscript{4,5}, J.R. Spencer\textsuperscript{2}, W.M. Grundy\textsuperscript{6,7}, J.M. Moore\textsuperscript{6}, S.A. Stern\textsuperscript{2}, H.A. Weaver\textsuperscript{3}, C.B. Olkin\textsuperscript{2}, and the New Horizons Science Team. \textsuperscript{1}Dept. Earth and Planetary Sci. and McDonnell Center for the Space Sci., Washington University in St. Louis, Saint Louis, MO 63130 (mckinnon@wustl.edu), \textsuperscript{2}Southwest Research Institute, Boulder, CO 80302, \textsuperscript{3}LPI, Houston, TX 77058, \textsuperscript{4}SETI Inst., Mountain View, CA 94043, \textsuperscript{5}NASA Ames Res. Center, Moffett Field, CA 94035, \textsuperscript{6}Lowell Observatory, Flagstaff, AZ 86001, \textsuperscript{7}Dept. Astronomy and Planetary Sci., NAU, Flagstaff, AZ 86011, \textsuperscript{8}JHUAPL, Laurel, MD 20723.

\textbf{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, \(\sim 250\) 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, \(532 \pm 7\) 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 \textit{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 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, \(\approx 75\%-85\%\) [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 siliceous 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 (\(\approx 70\%\)) likely appropriate to comets, Arrokoth, and other small KBOs. Because the transition to compaction cratering occurs when \(\rho g H \gtrsim 0.005Y_c\), where \(\rho\) is density, \(g\) is surface gravity, and \(H\) is crater depth [13], even \(Y_c \sim 25\)-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 “\(\beta\)” 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).

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

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

where \(\pi_Y \equiv \rho V/m\) is cratering efficiency and \(\pi_2 \equiv gaU^2\) 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 \(\mu\) in this scaling is 0.54, and \(\text{psf}(n) = 10.4\exp(-5.07n)\) 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-
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 encounters, 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) armor 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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