EXPERIMENTAL STUDY OF ABRASION OF TEKTITES AND OTHER GLASSES IN THE COURSE OF FLUVIAL TRANSPORT OVER LONG DISTANCES. M. Hurtig, Dipl.-Min. (lausitzer.moldavite@gmx.de)

Introduction: Tektites and other natural glasses, such as obsidian, have been subject to destructive corrosion and redeposition processes since their formation. Although the tektites in particular are considered to be chemically highly durable [1], opinions about their mechanical resistance differ widely. Some authors argue that moldavites, as representatives of tektites, can only be transported by rivers for a few tens of kilometers before complete abrasion [2, 3, 4]. Contrary is the assumption that Lusatian moldavites derived from South Bohemia by river transport and thus have survived fluvial transport distances of several hundred kilometers [5]. Under natural conditions, the abrasion of tektites and other materials can not be observed or with considerable effort only. However, it is known that sediments in rivers are transported shoving-sliding, rolling, jumping (bed load) or floating (suspended load) [6]. The moldavite-bearing sediments of the ancient Elbe River in Lusatia show a dominance of the bed load in a braided river system [7, 8]. Based on new experiments, the abrasion of different tektites, obsidians, artificial glasses and minerals was analyzed.

Methodology: Since previous experiments on tektites are considered to be far from reality [3, 4], a suitable and easy feasible method was sought to simulate sediment transport in a river. A concrete mixer ATIKA Rapid, type RA, year of manufacture 1995, capacity 140 l, drum n = 28 rpm ($C_{in.}$ = 188.5 cm; r = 30 cm) was used. It was filled with 25 l sand-gravel-mixture (taken from the in-situ gravel body in the open pit gravel mine "Laußnitz I" near Ottendorf-Okrilla; biggest gravels: 71.9x30.3x19.4 and 56.6x41.3x40.4 mm) plus 10 l water. The samples were added (2 Lusatian moldavites, 4 South Bohemian moldavites, 6 indochinites, 2 australites, 5 sharp-edged obsidians, 2 tumbled obsidians, 4 artificial glasses and 7 recognizable mineral pebbles). In advance they were photographed, measured, weighed and described by some characteristics (Tab. 1; Fig. 1 top). Still at non-operating state of the mixer the water-saturated sediment package showed a maximum height of 22 cm covered by a water column of 3 cm. During operation, the sediment body was compressed ($h_{Sed.}$ = 20 cm; water column = 5 cm). The inner drum radius above the sediment was thus approx. 10 cm. A one-hour test run was implemented on July 11, 2018. In the period from July 12 to July 15, 2018 the filled mixer was put into operation for further 46 h 35 min. This was followed by the final examination of the samples (Tab. 1; Fig. 1 bottom). The transport distances of the sediment and therefore also of the samples were calculated approx. by multiplying the operating time by the inner circumference of the drum at the base ($C_B = C_{in.}$ = 188.5 cm) and at the top of the sediment package (C_T = 60.8 cm), respectively. After one hour operating time, the sediment covered a distance of about 1.021 km (top) to 3.167 km (base) and an average of about 2.111 km (middle of sediment package). For the entire duration of the experiment (47 h 35 min), the average transport distance was about 100.5 km (top: 48.6 km; base: 150.7 km).

Results: After an operating time of one hour ($d_{av.1h}$ ~ 2.1 km) only 3 out of 14 tektites showed a very low mass loss (ML ~ 0.2–0.4 %). All sharp-edged obsidians showed slightly higher ML (0.3–0.6 %). With the tumbled obsidians, however, a nominal ML (0.1 %) could only be detected in 1 out of 2 samples. A larger range was provided by the artificial glasses (0.2–2.0 %). In the case of mineral pebbles, no ML could be measured. Quite the opposite, an agate and the feldspar were heavier than before the experiment (due to water storage and weight measurements being taken prior to sufficient drying). After 47 h 35 min ($d_{av.47.5h}$ ~ 100.5 km) all samples showed ML. The range of the abrasion-induced ML for the 14 tektites was between 1.7 and 4.1 % (+ fragmentation up to 4.3 %; $ML_{av.Tek.Abr.}$ ~ 2.3 %; $ML_{av.Tek.Abr.+Fra.}$ ~ 2.4 %). The values of the 7 obsidians ranged from 1.6 to 6.3 % (+ fragmentation up to 31.3 %; $ML_{av.Obs.Abr.}$ ~ 3.7 %; $ML_{av.Obs.Abr.+Fra.}$ ~ 7.5 %). Those of the artificial glasses varied from 3.7 to 9.3 % (+ fragmentation up to 39.6 %; $ML_{av.Gla.Abr.}$ ~ 6.4 %; $ML_{av.Gla.Abr.+Fra.}$ ~ 14.7 %) and those of the mineral pebbles from 1.4 to 1.7 % ($ML_{av.Qtz.Abr.}$ ~ 1.5 %) for the 3 quartz samples and from 0.3 to 1.1 % ($ML_{av.A./F.Abr.}$ ~ 0.6 %) for the agate/flint specimens. The abrasion in general (independent of the material) was particularly intense on sharp-edged, freshly broken or clearly sculptured samples. The feldspar was subject to stronger fragmentation and could not be identified without any doubt after the experiment.

