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Dating the Morasko meteorite fall by natural thermoluminescence of the fusion crust

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Abstract

The date of fall of the Morasko iron meteorite was determined by means of thermoluminescence measurements of the fusion crust and related local materials. Three small pieces, commonly referred to as 'shrapnel', were used. The results obtained are 4.5–5.0 ka, which is in good agreement with previous estimates of 4–6 ka on the basis of radiometric, dosimetric and palynological methods.

Keywords: iron meteorite, terrestrial age, dosimetry, Poland

1. Introduction

The high surface temperature of a meteor that passes through the Earth's atmosphere produces varied superficial ablative niches and a thin fusion/melt zone, or film. In stony meteorites real luminescence resetting is affected, while in metallic ones only the status of the matter is changed. When iron meteorites fall onto mineral substrates, there is zonal variety of thermal effects around the meteorite. That lead to the formation the extremely thin fusion layer and also the spatially limited "encapsulation" of the fused/molten matter of the encountered meteorite mineral grains. A very thin "semi-fused unit"/"semi-melt" is formed, enabling luminescent dating on account of the presence of mineral grains. The outer, different in size sinter layer is created. Weathering processes occur later and lead to some changes in these two crusts. Most small meteorites recovered (usually "shrapnel" of larger-sized extraterrestrial bodies) possess two types of crusts: (1) a fusion-weathering crust, covering the external surface of the initial meteorite interior, and (2) a sinter-weathering crust, consisting of sediments or rocks onto which the meteorite fell. In material thus defined, obtained from small meteorites collected in the northeasternmost part of the Morasko Meteorite Nature Reserve, dating was performed by thermoluminescence (TL). This is the main scope of research into the Morasko meteorite shower, leading to addition of new data that are complementary to previous studies. The dating of the meteoritic material was verified by comparison with data from mineral deposits in the immediate vicinity of the meteorite. Additionally, TL data of sinter-weathering crust that covered great meteorites obtained earlier were included as comparative data. The age of ~5,000 years BP thus obtained confirms previous similar findings with regard to the time of the main (primary) Morasko impact. It should be added that during the last 5,000 years another, younger (~2,000 BP) meteorite fall appears probable in the Morasko area (see Stankowski, 2009). However, possibility that the second meteorite impact could occur in the some place on the Earth, seems to be almost exceptional.

Studies of the Morasko meteorite shower (Morasko Meteorite Nature Reserve, Poland, and its surroundings; see Fig. 1) have yielded a significant amount of data on the mineralogy, geochemistry and timing of this cosmic event, as well as on geoenvironmental issues (Hurnik, 1976; Stankowski, 2009, 2011; Stankowski et al., 2007; Stankowski & Bluszcz, 2012; Dworzyńska & Muszyński, 2010; Muszyński et al., 2012). The fundamental piece of evidence for this impact (countering views that the Morasko meteorites had been brought by an ice sheet/ice sheets, as erratics), was the 2011 discovery of a meteorite lump of ~34 kg at a depth of ~160 cm. It was found in glaciotectonically disturbed Neogene sediments of the “Poznań Series”, which are present just beneath the present-day surface (data on this find: Meteorite Men, episode 302 ‘Morasko Poland’, Science Channel, 2011). The object penetrated the thin, superficial layer of Quaternary sediments, which explains the presence of fragments of granitic material found in the leading part of the meteorite. The relevant lithological characteristics of the impact site are documented in the form of mineralogical data (see Karwowski et al., 2011).

Amongst the smaller meteorites found at Morasko, the 970-g specimen, has the best-developed crust with two units (well seen under petrographic microscope and supported by SEM/ESD analyses): fusion/melt/’semi-melt’ layer and sinter layer (see Figs 2, 3).

