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Variations in fluvial reworking of Polish moldavites induced by hydrogeological change

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Abstract: Moldavites as ejecta glasses are fragile and transient: they are quickly abraded in fluvial conditions, this was confirmed by tumbling experiments. In the present study, multiple tumbling experiments were conducted to simulate the hydrogeological conditions of deposition of moldavites found in several different gravel pits. These experiments threw new light on the evolution of tektites during reworking. It appears that the original glass shape and mass as well as environmental conditions such as river velocity and the type of sediment with which they are associated are all important variables. However, the experiment did not simulate other significant variables, such as the variability of environmental energy. With given advantageous conditions, moldavite glasses could probably have withstood dozen kilometers of reworking, but this assertion is not sufficient to constrain the distance to their supply areas.

Key-words:

- moldavite;
- tektite;
- fluvial abrasion;
- redeposition;
- reworking

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Résumé : *Variations dans le remaniement fluviatile de moldavites polonaises induites par modification hydrogéologique.-* Les moldavites, comme tout verre d'impact, sont fragiles et éphémères : Elles sont facilement réduites à l'état de fines particules lors de leur transport hydraulique comme le confirment des études expérimentales d'écoulement gravitaire. Dans cette nouvelle étude, différents cycles de transport sont considérés afin de reconstituer les conditions hydrogéologiques caractéristiques de chaque gravière où ont été récoltées ces moldavites. Ces expériences apportent des informations nouvelles sur l'évolution des tectites au cours de leur remaniement. La forme originale et le poids initial du verre d'impact, mais aussi les conditions environnementales (telles que la vitesse d'écoulement de l'eau et la nature du sédiment encaissant), constitueraient les variables les plus importantes. Notre expérimentation n'aura cependant considéré qu'un nombre limité de paramètres significatifs, tels que la variation de l'énergie du milieu. Dans des conditions favorables, les moldavites ont pu parcourir plusieurs douzaines de kilomètres lors de leur remobilisation. Cette conclusion n'est toutefois guère satisfaisante car il nous est impossible de déterminer précisément la distance totale parcourue depuis le gisement originel.

Mots-clefs :

- moldavite ;
- tectite ;
- érosion fluviatile ;
- resédimentation ;
- remaniement

1. Introduction

Moldavites are usually bottle-green glass ejecta with the characteristic homogeneous structure, ejected by the Ries event as a by-product of the melting of quartz sands, clay minerals and carbonates (RODOVSKÁ *et al.*, 2016; SKÁLA *et al.*, 2016; ŽÁK *et al.*, 2016). Tektite hardness falls between 5 and 6 on the Mohs scale (SIMMONS and AHSIAN, 2007), making them susceptible to abrasion during transport with gravel. In most central European locatilities, moldavite glasses are re

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Figure 1: Schematic map of towns and modern river systems in SW Poland (modified after Adamska, 2013; Adynkiewicz-Piragas and Lejcuś, 2013) with respective location of moldavite-bearing pits (red stars).

worked and redeposited in the Miocene rivers (Bouška, 1964, 1988; Žebera, 1972; Lange, 1996; Bouška *et al.*, 1999; Trnka and Houzar, 2002; Buchner and Schmieder, 2009). This explains why the age of moldavite-bearing deposits differs so drastically from the age of these tektites' formation. The preliminary results of the experimental tumbling of moldavites confirmed their high susceptibility to fluvial abrasion (Brachaniec, 2018). However, the generally accepted river-flow velocities in SW Poland and sedimentary deposition variability did not allow for the precise determination of the relationship between river flow velocity, sedimentary type, and distance of fluvial transport of tektites at hand (Brachaniec, 2018). An important factor determining the distance of glass transport in river environments seems to be the amount of gravel: in the case of moldavite-bearing sediments of SW Poland, the percentage of gravel in these deposits increases from the West to the South-East (fieldwork observations). In connection with this, supplementary tumbling cycles were carried out: according to the respective tektite-bearing deposits, proper hydrogeological conditions were adopted to check how it affects the distance of glass reworking respectively.

2. Localities and their geological setting

All Polish moldavites were found in SW Poland (Fig. 1). Moldavite-bearing sediments are the fluvial sandy gravel of theLate Miocene Gozdnica Formation and the Pleistocene fluvial terraces of the Lusatian Neisse (see more details in Brachaniec, 2017; Brachaniec *et al.*, 2014, 2015, 2016; Szopa *et al.*, 2017).