Discussion & Conclusion: The experimentally determined mass losses due to abrasion are in the lowest range of the expected values, which can be calculated on the basis of Sternberg's law ($M_x = M_0 \cdot e^{-cx}$) [9]. M_0 and M_x correspond to the mass of a pebble at a zero point and after x km of river transport. The material-dependent abrasion coefficient c is given in the corresponding literature for various minerals and rocks. Due to different conditions, however, the values vary widely, e. g. for the group quartz, quartzite and chert (0.0001–0.1 km^{-1}) [10, 11, 12]. At a concrete c-value of 0.0033 km^{-1} given for quartz [13], the ML would amount to ~ 28.2 % (18.8 times the experimental value) for the transport distance of 100.5 km. Based on the experimentally determined ML ($ML_{av.Tek.Abr.}$ ~ 2.3 %; $ML_{av.Qtz.Abr.}$ ~ 1.5 %) a corresponding c-value for tektites can be calculated ($c_{Tek.} = c_{Qtz.} \cdot 2.3/1.5$ ~ 0.0051 km^{-1}). If the ML is negligible due to fragmentation, it would be ~ 40 % with respect to abrasion for tektites after a transport distance of 100 km. This contrasts greatly to the experimental values. The reason for the deviations is that c is not only material-dependent, but is also influenced by the type and velocity of transport and by the properties of the transport medium and the river itself. A general abrasion rate of 0.001 km^{-1} was determined for the Elbe River, which can be *"regarded as relatively safe"* (translated from the German original *"als relativ sicher angesehen werden"*) [14, p. 59]. For the assumption that $c_{Elbe} = c_{Qtz.Elbe}$, and considering the experimental values, $ML_{av.Tek.Abr.Elbe}$ for tektites after being transported 10 km in the Elbe River ($c_{Tek.Elbe}$ = 0.00153 km^{-1}) is ~ 1.5 % (50 km: 7.4 %; 100 km: 14.2 %; 200 km: 26.4 %; 300 km: 36.8 %; 400 km: 45.8 %; 500 km: 53.5 %). These values are compatible with the terrain observations for Lusatian moldavites and their find layers. The transport distances covered from South Bohemia (Týn n. V. / Písek area) to Ottendorf-Okrilla and Calau amount to about 400–500 km. The average mass of moldavites at the northern edge of the South Bohemian moldavite substrewn field is between 7 and 10 g, that of the Lusatian moldavites is ~ 4.1 g [5]. Also the heaviest Lusatian moldavite from Ottendorf-Okrilla (m = 73.81 g) can be easily derived from South Bohemia, assuming $ML_{av.Tek.Abr.Elbe}$ ~ 45.8 % for a distance of 400 km (M_0 ~ 136.2 g). According to the Hjulström diagram, the flow velocity of the ancient Elbe River, which the moldavite-bearing sediments deposited in Lusatia, must have been at least 1 m/s [8, 15]. In the experiment, the device-related transport velocity of ~ 0.59 m/s was too low. This could be a reason for the insufficient ML. But in conclusion it can be said that tektites and other glasses can survive several hundred kilometers of river transport, whereby obsidian (usually) and artificial glasses are more strongly abraded (or also fragmented).

