INTERACTION OF EJECTA DURING MULTIPLE CRATER FORMATION ON EARTH: KAALI 2/8 CASE AND LABORATORY EXPERIMENTS.

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Introduction: A multiple crater is a group of overlapping of closely spaced or overlapping impact craters formed at approximately the same time so that features from those impacts interact with each other during their formation [1]. Although such features may be formed by the impact of a double impactor [2,3,4,5,6], most of the confirmed examples of such structures on Earth are related to the disruption of a bolide during its atmospheric entry [7,8]. On Earth, multiple craters are known from a handful of sites, including Kaali [9], Sikhote-Alin [10], Henbury [11], Morasko [12], and Douglas [13] strewn fields, among others. Past studies of multiple crater formation have included a single experimental laboratory campaign [14], multiple numerical modeling studies related to both terrestrial and extraterrestrial structures [e.g., 4], and remote sensing analyses of features on extraterrestrial bodies (e.g., [3,15]. Field studies typically only note the existence of multiple craters, without much further analysis, although recent studies have attempted to more carefully analyze the process [5,6].

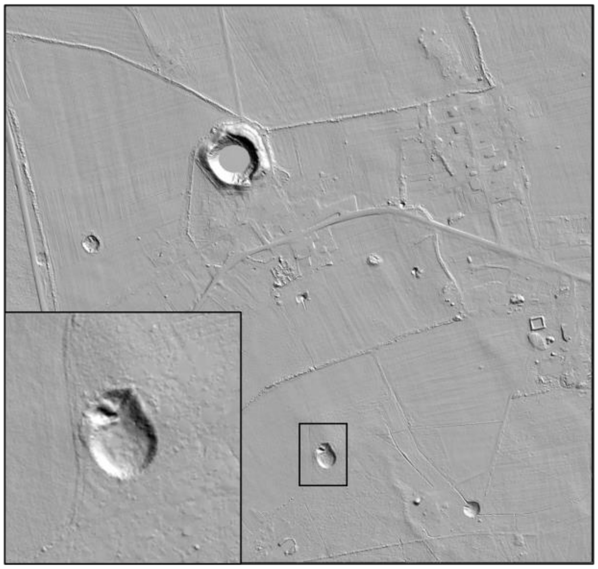

Fig. 1. Lidar map of the Kaali strewn field in Estonia. The location of a trench dug within the Kaali 2/8 crater is indicated by a white arrow. Two pits visible within the northern section of the crater were made in 1930's by [9]. Source: Estonian Land Board

The aim of this study is to investigate the process of formation of double/multiple crater within a terrestrial strewn field by means of 1) studying its proximal ejecta blanket, 2) performing laboratory experiments.

Kaali strewn field is among the best-preserved multiple impact sites on Earth. The strewn field includes nine identified craters located on the island of Saaremaa in Estonia [16]. The largest crater is 110 m in diameter (centred at 58°22’21.94“N, 22°40’09.91” E). It was formed by the impact of an IAB iron meteoroid weighing between 400 and 10,000 tons into Silurian dolomite target rocks covered by ~2-3 meters of glacial till. The age estimates of the Kaali craters is ~1530 - 1450 BCE (3237±10 14C yr BP) [17].

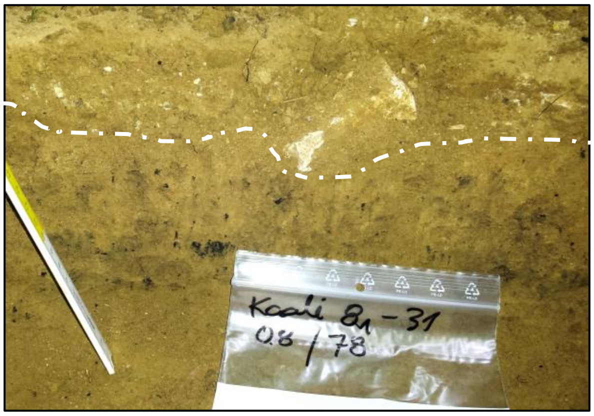

Fig. 2. The contact between dolomite rich ejecta and till rich ejecta with a charcoal rich zone. The white line indicates contact between dolomite rich ejecta (top) and till rich ejecta with the charcoal-rich zone.

The Kaali craters 2 and 8 form a doublet, with overlapping 27 m and 36 m diameter features that are located about 800 m to the south from the Kaali Main. As with all of the smaller Kaali craters, they have been significantly modified by the anthropogenic activity, but a small rim is still identifiable in the field and is well preserved in the area between two sub-craters.

