DATING A SMALL IMPACT CRATER: AN AGE OF KAALI CRATER (ESTONIA) BASED ON CHARCOAL EMPLACED WITHIN PROXIMAL EJECTA

A. Losiak[1], E.M. Wild[2], W.D. Geppert[3], M.S. Huber[4], A. Jõeleht[5], A. Kriiska[6], A. Kulkov[7], K. Paavel[6], I. Pirkovic[8], J. Plado[5], P. Steier[2], R. Välja[5], J. Wilk[9], T. Wisniowski[10], M. Zanetti[11]. [1]Institute of Geological Sciences PAS (anna.losiak@twarda.pan.pl); [2]University of Vienna; [3]Stockholm University [4]University of the Free State; [5]University of Tartu; [6]University of Tartu; [7]Saint-Petersburg State University; [8]University of Belgrade; [9]University of Freiburg; [9]Space Research Center PAS; [11]Washington University in St Louis and McDonnell Center for Space Science.

Introduction: Dating of small (<~120 m in diameter) impact craters developed in unconsolidated sediment is a complex topic, because most methods used successfully for determining age of larger craters cannot be applied (e.g., using radioisotopic systems such as Ar/Ar, K/Ar, Rb/Sr, U/Pb; exposure and burial dating cosmogenic radioisotopes). Apart from radioisotope dating, the age of young craters can be estimated using stratigraphy, biostratigraphy, dendrochronology, and archeology although those methods cannot be used in all cases and tend to be imprecise.

The most precise and accurate age of small (<~120 m) and young (<50 ka) craters can be obtained by means of ^{14}C dating of organic material associating with an impact structure. Most commonly, organic material from within the crater is used. However, this method can reveal only a minimum age of the structure [1,2], which often is significantly different from the real age, because datable material can start forming long after the crater formation, and the extent of the time lag is hard to estimate. A maximum estimate of the age of a crater can be obtained by ^{14}C dating of the paleosol that is covered by proximal ejecta [1, 3]. Dating paleosols, however, tends to be problematic because different fractions of soil may yield dissimilar ages [4]. <u>The best way to date a young impact crater is to ^{14}C date a shortlived organism that was killed by the impact event.</u>

Age of the Kaali impact craters: The Kaali impact field consists of nine identified craters located on the Saaremaa Island in Estonia. The largest crater is 110 m in diameter (centered around 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 up to a few meters of glacial till [5].

The age of the Kaali impact structure is still a matter of debate, and the estimates provided by different authors vary considerably between ~6400 BC and ~400 BC. Proposed ages can be divided into three groups: "old" Kaali ~6400 BC [6, 7, 8], "middle" Kaali ~1750-1500 BC [9, 10, 11, 12], and "young" Kaali ~800-400 BC [13, 14]. Those ages were obtained using a wide range of methods. Some of the youngest and the oldest ages were derived by ^{14}C dating of marker horizons, characterized either by a slightly elevated iridium content within the nearby Piila bog yielding a calibrated age of 800-400 BC [13, 14], occurrences of glassy siliceous material in the same bog (~6400 BC: [6] or iron microspherules in an organic-rich layer of the Reo gravel pit (6400 BC: [7]). However, the source of the foreign material within those layers was never unequivocally connected with the Kaali crater. ^{14}C dating of material from within Kaali impact craters yielded ages between 1800-1500 BC [10,11] and 1741-537 BC [12,15, 16]. These dates could underestimate the age of impact as organic sediments within the crater started to form at an unknown period after the impact. Additionally, [11] suggested that those ages might have been corrupted by a reservoir effect. According to this author, this effect might have caused artificial "aging" of the organic matter because the crater was emplaced within Silurian dolomite, which is rich in old carbon. The age of Kaali was also determined based on palynological dating of sediments within the main crater to be ~1750 BC (~3700 BP, [9]). Additionally, luminescence methods were applied for dating Kaali [8, 17, 18] yielding a wide range of ages from 2300 BC (4250 ±320 BP) to 7850 BC (9800 ± 2300 BP) with an author-preferred age of the craters of 5150 BC (~7100 BP [8]).

Samples and methods: We have collected samples from a 5 m long, 1 m wide and up to 1.7 m deep trench located ~12 meters to the SW from the rim crest of the main crater (trench center: 58°22'19.98" N, 22°40'7.97"E). All identified fragments were found within the Kaali Main continuous ejecta blanket.

