DATING ILUMETSA CRATERS (ESTONIA) BASED ON CHARCOAL EMPLACED WITHIN THEIR PROXIMAL EJECTA BLANKETS. A. Losiak[1], A. Jõeleht[2], J. Plado[2], M. Szyszka[3], E.M. Wild[4], M. Bronikowska[3], C. Belcher[5], K. Kirsimäe[2], P. Steier[4]. [1]Planetary Geology Lab, Institute of Geological Sciences, Polish Academy of Sciences, Poland (anna.losiak@twarda.pan.pl); [2]Department of Geology, University of Tartu, Estonia (argo.joeleht@ut.ee, juri.plado@ut.ee, kalle.kirsimae@ut.ee), [3]Institute of Geology, Adam Mickiewicz University in Poznan (mateusz.szyszka@amu.edu.pl, malgorzata.bronikowska@amu.edu.pl); [4]VERA Laboratory, Faculty of Physics—Isotope Research & Nuclear Physics, University of Vienna (peter.steier@univie.ac.at, eva.maria.wild@univie.ac.at); [5]wildFIRE Lab, Hatherly Laboratories, University of Exeter, UK (c.belcher@exeter.ac.uk).

Introduction: The Ilumetsa crater field in SE Estonia consists of two structures with diameters of 75-80 m (Põrguhaud /Hell's Grave /Ilumetsa Large (IL)) and ~50 m (Sügavhaud /The Deep Grave /Ilumetsa Small – (IS)) with true depths of about 8 and 3.5 m, respectively [1, Fig. 1]. Both structures are surrounded with a rim up to a few meters high which is highest in the eastern parts (max. rim heights are 4.5 and 1.5 m, respectively). Ilumetsa is listed as a proven meteorite impact in the Earth Impact Database, but neither remnants of the projectile nor other identification criteria (e.g., PDFs) have been found up to this point [1].

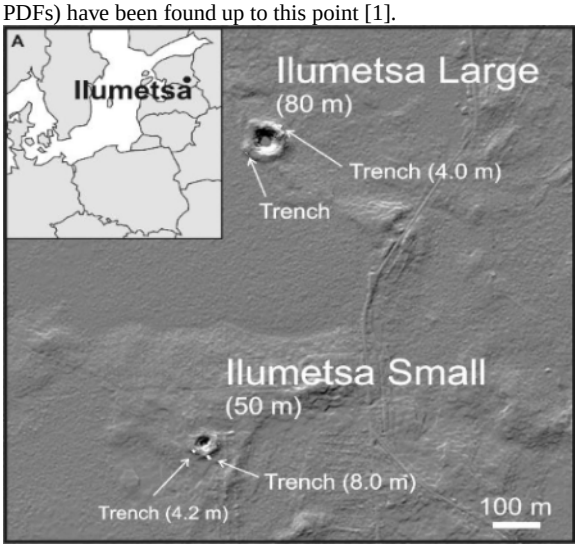

Fig. 1. A) Location of the Ilumetsa craters. B) Digital elevation model of two Ilumetsa structures with location of the trenches (lengths of trenches are up to scale). A large, flat area south from IL is a bog.

The target rocks consist of middle Devonian weakly cemented light-yellow to reddish silt- and sandstones, overlain by up to ~2.5 m thick layer of brown basal till and glaciofluvial sand. Based on [2], the rim consists of Devonian and Quaternary sands mixed with numerous till-forming clayey lenses. Deformed sedimentary beds and small thickness of glacial sediments favor an impact rather than a possible glacial (e.g., kettle- or sink-hole) origin of Ilumetsa.

Structures were previously dated by the ^{14}C analysis of gyttja and peat from the very bottom of IL [3]. The lowermost organic beds date back to 6030±100 ^{14}C years (7170-6660 cal. years BP; recalibrated with IntCal13). About 600 years older age (6542±50 ^{14}C years or 7570-7320 cal. years BC; IntCal13) of Ilumetsa was proposed by [4]. This date was based on peat with glassy spherules found in a depth of 5.7 m from the Meenikunno bog, ~6 km SWW from the structures. The spherules were reported as being up to a few millimeters in size and interpreted as dissipated melt or condensed vapor however their chemical composition was not reported.