A similar structure of meteorite crust development was recognised and TL dating carried out on the 62-g, 70-g and 1201-g specimens. In the case of the 70-g meteorite “shrapnel”, the surrounding ma-

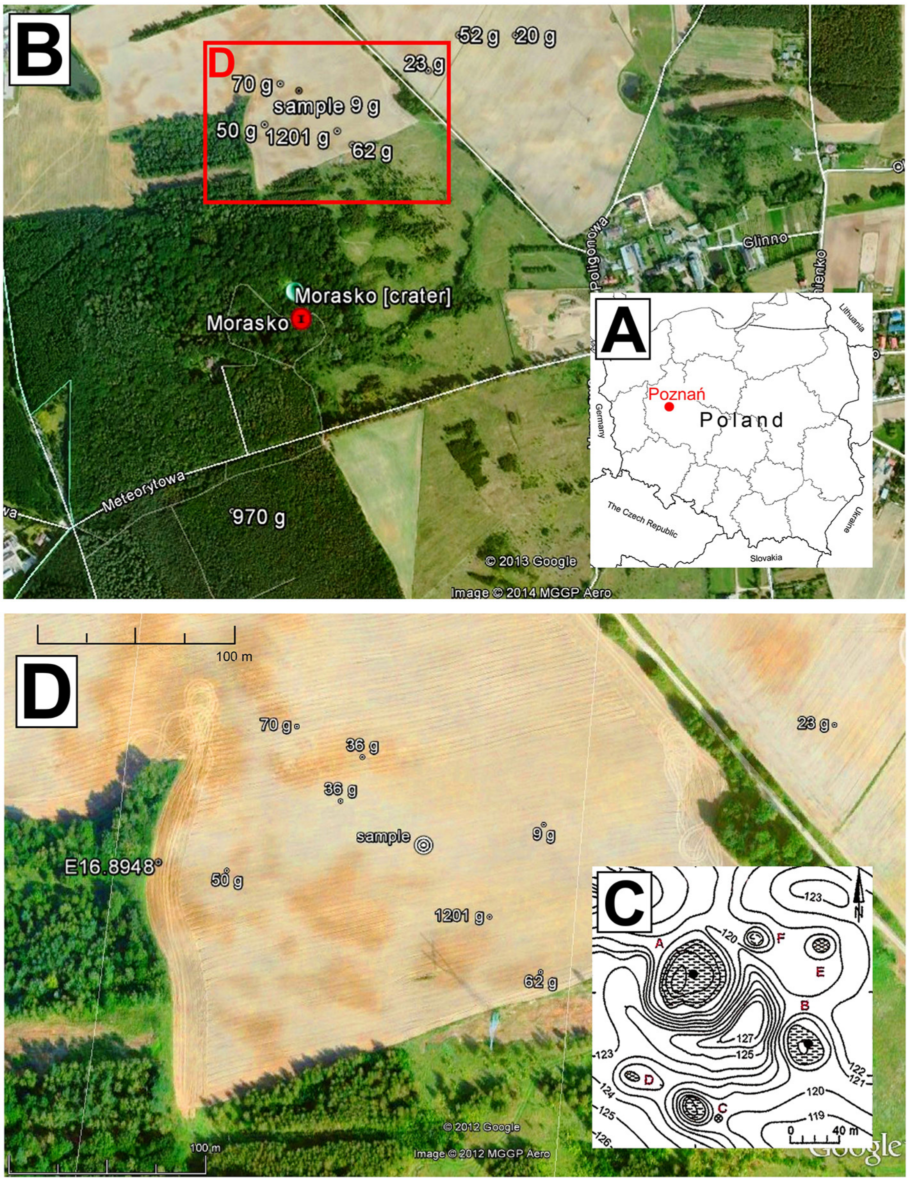

Fig. 1.A – Location of the site studied; **B –** Position of meteorite finds (about 500 m north of the largest crater); the signature ‘sample’ indicates the location of the ~70 g meteorite, found at a depth of ~30 cm (co-ordinates N 52º29.60’, E 16º53.84’) from which the sample for luminescence dating was obtained, from a thin fusion crust. The newest meteorite, of 970 g, examined was found about 400 m to the south-southwest of the largest crater (co-ordinates N 52º29.42’, E 16º53.80’); **C –** Topography of the Morasko Meteorite Reserve, A-F – meteorite craters, a 7.5-kg meteorite was found near crater C; a 164-kg meteorite was recovered from the top of the hill between craters A, B and C in 2006; a 261-kg meteorite was collected from ~300 m to the southwest of the top of the hill in 2012; **D –** Enlarged area of meteorite finds.

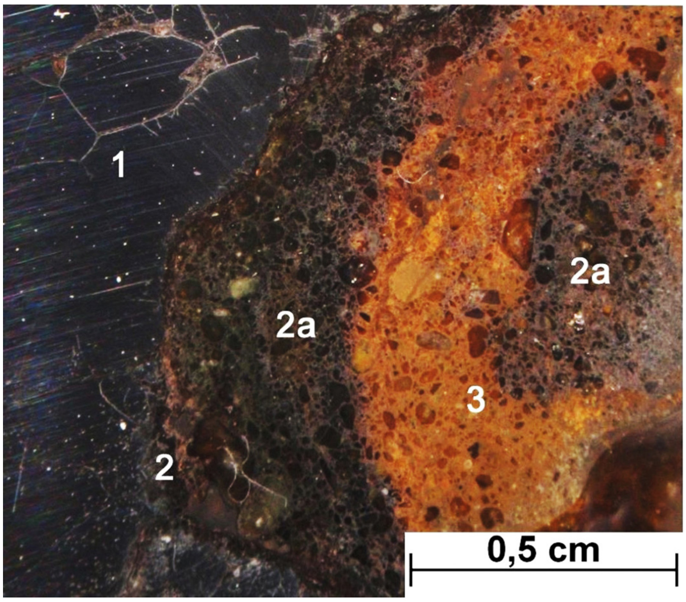

Fig. 2. The 970-g meteorite found in 2014 by M. Szyszko, with fusion/molten and sintered coating. 1 – iron-nickel alloy; 2 – remainder of fusion/molten area; 2a – zone and packs of interaction – fusion/molten matter of meteorite ('matrix') and material of the place of impact (grains) = 'semi-fusion'/'semi-molten' layer; 3 – sinter/sintered layer.