Thirteen samples collected from different locations within the trench and at different depths with respect to the ejecta-underlying till boundary were processed separately. In most cases, those samples consisted of numerous small charcoal pieces handpicked from the sediment and combined to form a sample sufficiently large (>10 mg) to be datable by Accelerator Mass Spectrometer.

^{14}C dating was performed at the Vienna Environmental Research Accelerator at the University of Vienna (Austria). A description of the standard analytical method used at VERA is available in [19]. This method was slightly modified for the Kaali crater samples, i.e.

the first HCl step of the ABA method was performed twice. Additionally, a morphological examination of selected charcoal fragments was performed.

Results: The calibrated (95,4% probability) time ranges of eleven out of thirteen separate samples span the time interval from ~1642 BC to ~1400 BC (3300±30 to 3185±35 ^{14}C yr BP). Two further samples (both coming from the same location within the trench) yielded initially younger ages, with dates of ~1500-1304 BC (Kaali 4.4a: 3145±35 ^{14}C yr BP) and ~1401-1226 BC (Kaali 4.4b: 3050±30 ^{14}C yr BP) respectively. Those two samples were re-dated resulting in Kaali 4.4a*: ~1497-1229 BC; 3105±55 ^{14}C yr BP and Kaali 4.4b*: 1601-1297 BC; 3170±50 ^{14}C yr BP). Repeated measurement of the sample Kaali 4.4a is consistent with the previous measurement, but for sample Kaali 4.4b the newly acquired date is significantly older than obtained formerly (but consistent with ages determined for other samples studied in this project). This may suggest that sample Kaali 4.4b may be a inhomogenous mixture of charcoal pieces slightly divergent in age or might have been corrupted by addition of younger carbon either in the field (e.g., from a tree root) or – less probably – in the laboratory. Because of this possibility, we have excluded those samples from further analysis.

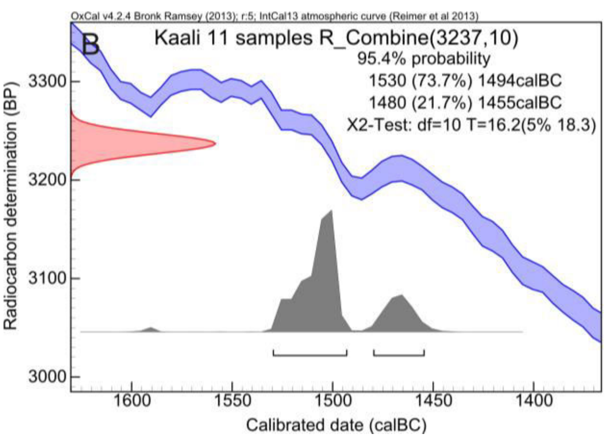

Figure 1. An age (1530-1455 BC) of the Kaali crater based on combined results of eleven samples (3237±10 14C yr BP), excluding potentially corrupted samples Kaali 4.4a, 4.4a*, 4.4b and 4.4b*. Calibration is based on IntCal13 atmospheric curve [21], plot is from OxCal v3.10 [22].

Excluding the two younger samples, the time range based on the combined results of eleven samples (mean value of the uncalibrated ^{14}C age: 3237±10 ^{14}C yr BP), is 1530 - 1455 BC (Figure 1). Because we are dating charcoal from tree fragments buried by the impact it is a terminus post quem (tpq) date of the Kaali crater formation.

All of the pieces of charcoal subjected to anthropological analysis belong to spruce, Genus Picea. All analyzed samples show: 1) a gradual transition from early to late wood, 2) uniseriate rays that are 10-15 cells high and 3) occasionally 2-seriate rays with resin canals. The analyzed samples most probably come from fragments of branches, not roots, because of abundant rays (up to 30 cells) and low density of resin canals [20].

Conclusion: The Kaali crater was formed shortly after (tpq) 1530 - 1455 BC (3237±10 ^{14}C yr BP). This age is based on dating charcoal within the ejecta blanket that makes it directly related to the impact structure, and not susceptible to potential reservoir effects. Saaremaa was already inhabited when the bolide hit the Earth, and the crater forming event was probably witnessed by people, although there is no evidence that this event caused significant changes in material culture or human habitation.

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