The aim of this current study was to determine/confirm the age of those structures by ^{14}C dating of organic material covered by the proximal ejecta and search for possible impact related charcoals. This approach was recently successfully applied to dating crater Kaali Main [5]. Additionally, our study attempts to determine if Ilumetsa was indeed created during an impact of an extraterrestrial body with the Earth surface.

Samples: We have collected charcoal-containing samples from trenches located in the outer rim of both Ilumetsa structures (Fig. 1). *IL* hosted two trenches: the first one 4 m long (N 57° 57' 37.28" E 27° 24' 12.59": the end of the trench closest to the rim was located ~12 meters from it); the second one (at the 180° radial angle from the first one) was not completed due to the high ground water level. The ejecta blanket consisted mostly of massive sand, but on the depth of 130 cm (at the rim-end of the trench) there was a nearly horizontal, 5-10 cm thick, slightly inclined in the direction outside of the crater, layer of reddish till. At the surface a well-developed podzol soil with a well-developed bleached eluvial horizon was present. All charcoal samples came from a single 10-20 cm thick layer within the massive sand. This layer was slightly inclined in the direction outside the crater and located at the depth of 55-65 cm. Charcoal was not evenly distributed along the trench, but it was mostly present at the distance between 1.7-2.8 m (measuring from the rim of the trench furthest away from the crater center). In the same zone a single piece of glass-like material was found (no analysis has been made up to this point). Most pieces of charcoal were very small, 1-2 mm in length, but few larger pieces (up to 1 cm) were identified.

IS hosted two trenches located at ~90° radial angle from each other: a longer trench (8.0 m long, and up to ~150 cm deep (where groundwater was present) – starting at the: N 57° 57' 12.60" E 27° 24' 00.99" (located at the place where crater rim is the steepest) and a shorter trench (4.2 m long, up to ~120 cm in depth – starting at the: N 57° 57' 12.99" E 27° 23' 59.29" – located at the shallow gradient end of the crater rim). Both trenches were dug in a massive, medium-grained sand with lenses/undulating layers of gravel and coarse sand. In the deepest part of the longer trench (at depths >140 cm) undisturbed Devonian reddish siltstone-sandstone bedrock was exposed. In the middle part of the section at depth 60-80 cm irregular clayey lenses of till-like material occurred. Additionally, locally horizontal red staining was present (probably related to oxidation caused by the water table fluctuation). In the shorter trench only 6 charcoal samples were collected - but all of them were at least 5 mm in length (Ilume_S_2_3). All of them came from approximately the same depth, but did not forming a continuous layer (because very small pieces were not found). In the longer trench, significantly more charcoal was present, but its distribution within the strata was more complex. Similarly to the Kaali Main and IL crater, charcoal pieces were not distributed along the entire trench but at the distance of 4.9-7 m (with a couple of pieces at 8 m distance – but on significantly lower depth

than other pieces from the "main sequence"). Most of the charcoal was found within a lens like (~20 cm in diameter) grey zone located at the depth of 65-85 cm. The color of this clayey-siltstone is most probably due to a large amount of charcoal and organic material. A large, 2.5 cm in length, piece of charcoal was found in the middle of this zone (Ilume_S_1_11g). A similar, but smaller grey zone was identified in one more place (50 cm from the first one). A couple of pieces were also found just above the level of ground water (90-110 cm). Some charcoal was also visible at the much shallower depths of 50 cm – below the soil level (Ilume_S_1_48). Most charcoal was dispersed as pieces of <5mm in length at a depth of 60-70 cm.

Methods: *^{14}C dating* was performed at the VERA (Vienna Environmental Research Accelerator) laboratory at the University of Vienna (Austria). The samples were chemically pretreated with the standard ABA (acid – base – acid) procedure used at VERA [6]). *Charcoal reflectance measurements* of a sample (Ilume_S1_32) were performed on material embedded in resin, polished and analyzed under oil using a Zeiss Axio-Scope A1 optical microscope, with a TIDAS-MSP 200 microspectrometer [7]. *Chemical composition* of the sediments exposed in IL and SL profiles was determined by ICP-MS. In the field we *searched for pieces of meteorites* using a Lorenz deepmax z1 metal detector. Preliminary *numerical modelling* of the Ilumetsa case as an impact crater (mainly meteoroid movement and break-up process in the atmosphere) we used a modified Pancake as an approximation [8].

