Geological Quarterly, 2019, **63** (1): 150–161
DOI: http://dx.doi.org/10.7306/gq.1461

Susceptibility of various tektite types to fluvial abrasion

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Brachaniec, T., 2019. Susceptibility of various tektite types to fluvial abrasion. Geological Quarterly, **63** (1): 150–161, doi: 10.7306/gq.1461

Associate editor: Wojciech Granoszewski

Tektites are glass bodies, rich in silica, resulting from the impact of a large bolide into ground rocks. Similar to other impactites they are prone to erosive processes, including fluvial abrasion. This study reports the results of an experimental tumbling that aimed at estimating the potential distance that tektites from different strewn fields (moldavites, bediasites and indochinites) and Libyan Desert Glass (LDG) can withstand depending on the experimental conditions. The present study consisted of 15 cycles, in which the type of sample deposits (i.e. sand/gravel ratio) and computed transport velocity were changed, the latter being estimated at 2.5-6.5 km/h. The results clearly confirm the susceptibility of tektites to abrasion during tumbling. None of the tektites withstood the estimated distance of 12 km during the experiment, but this may have been the result of the relatively small initial size of the glasses (~1.5 g). These experiments document that LDG, despite its even smaller initial size in the experiments, can resist abrasion and fragmentation better than the tektites, thus, could probably be transported farther in a stream environment. This is most likely caused by a much higher silica content in relation to the tektites from other groups. The estimated maximum transport distances, over which moldavites, bediasites and indochinites survived in the experiments, are all very similar. The greatest weight loss for all the specimens was found after the first estimated 2 km of tumbling. This is undoubtedly caused by the irregular initial shape of the tektites and LDG. Subsequent observations recorded minor weight losses, in association with more and more rounded glass shapes. The results of the study should be treated only as a general scheme for the fluvial abrasion of tektites, due to the inability to accurately reproduce the natural fluvial environment.

Key words: tektites, reworking, abrasion, redeposition, river, gravel.

INTRODUCTION

The fall of a sufficiently large asteroid into ground deposits sometimes leads to the formation of microtektites and/or tektites (Koeberl, 1993, 1994; Glass and Simonson, 2012; Brachaniec et al., 2014a). Tektite is a glass, the main component of which is silica (SiO_2), originating from the rocks of Earth's crust (Koeberl, 1986). Tektites often display a high degree of homogeneity (Werner and Borradaile, 1998; Rodovská et al., 2016; Skála et al., 2016).Tektites differ from each other by physical and chemical features, determined partly by the melting of various rock types (Koeberl, 1990). So far, the occurrence of tektites on Earth is related mainly to the following Cenozoic strewn-fields (Fig. 1; McCall, 2001; Glass and Simonson, 2013): the Central European (moldavites), the North American (bediasites, georgiaites), the Ivory Coast (ivorites), and the Australasian (Australian tektites – australites, Asian tektites – indochinites, thailandites, malaysianites, philippinites, rizalites, billitonites and javanites). Additionally, there are also Darwin Glass from Tasmania and Libyan Desert Glass (LDG) from the Libyan Desertin, western Egypt (Glass and Simonson, 2013). According to non splash-forms of LDG, it should be classified as impact glass not tektite (B. Glass, pers. comm., 2018). In the geological record, tektites are subject to many processes that can change their stratigraphic position (so-called "age paradox") and make the identification of their source crater difficult. Such a process is undoubtedly erosion and redeposition, which was recorded in each of the four largest strewn-fields on Earth (McCall, 2001). Tektite reworking can be induced by tsunamites, fluvial processes, turbidites and glaciers, or even human activity and tornadoes (Shoemaker and Shoemaker, 1997; Shoemaker and Uhlherr, 1999; McCall, 2000, 2001; Osinski et al., 2008; Buchner and Schmieder, 2009; Jimenez-Martinez et al., 2015; Szopa et al., 2017). Bearing in mind that the transport of tektites in the fluvial environment (rivers and streams) is relatively poorly understood, the main purpose of this work was to test the susceptibility of different tektite types to abrasion, in order to check which of them were theoretically able to withstand the longer distance of reworking, depending on the conditions (velocity) and type of sediment (sand/gravel ratio). It was not

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Received: March 7, 2018; accepted: January 11, 2019; first published online: March 22, 2019

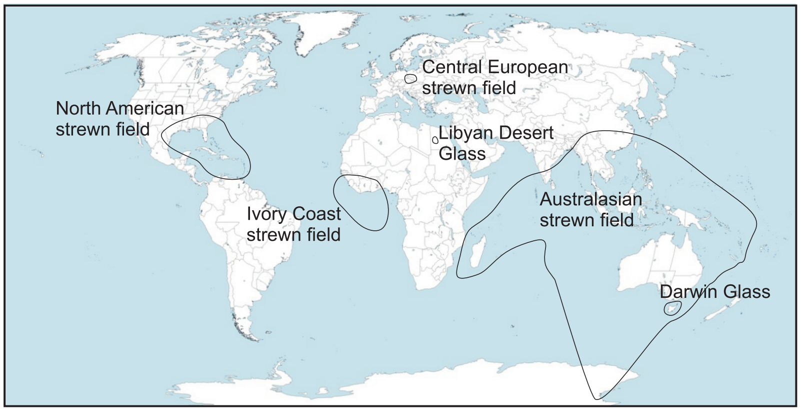

Fig. 1. The largest Cenozoic tektite strewn-fields on Earth (after McCall, 2001; Glass and Simonson, 2013; Giuli et al., 2014)

about accurately reproducing the exact hydrogeological conditions for each type of tektite, but about generating a general model of their respective abrasion in similar conditions. This study was inspired by the experimental tumbling carried out on moldavites by Brachaniec (2018a, b).

METHODOLOGY

The tumbling experiment on tektites had been conducted at the Faculty of Earth Sciences of the University of Silesia, using a rotating barrel LPM-20 (Glass GmbH & Co. KG Spezialmaschinen), which was modified to be rotated with predefined speed. Its radius was 15 cm and height 40 cm. The volume of the barrel was estimated to 0.028 m^3 from these dimensions.