Methods and results:

Trenching in proximal ejecta: In order to determine the internal structure of the ejecta blanket of Kaali 2/8 doublet crater, we dug a 2 m long, 1 m wide and up to 150 cm deep, radially oriented trench in the west section of the crater (see [17, 18]. The specific location of the trench was selected in the field so that it is within the small, raised rim, away from material removed from the trenches dug in 1930's [9] and away from an agricultural fence.

The stratigraphy of the ejecta is similar to the stratigraphy around Kaali Main ([17] field work 2014 and 2017). Below ~20 cm of soil, there is a dolomite rich ejecta layer with multiple angular pieces of dolomite and rare small lenses of till rich material, as well as semi-imbricated groups of rocks and boulders (dolomite and crystalline) that seem to be anchored at the base of this layer. This layer contains small amounts of charcoal pieces that are distributed throughout, with some charcoal pieces directly on the crushed dolomite. Below (at the depth of ~70 cm from the surface), there is a ~20 cm layer similar to till-rich ejecta. The contact between dolomite- and till- rich ejecta is quite sharp but undulating (Fig. 2). Two distinct charcoal-rich horizontal zones were identified: one is located directly below the contact with dolomite-rich zone (at 73-80cm), the second one 12-20 cm deeper (at 92-100 cm). At Kaali Main, only one charcoal-rich zone was detected. The two charcoal enriched zones are divided by a till-dominated layer with only a small addition of up to 1 cm in diameter dolomite fragments. At the depth of 140 cm, there is a layer rich in dolomite fragments (and few crystalline rocks) that is highly compacted and prohibits digging by hand.

Charcoal reflectance: Measuring charcoal reflectance allows the level of ordering of the carbon atoms within the char that correlated to the environment in which it was formed to be determined [19]; this allows wildfire and impact charcoal that can be found in proximal ejecta blankets of confirmed impact craters to be distinguished [17,18]. Reflective properties of the charcoals from proximal ejecta of Kaali 2/8 are like those from Kaali Main and other confirmed impact craters (e.g., Morasko and Whitecourt). The charcoal formed in a low energy environment (median reflectance <0.9%), and grains were roasted to similar extent (st. dev <0.135).

14C dating at the Vienna Environmental Research Accelerator at the University of Vienna (Austria) [20] calib. ages (95.4% probability) are calculated using the OxCal v4.2.4 IntCal13 atmospheric curve [21,22]. We dated one sample from the Kaali double crater 2/8 (Kaali2-8_1_26) from the higher charcoal layer (75 cm depth) and has reflectance properties characteristic to impact charcoals (mean reflectance ~0.8%, low st.dev within particles and sample, no max reflectance >1.5%). The analysis was performed twice (VERA- 6362 and 6362) with slightly modified level of HCl cleaning. Both provided identical results (within error): 3036±36 14C yr BP (1410-1130 cal. BCE) and 3085±35 14C yr BP (1430-1260 cal. BCE).

Fig. 3. A frame from an EPIC impact experiment at the INTA-CSIC. A white arrow indicates a ray formed by collision of two impact ejecta curtains.

Lab experiments were conducted at the Experimental Projectile Impact Chamber (EPIC) at Centro de Astrobiología (INTA-CSIC) in Spain [23]. The projectiles were standard 6mm, plastic air-soft balls in loose cluster launched at approximately 300m/s. One of the shoots with two projectiles produced a doublet crater (two impact points 4 cm apart). The left-hand, smaller ball (damaged while being ejected from the gun) hit the surface first, but its ejecta was overtaken by the larger impactor. The ejecta seemed to partially mix and fall as a single, thick ray (Fig. 3).

Discussion: The charcoal formation process in impact cratering must accommodate the formation of a double charcoal layer in the "neck" of the doublet crater. Numerical modeling [4] and laboratory experiments (Fig. 3) suggest that if the fall of the impactors take place at approximately the same time, there should be only one layer of ejecta, and by inference, one layer of charcoal rich material. One potential explanation of those observations is that there was a time lag between formation of those two impacts, similar to the experiment, that was sufficient for one of the ejecta curtains to land on the surface before the other. This observation could constrain the precise time of impact of different impactors within a single strewn field, with relevance to the interaction of asteroids with atmosphere. More research is needed.

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