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References: [1] Barkatt A. et al. (1984) *Chem. et Cosm. Acta, 48(2),* 361–371. [2] Žák K. (2009) *Bull. min.-petr. odd. Národ. Muz. Praze 17(1),* 79–90. [3] Brachaniec T. (2017) *Met. & Plan. Sc. 53(3),* 505–513. [4] Brachaniec T. (2018) *Carn. Geol. 18(10),* 225–232. [5] Hurtig M. (2017) *Mold. – Veröff. Mus. Westl. Sonderh.*, Kamenz, 234 p. [6] Prothero D. R. and Schwab F. (1996) *Sed. Geol.*, New York, 575 p. [7] Lange J.-M. (1995) *L. Mold. – Schriftenr. Geow. 3,* Berlin, 134 p. [8] Lange J.-M. et al. (2015) *Jber. Mitt. oberrhein. geol. Verl., N.F. 97,* 301–320. [9] Bendel, L. (1944) *Ing.geol. I,* Wien, 832 p. [10] Malcherek, A. (2007) *Sedimenttr. u. Morphodyn.*, München, 184 p. [11] Kodama, Y. (1994) *Jour. Sed. Res. A64,* 76–85. [12] Chatanantavet, P. et al. (2007) in Dohmen-Janssen C. M. and Hulscher S. J. M. H. (eds.) *RCEM 2007,* 571–579 [13] Redlich, K. A. et al. (1929) *Ing.geol.*, Wien Berlin, 721 p. [14] Author collective bfG (2014) *KLIWAS Schriftenr. 67,* Koblenz, 100 p. [15] Genske, D. D. (2014) *Ing.geol., 2. ed.,* Berlin, 613 p.