CYCLES, TUMBLING SPEED AND OBSERVATIONS

During the experiment, 15 separate cycles were carried out, all differing from each other by the tumbling speed and/or the type of sediment used. Before every cycle, separated sediment sample (Table 1) and all tektites (for every cycle) were put into the barrel. Each cycle was divided into several stages that corresponded to transport distances (see Table 2). Due to the fact that, in most cases, tektite abrasion takes place in streams deeper than 30 cm, the barrel was filled with water. For the purposes of the experiment, tumbling speed for each cycle had to be determined. Due to the fact that the aim was to elaborate a general scheme for the tektite abrasion, the river speeds were averaged from literature data: in the USA up to 7 km/h (Schulze et al., 2005; Magirl et al., 2009), in Poland up to 3 km/h (Haładyj-Waszak, 1975, 1978, 1980), and in China up to 5 km/h (Jia et al., 2016). Additionally, based on the results of Ziada (2010), 3 km/h was accepted for the River Nile. An average speed of 4.5 km/h was accepted for the whole experiment, in which this value was central (Table 1). Bearing in mind the results of Brachaniec (2018a), the observation of progressive abrasion every 2 km of transport was thus considered to give the best picture of the successive stages of tektite erosion.

Due to the different tumbling speeds, this distance corresponded to different time intervals which were calculated from RPM (revolutions of barrel per minute; Table 1). During every observation stage, the barrel was stopped and all material (deposits, tektites, LDG) was sieved on a 5 mm mesh. Once removed from the barrel, state preservation of glasses was recorded. After each tumbling step, they were weighed, described and put back in the barrel for the next tumbling step. A new de-

Table 1

Methodology involved in experimental tumbling of tektites

River velocity [km/h]	Deposit sample		Cycle	RPM (revolutions of barrel per minute) m/s of transport	Observation
	sand [kg]	gravel [kg]			
2.5	1	3	Cycle no. 1	40–0.6	every 48 min (~2 km of transport)
	2	2	Cycle no. 2	40–0.6	
	3	1	Cycle no. 3	40–0.6	
3.5	1	3	Cycle no. 4	60–0.9	every 34 min (~2 km of transport)
	2	2	Cycle no. 5	60–0.9	
	3	1	Cycle no. 6	60–0.9	
4.5	1	3	Cycle no. 7	80–1.2	every 27 min (~2 km of transport)
	2	2	Cycle no. 8	80–1.2	
	3	1	Cycle no. 9	80–1.2	
5.5	1	3	Cycle no. 10	100–1.6	every 22 min (~2 km of transport)
	2	2	Cycle no. 11	100–1.6	
	3	1	Cycle no. 12	100–1.6	
6.5	1	3	Cycle no. 13	120–1.9	every 18 min (~2 km of transport)
	2	2	Cycle no. 14	120–1.9	
	3	1	Cycle no. 15	120–1.9	

Table 2

Compiled results from experimental tumbling. Weight loss values rounded to zero decimal places

Cycle	River velocity [km/h]	Deposits: sand/gravel [kg]	Tektite	Stages and weight loss [%]					Maximum distance [km]
				Stage 1 (0–2 km)	Stage 2 (2–4 km)	Stage 3 (4–6km)	Stage 4 (6–8km)	Stage 5 (8–10km)	
Cycle no. 1	2.5	1/3	mol.	56	23	15	–	–	8
			bed.	52	19	15	–	–	8
			indo.	53	20	15	–	–	8
			LDG	40	15	11	8	–	10
Cycle no. 2	2.5	2/2	mol.	51	19	16	–	–	8
			bed.	48	20	13	9	–	10
			indo.	51	23	16	–	–	8
			LDG	38	17	11	6	–	10
Cycle no. 3	2.5	3/1	mol.	46	17	15	12	10	12
			bed.	44	16	10	9	6	12
			indo.	47	20	15	11	5	12
			LDG	33	15	11	9	6	12
Cycle no. 4	3.5	1/3	mol.	59	24	17	11	–	10
			bed.	55	21	17	–	–	8
			indo.	56	23	15	–	–	8
			LDG	44	17	14	11	–	10
Cycle no. 5	3.5	2/2	mol.	54	21	18	11	–	10
			bed.	52	23	15	11	–	10
			indo.	55	25	20	–	–	8
			LDG	41	19	13	11	9	12
Cycle no. 6	3.5	3/1	mol.	49	15	13	10	8	12
			bed.	47	19	13	10	8	12
			indo.	50	23	18	12	8	12
			LDG	37	18	12	11	9	12
Cycle no. 7	4.5	1/3	mol.	61	27	18	–	–	8
			bed.	58	29	17	–	–	8
			indo.	58	25	19	–	–	8
			LDG	46	20	16	9	–	10
Cycle no. 8	4.5	2/2	mol.	56	22	17	14	–	10
			bed.	55	26	17	–	–	8
			indo.	58	28	23	–	–	8
			LDG	45	24	16	11	–	10
Cycle no. 9	4.5	3/1	mol.	51	20	14	–	–	8
			bed.	51	22	14	12	–	10
			indo.	54	24	16	11	–	10
			LDG	41	19	13	12	10	12
Cycle no. 10	5.5	1/3	mol.	75	35	–	–	–	6
			bed.	65	30	21	–	–	8
			indo.	63	26	21	–	–	8
			LDG	50	23	14	11	–	10
Cycle no. 11	5.5	2/2	mol.	61	32	16	–	–	6
			bed.	61	29	18	–	–	6
			indo.	61	31	24	–	–	6
			LDG	50	26	18	13	–	8
Cycle no. 12	5.5	3/1	mol.	56	21	15	–	–	8
			bed.	55	24	15	–	–	8
			indo.	57	27	20	–	–	8
			LDG	45	21	12	9	–	10

Tab. 2 cont.

