

Height of the turbulent gas flow and transport distance of glassy spherules on the example of the Kaali impact, Estonia

Anto Raukas^a and Kustav-Olimar Laigna^b

^a Institute of Geology at Tallinn University of Technology, Estonia pst. 7, 10143 Tallinn, Estonia; raukas@gi.ee

^b OÜ Teadusloome, Tartu mnt. 70–18, 10144 Tallinn, Estonia

Received 21 December 2004, in revised form 10 February 2005

Abstract. Impact ballistics of the Kaali impact group has been considered by a number of authors giving extremely different interpretations. The exact time of the impact is also debatable, but according to direct dates the age of the craters is at least 4000 years. Spherule studies in the mires of the islands of Saaremaa and Hiiumaa show that the impact took place some 7600 years ago. As the more or less vertical gas stream could have reached a height of 6.8–7.9 km, the small glassy particles, often hollow inside, were easily transported over long distances.

Key words: emitted gas flow, Kaali impact, crater age, spherule transportation.

INTRODUCTION

At least nine impact craters are located at Kaali (58°24' N, 22°40' E), 19 km NE of the town of Kuressaare on Saaremaa Island. The main crater has a diameter of 105–110 m and is about 22 m deep. The energy needed for the formation of the main crater is traditionally estimated as 4×10^{19} ergs (Koval 1974). Many authors have considered impact ballistics of the Kaali group and obtained extremely different results (see a review in Czegka & Tiirmaa 1998). At the time of the impact, the meteorite weighed probably 20–80 t and its velocity was 10–20 km/s (Bronshten & Stanyukovich 1963). According to Pokrovski (1963), the Kaali meteorite was about 4.8 m in diameter; its mass was 450 t and impact velocity 21 km/s. Koval (1974) suggested that the mass of the meteorite, which formed the main crater, was 40–50 t and the impact velocity about 13 km/s.

The exact time of this event is also debatable. From simultaneous ¹⁴C and palynological studies Saarse et al. (1992) concluded that the ¹⁴C age of bottom sediments of Lake Kaali in the main crater is at least 3390±35 years BP (sample

Tln-1353) and that the meteorite fell about 4000 years BP. AMS dating of terrestrial macrofossils from these sediment layers places the age of the impact at 1690–1510 BC or some 3500–3700 years BP (Veski et al. 2004). Rasmussen et al. (2000) found a distinct Ir-enriched layer in Piila mire about 10 km northwest of the craters (Fig. 1). Radiocarbon dating of the layer produced the age of 2305 ± 20 ^{14}C years BP (the calibrated date is 400–370 years BC at $\pm 1\sigma$). The above-named authors believed that it was the time of the impact. After dendrochronological calibration, Veski et al. (2001) changed the age of enrichment (2560 ± 85 ^{14}C years BP) and the impact to about 800–400 BC. The last two conclusions must be wrong, because according to direct dates from the bottom of Lake Kaali, the age of the impact is undoubtedly more than 3500 years (Raukas et al. 2003). Already peat from a depth of 1.18–1.25 m gave the ^{14}C age of 2958 ± 51 BP (Tln-2576), which after dendrochronological calibration is some 3260–3050 years BP. Heavy pollution is excluded, because a tree trunk from a nearby excavation yielded the age of 2673 ± 47 ^{14}C years BP (Tln-2573). We would

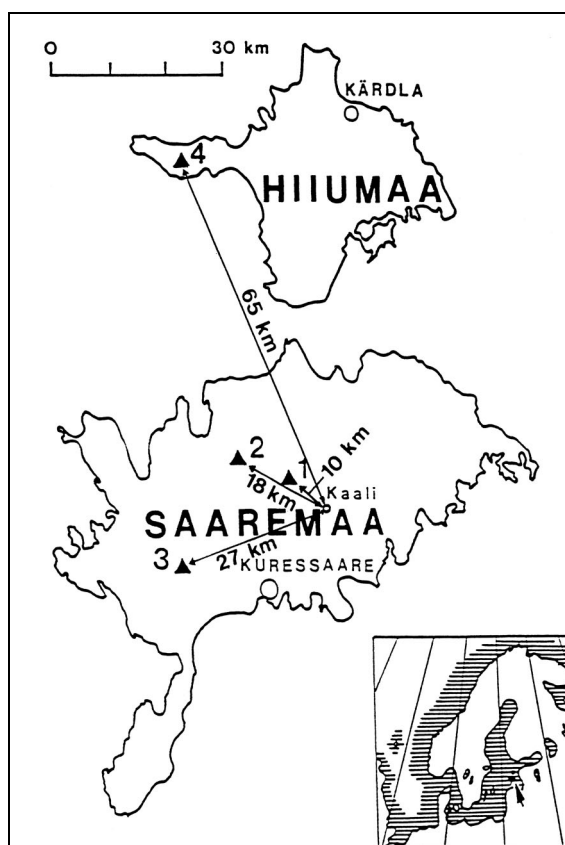


Fig. 1. Location map of Kaali craters and the distances of investigated mires from the crater field. Mires: 1, Piila; 2, Peli; 3, Pitkasoo; 4, Kõivasoo.

