AN IMPACT-CRATER EJECTA DEPOSIT ON BENNU. M.E. Perry[1], O.S. Barnouin[1], R.T. Daly[1], R.L. Ballouz[2], K.J. Walsh[3], M.G. Daly[4], D.N. DellaGiustina[2], J.P. Emery[6], C.M. Ernst[1], E.B. Bierhaus[7], E.R. Erwin[8], M.C. Nolan[2], and D.S. Lauretta[2]. [1]Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA (mark.perry@jhuapl.edu), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [3]SWRI, Boulder, CO, USA, [5]York University, Toronto, M3J 1P3, [6]University of Tennessee, Knoxville, TN, USA, [7]Lockheed Martin Space, Littleton, CO, USA, [8]National Museum of Natural History, Smithsonian Institution, Washington, DC, USA.

Introduction: In the microgravity environment of Bennu, where the escape velocity is less than 20 cm/s, impact ejecta will escape unless the target strength is extremely low, a condition that permits low ejecta velocities. This criterion was apparently met for the event that created the crater at 45S, 325E. An extensive ejecta field covers more than 3% of Bennu's southern hemisphere downslope of the crater. We present data on the posited ejecta field, the source crater, the range of impact conditions that could emplace an ejecta deposit on Bennu, and the mass flow that created the extensive field.

Crater and distinctive terrain (Fig. 1): The crater has a diameter of ~70 m. Its well-defined topographic signature (raised rim that goes around the entire crater; bowl-shaped floor) marks it as one of the most pristine impact craters larger than 10m on Bennu and indicates that it is relatively young. It has a depth-diameter ratio of 0.08 ± 0.01 with respect to geometric height. The ratio is unremarkable compared to similar-sized Bennu craters [1]. The crater resides on a ~23° regional slope. The northern crater wall slopes more steeply than the southern wall; the northern wall also appears rougher than the southern side.

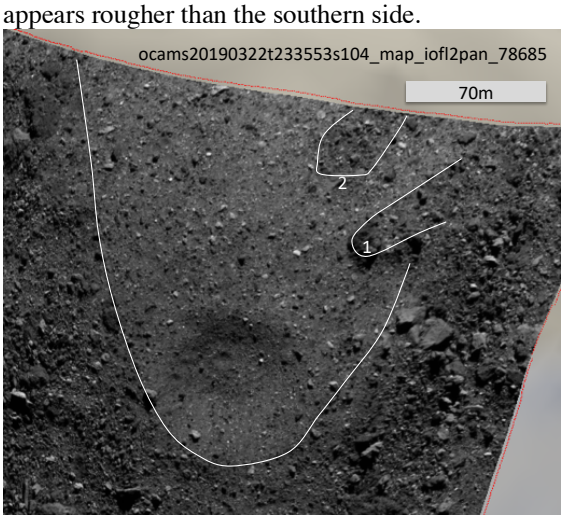

Fig. 1. OCAMS image with an outline around the crater at 44S 325E and much of the ejecta field to the north. The region behind the two labeled rocks appears free of ejecta.

The distinctive terrain that appears to be an ejecta field fans northward toward the equator and covers approximately 20,000 m². The color is homogenous with a distinct phase slope [2]. The surface is smoother than the surrounding terrain as determined by both boulder counts and measures of roughness such as tilt variation. A small area south of the crater appears to contain the same material. The ejecta field is texturally uniform from the edge of the crater out to two crater diameters in the equatorward direction. The material is absent behind the two boulders indicated in Fig. 1.

The distinctive terrain surrounds and inhabits the crater, a clear indication that the crater and terrain are associated. A crater that post-dated the terrain would produce a disturbed region surrounding the crater, which would also be the case if the impact event initiated a landslide in pre-existing terrain. For the rest of this paper, we assume that the material that comprises the distinctive terrain is ejecta, and we examine the processes by which it reached its current position: ballistic trajectories followed by surface travel.

Impact event: An essential question when employing scaling relationships to estimate the event parameters such as ejection velocities and mass is whether or not material strength controls crater formation [3,4]. The recent impact experiment on Ryugu by Hayabusa2 suggests that gravity scaling (negligible strength) is applicable to rubble pile bodies, at least to those the size of Ryugu and Bennu [5].

During crater formation, most ejecta mass leaves near the crater edge, where ejecta velocities are lowest and the scaling relationship for a gravity-controlled impact [3] can be simplified to $v=\sqrt{gR}$, where g is the local acceleration of gravity and R is the crater radius. For Bennu at 45° S, v= ~5 cm/s. Lab experiments show that the ejecta angle will be approximately 45° from the local slope, and that the total ejected volume is approximately half of the crater volume [3,6], which we measure to be 1.5×10^4 m³ ±50%.