Cycle	River velocity [km/h]	Deposits: sand/gravel [kg]	Tektite	Stages and weight loss [%]					Maximum distance [km]
				Stage 1 (0–2 km)	Stage 2 (2–4 km)	Stage 3 (4–6km)	Stage 4 (6–8km)	Stage 5 (8–10km)	
Cycle no. 13	6.5	1/3	mol.	84	–	–	–	–	4
			bed.	74	38	–	–	–	6
			indo.	70	31	25	–	–	8
			LDG	55	25	17	13	–	10
Cycle no. 14	6.5	2/2	mol.	67	35	–	–	–	6
			bed.	69	36	–	–	–	6
			indo.	64	32	–	–	–	6
			LDG	54	29	19	–	–	8
Cycle no. 15	6.5	3/1	mol.	59	27	18	–	–	8
			bed.	58	28	–	–	–	6
			indo.	61	29	21	–	–	8
			LDG	50	22	15	11	–	10

See text for explanations; mol. – moldavite, bed. – bediasite, indo. – indochinite, LDG – Libyan Desert Glass (see also Appendixes 1–15*, Fig. 7)

posit sample was also put into the barrel. Each cycle ended when the glass became <5 mm in diameter, which was accepted as complete destruction of the tektite. Due to the fact that the average size of the tektites is at least 1 cm and the weight is a few grams (Glass, 1982), glasses of such sizes were chosen for the experiment.

SELECTED TEKTITES

A total of 60 glasses were used in the experiment, 15 from each group: moldavites, bediasites, indochinites and LDG. This means that three different tektites (moldavite, bediasite, moldavite) and LDG were used in each cycle. For the most sensible interpretation of the tumbling results, the selected specimens were chosen based on their masses as close as possible. The glass shape during the experiment was determined using Power's pattern (1953).

SEDIMENT SAMPLES

The aim of the experiment was to check how the abrasion affects various types of tektite in different types of sediment. Because fluvial abrasion occurs mainly in rivers, typical fluvial sediments, such as sands and oval gravel grains, were used. By changing the tumbling speed, the proportion of these two fractions also changed in relation to 25–75 vol.%, 50–50 vol.% and 75–25 vol.% (Table 1). The used sand was yellow and moderately sorted, while the gravel was made mostly of quartz pebbles with a diameter varying from 1 to 10 cm. One sand grain was ~1 mm in diameter.

RESULTS

The results of all performed cycles are described below. The tumbling results are presented in Appendixes 1–15 and Table 2. The average percentage weight loss in relation to the reworking distance covered by tektites in each cycle is shown in Figures 2–6.

CYCLE NO. 1
(2.5 km/h AND SAND/GRAVEL RATIO OF 1/3)

Generally, the patterns of abrasion of the tektites in this cycle were very similar, although their initial shapes were very diverse: very angular (moldavite), sub-rounded (bediasite and indochinite) and rounded (LDG). The tektites lost ~40–56% of their initial weight in stage 1. Moldavite became sub-rounded in shape, while the rest of the tektites retain their original shape. The surface of the tektites became partially smooth and, in the case of LDG, completely smooth, while the edges were rounded. After stage 2, the weight loss reached 11–23 vol.%; all tektites became rounded/well-rounded with a completely smooth surface. The next observation only revealed another loss of glass mass. Moldavite, bediasite and indochinite did not withstand further than 6 km of reworking (less than 5 mm), while LDG did up above stage 4.

CYCLE NO. 2
(2.5 km/h AND SAND/GRAVEL RATIO OF 2/2)

The abrasion pattern was relatively similar to that of cycle no. 1. However, due to the different proportions of the deposits (i.e. sand/gravel ratio), the tektites were slightly abraded at a slower pace. Once again moldavite differed in shape quite clearly from any other tektite (very angular in shape). During the first observation, a weight loss of 37–51% was recorded. In contrast to the previous cycle, the glass surface became partially matt. The shapes of all tektites were determined as sub-rounded. During this next stage, they became rounded with incomplete matt and flat surface. Moldavite and indochinite withstood up through stage 3 of tumbling in contrast to other tektites that made it through stage 4.

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1461

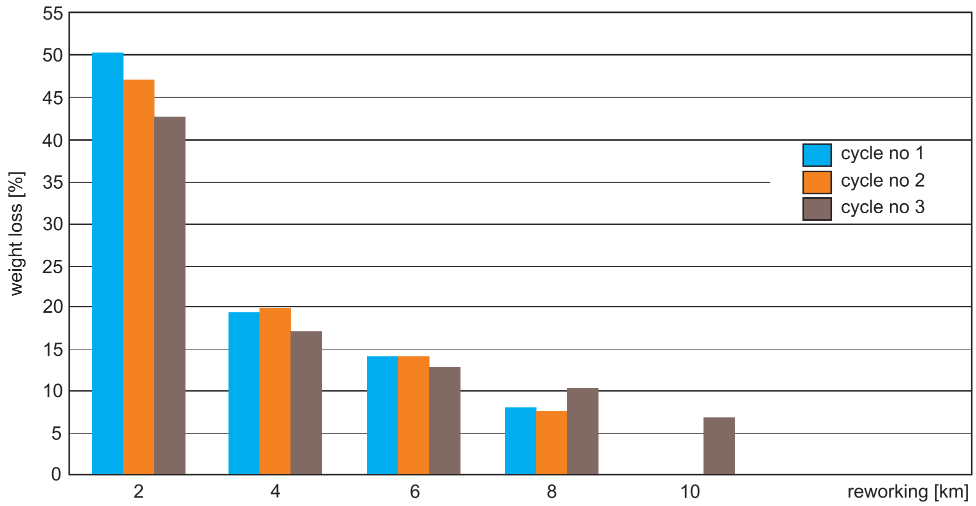

Fig. 2. Average tektite weight loss related to the reworking distance for each cycle at tumbling speed of 2.5 km/h (see also Appendixes 1–3, Table 2)

CYCLE NO. 3
(2.5 km/h AND SAND/GRAVEL RATIO OF 3/1)

The results of this cycle differed from the preceding two, especially from cycle no. 1. It was mainly due to the higher amount of sand in the deposit sample. Original shapes of tektites, except LDG (sub-rounded), were classified as sub-angular. During the first stage, there was a noticeably smaller weight loss (32-47%) in contrast to cycle 1 and slightly less to cycle 2. Tektites became sub-rounded with a partially matt surface. After stage 2, the specimens lost weight, but no significant difference in shape and surface sculpturing was noted. After stage 3, the specimens became rounded with a completely matted surface without relief. Another weight loss was noted after stage 5.

