DEATH FROM SPACE: ORIGIN OF CHARCOAL FOUND IN PROXIMAL EJECTA BLANKET OF KAALI CRATERS (IS NOT WHAT WE THINK ☺). A. Losiak[1,2], C. Belcher[1], A. Jõeleht[3], J. Plado[3], M. Szyszko[4]. [1]Planetary Geology Lab, Institute of Geological Sciences, Polish Academy of Sciences, Poland (anna.losiak@twarda.pan.pl); [2]wildFIRE Lab, Hatherly Laboratories, University of Exeter, UK (c.belcher@exeter.ac.uk, v.a.hudspith@exeter.ac.uk); [5]Department of Geology, University of Tartu, Estonia (argo.joeleht@ut.ee, juri.plado@ut.ee); [4]Institute of Geology, Adam Mickiewicz University in Poznan (mateusz.szyszka@amu.edu.pl).

Introduction: Pieces of charcoal have previously been found within the proximal ejecta blanket of small impact craters developed in unconsolidated material such as Campo del Cielo (Argentina [1]) or Whitecourt (Canada: [2]). Charcoals were assumed to be part of the paleosoil covering the pre-impact surface, and apart from ^{14}C dating to determine minimal age of the craters, no other research has been undertaken on them.

Recently, pieces of charcoal have also been found in the proximal ejecta blanket of Main and double 2/8 Kaali craters (Estonia: [3]). However, in contrast to previous studies, the charcoals were determined to be formed during the impact cratering process. This interpretation was based on the fact that charcoals: 1) were found within a ~20 cm thick layer composed of the till-rich ejecta and dolomite-rich ejecta (in the pre-impact target stratigraphy dolomite was located at depth of >3m); 2) some pieces were found strongly adhering to impact crushed dolomite pieces; 3) all identified charcoal pieces had the same ^{14}C age (within error) that was also the same (within error) as the earliest ^{14}C ages of material from inside the crater (indicating that the lake deposition started directly after crater was formed).

The aim of this project is to determine the formation mechanism of the Kaali charcoals by comparing their reflective properties to those produced by a range of different energy fluxes in a laboratory experiment, where we test the hypothesis proposed by [3] where: (1) the projectile entered the atmosphere and began to heat up [4]; (2) shortly before hitting the ground, the radiative heat of the bolide ignited trees [5]; (3) the hot air-blast heated trees in the vicinity of the impact site; (4) the excavation process then mixed heated charred wood and “colder” rocks into the ejecta deposits; (5) heated wood continued pyrolysis to charcoal for a relatively short time within the ejecta blanket.

Site - Kaali Crater: The Kaali impact field consists of nine identified craters located on the Saaremaa Island in Estonia. It was formed by impact of an IAB iron meteoroid with entry mass between 800 and 3000 t into Silurian dolomite target rocks, covered by ~1-3 m of glacial till [6]. This structure was formed shortly after 1530-1450 BCE (3237±10 ^{14}C yr BP) [3]. The largest crater is 110 m in diameter (centered around 58°22’21.94“N, 22°40’09.91”E). One of satellite structures Kaali 2/8, is a double crater consisting of partially overlapping craters of 27 and 36m in diameter.

Samples: Samples of charcoal were taken from the trenches dug within proximal ejecta of Kaali Main in 2014 and 2017, and Kaali 2/8 in 2016. Trench in the Kaali Main 2014 was described in detail in [3], the 2017 trench was an extension of the previous outcrop (in the direction of the crater rim). In trenches of both craters, two types of material were found: 1) dolomite-rich ejecta (mostly angular dolomite from <1 mm up to boulders ~80 cm in diameter – pieces larger than 30 cm were present only in Kaali Main) and 2) underlying till-rich ejecta (with rounded glacial boulders) that merges into target material (glacial till).

Fig. 1. Large charcoal pieces found within proximal ejecta blanket of the Kaali 2/8 (a hand (almost cut off during a heroic fight with a watermelon) for scale). White particles above charcoal are pieces of crushed dolomite.

In Kaali Main, all fragments of charcoal were found within approximately 10 cm above and below the contact between dolomite-rich and till-rich ejecta. It occurred most abundantly within the top 5 cm of the till-rich ejecta layer. Most charcoal fragments were <1 mm in diameter, but a few were >1 cm in length (and up to a few mm in width and thickness). A nearly continuous layer containing small fragments of charcoal was found ~14 m from the crater rim and continued for 5 meters until the proximal end of the trench. Charcoal pieces were also found within the dolomite-rich ejecta layer. Some of those fragments were strongly adhering to the surface of angular dolomite fragments located within the ejecta layer.

The trench of the Kaali 2/8 crater was located “in the neck” region of the two-crater “snow-man”, where ejecta of both craters were expected to be present. Unexpectedly, two, approximately parallel levels of charcoal, divided by 20-30 cm of till-rich ejecta were discovered. Their ^{14}C dating revealed they are of practically the same age (3085±35 ^{14}C yr

BP 1430-1260 cal. BCE: [7]) as charcoals dated from Kaali Main. The crushed dolomite was present only directly above the upper layer of charcoal (Fig. 1).