Aftermath of impact event: Material ejected at a uniform angle to the local slope will land on the upslope side closer to the crater than material ejected downslope More importantly, the downslope ejecta contacts the surface at a relatively shallow angle (27° downslope vs. 87° upslope) with a high velocity component along the surface (Fig 2). In the low-gravity, low-friction environment, downslope material continues in its original direction, radiating away from the crater and flowing along the surface, almost in freefall. Acceleration due to the slope is possible. Material

continues until encountering an obstacle that it cannot dislodge or reaching the equator, the lowest elevation. The environment is essentially frictionless, so, despite slow velocities, material continues moving. For material moving at an angle to the slope, there is a slight downslope acceleration, but this has a small effect on the original velocity for material within 45° of the downslope direction.

Discussion and implications: The asymmetry in the ejecta field is due to slope effects, both the asymmetric deposition of ejecta and the subsequent flow downslope after re-impact with the surface. An oblique impact toward the north could contribute to the asymmetry [7], but it is not necessary. The landed ejecta flowed along the surface radially from the crater, explaining the lack of ejecta material on top or behind boulders 1 and 2, which were too large or too deeply imbedded to be dislodged by the ejecta flow.

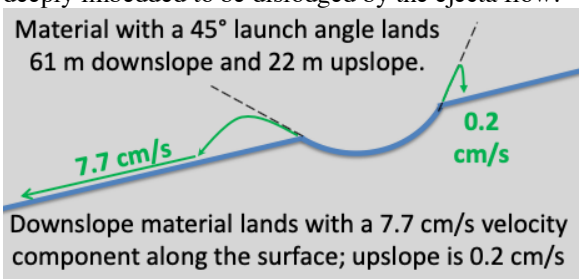

Fig. 2. On a slope, the ejecta deposit is asymmetric even for impacts that are near normal incidence. The distances and surface velocities are for a 5 cm/s ejection speed. The time that ejecta were aloft is ~20min. Downslope ejecta underwent a 30-m drift westward due to the Coriolis effect.

The ejecta flow was sufficiently massive to scour the surface over which it flowed, removing the unanchored rocks and boulders and leaving a relatively smooth terrain. With negligible friction, the momentum of the flowing material transferred efficiently to existing material in the path. Filling of low areas also contributed to terrain smoothness. Material continued to the lowest elevations at the equator. The east-west boulder field at the northern edge of the ejecta field may contain rocks displaced by the ejecta flow. The lack of tracks from rolling boulders is not surprising as all of the material flowed together.

There are no other clear ejecta fields on Bennu. The crater at 44S 325E is the only Bennu crater with three necessary characteristics: large size, high latitude, and relative youth. Its ejecta field is highly visible because of its surface flow downslope. The other large craters are near or on the equator, so ejected material is already at low elevation and lands with negligible surface velocity. There are a few other large candidate craters at high latitude, but they appear older and degraded [8], and possible associated ejecta fields are weathered past recognition.

Terrestrial experiments show that for an impact on a slope, the upslope wall undergoes enhanced collapse in granular targets, producing an overall shallower slope on the upslope side [9, 10], as with this crater.

For the ejecta to land and then flow as observed, the rotation rate must be sufficient to create a slope at the location of the crater. If Bennu's rotation period was 50% longer than its current 4.3 hours, the gravity vector is 10° closer to vertical, producing a more-symmetric ejecta pattern, a lower surface velocity, and less or no surface flow. Future study may be able to put constraints on Bennu's recent rotation history.

Estimating the volume of ejecta in the flow area to be approximately half of the ejected volume, a uniform thickness would be approximately 0.2 m. The observed terrain may be a mixture of ejecta and pre-existing terrain, creating a thicker layer. The ejecta-free areas behind rocks 1 and 2 are less than 1 m lower than the adjacent ejecta; high-resolution altimetry data will provide a high-fidelity measurement.

Extrapolating results from terrestrial experiments to such low gravity environments is problematic, but the approximations needed to model relatively large craters in the gravity regime are less severe than for smaller craters and for the strength regime. The quoted velocities are plausible and produce a feasible explanation for the ejecta field.

The gravity scaling implied by this crater and its ejecta has implications for interpreting craters distributions and using those to date asteroid surfaces. Negligible strength leads to larger craters for the same impact size and velocity, reducing the estimated age for a given distribution. On Bennu, this could resolve some of the discrepancies between the dynamic evolution of Bennu and its crater-dated surface age [8, 11].

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