Table 1: Methodology involved in experimental tumbling of moldavites.

Cycle	Pit(s) - River	Age of Sediments	River velocity (km/h)	Sediment sample				Observation	Moldavite specimen weight/dimensions - length x width x height
				Sand (kg)	Gravel (kg)				
					up to 3 cm	from 3 to 8 cm	more than 8 cm		
Cycle no. 1	Gozdnica and Lasów pits - Lusatian Neisse	Late Miocene / Pleistocene	3.8	2.1 - 42%	1.0 - 20%	1.4 - 28%	0.5 - 10%	every 30 min (~1.9 km of transport)	1.372 g/20x17x15 mm
Cycle no. 2	Bielany pit -Cicha Woda	Late Miocene	2.2	1.2 - 24%	1.3 - 26%	1.6 - 32%	0.9 - 18%	every 50 min (~1.8 km of transport)	1.615 g/32x16x14 mm
Cycle no. 3	Nowa Wieś Kącka, Mielęcin and North Stanisław pits - Bystrzyca	Late Miocene	2.2	0.3 - 6%	1.7 - 34%	1.9 - 38%	1.1 - 22%	every 50 min (~1.8 km of transport)	1.493 g/25x19x15 mm

3. Methodology

Tumbling experiments on moldavites were conducted at the Faculty of Earth Sciences of the University of Silesia, using a rotating barrel LPM-20 (Glass GmbH & Co. KG Spezialmaschinen). Its radius was 15 cm and height 40 cm. According to this dimensions volume of the barrel was estimated to 0.028 m^3. In each cycle one moldavite was used. The experiment ended after complete destruction of tumbled moldavites (*i.e.*, no tektite was found in the barrel).

3.1 Sediment samples

Sediment samples to test this experiment were taken from every pit where Polish moldavites were found (Fig. 1). In everypit with moldavites (Fig. 1), a 100 kg sample of bulk sediments was taken back to the laboratory facility. Subsequently the percentage composition of sand and gravel was measured by sieving. In addition, the percentage content in the gravel fraction was determined for the following size classes: diameter up to ca 3 cm, diameter ranging from 3 to 8 cm, and larger clasts (more than 8 cm in diameter). On this basis, a 5 kg sediment sample (built based on percentage composition of 100 kg sample) for each cycle was elaborated (Table 1), and then put into the tumbling barrel filled with 10 l of water.

From the high compositional similarity of both the Late Miocene deposits from the Gozdnica pit and the Pleistocene sediments from the Lasów pit, and from their location within the alluvial accumulation area of the Lusatian Neisse, they were included in a single cycle (cycle no. 1). In cycle no. 2 was a deposit sample from the Bielany pit that is located next to the River Cicha Woda. As for cycle no. 3,the Nowa Wieś Kącka, North Stanisław and Mielęcin pits were lumped together due to the same sediment and their location near the Bystrzyca river. The same situation was in the cycle no. 1 for Gozdnica and Lasów pits.

3.2 Speed tumbling

In this study, the yearly average value of river flow was chosen independently for river in the moldavite distribution area (HAŁADYJ-WASZAK, 1975, 1978, 1980). The rotation speed of the barrel was then adjusted accordingly in each cycle (Table 1).

Keeping in mind the lower tumbling speeds used formerly (BRACHANIEC, 2018), during these new cycles tumbling was stopped after ca. 2 km of transport. This corresponds to different time intervals pending on the river-flow velocity (Table 1). Once removed from the barrel, tektites were then sieved by hand on 5 mm mesh, and their state of preservation and dimensions being recorded. After each tumbling step, they were put back in the barrel for the next tumbling step.

3.3 Selected moldavites

For reliable comparisons (results of each cycle) moldavites of similar weight were chosen. Their dimensions are shown in Tables 1-4.