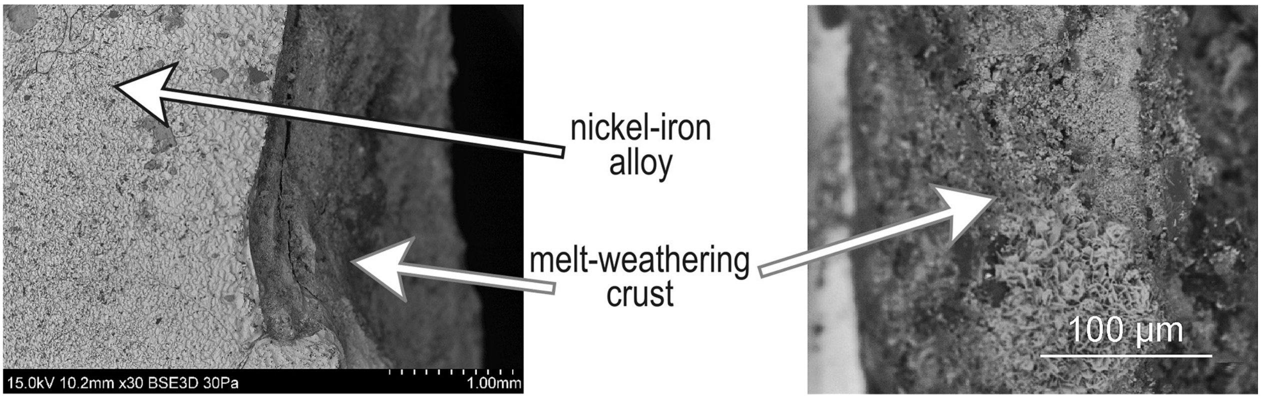

Fig. 3. Part of the interior and true melt/molten crust and 'semi-molten' part with mineral grains of the 62-g meteorite. The chemical analyses (mean semi-quantitative wt. percentage data in oxides for 26 measurements) run for both parts: a) nickel-iron alloy: Fe_3O_4 = 92.6; NiO = 6.8; others = trace only, b) melt crust/'matrix': Fe_3O_4 = 81.3; NiO = 4.5; MgO = 2.7; SiO_2 = 2.4; Al_2O_3 = 1.8; others ~7, grains: Fe_3O_4 = 12.6; NiO = trace; SiO_2 = 75.4; Al_2O_3 = 7.8; others ~4.

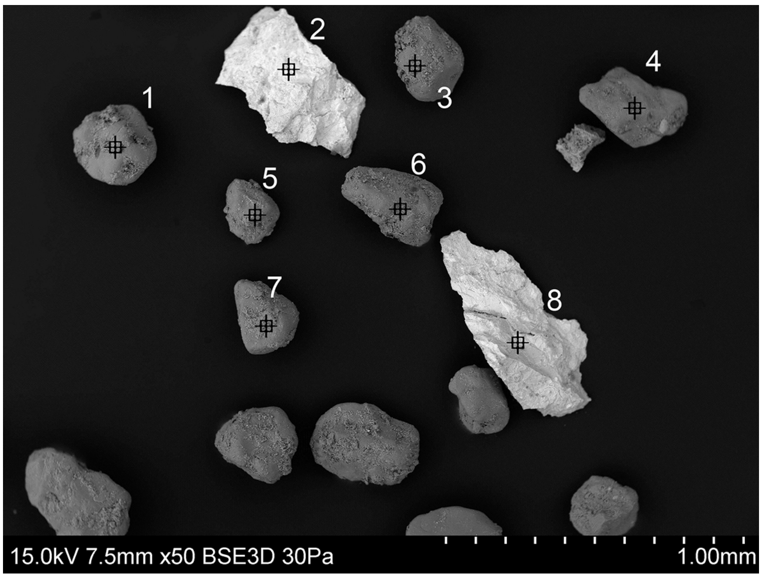

Fig. 4. Grains analysed from sediments surrounding the 70-g meteorite; exemplary group of grains; the white colour are iron ones.

Table 1. Chemical composition of grains from above (depth: 25 cm) and below (depth: 30 cm) the 70-g meteorite – mean wt. percentage data in oxides. Some grains have a composition that is characteristic of nickel-iron meteorites (nos. 2 and 8 in Fig. 4).

Grains/measurements	Al_2O_3	SiO_2	TiO_2	Fe_3O_4	NiO	Cu_2O
ironic (4 measur.)	0.8 (0.5–0.9)	1.6 (1.0–2.4)	trace	90.1 (86.6–91.2	6.6 (4.9–7.1)	
others: a (5 measur.)	4.5 (2.7–5.6)	15.8 (7.0–20.5)	trace	78.6 (69.1–87.5	0.6 (0.1–1.5)	
b (7 measur.)	8.2 (1.4–18.2)	75.4 (52.5–93.2)	0.3	15.2 (2.4–25.6)	0.2 (0.0–1.5)	
c (9 measur.)	81.2 (71.0–89.6)	1.2 (0.0–10.5)		5.1 (0.0–14.6)		12.1 (0.0–15.6)

terial was analysed using SEM and ESD techniques, and TL dating performed (see Fig. 4; Table 1).

The chemical composition of crusts covering the metallic Morasko meteorites reveals opportunities for TL dating of the time of zeroing luminescence. These data seem to be real time indicators of the impact event.