like to underline that our excavations were far from the bottommost part of the main crater (Raukas et al. 2003). As sedimentation in the crater started long after the event, indirect methods are needed to estimate the real age of the impact.

During the studies of 1994 we found a high concentration of glassy spherules (microimpactites) in the Lower Atlantic peat of Piila mire 10 km northwest of the Kaali craters (Fig. 2), dated at 7586 ± 67 years BP with the ^{14}C method (Raukas et al. 1995). In the next years, spherules of the same age were discovered in Peli mire, ca 18 km northwest of the Kaali craters and in Kõivasoo mire on Hiiumaa Island ca 65 km from the craters (Fig. 1). In 1996, coeval spherules were detected also in Pitkasoo mire in the western part of Saaremaa, about 27 km southwest of Kaali (Raukas 1997).

Since in all the above-mentioned mires silicate spherules were detected only in one layer, we proposed a new precise correlation method for Holocene sequences, based on these microimpactites. Using this method, we suggested that the age of the Kaali impact is 7600 ± 50 years BP (Raukas 2000).

Our main tasks have been to prove the impact origin of the spherules found (Raukas 1997; Marini et al. 2004) and to explain the possibility of the distribution of spherules over the territory of several hundred square kilometres. There is no doubt that the Kaali main crater was generated by a mighty explosion (Raukas & Laigna 2003), which destroyed the surroundings nearby and formed a crater mound with uplifted dolostone blocks (Fig. 3). Heated gases were directed upwards to a

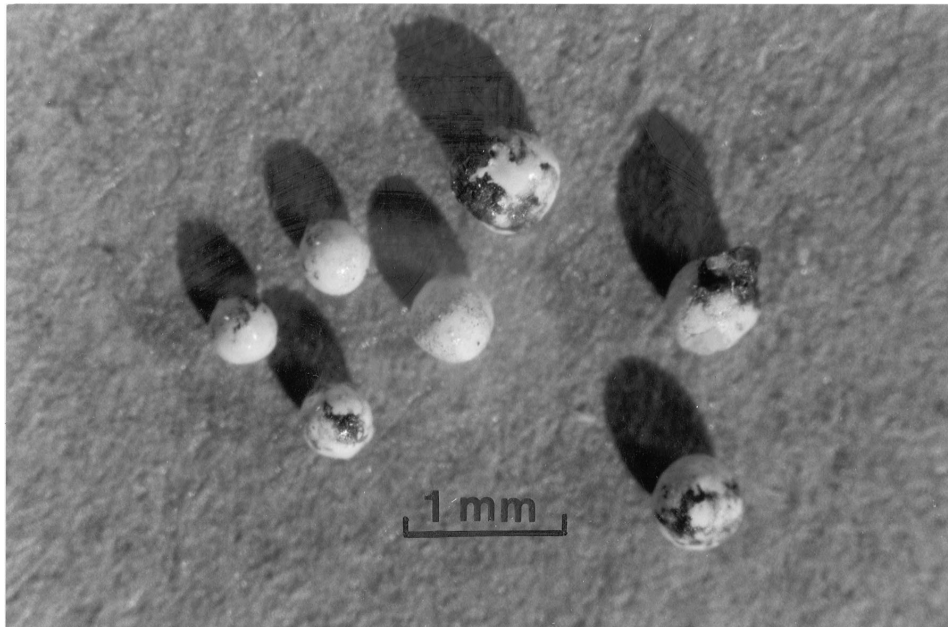


Fig. 2. Typical spherules from Piila mire (about 10 km NW of the Kaali crater area, Fig. 1). Photo by G. Baranov.



Fig. 3. Some 60% of the crater-forming energy in the main crater was transferred to the formation of the crater and its mound, as well as to the damage of the surrounding rocks. Uplifted dolostone blocks on the crater wall. Photo by R. Tiirmaa.

height of several kilometres and, therefore, complete melted spherules (sometimes hollow internally), originating from the impact of crater-producing meteorite, could be distributed over a vast area, and easily during heavy wind.