No.	Name	Area (Location)	Additional Details	Dimensions (mm)	Mass (g)	Mass (g) after 1 h (av. 2.1 km)	Dimensions (mm) after 47.5 h (av. 100.5 km)	Mass (g) after 47.5 h (av. 100.5 km)	Mass Lost (%) after 47.5 h (av. 100.5 km)
1	moldavite	Lusatia (Ott.-Okr.)	broken off, small pits	16.2 x 12.4 x 4.8	1.19	1.19	15.9 x 12.3 x 4.7	1.17	**1.7**
2	moldavite	Lusatia (Ott.-Okr.)	broken off, small pits	16.2 x 12.7 x 5.3	1.07	1.07	15.9 x 12.6 x 5.2	1.05	**1.9**
3	moldavite	S Bohemia (Chlum)	small chip, sculptured	24.6 x 14.0 x 11.3	2.63	2.63	24.2 x 13.2 x 10.7	2.55	**3.0**
4	moldavite	S Bohemia (Chlum)	small chip, sculptured	24.8 x 12.6 x 7.9	2.38	2.38	24.5 x 12.2 x 7.9	2.29 + 0.03 (2 pcs.)	**2.5** (+ fragm. 3.8)
5	moldavite	S Bohemia (Slavče)	big chip	31.1 x 15.4 x 8.4	4.29	4.28	30.0 x 15.0 x 8.4	4.15	**3.3**
6	moldavite	S Bohemia (Slavče)	big chip, gas bubble	20.7 x 16.9 x 10.3	4.10	4.10	20.6 x 16.6 x 9.8	4.01	**2.2**
7	australite	WA (Nullarbor Pl.)	core	18.7 x 17.2 x 14.9	5.23	5.23	18.6 x 17.0 x 14.9	5.13	**1.9**
8	australite	WA (Nullarbor Pl.)	half core	30.9 x 26.4 x 22.2	19.65	19.65	30.6 x 26.1 x 22.2	19.28	**1.9**
9	indochinite	China?	fragment	22.4 x 21.9 x 14.3	8.52	8.52	22.1 x 21.7 x 13.9	8.34	**2.1**
10	indochinite	China?	teardrop	55.9 x 18.8 x 17.0	17.02	17.02	53.7 x 18.6 x 16.3	16.65	**2.2**
11	indochinite	China?	small chip	26.2 x 19.5 x 16.7	9.55	9.55	26.2 x 18.8 x 16.2	9.36	**2.0**
12	indochinite	Thailand?	big chip, flat	47.0 x 41.0 x 9.4	15.14	15.08	46.0 x 35.4 x 9.3	14.49 + 0.03 (5 pcs.)	**4.1** (+ fragm. 4.3)
13	indochinite	China?	broken off, sm. teardr.	30.1 x 17.6 x 14.4	7.43	7.43	29.5 x 17.4 x 14.0	7.30	**1.7**
14	indochinite	China?	small pits	21.3 x 17.6 x 16.9	6.92	6.91	21.2 x 17.3 x 16.6	6.78	**2.0**
15	obsidian	Lipari ("Rocche R.")	sharp-edged, layered	46.9 x 34.2 x 12.3	15.45	15.35	45.1 x 30.5 x 11.5	14.39 + 0.09 (1 pc.)	**6.3** (+ fragm. 6.9)
16	obsidian	Lipari ("Rocche R.")	sharp-edged, oblong	53.9 x 23.2 x 12.4	13.98	13.89	– (broken)	9.61 + 3.61 (3 pcs.)	**5.4** (+ fragm. 31.3!)
17	obsidian	Lipari ("Rocche R.")	sharp-edged, blocky	36.8 x 29.6 x 20.9	20.65	20.58	36.5 x 27.4 x 20.2	19.98	**3.2**
18	obsidian	Lipari ("Rocche R.")	sharp-edged, layered	29.7 x 14.8 x 10.9	4.26	4.24	27.3 x 13.9 x 10.9	4.09	**4.0**
19	obsidian	Lipari ("Rocche R.")	sharp-edged, layered	25.3 x 14.0 x 10.1	3.22	3.20	23.7 x 13.5 x 9.7	3.10	**3.7**
20	obsidian	Arizona?	tumbled	35.7 x 29.7 x 25.8	30.02	30.00	35.6 x 29.6 x 25.4	29.54	**1.6**
21	obsidian	Arizona?	tumbled	30.2 x 25.7 x 20.2	17.57	17.57	30.0 x 25.7 x 20.1	17.29	**1.6**
22	artif. glass	waste (Ott.-Okr.)	sharp-ed., gas bubbles	59.9 x 55.8 x 32.5	104.1	103.3	52.2 x 51.6 x 32.0	93.87 + 0.52 (12 pcs.)	**9.3** (+ fragm. 9.8)
23	artif. glass	waste (Ott.-Okr.)	sharp-edged	39.6 x 26.4 x 18.1	18.55	18.52	37.9 x 24.9 x 17.3	17.71 + 0.08 (2 pcs.)	**4.1** (+ fragm. 4.5)
24	artif. glass	waste (Ott.-Okr.)	sharp-ed., few gas b.	31.7 x 25.6 x 18.2	16.34	16.27	31.6 x 24.2 x 17.4	15.57 + 0.16 (3 pcs.)	**3.7** (+ fragm. 4.7)
25	artif. glass	waste (Ott.-Okr.)	sharp-ed., lots of gas b.	31.4 x 25.8 x 13.5	8.08	7.92	– (broken)	4.90 + 2.51 (3 pcs.)	**8.3** (+ fragm. 39.6!)
26	flint	(Königs Wusterh.)	ellipsoid	33.1 x 26.1 x 15.8	20.19	20.19	33.1 x 26.1 x 15.7	20.12	**0.3**
27	agate	Lusatia (Ott.-Okr.)		35.4 x 27.1 x 22.3	21.31	21.52 (+ H_2O!)	35.3 x 27.1 x 22.3	21.22	**0.4**
28	agate	Lusatia (Ott.-Okr.)	weathered	39.9 x 25.1 x 15.6	23.33	23.33	39.8 x 25.1 x 15.5	23.07	**1.1**
29	smoky quartz	Lusatia (Ott.-Okr.)		22.1 x 17.4 x 14.4	7.73	7.73	22.1 x 17.4 x 14.3	7.62	**1.4**
30	amethyst	Lusatia (Ott.-Okr.)	crystal	18.8 x 15.3 x 11.5	3.60	3.60	18.6 x 15.3 x 11.5	3.55	**1.4**
31	clear quartz	Lusatia (Ott.-Okr.)		20.3 x 17.3 x 11.4	5.21	5.21	20.1 x 17.3 x 11.4	5.12	**1.7**
32	feldspar	Lusatia (Ott.-Okr.)	rhombohedral	17.5 x 16.2 x 9.5	2.71	2.75 (+ H_2O!)	– (broken)	unidentifiable	**?** (undetectable)

Tab. 1: Sample data. Red marked values show changes due to the experiment.

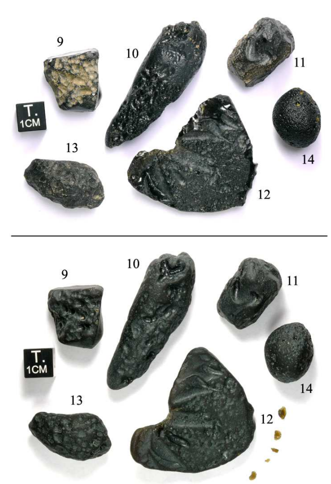

Fig. 1: Sample selection. Tektites no. 9–14 before (top) and after (bottom) the experiment (av. transport dist. ~ 100.5 km).