2. Luminescence (TL) dating, procedures and sample preparation

In order to determine the luminescence age of the sediment under study, it is important to determine the equivalent dose (d_e) and the annual dose (d_r). The former can be determined with a luminescence reader, while the latter dose (dose rate) can be assessed by different methods. Usually, it is determined by gamma spectroscopy and ormass spectrometry (ICP-MS).

Before starting luminescence measurements, the activity of natural radionuclides (^{238}U and ^{232}Th series and ^{40}K) in the material to be TL dated was measured in order to determine the annual dose. Simultaneously, an artificial isotope ^{137}Cs in samples was calculated. This was done with a semi-conductor gamma spectrometer equipped with a coaxialH-PGe detector with a relative efficiency of 35 per cent at energy 1330 keV manufactured Canberra. Before measuring radioactivity, the samples were dried and placed in measurement containers for about four weeks in order to achieve equilibrium between ^{226}Ra and its daughter ^{222}Rn. The counting time was typically about two days.

The standards, RGU–1, RGTh–1 and RGK–1 (provided by the IAEA), were used to calibrate the germanium detector in case of analytical activities of ^{238}U and ^{232}Th series and ^{40}K in samples; for calculation of activity of ^{137}Cs in a sample the standard Soil–375, also provided by IAEA, was used. The values thus obtained were subsequently converted to a dose rate (Adamiec & Aitken, 1998).

For the sequence of ^{238}U, the activity calculations were performed on the basis of the following lines of gamma radiation: 295.1 keV ^{214}Pb, 352.0 keV ^{214}Pb, 609.3keV ^{214}Bi and 1120.3 keV ^{214}Bi, whereas analyses for the sequence of ^{232}Th were based on the lines 583.0 keV ^{208}Tl, 911.2 keV ^{228}Ac and 2614.4 keV ^{208}Tl . For ^{40}K, the computations were performed on the basis of the energy line of 1460.8 keV and for ^{137}Cs the calculation was done as based on the line 661.7 keV. ^{137}Cs is an artificial isotope which is liberated into the atmosphere as a result of nuclear weapon tests and the Chernobyl nuclear disaster. Following deposition on the Earth's surface this is rapidly and intensey absorbed by soil particles. The maximum fall out was in the mid–1960s and, in the case of Polish territory, high deposition occurred in 1986 following the Chernobyl accident.

In addition to data on the radioactivity of a sample, it is also necessary to determine the contribution of cosmic rays in the annual radiation dose. The space component of the annual dose was determined by using the equation proposed by Prescott& Hutton (1994). The resultant annual dose (Adamiec & Aitken, 1998) also includes a correction for humidity, as described by Aitken (1985). In the present study, a humidity of 10 per cent was assumed. For further calculations, a mean value of 10±5 per cent was used. Results of the measurement of the activity and dose rate for the Morasko samples are listed in Table 2.

The TL dating was done on two types of material: three samples of the meteorite crusts and two samples of the sandy material surrounding the 70-g meteorite. To do so, samples were subjected to different preparation methods for the measurement of the equivalent dose in luminescence dating. The measurement of the equivalent dose for both materials was performed by using the standard multiple-aliquot regenerative thermoluminescence method. The material from the melt crust of the meteorite

Table 2. Results of measurements of radioactivity and calculated annual and equivalent doses and TL age of samples from melt-crusts of the 70-g, 1201-g and 62-g meteorite and the comparative meteorites, as well as material surrounding the 70-g meteorite from Morasko (dose rate determined by G. Poręba, Institute of Physics, Silesian Technical University).

