URANUS' MOON MIRANDA EXHIBITS A THICK REGOLITH FROM AN UNKNOWN SOURCE.

C. B. Beddingfield[1,2], R. J. Cartwright[1]. [1]The SETI Institute, [2]NASA Ames Research Center, (chloe.b.beddingfield@nasa.gov, cbeddingfield@seti.org).

Introduction: The Uranian satellite Miranda has a complex surface, with three large regions of deformation called "coronae" that were likely formed by tectonism [1,2] and might be partially cryovolcanic in origin as well [3,4]. Miranda also displays the Global Rift System, composed of large sets of faults and fractures, that cut across its surface and bound the coronae [1]. Miranda's geologic setting and high heat fluxes [5,6] point to long-lasting geologic activity, likely driven by past orbital resonances shared between its neighboring moons Ariel and Umbriel [7,8]. In this work we investigated if Miranda's "muted" craters and scarps within the cratered terrain are a result of a mantling regolith, erosion, and/or viscous relaxation.

Muted Craters and Scarps: Miranda's muted craters and scarps exhibit more subtle features (e.g., smooth crater rims and scarp slopes) that are more difficult to distinguish from the surrounding terrain than sharper "non-muted" craters and scarps (Fig. 1). Miranda's cratered terrains exhibit both non-muted and muted craters and scarps. Non-muted (fresher) craters have relatively sharp and prominent rims, whereas muted craters have rounded and more subtle rims [1,9-11]. Non-muted fault scarps are composed of relatively sharp ridges with clear vertical corrugations [2], which reflect the displacement of the hanging wall during fault motion, and have albedos that may be different from the surrounding terrain. In contrast, muted scarps have rounded ridges at the top of their footwalls, with corrugations that are difficult to discern and scarps that are similar in tone and brightness to the surrounding terrain.

The presence of widespread muted craters across Miranda's cratered terrain is unusual compared to other icy bodies. Typically, icy body surfaces exhibit craters with rims that are relatively sharp, similar to Miranda's non-muted craters. Like muted craters, the presence of widespread muted scarps, like those observed on Miranda, is uncommon on other icy bodies. Typically, scarps located in cratered terrains are relatively sharp.

Miranda's muted craters are morphologically most similar to mantled craters on Vesta, and they are somewhat similar to mantled craters on Mars and the "muted craters" on Enceladus, which may be mantled by plume deposits. Thus, after identifying the dominant morphologies for craters and scarps on Miranda and comparing them to craters and scarps on other planetary bodies, we find that the best explanation for Miranda's muted features is mantling by regolith and not degradation or relaxation. Our findings are in agreement with the interpretation by [10] that Miranda's cratered terrain has been mantled by regolith.

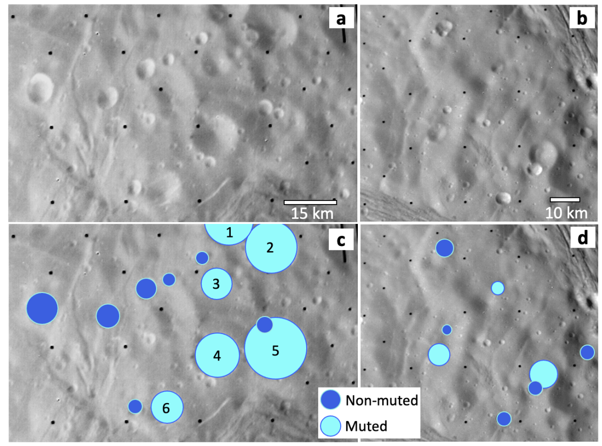

Fig. 1: Miranda's muted and non-muted craters.

Estimating Regolith Thickness: Using our measurements of the depths and diameters of the five non-muted and six muted craters, we estimate that regolith thickness within the muted craters ranges between 0.3 and 1.2 km, with an average thickness of 0.6 km. The range in thickness between the craters could result from differences in formation ages. In this scenario, older craters would have had more time to accumulate thicker layers of regolith.

Based on our estimated d-D ratio for Miranda's non-muted craters, the regolith depth required to completely fill the interior bowl of a crater for the minimum muted crater diameter identified on Miranda (~7 km) [1] was found. Therefore, the resulting regolith thickness values indicate that a 1.0 ± 0.2 km layer of regolith is required to fill Miranda's smallest muted craters, making them indistinguishable from the surrounding terrain.

Some of Miranda's craters show evidence of central floor mounds within their bowls. As derived from physical laboratory experiments [12], and utilized to estimate lunar regolith thicknesses [13-15], the thickness of a pre-existing layer of regolith that experiences an impact event can be estimated using central mounds on their floors [13]. Because the non-muted craters on Miranda's cratered terrain formed in regions that are mantled by a thick blanket of regolith, we measured the interior slope angles of the five nonmuted craters on Miranda's cratered terrain to estimate the angle of repose (α). We used this α range to estimate the regolith thickness associated with the non-muted crater Alonso.

Miranda's regolith thickness estimated from this method may represent an upper limit to the true thickness prior to the impact event that formed Alonso, because subsequent deposition of regolith may have occurred. Based on our results, we estimate that the regolith thickness in the area of Alonso Crater is 1.4 (-0.4/+0.3) km. Another important caveat is that this method has only been utilized for craters within much thinner regolith. Ongoing laboratory studies are investigating the accuracy of this method [16-18].

Some scarps like Verona Rupes and those comprising the SPT Chasma bounding Inverness exhibit streaks of material that are notably brighter than the surrounding cratered terrain [19]. This bright layer is estimated to be ~1 km thick [19], and it may have originated in Miranda's interior. This bright layer may represent a regolith profile, and its thickness might be representative of the thickness of Miranda's regolith [19].

