REASSESSING THE PAST MILLION YEARS OF NEO IMPACT CRATERING ON EARTH VIA HIGH RESOLUTION DIGITAL TOPOGRAPHY.
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Introduction: The past ~ 1 million years of Earth history records the best-preserved history of NEO impact events in terms of deposits and associated crater landform features on continental land masses. As part of Planetary Defense-related studies, we have re-assessed the key dimensions (apparent diameter: D_a, volume excavated: V_e) of the largest currently known impact structures during this time interval using new digital elevation model (DEM) data recently generated using satellite lidar altimetry (GEDI, ICESat-2) and commercial stereo imaging (*Planet* and *Maxar* WorldView). These DEM's have spatial sampling between 2 m and 4 m, with 1-2 m vertical precision (bare Earth, flat ground), and offer a major improvement over existing topography from NASADEM (30 m x,y) and Germany's TanDEM-X SAR (TDX DEM at 12 m x,y) [1-3].

Our primary focus involves the quantitative analysis of these newly available high-resolution DEM datasets for critical dimensions of larger "complex" impact events where final, apparent diameters (D_a) and other parameters are uncertain or in question in current compilations [3-6]. Based on [4,10], specialized topographic analysis using new tools for identifying the putative outer rims [7] of these larger NEO impact craters is relevant to the energy input to the Earth system at a time of environmental change and hominin rise.

In this study, we investigate a set of benchmark complex craters (**Table 1**) via DEM's and lidar cross-sections with the best available spatial and vertical precision in order to approximate the total kinetic energy (KE) of these impacts using methods described in Davison & Collins & others [8,9], and from these values also investigate the total excavated volume [11-12] over this short time interval in Earth history [10].

Methods: We primarily employ the emergent 4 m spatial scale PlanetDEM data and both GEDI and ICESat-2 lidar transects (centerline of crater) with their sub-meter geodetic vertical precision. We compare results of our studies to 12 m spatial scale TDX DEMs [3] and when possible crosscheck results with 2 m EarthDEMs from *Maxar* WV stereo. We employ a **Radial Profile analysis System** (RPS) for identification of topographic rings and the putative outer apparent rim [4,7] based upon approaches tested with MOLA topography of Mars in various studies including Garvin and others [13]. In this RPS approach, a systematic computation of normalized radial profiles within a given DEM centered on the NEO impact crater center (defined on the basis of a 3D watershed analysis of its innermost cavity) is established across a full range of azimuths (360 degrees) using filtered and de-trended DEM topography with specific thresholds of detection. We have tested this RPS approach on DEM's of simple NEO impact craters such as *Tswaing* (D_a ~ 1.2 km) where independent confirmation of D_a has been established via geophysics. Results for the four cases studied thus far (**Table 1**) have been consistent at scales from 2 m (EarthDEM) to 4 m (PlanetDEM) to 12 m (TDX DEM). Beyond these horizontal scales, results differ widely, suggesting the establishment of a reliable measure of an effective crater diameter requires high enough resolution DEM topography to detect subtle rim-related features not recognizable at coarser scales.

New NEO crater diameters: We have focused attention on four complex impact craters that span the past ~1.0 Ma of Earth history, mostly within tropical regions, with differing target rock characteristics. **Table 1** summarizes these features (*Pantasma, Bosumtwi, Itturalde,* and *Zhamanshin*) and our results. Other complex craters are under evaluation including *Bigach, Oasis, Elgygytgyn,* and *Goat Paddock.* Ultimately, we will complete analysis of a reference "index set" of reasonably preserved complex impact features, reassess their apparent rims, and derive potential KE values for them. Here our emphasis is on the youngest known NEO impact events on Earth (**Table 1**) because of their states of preservation.

TABLE 1: *NEO impact craters considered with values from RPS analysis of high-res. DEMs* (see [8,9] for KE*, and [14] for *Pantasma*). Megatons are TNT equivalent. D_a presumed to be *outermost rim* and **not** external ring fractures.

Parameter → / NEO Crater ↓	D_a (outer) (km)	D_{inner} (km)	Modeled KE* (Megatons TNT equivalent: Mt)	Age (Ma)
Pantasma	35.2	14.8	660,000 - 727,000	0.80
Bosumtwi	26.8	10.8	300,000 - 400,000	1.05
Zhamanshin	30.4	12.0	400,000 - 500,000	0.87
Itturalde	30.4 (23.2)	10.8	400,000 ?	< 0.030

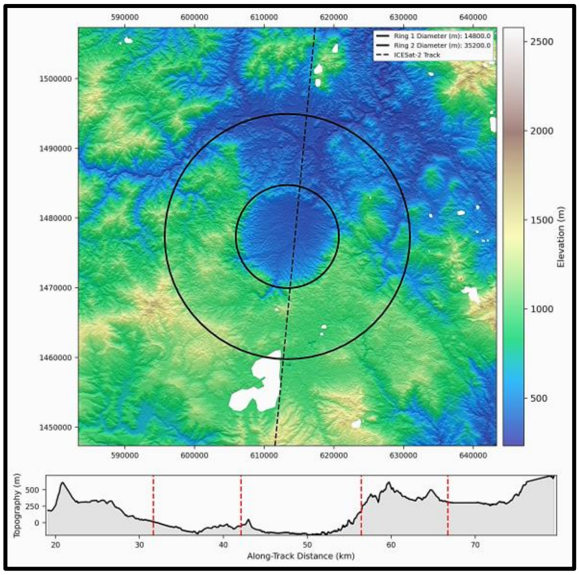

Figure 1. *Example of* **Pantasma** *(Nicaragua) complex crater with outer rim identified at ~35 km from PlanetDEM data (see text for detail*: also [14]). *Lidar Profile below is from GEDI.*

