ARE MARYLAND AND OTHER CRATERS ON CCKBO ARROKOTH COMPACTION CRATERS, AND DOES IT MATTER? William B. McKinnon[1], Xiaochen Mao[1], K.N. Singer[2], J.T. Keane[3], P.M. Schenk[4], O.L. White[5,6], R.A Beyer[5,6], S.B. Porter[2], D.T. Britt[7], J.R. Spencer[2], W.M. Grundy[8,9], J.M. Moore[6], S.A. Stern[2], H.A. Weaver[10], C.B. Olkin[2], and the *New Horizons* Science Team; [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), [2]SwRI, Boulder, CO 80302, [3]JPL, Pasadena, CA 91109, [4]LPI, Houston, TX 77058, [5]SETI Institute, Mountain View, CA 94043, [6]NASA Ames Res. Center, Moffett Field, CA 94035, [7]Dept. Physics, Univ. of Central Florida, Orlando, FL 32816, [8]Lowell Observatory, Flagstaff, AZ 86001, [9]Dept. Astronomy and Planetary Sci., NAU, Flagstaff, AZ 86011, [10]JHUAPL, Laurel, MD 20723.

Introduction: Both Arrokoth's slow spin and gravitational surface slope distribution suggest that it may be a remarkably low density body [1-4], with a density even lower than that accurately measured for comet 67P/Churyumov-Gerasimenko, 532 ± 7 kg/m^3 [5]. Cold classical Kuiper belt objects (CCKBOs) are not the direct source population for Jupiter-family comets, but the accretional physics that created the short-period source population in the original trans-Neptunian disk, which begat the scattered disk (which is the proximate source), is unlikely to have been very different in the cold classical region [6,7]. A bulk density between 200 and 500 kg/m^3 would imply a substantial porosity (>70%) for Arrokoth's presumed composition [8], which as with 67P would not be particularly ice-rich (though icier in bulk). Such extremes of porosity are not unknown in very low pressure environments, where irregular particles are governed by weak frictional and cohesive contact forces, such as apply to relatively fresh, cold snow. Moreover, such porosities, and the low resistance to crushing (densification) pressure change the way a body responds to impacts, both in terms of cratering mechanics and globally [9]. Here we discuss these possibilities in the context of Arrokoth's craters, and especially its largest, Maryland (informally so named).

Preliminaries: Figure 1 plots the stresses on the neck between Arrokoth's two lobes as a function bulk density (assumed the same for both the large and small lobes, hereafter LL and SL). At 250 kg/m^3 there is effectively zero contact stress, whereas nominal theoretical estimates for the tensile strength and cohesion of cometary materials (~100 Pa and 1 kPa, respectively) permit a wider range of densities. We note that geological estimates of cometary compressive strengths, estimates from the lunar regolith, and laboratory measurements and modeling generally imply lower (and scale-dependent) strengths than these values [5], further supporting the inference that Arrokoth may be a very low-density body. In addition, many comets are thought to be of similarly low density from non-gravitational force measurements [5], but such values are not as definitive as the value for 67P.

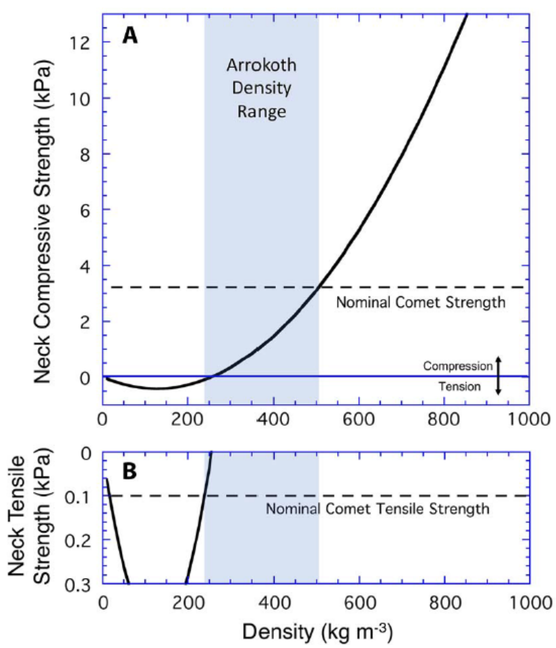

Fig. 1. Compressive or tensile stress supported at Arrokoth's neck as a function of bulk density. The solid blue line in (**A**) separates the unconfined compression and tension regimes. Compressive strength is a function of cohesion and friction angle. The tensile regime is shown in an expanded scale in (**B**). From [3].