4. Results

4.1 Cycle no. 1

During this cycle six abrasion stages were observed (Fig. 2.A, see also Table 2). Originally, the moldavite specimen weighed 1.372 g and its dimensions were 20x17x15 mm. After 30 minutes of tumbling (ca. 1.9 km of transport) this tektite lost about 44% of its preliminary weight. It was sub-angular with low-sphericity in shape. The glass surface became smoother and matte.The glass edges blurred and became noticeably blunt. In the next stage (ca. 3.8 km of transport) the moldavite became more rounded with an additional weight loss of about 23%. The glass surface became matt with abrasion signs. It was sub-angular with a high-sphericity shape. Observation after a distance of 5.7 km recorded a further

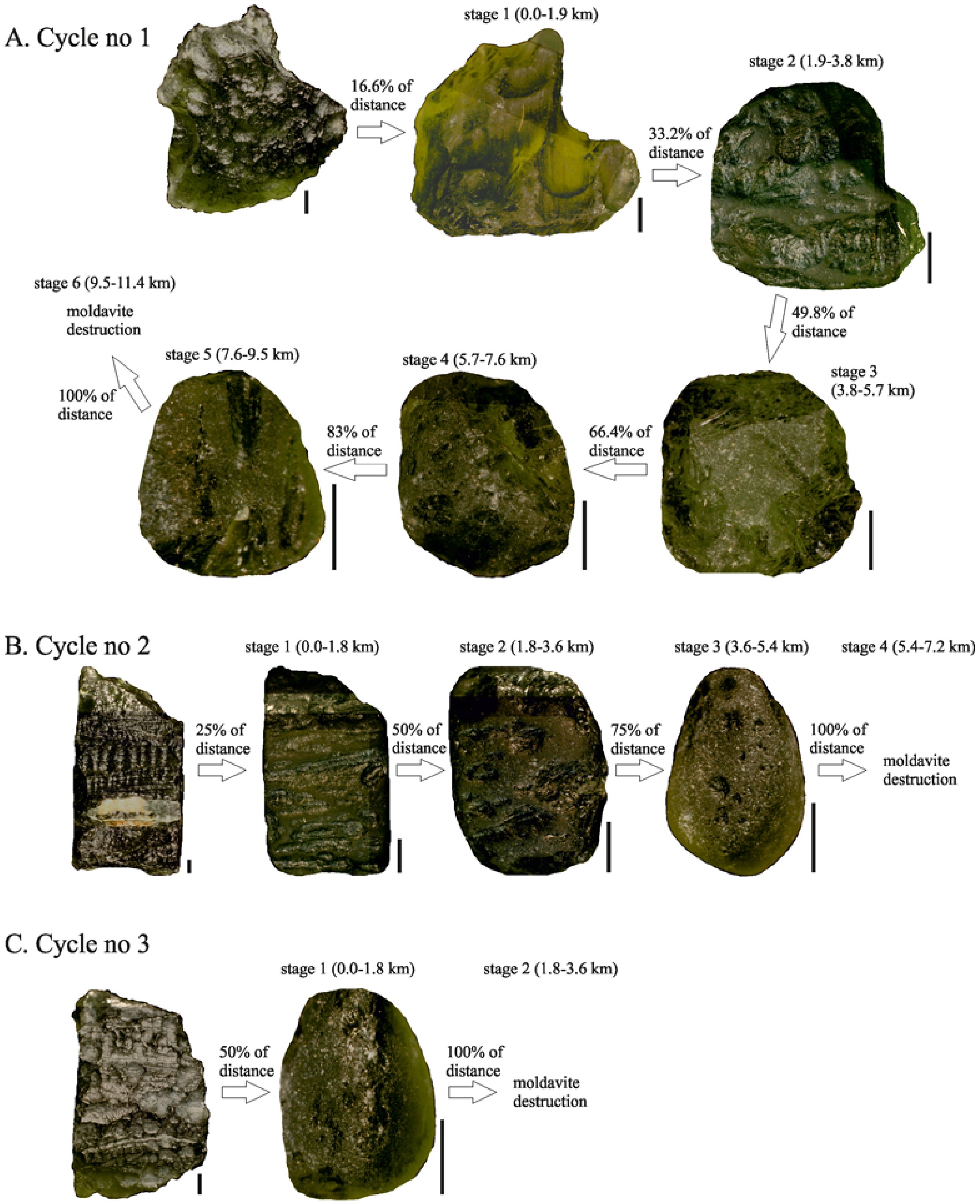

Figure 2: Diagram showing the respective stages of moldavites abrasion during three cycles (see also Fig. 3 and Tables 1-4). Scale bar = 2 mm.

weight loss of ca 15%. From this stage, the moldavite became sub-rounded with high sphericity. During the last two stages the weight loss reached 10 and 7% respectively. The glass shape remains generally unaffected. It was a characteristic small, rounded with high-sphericity, grain with smooth surface. Between 9.5 and 11.4 km of transport, the moldavite was totally destroyed.