The average tektite weight loss on different stages related to the reworking distance for cycles 1, 2 and 3 is presented in Figure 2.

CYCLE NO. 4
(3.5 km/h AND SAND/GRAVEL RATIO OF 1/3)

Despite the increase of the tumbling speed, the results of this cycle did not significantly differ from those from cycles 1, 2 and 3. All tektites were initially sub-angular in shape. The first range of weight loss fluctuated between 44 and 59%. Actually, the shape of glasses was not altered, and their surface became partly smooth. After 4 km of transport, with a 17–24% weight loss, all tektites became rounded with a completely smooth surface. After 6 km reworking, the tektites were just well-rounded in shape. Moldavite and LDG withstood a somewhat longer distance of reworking in contrast to bediasite and indochinite.

CYCLE NO. 5
(3.5 km/h AND SAND/GRAVEL RATIO OF 2/2)

Increasing the amount of sand in the deposit sample induced a reduction of weight loss during stage 1 (41–55%). The tektite glass became sub-rounded with a visible matt surface and smoothing. After stage 3, all the tektites were rounded in shape and completely worn out. During this stage the last indochinite observation was also noticed. Moldavite and bediasite were destroyed before stage 5. LDG made it through stage 5 and became well-rounded.

CYCLE NO. 6
(3.5 km/h AND SAND/GRAVEL RATIO OF 3/1)

In this cycle, all tektites made it through stage 5 as a result of the higher amount of sand at this tumbling speed. Their preliminary sub-angular shapes turned to rounded after stage 3. The weight decrease after the first stage is ~37–49%; meanwhile, the first signs of abrasion were showing. After stage 4 the specimens were already completely matted.

The average tektite weight loss on different stages related to the reworking distance for cycles 4, 5 and 6 is presented in Figure 3.

CYCLE NO. 7
(4.5 km/h AND SAND/GRAVEL RATIO OF 1/3)

Original tektites were sub-rounded in shape, except moldavite, which was angular. Increasing the tumbling speed resulted in a higher weight loss after stage 1 than in the previous cycles (46–61%). The roundness of the specimens also increased. On the surface of moldavite and LDG, characteristic semi-circular traces of gravel abrasion were observed. In this cycle, LDG was the only one to make it through stage 5, while the remaining specimens made it only through stage 4.

CYCLE NO. 8
(4.5 km/h AND SAND/GRAVEL RATIO OF 2/2)

Tektite abrasion was similar to that from cycle no. 7. However, due to the different type of sediment, the glasses were eroded at a slower pace. Initially, moldavite differed in shape from other tektites because it was very angular in shape. During stage no. 1, the weight loss of all tektites was in the range of 45–58%. Like in the previous cycles, the glass surface became partially matted already at this stage, and the tektites were de-

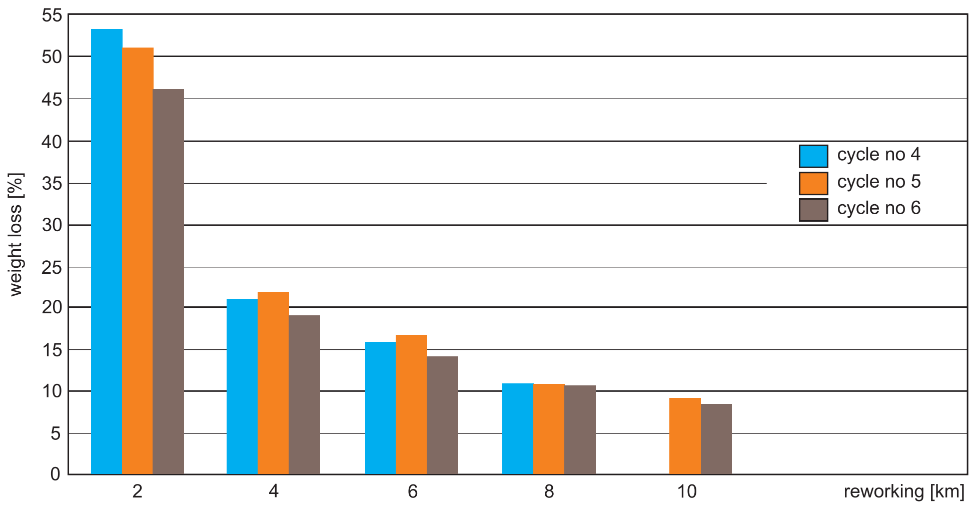

Fig. 3. Average tektite weight loss related to the reworking distance for each cycle at tumbling speed of 3.5 km/h (see also Appendixes 4–6, Table 2)

termined as rounded. During the next stage the surfaces became completely matted and smooth. Moldavite and LDG made it through stage 4 in contrast to bediasite and indochinite that made it only through stage 3.

CYCLE NO. 9
(4.5 km/h AND SAND/GRAVEL RATIO OF 3/1)

Likewise in cycle no. 3, primary shapes of tektites, except LDG (sub-rounded in shape), were classified as sub-angular. After 2 km, the weight loss of 41–54% was recorded. All tektites became sub-rounded with a matt surface. During the next stage the glass became rounded with a completely matt and flat surface. The shortest distance (up to 8 km) was withstood by moldavite, while the longest one was by LDG (up to 12 km).