Sample		No lab.	^{40}K [Bq/kg]	^{238}U [Bq/kg]	^{232}Th [Bq/kg]	Dose rate d_r [Gy/ ka]	Equivalent dose d_e [Gy]	TL age [ka]
Fusion/ melt-crusts of meteorites	70 g	6603	109.6±8.9	10.3±0.8	7.9±0.6	0.75±0.08	3.5±0.4	4.7±0.7
	1201 g	6682	126.2±10.5	20.7±1.3	8.6±1.7	0.91±0.09	4.5±0.6	4.9±0.9
	62 g	6683	92.7±11.2	40.5±2.4	8.0±1.8	1.17±0.10	5.4±1.0	4.6±0.8
Material surrounding 70-g meteorite	top sample (depth ~25 cm)	6604	404.0±10.6	16.1±1.2	17.1±1.2	1.85±0.10	10.0±1.0	5.4±0.8
	basal sample (depth ~30 cm)	6605	375.5±9.9	13.1±1.2	17.1±1.2	1.80±0.10	9.9±1.0	5.5±0.8

was crushed in a hand mortar. After grinding, the particle size was below 40 μm. This material was rinsed in distilled water and dried. After this treatment the equivalent dose (d_e) was measured with the multiple-aliquot regenerative technique (Wintle & Prószyńska, 1983). The sandy material from the surrounding area underwent a slightly different pre-treatment and luminescence procedure. In this case the equivalent dose (d_e) was determined for quartz grains in the size range of 80–100 μm; the multiple-aliquot regenerative technique was applied here as well. In this case, the separated grains were treated with 10% HCl for two hours, then for the same time with 2% NaOH and subsequently with 40% HF for 45 minutes (Bluszcz, 2000; Fedorowicz, 2006). After each of these steps, the samples were rinsed several times with distilled water.

After the initial preparation, both material types were divided into two parts. The first one, left in its original state, was used to measure natural thermoluminescence (NTL). The remaining, larger part was optically bleached for up to 12 hours by exposure to UV light simulating sunlight. For this purpose, an Osram Ultra-Vitalux 300 W lamp was used. The bleached material was divided into five equal portions. The first one was used to measure the residual thermoluminescence, while the four remaining parts were irradiated with cobalt that would regenerate the previously acquired energy. The bleached parts were irradiated with cobalt radiation of 10, 20, 30 and 50 Gy, respectively. In addition, doses of 10 and 20 Gy were used to irradiate the previously non-bleached portions, of which the material was used for measuring natural thermoluminescence.

The equivalent dose (*De*) was measured with a reader/analyser, model RA'94 equipped with a filter BG–28 (360–510 nm). Samples of 5 mg were heated in an argon atmosphere up to 400°C with a heating rate of 8°/s.

TL curves of meteorite samples usually have two maxima, the first of about 240° C, the second about 320° C. The method of bleaching was experimentally examined. The temperature bleaching caused a decrease in the height of the peaks mentioned to the level of 2–3 per cent of maximum NTL, whereas optical bleaching caused a decrease to 3–4 per cent. In further research the optical bleaching and TL glow curve were used in the performed analysis. The sensitivity of the test samples was checked and a plateau test was performed in the temperature range of 180 to 280°C. The plateau for this temperature range was linear. An example of TL glow curves is shown in Fig. 5.

3. Dating results

Instrumental analysis was carried out for the fusion/melt-crust material of the ~70-meteorite and two comparative samples weighing ~62 g and 1201 g (Table 2; Fig. 5). Material surrounding the 70-g meteorite was also analysed (see Table 2; Fig. 6); it shows a slightly smaller resetting.