4.2 Cycle no. 2

During this cycle four abrasion stages were observed (Fig. 2.B, see also Table 3). Originally, the moldavite weighed 1.615 g and its dimensions were 32x16x14 mm. After 1.8 km of transport, a weight loss of about 57% was recorded. The shape of the tektite became sub-rounded with low sphericity. Subsequent observations documented a reduced weight loss of moldavite. After 3.6 km oftransport, the tektite became rounded with low-sphericity, with surface abrasion signs. During the last step observation (after 5.4 km of transport) moldavite was well-rounded with low-sphericity. It clearly showed surface abrasion signs. Between this distance and 7.2 km, the remaining moldavite speck was completely destroyed.

4.3 Cycle no. 3

During this cycle only one abrasion stage was characterized (Fig. 2.C, see also Table 4). Originally moldavite weighted 1.493 g and its dimensions were 25x19x15 mm. After 1.8 km of transport, the moldavite lost almost 76% of its weight, and became smoother and rounded with low-sphericity shape. Glass was completely destroyed between 1.8 to 3.6 km of reworking.

Table 2: Progressive steps of moldavite abrasion during cycle no. 1. Comments and explanations in text (see also Figs. 2-3).

Distance (km)	Weight (g)	Dimensions - length x width x height (mm)	Weight loss (g)	Weight loss from initial weight (%)
Primary moldavite	1.372	20x17x15	0.000	0.000
0-1.9	0.764	12x10x8	0.608	44.376
1.9-3.8	0.584	10x9x7	0.180	23.622
3.8-5.7	0.495	9x9x6	0.089	15.394
5.7-7.6	0.445	7x7x5	0.050	10.118
7.6-9.5	0.413	6x6x5	0.032	7.377

Table 3: Progressive steps of moldavite abrasion during cycle no. 2. Comments and explanations in text (see also Figs. 2-3).

Distance (km)	Weight (g)	Dimensions - length x width x height (mm)	Weight loss (g)	Weight loss from initial weight (%)
Primary moldavite	1.615	32x16x14	0.000	0.000
0-1.8	0.689	15x8x8	0.926	57.347
1.8-3.6	0.520	10x7x6	0.169	24.566
3.6-5.4	0.426	7x5x5	0.094	18.241

Table 4: Progressive steps of moldavite abrasion during cycle no. 3. Comments and explanations in text (see also Figs. 2-3).

Distance (km)	Weight (g)	Dimensions - length x width x height (mm)	Weight loss (g)	Weight loss from initial weight (%)
Primary moldavite	1.493	25x19x15	0.000	0.000
0-1.8	0.362	6x5x4	1.131	75.783

5. Discussion

5.1 Fluvial abrasion of studied moldavites

Initial results of experimental reworking of moldavites showed that their abrasion progresses very quickly (mainly during the early phase of cycles) and their transport is only possible on relatively short distances (Brachaniec, 2018). For the purpose of experiment tumbling cycles carried out by Brachaniec (2018) are provided as "cycles no. 0" (see also Table 5) since they constitute preliminary results. Undoubtedly, results of cycles no. 0 evidence that the initial size and shape of moldavites are influential on the total reworking distance, despite the same sedimentary type and river velocity used in the cycles. Nevertheless, these new results provide more accurate data on the suspected original hydrogeological conditions. Based on the results of the three cycles, four main steps of fluvial abrasion of moldavites are distinguished:

- Step 1 (stages 1 in cycles nos. 1, 2). This step can be distinguished in cycles where the sand proportion in the sediment sample reaches a minimum of ca. 25%. It covers the first stage of transport, in this case ca. 20-25% of the total distance. The edges become then rounded; there are also traces of abrasion on the glass surface, rendering it matt. Despite the significant weight loss (up to 57%), the original shape of the tektite is still recognizable.
- Step 2 (stages 2 in cycles nos. 1, 2). This step covers the abrasion change occurring during the last ca. 30-50% of the total distance. The glass becomes much more rounded than that in previous step, making it impossible to recreate the original shape. The surface becomes dull and practically flat. In cycle no. 2, clear abrasion marks appear on the tektite surface.

- Step 3 (stages 3-5 in cycle no. 1, stage 3 in cycle no. 2 and stage 1 in cycle no. 3). Abrasion effects are occurring on the tektite from 50% transport distance until total destruction. The glass is rounded, first with alow, then with a higher sphericity. Its surface is completely matt. In step 3 of cycle no. 2, clear abrasion marks are visible on the surface.
- Step 4. Total moldavite destruction.