The average tektite weight loss on different stages related to the reworking distance for cycles 7, 8 and 9 is presented in Figure 4.

CYCLE NO. 10 (
5.5 km/h AND SAND/GRAVEL RATIO OF 1/3)

Further speed increase combined with a large amount of gravel in the deposit contributed to the rapid erosion of the tektites and LDG. After 4 km all glasses were already rounded with matted, smooth surfaces. Traces of erosion were only visible on the surface of moldavites. The weight loss was also significantly higher in contrast to previous cycles. Moldavite withstood only <6 km, while bediasite and indochinite <8 km. Again, LDG withstood the longest distance of up to 10 km.

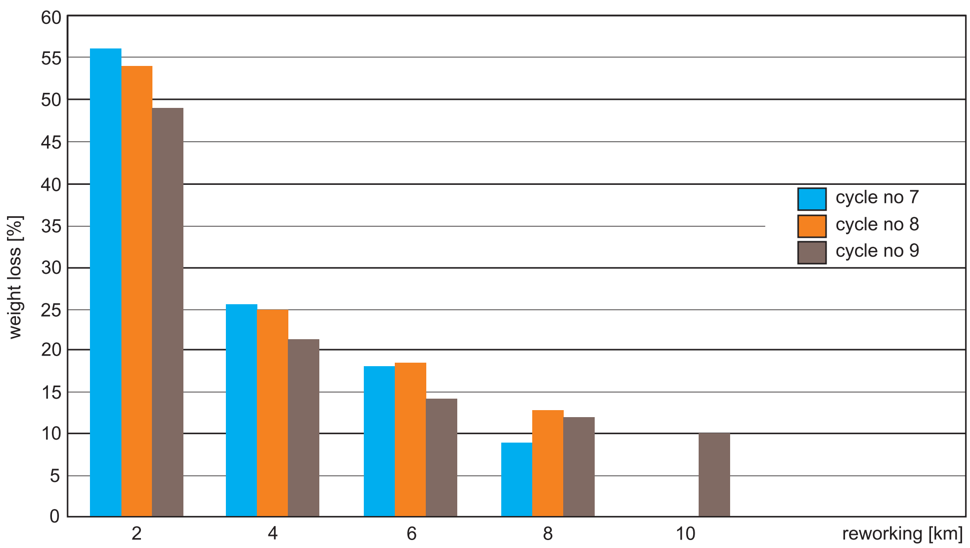

Fig. 4. Average tektite weight loss related to the reworking distance for each cycle at tumbling speed of 4.5 km/h (see also Appendixes 7–9, Table 2)

CYCLE NO. 11
(5.5 km/h AND SAND/GRAVEL RATION OF 2/2)

Results of stage no. 1 of this cycle were a unique case in the whole experiment: the weight loss of tektite (except LDG) was nearly identical and amounts ~61%. For comparison, LDG lost ~50% of its initial weight. In the case of cycle no. 10, strong abrasion was visible. Sub-rounded shapes of tektite were altered after 4 km of reworking. Additionally, their surface became matted. Again, LDG withstood the longest distance, earlier after 6 km, becoming well-rounded in shape.

CYCLE NO. 12
(5.5 km/h AND SAND/GRAVEL RATION OF 3/1)

In this cycle, the abrasion was slightly weaker than in the previous cycle, but none of the tektites withstood longer than 10 km. In the middle of their reworking, they became rounded with a characteristic matted surface.

The average tektite weight loss on different stages related to the reworking distance for cycles 10, 11 and 12 is presented in Figure 5.

CYCLE NO. 13
(6.5 km/h AND SAND/GRAVEL RATIO OF 1/3)

This cycle was characterized by the highest erosion in the entire experiment. Primary sub-rounded tektites became rounded during the first reworking distance step. Weight loss increased to 84% in the moldavite case. This results in stage 1, being the only one that was noticed on moldavite. Bediasite and indochinite withstood slightly farther, but they did not withstand even 8 km. LDG withstood up to 10 km of reworking with characteristic traces of abrasion on its surface.

CYCLE NO. 14
(6.5 km/h AND SAND/GRAVEL RATIO OF 2/2)

In this cycle, the highest tumbling speed contributed to the fastest abrasion of the tektites among all cycles with sand/gravel ratio of 2/2. During stage 1, the weight decrease was in the range of 54-69%. Sub-rounded tektites became rounded with matted surfaces. LDG withstood a maximum distance of 8 km, while the remaining ones did less than 6 km.

CYCLE NO. 15
(6.5 km/h AND SAND/GRAVEL RATIO OF 3/1)

Despite the same tumbling speed as in the previous cycle, more sand in the deposit sample was used. All tektites became matted after only 2 km of transport, and were rounded. Bediasite did not withstand up to 6 km of reworking contrary to moldavites and indochinite that theoretically withstood 2 km more. LDG, however, was completely destroyed after stage no. 4.

The average tektite weight loss on different stages related to the reworking distance for cycles 13, 14 and 15 is presented in Figure 6.

DISCUSSION

A SCHEME FOR TEKTITE ABRASION

This experiment confirmed the low resistance of tektites to fluvial abrasion. Earlier, Bouška (1964), Žebera (1972), Lange (1996), Bouška et al. (1999) and Trnka and Houzar (2002) confirmed such claims, based on the stratigraphic position and the glass shape of moldavites. Observations made during tumbling have enabled developing a general scheme of fluvial abrasion observed on tektites in this study. The speed of abra-