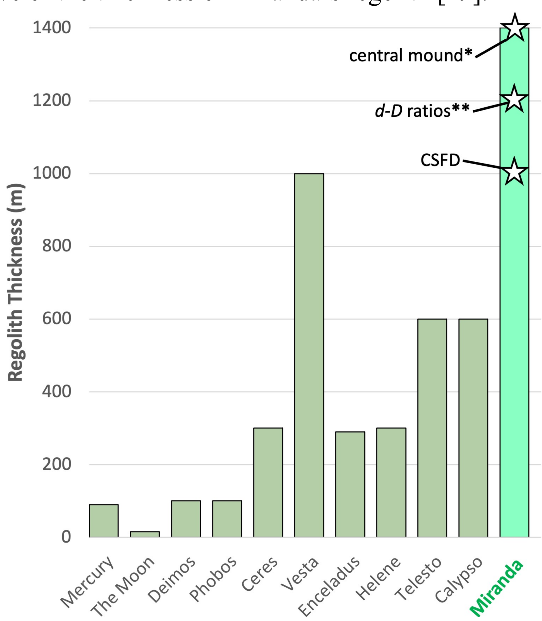

Fig. 2: *Regolith thickness comparison across the solar system. See [28] for references for each planetary body.*

Discussion: Thick regoliths serve as insulating layers, trapping heat in an icy body's interior and causing its ice shell to be warmer than its surface temperature [20,21]. Heat trapped in an icy body's interior could enhance endogenic activity, as examined for Enceladus by [22] and [23]. Consequently, Miranda's thick regolith might have insulated its interior and promoted endogenic activity, such as the formation of one or more coronae and the expansion and reactivation of faults in the Global Rift System. Thickness estimates of Miranda's regolith are similar to Vesta (Fig. 2), which has regolith deposits of at least 1 km thick in some locations [24,25].

<u>*Geologic History:*</u> Here, we provide an updated possible geologic history of Miranda: **(1)** The regions of Miranda's surface that would become the high-density cratered terrain formed 3.4 (-0.9/+1.1) Ga [26], and during this time, craters that would become muted began forming. **(2)** The parts of Miranda's surface that would become the low-density cratered terrain formed 1.2 to 3.4 Ga [26]. **(3)** The Global Rift System began forming, overprinting, and eventually being overprinted by craters that would become muted. These Global Rift System scarps would also become muted. **(4)** A major mantling event began blanketing Miranda's surface with a thick regolith. Craters and the existing Global Rift System faults were mantled by regolith, forming muted craters and scarps. The Global Rift System was still forming during this time, as evidenced by muted and non-muted fault scarps cutting muted craters. **(5)** Arden Corona formed 0.1 to 1 Ga [27]. Some scarps within Arden were mantled and became muted. **(6)** The mantling event ended. Faults within the Global Rift System continued to form, as evidenced by non-muted scarps. **(7)** Elsinore Corona formed (1.2 -0.8/+1.9 Ga) [26]. **(8)** Inverness Corona formed (0.1 -0.1/+0.4 Ga) [26]. **(9)** The Global Rift System remained active, as evidenced by large faults near Verona Rupes overprinting Inverness and polygonal impact craters overprinting Elsinore [4].

<u>*Possible Regolith Sources:*</u> We suggest three possible origin scenarios for Miranda's regolith: **(1)** burial by ejecta formed in a large impact event, **(2)** material sourced from Miranda's interior and deposited on its surface by plumes, and **(3)** accumulation of material sourced from the rings of Uranus. These scenarios represent end-member processes, and it is plausible that one or more processes formed Miranda's regolith.

References: [1] Greenberg et al. (1991) Uranus 693-735. [2] Pappalardo et al. (1997) JGR Plan. 102, E6. [3] Schenk (1991) JGR: Sol. Ear. 96, B2. [4] Beddingfield & Cartwright (2020) Icar. 113687. [5] Beddingfield et al. (2015) Icar. 247, 35-52. [6] Beddingfield et al. (2022) *PSJ* 3, 174. [7] Tittemore & Wisdom (1990) Icar. 85, 2. [8] Ćuk et al. (2020) PSJ, 1, 22. [9] Strom (1987) Icar. 70, 3. [10] Croft & Soderblom (1991) Uranus 561-628. [11] Cartwright et al. (2020a) LPSC 51, 2326. [12] Quaide & Oberbeck (1968) JGR 73, 16. [13] Bart et al. (2011) Icar. 215, 2. [14] Bart (2014) Icar. 235, 130-135. [15] Yue et al. (2019) Icar. 329, 46-54. [16] Anderson et al. (2020) LPSC 51, 2791. [17] Anderson et al. (2021) LPSC 51, 2791. [18] Cline & Cintala (2022) M&PS 57, 1441. [19] Smith et al. (1986) Science 233, 4759. [20] Passey & Shoemaker (1982) Sat. Jupiter 379-434. [21] Passey (1983) Icar. 53, 105-120. [22] Martin et al. (2017) Icar., 294, 209-217. [23] Bland et al. (2012) GRL 39, 17. [24] Jaumann et al. (2012) Science 336, 6082. [25] Denevi et al. (2016) Met. Plan. Sci. 51, 12. [26] Kirchoff et al. (2022) PSJ 3, 2. [27] Zahnle et al. (2003) Icar. 163, 2. [28] Beddingfield & Cartwright (2022) PSJ 3, 253.