The TL dates of the fusion/melt-weathering crusts turned out to be very similar. However, in terms of elements responsible for the annual doses and the annual dose (d_r) itself, the meteorite matter shows striking differences. Concentrations of uranium, thorium and potassium differ in the meteorite material. The estimated radioactivity in the meteorite does not include the contribution of cosmogonic nuclide. This may indicate that the samples analysed do not come from a single meteorite (but perhaps from a shower of meteorites, or possibly not from a single event(?), if it really existed), or that the Morasko meteor, exploding in the air, was charac-

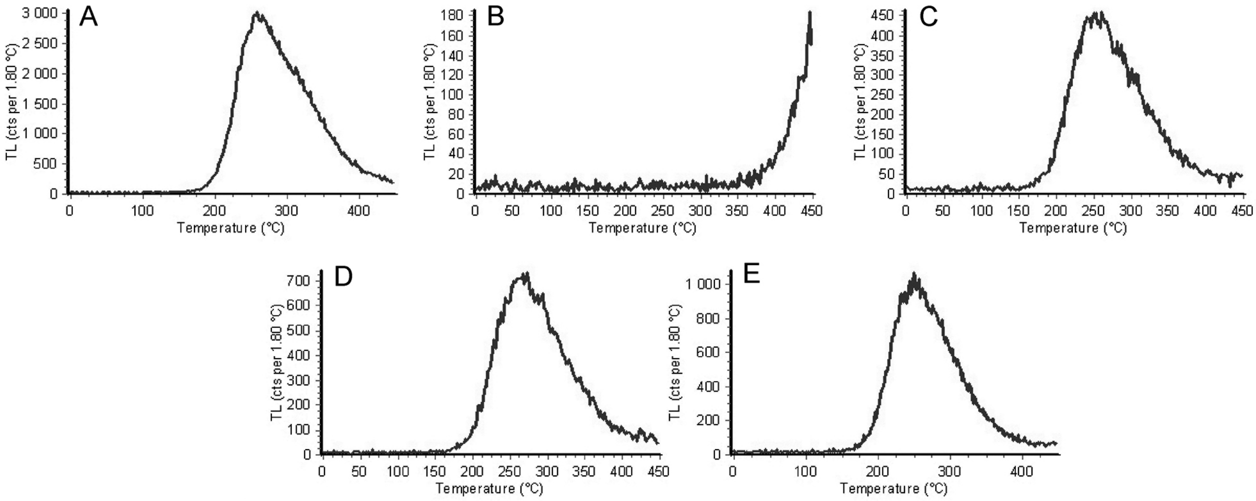

Fig. 5. Example of a TL glow curve measured for sample UG–6683. The material portions of 15 mg were heated at a speed of 3^{0}C/s in RISO TL/OSL READER MODEL DA–20 with a U340 200–350 nm filter. The measurements of single portions were done by K. Standzikowski at the Laboratory of Geoecology and Palaeography Department of the Maria Curie-Skłodowska University at Lublin.

A – Intensity natural TL (NTL); **B –** intensity residual TL (RTL) – preheated for 30 min at 400^{0} C; **C –** intensity RTL+0,9 Gy (beta irradiations were performed in the range 0.9 Gy); **D –** intensity RTL+1.3 Gy (beta irradiations were performed in the range 1.3 Gy); **E –** intensity RTL+1.9 Gy (beta irradiations were performed in the range 1.9 Gy).

terised by a diverse structure. It is confirmed by the outcome of mineralogical studies of the meteorite found in 2011 (Karwowski et al., 2011).

The resetting age of the studied fusion/melt-weathering crusts, ranging between 4.6 and 4.9 ka, is burdened with a considerable measurement error for the interval from ~14 up to even ~19 per cent. However, the dates, oscillating around ~5 ka, are within results previously obtained with regard to the time of the Morasko impact. This holds for (1) the luminescent age of the sinter-weathering crusts, (2) the reset time of the mineral material from the crater floors, and (3) the radiocarbon dating of organic matter filling the craters (Stankowski, 2001, 2009, 2011; Stankowski & Bluszcz, 2012; Stankowski et al., 2007; Stankowski & Muszyński, 2008).