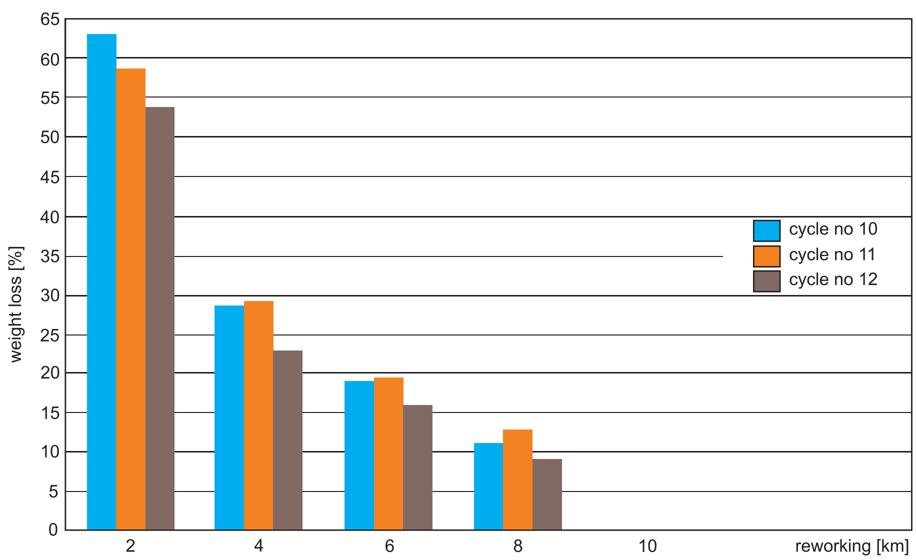

Fig. 5. Average tektite weight loss related to the reworking distance for each cycle at tumbling speed of 5.5 km/h (see also Appendixes 10–12, Table 2)

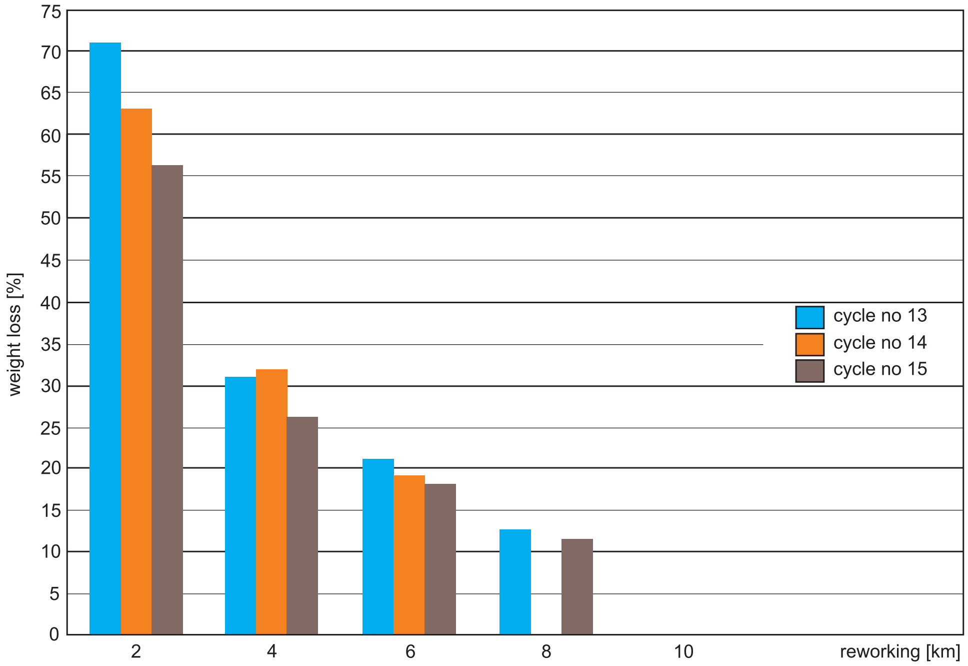

Fig. 6. Average tektite weight loss related to the reworking distance for each cycle at tumbling speed of 6.5 km/h (see also Appendixes 13–15, Table 2)

sion depends largely on the initial shape. Among the selected groups of tektites, moldavites had the most angular/sub-angular initial shapes and the most deeply and differentiated surface sculpturing. Therefore, in most cases, their weight loss at respective stages is the greatest (Figs. 2–6). In the currently developed abrasion model, two basic steps of abrasion with several abraded glass forms are distinguished, affecting tektites during their reworking. Both are shown in Figure 7. Unfortunately, they often overlap, making their identification even more difficult.

Step 1. This step is more debatable. It depends on the size, weight, shape, surface sculpturing of the glass, and on the type of deposit and potential river velocity. Based on the respective results, it can be assumed that this step covers up to 50% of the weight loss over the total reworking distance. During it, the tektite loses a significant part of its initial mass (sometimes even the vast majority of it). The angular glass shape becomes sub-angular, sometimes and even rounded in sediments with high gravel content. Sometimes, with less erosion it seems theoretically possible to recreate its original shape. The glass surface becomes flatter, sometimes even completely flat. In sediments containing much sand material, the surface of the specimens is partially matted. In cycles with a high content of gravel, traces of abrasion can be visible on the tektite surface.

Step 2. This step occurs over 50–100% of the total reworking distance. Generally, it occurs after step 1, although there is a chance of overlap. During this step, the tektite becomes rounded and later well-rounded, so that its weight decrease is already relatively low compared to step 1. It is not possible to reproduce initial tektite or LDG shape. The surface becomes smooth, sometimes matted (greater sand amount in deposits), and sometimes with traces of abrasion. After this step, tektites are totally destroyed.

RESULTS OF REPEATED CYCLES

The first and probably most important result of this experiment is the fact that, despite the considerable differentiation of tumbling speed and type of sediment, none of the tektites had withstood a distance longer than 12 km (Table 2 and Figs. 2–6). It obviously depends on the initial size of the glass that can be quite large. Trnka and Houzar (2002) mentioned that some Muong Nong tektites could possibly reach up to 100 kg. Fiske et al. (1999) claimed that these glasses could weight over 700 kg. Literature data shows that moldavites could weigh 40 g (Hanus et al., 2016) or even 200 g (R. Skála, pers. comm., 2018), and LDG even more than 2 kg (Clayton, 1933). Another noteworthy fact is clearly the greater potential of tektites for reworking in contrast to LDG. This cannot be solely explained by the difference in the initial mass, this latter being relatively low, or the difference in the initial shape of glass. This is probably due to the peculiar chemical composition of LDG, made of almost pure silica and thus displaying a higher hardness comparable to the reworking sediment (Table 3).