CALCULATION OF THE HEIGHT OF THE EMITTED GAS FLOW

Crater formation by a hypervelocity impact is a relatively well studied and mathematically modelled process (Melosh 1989). For comparison, data on artificial explosions could be taken. During a meteoritic impact, most of the impactor's kinetic energy is transferred to the target rocks, giving rise to a short pulse of high pressure and to particle motions and ejection (Deutsch & Schärer 1994). According to our calculations, some 60% of the crater forming energy (ca 1.85×10^{11} J) was transferred to the formation of the crater and mound, as well as to the deformation of the surrounding rocks consisting of Upper Silurian dolostones of the Paadla Regional Stage with a thin cover of till of the last, Weichselian glaciation (Raukas & Laigna 2003). According to seismic and electrometric measurements, the area of the shattered rocks surpasses the dimensions of the crater at least twice, covering about 0.1 km^2 (Aaloe et al. 1976).

If considering the main crater as a segment of a sphere with a radius $R = 55$ m and height $h = 18$ m, the volume of the main crater would be $81\,623\text{ m}^3$. The calculated amount of the material ejected from the crater is practically the same, $81\,291\text{ m}^3$. A hypervelocity three-dimensional gas flow ejected from the crater had a high temperature gradient with respect to the surrounding environment. The height of the velocity turbulent flow should be treated according to the equivalent heat transmission theory. Taking the initial parameters of the gas flow as follows: initial temperature 2500–3000 K, initial speed 6–9 km/s, initial density 1.02 kg/m^3 , initial pressure $5.6 \times 10^4\text{ atm}$, initial diameter 4.8 m, and solving the corresponding equation system (Vulis & Yarin 1978), we obtain 6.8–7.9 km for the height of the gas flow. According to our calculations, the temperatures of the gas flow and surrounding air are equal at that height.

The rate of the turbulent flow at a point of the cross-cut may be determined from the equation

$$u/u_m = \sqrt{\frac{\rho_m}{\rho_0}} \cdot \frac{F'(\varphi)}{\varphi}, \quad (1)$$

where the corresponding temperature gradient is

$$\frac{\Delta T}{\Delta T_{0m}} = \frac{\frac{\rho_m}{\rho} + \frac{\kappa-1}{2} M_m^2 \frac{u^2}{u_m^2} - \frac{\rho_m}{\rho_\infty}}{1 + \frac{\kappa-1}{2} M_m^2 - \frac{\rho_m}{\rho_\infty}}. \quad (2)$$

Here u_m is the rate of gas movement and ρ_m gas density on the cross-cut axis of the gas stream under consideration; ρ_0 is initial gas density;

$F'(\varphi) = (u/u_m)_{\rho=\text{const}}$; $\frac{\Delta T}{\Delta T_{0m}} = \frac{\Delta T_m}{(\Delta T_0)_{\rho=\text{const}}} \cdot \left(\frac{\rho_0}{\rho_m}\right)^{1/2}$; ΔT is temperature gradient;

$\kappa = c_p/c_v$ is adiabatic index; c_p , c_v are specific heat of gas with constant pressure and volume; M_m is Mach's number on stream axis; ρ_∞ is gas density outside the gas stream.

In case of gas stream dynamic task the equation of three-dimensional equivalent heat transmission may be expressed as follows:

$$\frac{\partial \rho u^2}{\partial \xi} = \frac{\partial^2 \rho u^2}{\partial \eta^2} + \frac{\partial^2 \rho u^2}{\partial \zeta^2} \quad (\xi = \xi(x), \eta = y, \zeta = z), \quad (3)$$

where the boundary conditions are

$$\rho u^2 = F_0(\mu, \zeta) \text{ if } \xi = 0, \quad \rho u^2 \rightarrow 0 \text{ if } \eta \rightarrow \infty, \quad \xi \rightarrow \infty. \quad (3')$$

Equation (3') is not closed. The maximum height of the gas stream can be found using the sources summation method

$$\frac{\rho u^2}{(\rho u^2)_0} = \frac{1}{4\pi\xi} \int_{-b-c}^{+b+c} \int F_0(y, z) \exp\left[-\frac{(y-\eta)^2 + (z-\zeta)^2}{4\xi}\right] d\eta d\zeta. \quad (4)$$

By giving the initial cross-cut a rectangular shape, Eq. (4) can be expressed in the following way:

$$\frac{\rho u^2}{(\rho u^2)_0} = \frac{1}{4} \left[\operatorname{erf}\left(\frac{y+b}{2\sqrt{\xi}}\right) - \operatorname{erf}\left(\frac{y-b}{2\sqrt{\xi}}\right) \right] \left[\operatorname{erf}\left(\frac{z+c}{2\sqrt{\xi}}\right) - \operatorname{erf}\left(\frac{z-c}{2\sqrt{\xi}}\right) \right], \quad (5)$$

where $\operatorname{erf}(\psi) = \frac{2}{\sqrt{\pi}} \int_0^\psi e^{-t^2} dt = \int_{(y+b)/2\sqrt{\xi}}^{(y+b)/2\sqrt{\xi} + \psi} e^{-t^2} dt$; $\psi = \frac{y \pm b}{2\sqrt{\xi}}$, $\psi = \frac{z \pm c}{2\sqrt{\xi}}$.