Preliminary results: *^{14}C dating (Fig. 2):* The calibrated (95,4% probability) time ranges of four dated samples from IL span the time interval from 7670-6950 cal. BP. Ages of three dated samples from the IS structure vary significantly: the first sample (from the shorter trench) is consistent with ages of charcoals from the larger crater (7250-7000 cal. BP). The second sample is significantly older (8540-8400 cal. BP), and the third one is younger (4830-4580 cal. BP). *Chemical analyses* of sediments exposed in profiles did not reveal any specific enrichment with respect the host rocks in elements (Ni, Cr) that could be related to extraterrestrial material.

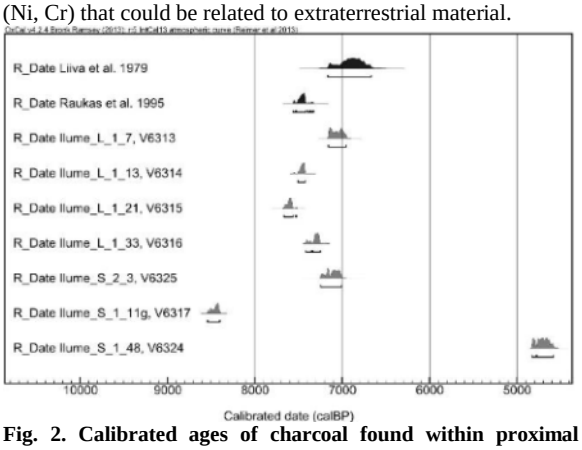

Fig. 2. Calibrated ages of charcoal found within proximal ejecta of Ilumetsa craters (Ilume_L - IL, Ilume_S - IS). Black plots at the top show age estimations of Ilumetsa Large based on ^{14}C dating of the gyttia [3] and peat where glassy spherules were found [4]. Calibration was performed with OxCal v4.2.4 [9] and the IntCal13 calibration curve [10].

Discussion: *Ages* determined for the charcoals from the IL structure, and for one of the samples from IS are consistent with the previous ages obtained for the gyttia within the IL crater [3]. Two samples are clear outliers. Ilume_S_1_48 was dated to be only 4830-4580 cal. BP. This sample was selected for dating because it was found at significantly lower depth than other charcoals found within the same trench (depth 50 cm at the 8th meter of the trench). Considering the location of the sample on a slope made of sandy material, the charcoal in this sample can be interpreted as a remnant of a more recent forest fire, later buried within the sediment derived from the erosion of the raised rim. Sample Ilume_S_1_11g was dated to be significantly older: 8540-8400 cal BP. It was taken from a grey zone located at a depth of ~70 cm in which multiple large (cm sized) pieces of wood (with tree-rings distinguishable), together with many small bits dispersed within. This material may be interpreted as an older plant material that was buried within the sediments before the impact happened. In order to determine exact age relations of charcoal pieces within this trench more samples will be measured for ^{14}C.

Reflectance measurements of the single sample (Ilume_S_1_32 – not dated yet) measured thus far are similar to the values characteristic to Kaali Main (average Ro ~0,75 [11], which appeared to be dissimilar to the charcoals produced by forest fire (average Ro ~1.40). However, more analysis is required to be undertaken before this can be confirmed. However, this single sample measurement may support an impact origin of this charcoal, but more measurements are needed to draw conclusions.

Preliminary studies on *the atmospheric entry modeling* of the Ilumetsa meteoroid shows that using standard value of strength ($4.4e^6$ - $4.4e^7$ N/kg) for a stony meteoroid (since no iron meteorites were found in the proximity of Ilumetsa), cannot lead to reproduction of the Ilumetsa craters formation due to cascade fragmentation specific for such weak bodies. This conclusion is consistent with observations – there are no terrestrial, moderate size (50 to 100 m in diameter) craters formed by stony projectiles [12]. Therefore, we conclude that Ilumetsa craters could have been formed by an atypical stony projectile and more studies are needed to reconstruct this unusual impact event.

Conclusion: The presence of charcoal under the rim of Ilumetsa structures supports their meteorite impact origin. Preliminary results suggest that the Ilumetsa structures were formed around 7000 cal. BP.

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