SCARP RETREAT ON (486958) ARROKOTH: EVIDENCE AND IMPLICATIONS FOR COMPOSITION AND STRUCTURE.
J.M. Moore[1], O.M. Umurhan[2,1], O.L. White[2,1], W.B. McKinnon[3], J.R. Spencer[4], S.A. Stern[4], D. Britt[5], B.J. Buratti[6], W.M. Grundy[7], S.B. Porter[4], P.M. Schenk[8], K.N. Singer[4], H.A. Weaver[9], J.W. Parker[4], A.J. Verbiscer[10], R.A. Beyer[2,1], C.L. Chavez[2,1], R.D. Dhingra[11], J.T. Keane[12], T.R. Lauer[13], C.M. Lisse[9], C.B. Beddingfield[2,1], and the *New Horizons* Science Team.
[1]NASA ARC, MS 245-3, Moffett Field, CA, 94035 (jeff.moore@nasa.gov), [2]The SETI Institute, [3]Dept. Earth & Planetary Sci., Washington Univ., [4]SwRI, Boulder, [5]Univ. of Central Florida, [6]JPL, [7]Lowell Observatory, [8]LPI, Houston, [9]APL, [10]Univ. of Virginia, Charlottesville, [11]Univ. of Idaho, Moscow, [12]Caltech, [13]NOAO,

Abstract: Crenulated scarps and other unit boundary patterns are consistent with scarp retreat. If indeed scarps have retreated on Arrokoth the most likely process is sublimation degradation. This explanation has implications for both original volatile composition, evolution, and structure (layering) of Arrokoth.

Introduction: The flyby of the cold classical Kuiper Belt Object (KBO) (486958) Arrokoth (formerly 2014 MU_{69}) by NASA's *New Horizons* spacecraft on January 1st 2019 revealed the surface geology of an object of this type for the first time [1]. Sublimation-modified landforms, as are commonly seen on comets and a number of other Solar System objects (including Pluto), could potentially have developed on Arrokoth even if it has never spent any time closer to the Sun than theory suggests for cold classical KBOs [2]. The common volatiles most able to sublimate and form erosional landforms would be surface exposures of N_2 and CO. If exposed at the surface, CH_4 will also sublimate, though much more slowly than N_2 and CO. The loss of these volatiles, if present in sufficient quantities and concentrations and susceptible to exposure at the surface, might form distinctive and diagnostic scarps, pits and perhaps lags [see refs in 3]. Here we discuss evidence in *New Horizons* data that just such scarps may well occur on Arrokoth, and the implications of such landforms for the composition and structure of this body.

Observations: Arrokoth is a contact binary formed of two separate, touching lobes, and the highest resolution imaging of the object has a 33 m pixel scale and a solar phase angle of 32°. The smaller lobe, shows a distinctive, darker toned surface material (*dm*) that has, in places, a boundary resembling outward-facing pointed and angular projections and rounded, inward-facing indentations (Fig. 1). Various lighter toned terrains border the dark material. These include the plateau material (unit *pm*), which is a flat-topped region that is bounded by a crenulated scarp, and which appears to be elevated relative to its surroundings in stereo anaglyph views. Running down the center of the principal mapped outcrop of dark material is a sinuous deposit of bright material (unit *bm*), which appears in stereo observations to occur within a V-shaped trough. The rest of the surface of the small lobe, including the probable, ~7 km diameter impact feature informally named Maryland, has been mapped as undifferentiated material (unit *um*). A few sub-km, circular patches of unit *um* are seen enclosed by the dark material. It cannot be determined in stereo views whether either of unit *dm* or *um* supersedes the other topographically. Crossing the undifferentiated material near the terminator between Maryland and the large lobe are a series of sub-parallel troughs, which are reminiscent of structural troughs seen on other small objects in the solar system [e.g., 2, 3].

Hypothesis and Conclusions: We suggest that the boundaries of the darker toned surface material (*dm*) have, at least in places, undergone scarp retreat. A very simple form of sedimentation and erosion involves the addition (accrescence) or removal (decrescence) of material uniformly over a regional surface [3]. A common example of accrescence and decrescence on icy surfaces is volatile condensation (uniform precipitation of ice) and sublimation. For a planetary surface, uniform removal of material from a landscape (decrescence) makes outward-facing projections increasingly pointed and angular while initial inward-facing indentations become rounded. During uniform accrescence, conversely, projections become rounded and inward-facing, and valleys remain or become sharply indented. These two processes are not reversible. The ground trace of the former edges of a plateau that has undergone scarp retreat through decrescence would not be matched if these same scarps later grew outward though accrescence. Martian south polar CO_2 scarps retreat by uniform decrescence forming "Swiss cheese" terrain [refs in 3]. If, in fact, scarp retreat has occurred on the small lobe, the dark tone of the material might be the consequence of a lag. This hypothetical lag could have formed from radiation-induced conversion of CH_4 into refractory hydrocarbons, and/or could be the collection of carbon-rich inclusions emerging from the originally volatile-rich deposit. In this scenario, the volatile loss armored the top of the deposit with a capping lag while the edges retreated, especially if the deposit's periphery rested on slopes.