Estimated Apparent Rims. Most current terrestrial impact crater databases list the apparent diameters of recent features based on their well-defined inner cavities [4]. For example, the newly discovered *Pantasma* complex crater in Central America is listed as having a rim diameter of ~14 km on this basis [14]. However, with the application of the RPS method on high spatial resolution DEM datasets, we discover that there is a detectable 'apparent' rim at 35.2 km (**Fig. 1**) with an inner peak ring diameter of 14.8 km. Given *Pantasma* is likely ~0.80 Ma (age), this represents a large NEO impact event within the past million years. Reanalysis of the *Bosumtwi* (Ghana) topography using the RPS method suggests an outermost rim of 26.8 km with an inner peak ring (with deep cavity within) of 10.8 km. The perhaps more bizarre *Zhamanshin* impact feature in Kazakhstan reveals an outer putative rim at 30.4 km with an inner 'peak ring with cavity' at 12 km diameter, broadly consistent with known gravitational anomalies.

Itturalde (Bolivia). While still considered unproven as a hypervelocity impact feature, the *Itturalde* structure of Bolivia is another tropical potential impact site with clearly defined ring-like features in high resolution DEM topography. Using PlanetDEM data for this region, we measured a potential outer rim at 30.4 km, with an inner ring at 10.8 km. Other possible solutions suggest a smaller outer rim value of 23.2 km based on inner cavity position and ongoing watershed analysis.

Implications. If we take the larger of the RPS-estimated outermost crater rims for *Pantasma*, *Bosumtwi*, *Itturalde*, and *Zhamanshin* (i.e., 26-35 km) and evaluate the implications of four large NEO impacts in the past ~ 1 Ma using *scaling relationships* [8,9,11], then we compute a range of KE's for these (assuming 45-90 degree impact angles and nominal velocities of 15-25 km/s) from 400,000 Megatons (TNT equiv.) to over 730,000 Mt (**Table 1**). These values are well above the KE required to blow-off part of the Earth's atmosphere and distribute impact glasses globally [10].

Connections. NEO impact events that produce complex craters 26 to 35 km in diameter with large KE values (**Table 1**) also excavate large volumes of materials, much of which is in the form of sub-mm fines. If we take *Pantasma* (D_a ~ 35 km) and apply suitable volume of excavation scaling laws [10-12], a total volume of materials displaced of ~ 2500 km^3 is derived (10% uncertainty). This value is *in family* with total volumes associated with large volcanic caldera eruptions (e.g., so-called mega eruptions with VEI = 8). Thus, with at least four such NEO impacts in the past million years, that is a total volume of ~10,000 km^3 from such events alone, on par with the most recent volcanism-related volumes associated with the Yellowstone caldera. The effects of such explosions on the Earth's climate and environment is appreciable, with long-term implications on global scales [5,10].

CONCLUSION: Recent NEO impact cratering events may have been larger and more energetic than currently published studies [5-6] suggest, because of our analysis of ultra-high resolution DEMs now available at spatial scales of 4 m or finer. Such topographic data permits reassessment of the role of such impacts in recent Earth history [10] and presents implications for Planetary Defense. The flux of 1.0-2.5 km diameter NEOs as impactors in the past ~ 1 million years is higher than the average Phanerozoic cratering rate and may reflect a previously unrecognized aspect. Further analysis of high resolution DEM's across the past ~100 Ma may resolve patterns in the NEO flux and re-calibrate the *KE vs Time interval* behavior.

References: [1] NASA JPL (2021) NASA DEM (30m); [2] TanDEM-X (2023) Global Earth DEM (12m); [3] Gottwald M. *et al.* (2021) *IEEE J. Sel. Topics Appl. Earth Obs. Rem. Sensing, Vol. 14*, p. 8128; [4] Turtle E. *et al.* (2005) *GSA Spec. Paper 384*, 1-24; [5] Schmieder M. & D. Kring (2020) *Astrobio. 20* (1), p. 91; [6] Impact Earth (2023) UWO crater database at : https://impact.uwo.ca/map/; [7] Croft S. (1985) *JGR/Planets vol. 90*, C828; [8] Johnson B. *et al*. (2016) *Icarus 271*, p. 350; [9] Davison T. & G. Collins (2022) *GRL 49 (21)*, 16 Nov. 2022; [10] Grieve R. (2017) *Geosci. Canada 44*, p 1-26; [11] Melosh H. J. (1989) Impact & Explosion Cratering; [12] Scott R. (2013) *Phys. Ed. 48*, p. 512; [13] Garvin J. B. *et al*. (2003) 6th Int'l Conf. on Mars, Pasadena, CA , paper # 3277 (3 pp.); [14] Rochette P. *et al*. (2019) *MAPS 54 (4)*, p. 890.