Methods: In order to test the proposed scenario, we devised a laboratory experiment: dry Pinus wood (4.5x4.5x3.5 mm & 13% moisture) was exposed to heat fluxes ranging from 15 to 100 kW/m^2 for time ranging from 4 s to 400 s (avoiding ignition) using an iCone calorimeter. After assigned time has passed (or when the wood ignited) samples were wrapped in aluminium foil and covered with sand (21°C) to mimic process of heated trees being buried in cold ejecta, as well as to limit the overwriting effect of continuous flaming on previously developed charcoal Ro [8].

Reflectance (Ro) of charcoal can be used to determine the level of graphitisation of charcoal which relates to the total amount of energy delivered to the sample [9]. Charcoals from the Kaali craters and those produced during the experiments were embedded in polyester resin, then ground and polished. The polished samples were analysed under oil (RI 1.514) using a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer. The system was calibrated with three synthetic mineral reflectance standards). Manual reflectance measurements were taken across the polished surface of the charcoal. For most samples 3-5 charcoal particles were measured, in 35-100 different points.

Table 1. Reflective properties of charcoal from Main and 2/8 Kaali craters compared to those from the field scale experimental boreal forest fires (NW Territories, Canada). Pinepoint was a low-intensity surface fire with mean max temp. recorded from the thermocouples attached to the wood pieces of 482°C. Triangle was a high intensity fast-moving crown fire, the mean max temp. of 842°C. More info on the forest fire samples in [9].

	Forest Fires				Impact craters	
	PinepointB		Triangle		Kaali	
	Cedar	Pine	Cedar	Pine	Main	2/8
Average	1.22	1.01	1.61	1.55	0.78	0.75
Median	1.24	1.03	1.55	1.47	0.79	0.73
Min	0.72	0.54	0.88	0.68	0.10	0.27
Max	1.76	1.53	2.93	2.74	1.58	1.30
St dev	0.23	0.24	0.41	0.44	0.20	0.15

Results: Reflective properties of charcoal (Table 1) collected in both Kaali sites are similar to each other, but different from charcoal collected from natural forest fires [9]. Kaali Main and Kaali 2/8 charcoal have average Ro% of 0.78 and 0.75 and standard deviation below 0.2, while even the lowest intensity Pinepoint samples had mean Ro of >1.0 and standard deviation above 0.2. Additionally, every particle of the impact charcoal was characterized by a uniform reflectance (all Ro measurements were in the range ±0.4). Forest fire charcoal particles have heterogeneous Ro deviating by as much as 1.0 Ro%.

iCone experiments indicated (Fig. 2), that in order to produce charcoal with Ro similar to that found in the Kaali craters it is necessary to heat pine samples for at least 7 seconds at 100 kW/m^2. Lower heat fluxes e.g. 35 kW/m^2 require 150 s of sustained heating to produce charcoal with Ro ~0.76. However, in all cases the charcoal produced was very variable in its Ro% properties – where the highest values (indicated on Fig. 2) were on the surface, and not charred wood was present within only couple of mm. The shorter the heating time (and higher energy flux), the more variable the Ro% change was through the depth of particles – in the case of the 100 kW/m^2/7s sample, the thickness of charcoal with Ro% 0.7 was <100 µm, below with this layer it sharply decreased to ~0.2 at 300 µm depth below sample surface.

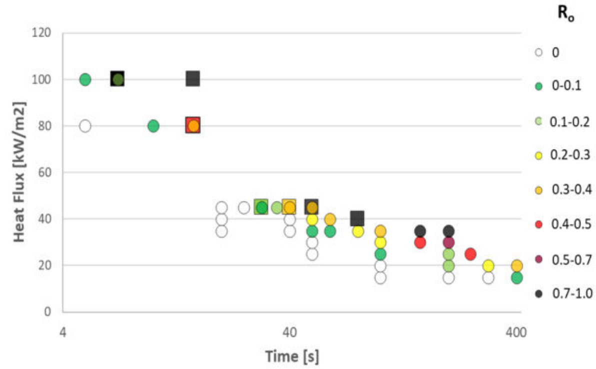

Fig. 2. Results of the ICone experiment showing relation of heat flux and time of heating on reflectance of charcoal produced. White circles mark experiments where samples were not charred, squares show samples that ignited (and within 3 seconds were put into sand for cooling).

Discussion: Our experiment (Fig. 2), that was guided by charcoal formation mechanism proposed in [3], was unable to reproduce charcoal with observed properties of the Kaali samples. The required heating time to produce any charcoal is at least a few seconds at heat rate of 100kW/m^2, a time span that cannot be expected to be produced by radiative heat of the Kaali-size bolide shortly before hitting the ground. Potential interaction would be <1 s, which is too short to produce any charcoal at such heating rate. Additionally, the char layer produced by the short time & high heat flux experiments is very thin – the surface layer, which has the highest Ro%, is up to a couple of hundreds of µm (or couple cells), and its Ro% decreases sharply to 0 producing pieces with a strong Ro gradient even within a single, small piece. In contrast, Kaali charcoals, even though they can be a couple of cm long and tens of mm thick, have uniform Ro% properties strongly suggesting that they were formed in different conditions.

An interaction with locally warm ejecta is being tested now, the future research involves also higher heating rates at inert gas environment.

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