Quartz, composing mainly river gravels, has a hardness of ~7 on Mohs scale, while tektites are ~5–6 (Simmons and Ahsian, 2007). Similar chemical composition and the same hardness of moldavites, bediasite and indochinite caused very similar results of their potential reworking – weight loss at individual stages and relative maximal transport distance. During cycle no. 1, they were destroyed between stages 3 and 4, unlike LDG, that made it through stage 5. Similar cases were recorded in cycles nos. 5, 7, 9–15. Obviously, the differences occur also in weight loss during stages no. 1. In each case, LDG lost much less weight percentage, although its shape and initial mass were similar to other tektites. An interesting issue lies in the results of stage 1 of cycle no. 11, when tektites, with the exception of LDG, lost practically the same weight percentage. In addition,

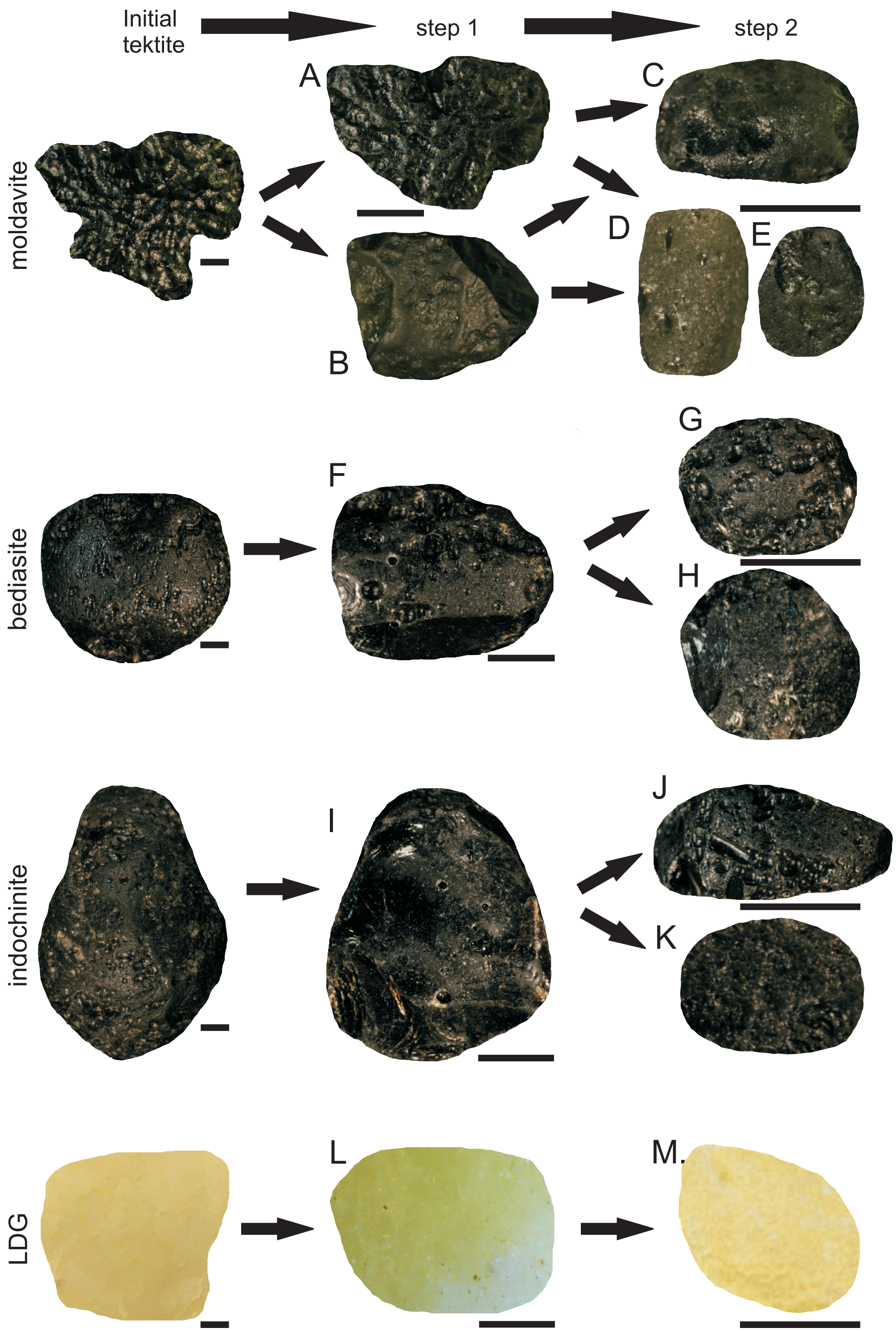

Fig. 7. Two main steps of tektites fluvial abrasion with main abraded glass forms, based on the results of tumbling cycles

A – sub-rounded glass with surface sculpturing; **B** – sub-rounded glass with matt surface; **C** – rounded glass with low sphericity and abrasion signs; **D** – rounded glass with low sphericity and matt surface; **E** – rounded glass with high sphericity and matt surface; **F** – sub-rounded glass with partially matt surface and abrasion signs; **G** – rounded glass with high sphericity and abrasion signs; **H** – rounded glass with high sphericity and almost flat surface; **I** – rounded glass with almost flat surface; **J** – rounded glass with low sphericity and abrasion signs; **K** – rounded glass with high sphericity; **L** – rounded glass with flat surface; **M** – rounded glass with high sphericity and flat surface; scale bar – 2 mm