The TL dates for the two samples of material from depths of ~25 cm and ~30 cm, just above and below the meteorite samples (~70 g) seem to be slightly younger than TL dates for the meteorite sample, but the statistical test does not confirm this. The sediment samples have similar concentrations of uranium, thorium and potassium. The calculated annual doses (*Dr*) are almost identical, which confirms the homogeneity of the material. Thus it can be deduced that the analysed grains of both samples underwent the same resetting of energy stored in them or an identical decrease in their energy when they came into contact with the hot meteorite. The TL age of about 5.5 ka of both samples, slightly older than the dates of the melt-weathering crusts, might indicate that the resetting of the luminescence signal in those grains was not completed during the impact. It must be noted, however, that the basic dates of both types of material fall within the limits of measurement errors (see Table 2; Fig. 6), so that they should statistically be considered as having occurred simultaneously.

The size of energy accumulated in the grains is identified with the value of equivalent dose (Table 2). This value is small, between 3.5 and 5.4 Gy. It was acquired within 4.6 to 4.9 ka. It is unclear if

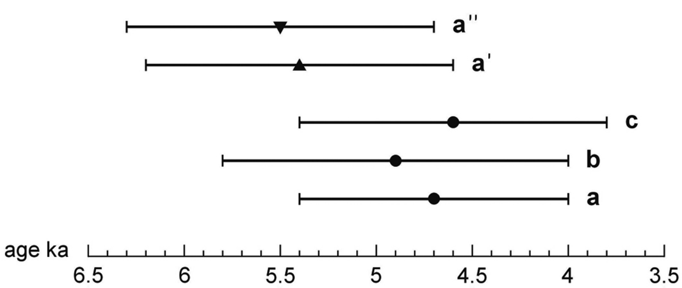

Fig. 6. Plot of TL dates of the fusion/melt-weathering crusts of the meteorites studied and the mineral deposits above and below the 70-g meteorite.

a –70-g meteorite; b –1201-g meteorite; c – 62-g meteorite. Sediment samples from near the 70-g meteorite: a′ – sample from a depth of ~25 cm; a′′ – sample from a depth of ~30 cm.

there was a total reset of the accumulated energy during the fall of the meteorite, but this is highly probable because the temperature of a meteorite that falls onto the Earth must have been high, and this was passed to the surroundings in a short time span, reducing the energy in the sediment grains that surrounded the meteorite. It is well known that the high temperature (several hundred degrees Celsius), during burning of clay pots, completely whitens the heated material.

With the exception of some differences in the basic dates, results of luminescence dating correspond well with the state of current knowledge of the Morasko impact. They confirm the impact of the meteorite at about 5,000 years BP.

During luminescence measurement, the presence of the nuclide ^{137}Cs (in existence only since the mid-twentieth century when this nuclide formed after detonation of atomic bombs) was documented in a number of samples. This begs the question of whether this reflects a progressive process of cesium absorption in the meteorite crusts still lodged in sediments, or that it rather illustrates specific contamination of the crusts, during or after the cleaning of the meteorites, for instance during laboratory work. The ^{137}Cs was measured by a semi-conductor gamma spectrometer simultaneously with measurements of natural isotopes of U, Th and K in these samples. As mentioned above, for calibration reference material provided by IAEA (Soil–375) was used, and cesium was calculated based on gamma line at energy 661.7 keV.

4. Conclusions

The dating of the luminescence resetting time in the outer zones of small-sized meteorites (i.e., less rich fusion/melt zones which were subjected to weathering changes following impact) demonstrates that it is possible to document impact events not only by studying large specimens (i.e., our earlier data obtained for 10–164 kg meteorites), but that also analyses of small shards of extraterrestrial material may do so. The results fit well and confirm numerous earlier datings of the Morasko meteorite impact, which took place ~5,000 years BP. The TL measurements obtained of the resetting time of superficial portions of large and small objects, confirm the second author's idea about possibilities of proving impact events of stony and metallic meteorites.

In the present paper, any reference to a potential, much younger, fall of meteorites at Morasko has been omitted due to a lack of material for verification of this hypothesis.

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