The complex $(\rho u^2)_m / (\rho u^2)_0$ can be expressed as

$$\frac{(\rho u^2)_m}{(\rho u^2)_0} = \operatorname{erf}\left(\frac{b}{2\sqrt{\xi}}\right) \operatorname{erf}\left(\frac{c}{2\sqrt{\xi}}\right). \quad (6)$$

Here $\operatorname{erf}(\psi) = \frac{2}{\pi} \int_0^x e^{-t^2} dt$; a, b are sides of the rectangle (in calculations $a = b$).

Analogously to Eqs. (3)–(6), the gas stream temperature task may be presented in the form

$$\frac{\partial}{\partial \xi} (\rho u c_p \Delta T) = \frac{\partial^2}{\partial \eta^2} (\rho u c_p \Delta T) + \frac{\partial^2}{\partial \zeta^2} (\rho u c_p \Delta T). \quad (7)$$

Solving the above equations, we obtained, as mentioned before, 6.8–7.9 km for the gas stream maximum height, if the speed of the meteorite at the moment of the impact was 16 km/s. Falling down from the height of the surroundings, explosion-generated microimpactite matter could have covered a large area, which has been confirmed by our studies (Raukas 2000).

As we do not know the exact velocity and other ballistic parameters of the Kaali meteorite, our results are preliminary. However, the main idea that small glassy particles could be transported over long distances is not debatable.

CONCLUSIONS

The gas streams ejected into the atmosphere as a result of the Kaali impact were three-dimensional turbulent flows. In respect of the surrounding environment, these may be treated as non-isothermal flows with a high temperature gradient. The results of the study of small impact craters and relevant laboratory experiments (e.g. Melosh 1989) allowed us, after mathematical calculations based on published data about impact ballistics of the Kaali group, to conclude that the heated gas stream reached a height of 6.8–7.9 km and the distribution of small (mainly less than 1 mm, Fig. 2) glassy silicate microimpactites over a vast area was a normal process. Based on direct datings, the age of the Kaali impact is undoubtedly older than 3500 years BP and, according to our spherule studies, can be placed to some 7600 years BP. The wall of the main crater is divided into several blocks and intersected with a dense system of cracks resembling typical karst hollows. Therefore, the water table in the newly-formed hollow was seasonally and annually very unstable and bottom sediments started to accumulate in Lake Kaali long after the time of the impact. This means that the real age of the impact can only be determined using indirect dating methods. Investigation of bottom deposits of the lake can give only the minimal age of the impact, which is some 4000 years BP.

ACKNOWLEDGEMENTS

The research was supported by State Target Funding Project 0331759s01. We are grateful to Helle Kukk who typed and made the preliminary linguistic revision of the manuscript, to Reet Tiirmaa and Gennadi Baranov for photos and Rein Vaher for drawing Fig. 1. Our special thanks go to the referees of the paper Wojciech Stankowski and Kalle Suuroja for their valuable comments.

REFERENCES

- Aaloe, A., Dabizha, A., Karnaukh, B. & Starodubtsev, V. 1976. Geophysical investigations of Kaali crater. *Eesti NSV Tead. Akad. Toim. Geol.*, **25**, 58–63 (in Russian).
- Bronshten, V. & Stanyukovich, K. 1963. On the fall of the Kaali meteorite. *Eesti NSV Tead. Akad. Geol. Inst. Uurimused*, **11**, 73–83 (in Russian).
- Czegka, W. & Tiirmaa, R. 1998. Das holozäne Meteoritenkraterfeld von Kaali auf Saaremaa (Ösel), Estland. *Aufschluss (Heidelberg)*, **49**, 233–252.
- Deutsch, A. & Schärer, U. 1994. Dating terrestrial impact events. *Meteoritics*, **29**, 301–322.
- Koval, V. I. 1974. About the mass and composition of the Kaali meteorite. *Astron. Vestnik*, **8**, 169–176 (in Russian).
- Marini, F., Raukas, A. & Tiirmaa, R. 2004. Magnetic fines from the Kaali impact-site (Holocene, Estonia): preliminary SEM investigation. *Geochem. J.*, **38**, 107–120.
- Melosh, H. J. 1989. *Impact Cratering. A Geologic Progress*. Oxford University Press, New York.
- Pokrovski, G. 1963. Computation of the parameters of a meteorite according to the crater caused by its fall. *ENSV Tead. Akad. Geol. Inst. Uurimused*, **11**, 61–71 (in Russian).