Table 3

General chemical composition of tektites

Elements [wt.%]	Moldavite*	Bediasite**	Indochinite***	Libyan Desert Glass****
SiO_2	78.72	77.27	77.38	98.26
TiO_2	0.2	0.7	0.71	0.07
Al_2O_3	10.75	13.07	10.93	0.53
FeO_{total}	1.83	3.41	4.08	0.05
MnO	0.05	–	0.09	0.002
MgO	1.41	0.65	1.73	0.03
CaO	2.2	0.62	1.43	0.02
Na_2O	0.54	1.63	0.98	0.27
K_2O	3.57	2.27	2.39	0.06
P_2O_5	0.04	–	–	0.01
TOTAL	99.31	99.64	99.71	99.3

* – average value from Koeberl et al. (1988), Lange (1995), Řanda et al. (2008), Skála et al. (2009), Brachaniec et al. (2014b, 2015, 2016); Brachaniec (2017); ** – average value from Chaussidon and Koeberl (1995), Koeberl and Glass (1988); *** – average value from Yagi et al. (1982), Mazer et al. (1992), Amare and Koeberl (2006); **** – average value from Koeberl (1997), Guzzafame et al. (2009), Szopa et al. (2015)

they all lasted over a similar distance. This can be explained by their very similar shapes. By far the farthest transport was supported by a sediment containing larger proportions of sand. Practically, in all cycles where deposits contained a high amount of sand, tektite reworking was longer and tektites and LDGs showed a lower weight loss for each stage. Additionally, the glass that was reworked in a greater percentage of sand showed a much larger matt surface than tektites from cycles containing more gravel. Noteworthy are the large differences in weight loss in stages no. 1 and no. 2. Depending on the tumbling speed and sand/gravel ratio of the deposits, these values vary from 33–84% for stage no. 1 to 15–38% for stage 2. This is first caused by the greater abrasion of initial tektites with irregular shapes and deep sculpturing of surface. When the tektite is already eroded and its shape becomes much more regular, the weight loss is much smaller – from 10 to 25% for stage no. 3 and from 6 to 14% for stage no. 4. Stages no. 5 are characterized by a very small weight loss, from 6 to 10%. It follows that the general pattern of abrasion looks relatively similar (Figs. 2–6), in spite of many differences between tektites and the conditions under which they had been reworked. From these results, it can also be concluded that the type of sediments is much more important for the progress of abrasion than the tumbling speed. In the case of moldavites from stages no. 1 of cycles 1 and 3, the difference in weight loss was 10%, although they were reworked at the same tumbling speed. A similar difference is noted in other cycles for all tektites. The highest value is 25% in the case of moldavite from stages no. 1 of cycles 13 and 15. There are also small differences in weight loss in the case of tektites from the same reworking distance (stages) and type of sediment (sand/gravel ratios), but different tumbling speeds. For instance, bediasite from stage no. 1 of cycle no. 1 lost 52% of its initial weight. In the same stage, but from cycle no. 4, it already lost 55% of its weight, and in cycle no. 7–58%. Comparison of the other cycles with each other suggests that this difference is caused by the variability of the sediments (i.e. sand/gravel ratio), not by the differences in the specimens. In the case of cycles nos. 1, 4, 7, 10, 13 and 15, moldavites lost their weight at the fastest pace. This can be explained by their initial irregular shapes and deep surface etching that was by far the most developed and thus the most exposed to abrasion. When comparing the results of cycle no. 13 with those obtained by Brachaniec (2018a), there are general similarities in the percentage weight loss and 'transport length', despite the difference in tumbling speed by 4 km/h. In cycles with a high gravel content, the highest weight loss occurs during stage no. 1, reaching 65% (Brachaniec, 2018a) and even 84% (this study).

Undoubtedly, the presented experiment validates the susceptibility of tektites to fluvial abrasion. However, these results and conclusions are purely theoretical ones. The natural environment of tektite reworking is continuously changing. The energy level of the surrounding environment will never be constant along the whole course of the river, just like the local changes of river deposits. Natural conditions have no chance of being reproduced in the laboratory; thus, the results should be subsequently treated only as a general scheme. Moreover, aiming at more reliable tumbling results, identical tektites would have to be used, which is also impossible. Bearing in mind the huge amount of tektites produced after an impact, e.g. 104 tons of moldavites located in a geological record (Trnka and Houzar, 2002), these very same tektites take many different forms and shapes that later affect their reworking. As they do not take the regular shape, the measurements of their dimensions can also be tainted by small errors. A similar situation exists when dealing with deposits where reworking takes place. For experimental purposes, a typically fluvial sediment was used for the entire Cenozoic. However, it should be kept in mind that the slightest change in facies will result in changes in the degree of tektite erosion, as exemplified with the proportions of sand and gravel as shown in this study. Nevertheless, the use of these both fractions in the presented tumbling experience was necessarily required since they usually occur together in river sediments. Furthermore, it should be taken into account that the reworking process itself can last hundreds, thousands or even millions of years, thus explaining the discrepancy between the age of the tektite-bearing deposits and that of the origin impact event. Bearing in mind the above-mentioned arguments, it should be noted that the results of such an experimental tumbling, especially the weight loss during successive cycles, should be only treated as an indicative order of magnitude highly variable depending on many environmental variables. Together with determining the reworking stage of found tektites, it is also necessary to analyse the conditions under which reworking had been taking place.

SUMMARY

1. Impact glasses have low resistance to fluvial abrasion. Longer reworking of LDG in contrast to other used tektites is probably caused by higher silica content;

2. Results of the presented experiment show that the main weight loss of tektites takes place during the first stage of reworking. It is strictly connected with their initial shapes and surface sculpturing;

3. Low energy of the environment and deposits with a considerable sand content determined longer reworking of glasses;

4. The presented scheme of glasses abrasion is only a tip of this process in real environment, due to the presence of many changing conditions, like energy flow and deposit lithology.

Acknowledgements. The author would like to thank A. Muszyński and R. Skála for providing valuable advice and constructive comments on the manuscript, as well as to W. Granoszewski for careful editorial handling. The author also thanks B. Glass for many comments during preparation of the manuscript. Photographic assistance of W. Krawczyński is gratefully acknowledged. The author also wishes to thank M. Salamon for providing the tumbling barrel, and B. Ferré for improving the English version.

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