Compaction cratering: When the porosity is high enough (above the usual close packing thresholds of 30-40%) and when the crushing strength is low enough, impact craters can form partially or wholly by compaction as opposed to excavation [9,10]. Arrokoth almost certainly meets the porosity requirement. In [10] crushing strength (Y_c) estimates were provided for a variety of porous asteroidal analogue materials (e.g., pumice, perlite), generally in excess of ~1 MPa. The transition to compaction cratering occurs when $\rho g d \gtrsim 0.005 Y_c$, where ρ is a body's bulk density, g surface gravity, and d crater depth. For $\rho = 500$ kg/m^3, $g \sim 10^{-3}$ m/s^2, and $d \sim 10^3$ m (for 7-km-wide Maryland), this criterion is not met. But if Arrokoth's crushing strength is more in line with the compressive strength limit in

Fig. 1, or even somewhat larger, then the criterion is met for Maryland if not for most identified craters on Arrokoth [11].

Geological Evidence: It is notable that no evidence of a raised rim can be seen for Maryland, although a slight one (≲50-75 m) would not have been resolvable in the *New Horizons* stereo [11]. Its rounded conical shape (Fig. 2) is also consistent with the morphology of compaction craters formed in the laboratory [10]. Neither are there albedo or morphological indications of an ejecta blanket in detailed mapping (By O.L. White in [2]). None of the other smaller craters on Arrokoth appear to possess rays or other ejecta patterns, though a couple have slightly raised rims [11]. In sum, crater formation on Arrokoth, at least on the scales resolvable by *New Horizons*, may have been dominated by displacement and compaction and not displacement and ejection, making Maryland on Arrokoth more akin to Karoo on Mathilde.

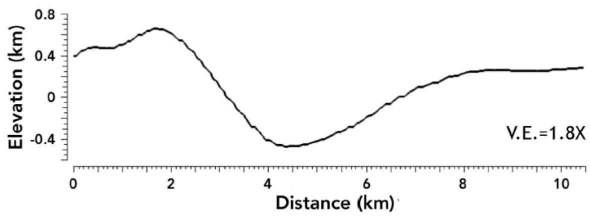

Fig. 2. Representative topographic profile across Maryland crater (informally named) on Arrokoth's small lobe, showing its asymmetric shape. From the stereo-derived DEM in [11].

Implications: In the compaction regime crater size is a fixed ratio to impactor size, for constant impact velocity and crushing strength [10]. Thus there is an opportunity to extract a more direct measure of the impactor population's size-frequency distribution from carter counts, though the high sun angles over most of Arrokoth's surface imaged by *New Horizons* makes this a someone frustrating endeavor [2]. The retention of ejecta makes spin and other dynamical evolution modeling easier however, as collisions can be treated as completely inelastic, without recoil. For example, in a companion abstract [12] we study the spin evolution of Arrokoth under bombardment in the cold classical region. We treat ejecta escape explicitly for each impact in a Monte Carlo model using standard ejecta scaling for a porous (but not highly porous) target [13]. If instead we simply assume compaction cratering in which all ejecta is retained (and thus angular momentum changes are simply a matter of vector addition), our results are modified as shown in Fig. 3. The differences between the two model simulations are not significant. However, because ejecta are effectively suppressed in the compaction regime, this opens the window to more explicit modeling of cratering using Arrokoth's true, complicated bilobate shape.

More important perhaps are the implications for Arrokoth's overall dynamics, assuming Maryland formed after lobe merger. Compaction cratering is highly dissipative, with impact kinetic energy largely absorbed by crush up and heating near the impact site [9]. For a highly porous body, crushup and near-field plastic deformation ("bumper effect") will limit far field damage to elastic reverberations, effectively shielding the SL (e.g.) from any catastrophic disruption due to Maryland's formation. Impactor momentum is of course not eliminated, but neck stability requires careful consideration of the relatively slow propagation of elastic waves in a highly porous medium [cf. 14].

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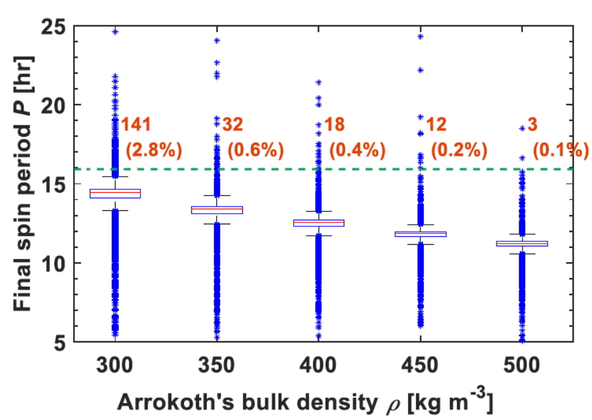

Fig. 3. Boxplot of Arrokoth's spin distributions as a function of initial density and spin period chosen to minimize neck stress. Red lines are the median values in each suite of simulations, the box width equals the interquartile range (IQR), and the whisker length is 1.5×IQR. Green dashed line indicates Arrokoth's observed spin. These simulations assume 100% ejecta retention and can be compared with Fig. 3 in [12].