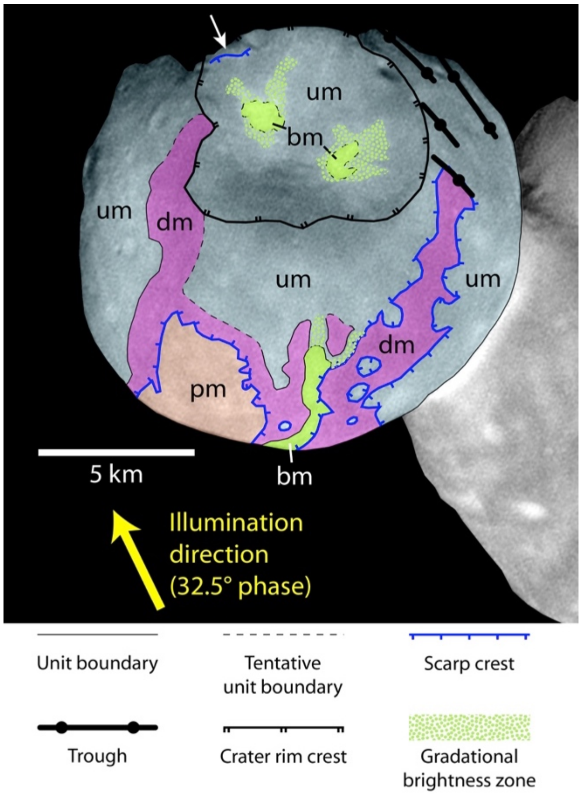

Figure 1. Geomorphological map of the small lobe. The base map used is a processed version of the CA06 LORRI observation (33 m pixel scale and 32° phase angle). *bm* = bright material; *dm* = dark material; *pm* = plateau material; *um* = undifferentiated material. Arrow: scarp well illuminated near terminator

The location of the putatively retreated dark material near Maryland (Fig. 1) is consistent with impact related disruptions (extensional breaches) initially exposing near surface deposits of dark material to sunlight and making them susceptible to erosion. It may be the lack of such "large-scale" disruptions on the larger lobe that explains why surface materials with boundaries like those of *dm* are not seen there. If the dark material on the small lobe did form a discrete layer before being exposed to erosion, it might be taken as an indication that the small lobe is layered, as has been suggested for comet 67P/Churyumov–Gerasimenko and some other comets [refs in 2].

If this hypothesis is valid, then there are a number of candidate volatiles that could have sublimated to cause the lag formation and scarp retreat [1, 2]. CH_4 has already been mentioned and is thought to be an abundant constituent in a primordial CCKBO [2]. Also N_2 and CO are good candidates [2]. Additionally methanol, which as yet is the only material to have been detected by the spectrometer on *New Horizons* [1, 4], must be evaluated as to whether it could sublimate sufficiently at Arrokoth's distance from the Sun to produce the hypothesized scarp retreat.

We provide some estimates for the rate of scarp retreat based on some of the volatile ices found in the Kuiper Belt (see Table I. below). Following [5], the amount of diurnally averaged sublimated ice is given by the expression (in units of m/s),

$$\dot{q} = \min\left(\frac{P_{\mathrm{vap}}(T)}{2\pi\rho_{ice}L^{1/2}}, \frac{F(1-A)}{2\rho_{ice}L}\right), \qquad (1)$$

where P_{vap} is the vapor pressure, T is the noontime temperature, L is the enthalpy of ice sublimation, ρ_{ice} is the ice density, $F \approx 0.7$ W/m^2 is the solar irradiance at 42 AU, and A is surface material albedo. The above choice selects between temperature-limited versus irradiation-limited sublimation outgassing. Based on the thermal models of Arrokoth reported in [4] we adopt T=57 K, and A=0.06. We assume an ice density of 500 kg/m^3. Values of L and P_{vap} are drawn from various sources including [6].

Ice	$\dot{q}$ (m / Ma)	Ice	$\dot{q}$ (m / Ma)
N_2	0.71×10^5	CO_2	1×10^{-4}
CH_4	1.23×10^5	CH_3OH	~0#
CO	0.71×10^5	H_2O	~0#

Table I. Note that the rates quoted for the left column are irradiance limited while the ones on the right column are thermally limited. # Based on extrapolation.

We will expand upon these calculations and provide more realistic scarp retreat rates based on more physically plausible modeling like done in [7].

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