- Rasmussen, L. K., Aaby, B. & Gwozdz, R. 2000. The age of the Kaalijärv meteorite craters. *Meteor. & Planet. Sci.*, **35**, 1067–1071.
- Raukas, A. 1997. An attempt to use microimpactites in establishing the age of impact events on the example of the Kaali crater field (Estonia). *Sphaerula*, **1**, 32–41.
- Raukas, A. 2000. Investigation of impact spherules – a new promising method for the correlation of Quaternary deposits. *Quat. Intern.*, **68–71**, 241–242.
- Raukas, A. & Laigna, K.-O. 2003. Kaali meteoriidiplahvatuse purustusjäädust. In *Eesti geoloogide neljas ülemaailmne kokkutulek. Eesti geoloogid uue sajandi künnisel. Konverentsi materjalid ja ekskursioonijuhud* (Plado, J. & Puura, I., eds.), pp. 74–76. Eesti Geoloogia Selts, Tartu Ülikooli geoloogia instituut, Tartu.
- Raukas, A., Pirrus, R., Rajamäe, R. & Tiirmaa, R. 1995. On the age of the meteorite craters at Kaali (Saaremaa Island, Estonia). *Proc. Estonian Acad. Sci. Geol.*, **44**, 177–183.
- Raukas, A., Laigna, K. & Moora, T. 2003. Olematu looduskatastroof Saaremaal 800–400 aastat enne Kristust. *Eesti Loodus*, **1**, 12–15.
- Saarse, L., Rajamäe, R., Heinsalu, A. & Vassiljev, J. 1992. The biostratigraphy of sediments deposited in the Lake Kaali meteorite impact structure, Saaremaa Island, Estonia. *Bull. Geol. Soc. Finland*, **63**, 129–139.
- Veski, S., Heinsalu, A., Kirsimäe, K., Poska, A. & Saarse, L. 2001. Ecological catastrophe in connection with the impact of the Kaali meteorite about 800–400 B.C. on Saaremaa Island, Estonia. *Meteor. & Planet. Sci.*, **36**, 1367–1375.
- Veski, S., Heinsalu, A., Lang, V., Kestlane, Ü. & Possnert, G. 2004. The age of the Kaali meteorite craters and the effect of the impact on the environment and man: evidence from inside the Kaali craters, island of Saaremaa, Estonia. *Veget. Hist. Archaeobot.*, **13**, 197–206.
- Vulis, L. A. & Yarin, L. P. 1978. *Aerodynamika fakelya*. Energiya, Leningrad (in Russian).

Turbulentse gaasijoa kõrgusarvutus ja klaasjate sfäärulite kandumiskaugus Kaali meteoriidiplahvatuse näitel

Anto Raukas ja Kustav-Olimar Laigna

Osa Kaali meteoriidi plahvatusenergiast kulus kraatrisüvendi ja kraatrivalli kujundamiseks, osa (ligikaudu 40%) suundus üleheliikiirusega gaasijoana vertikaalselt üles. Sellel kolmemõõtmelisel turbulentsel gaasijoal oli ümbritseva keskkonna suhtes kõrge temperatuurigradient. Lugesed joa algtemperatuuriks 2500–3000 K, algkiiruseks 6–9 km/s, algtiheduseks 1,02 kg/m³, algrõhuks 5,6 × 10⁴ atm ja algsuuremõõtriiks 4,8 m ning lahendades vastava võrrandisüsteemi, saame kuuma joa õhkupaiskumise kõrguseks 6,8–7,9 km. Sellel kõrgusel omandas juga välisõhu temperatuuri. Juga kandis atmosfääri rohkesti kõrgel temperatuuril klaasjaks sulanud peent mikroimpaktiitset materjali, mis hajus väga ulatuslikul alal, kandudes näiteks Hiiumaalegi (joon 1). Saaremaa ja Hiiumaa sfääruleid sisaldavate soosetete vanuseks on ligikaudu 7600 aastat, mis on ka Kaali kraatrite kõige tõenäolisemaks vanuseks. Otseste kraatriuringutega ei ole plahvatuse aega võimalik täpselt määrata. Sel teel saadud kraatrite vanuseks on vähemalt 4000 aastat.