5.2 River velocity and deposits importance

From these results it was noticed that both the type of sediment and the river velocity are equally important to state the rate of fluvial abrasion (Table 5). In the case of the Lusatian Neisse (cycle no. 1), moldavite survived longer reworking, in contrast to cycles 2 and 3, with river velocity lower by 42% and a higher proportion of gravel fraction. In addition, the same applies in cycles 2 and 3, with similar river velocity but a different amount of gravel (in cycle 3 there was a higher proportion of gravel). However these values remain approximate but are nonetheless highly indicative. Comparing accurately such results between all cycles requires having available three identical moldavites, of similar shape and weight. In the results of cycle no. 1, the sedimentary type and initial size of moldavite were very similar to those of cycles no. 0 (Table 5). Nevertheless, due to the much lower speed of tumbling (by about 65%) in the current study, 6 stages were recorded and moldavite withstood up to 11.4 km of transport, more than the 7.2 km of cycles no. 0, all this indicates the importance of the speed of tumbling. It is also worth noticing that the currently used tektite had a lower initial weight of 0.3 g. Interestingly, the results obtained by Brachaniec (2018) and these from cycle no. 2 are similar despite the difference in the river velocity and the sedimentary type. The weight of the tektites in this case was similar, so it does not have an influence on the final results. In the case of cycle no. 2 the same reworking distance is probably caused by a combination of a lower river velocity and a higher gravel amount. The gravel amount plays a major influence on the glass reworking distance, as shown in cycle no. 3. The significant increase of gravel fraction in the host sediments highly contributed to the rapid destruction of the tektite. Of special interest also is the percentage of weight loss during stages no. 1. The first episode of reworking seems to be the most important, because of the highest weight loss, and a clear change in the tektite shape. In cycle no. 1, the weight loss was approx. 44%. In the previous results from cycles no. 0, this value even reached 64%. This difference is mainly due to the tumbling speed, since the deposits at hand were practically identical. So a huge weight loss is induced by the primal, irregular glass shape making it much more vulnerable to abrasion in contrast to regular shapes. The percentage rate of weight loss decreases stepwise with the increased rounding of the glass (Fig. 3). In stages 2 of cycles 0 and 1 the weight loss is noticeably different (ca. 5%). However, it most likely results from quite significant differences in the initial shape of tektite. In stage 1 of cycle no. 2, the weight loss is 57%. This value is comparable to those of cycles no. 0. The same rate of fluvial abrasion contributes evenly to the same reworking distance (7.2 km). When the tektite gets fully rounded, the rate of erosion is subsequently strongly reduced. It is interesting to note that moldavite was completely destroyed after stage 3 in cycle no. 2, when the mass loss decreases with the transport distance (Fig. 3). More stages should havebeen expected, as in the case of cycle no. 1, in which the weight decrease is slighter. Nevertheless, the lack of stage 4 in cycle no. 2 indicates an uneven rate of fluvial abrasion, probably due to the destruction of large gravel.

Table 5: Reference summary showing the distance of moldavite reworking depending on the hydrogeological conditions adopted in experimental tumbling.

	River velocity (km / h)	Deposits - sand / gravel (kg)	Moldavite weight (g)	Total distance of transport (km)
Brachaniec (2018) (cycles no. 0)	10.8	2/3	1.642	to 7.2
	10.8	2/3	1.497	to 5.4
this study (cycle no. 1)	3.8	2.1/2.9	1.372	to 11.4
this study (cycle no. 2)	2.2	1.2/3.8	1.615	to 7.2
this study (cycle no. 3)	2.2	0.4/4.6	1.493	to 3.6

5.3 Reworking of Polish moldavites

The present results clearly indicate that the most favourable environments delivering redeposited moldavites are rivers closer to the German border, in sediments with a significantly larger quantity of sand. Nevertheless it should be noted that the experimental conditions only theoretically reflect genuine environmental conditions. The velocity of rivers depends on the area they are running through, the climate and the geomorphology of the ground surface. It should also be kept in mind that the velocity of rivers varies along its many sections. Numerous bends and river meanders as low-energy environments could contribute to the settlement and to the good preservation of the tektite glass. Unfortunately, such conditions cannot be faithfully reproduced in laboratory

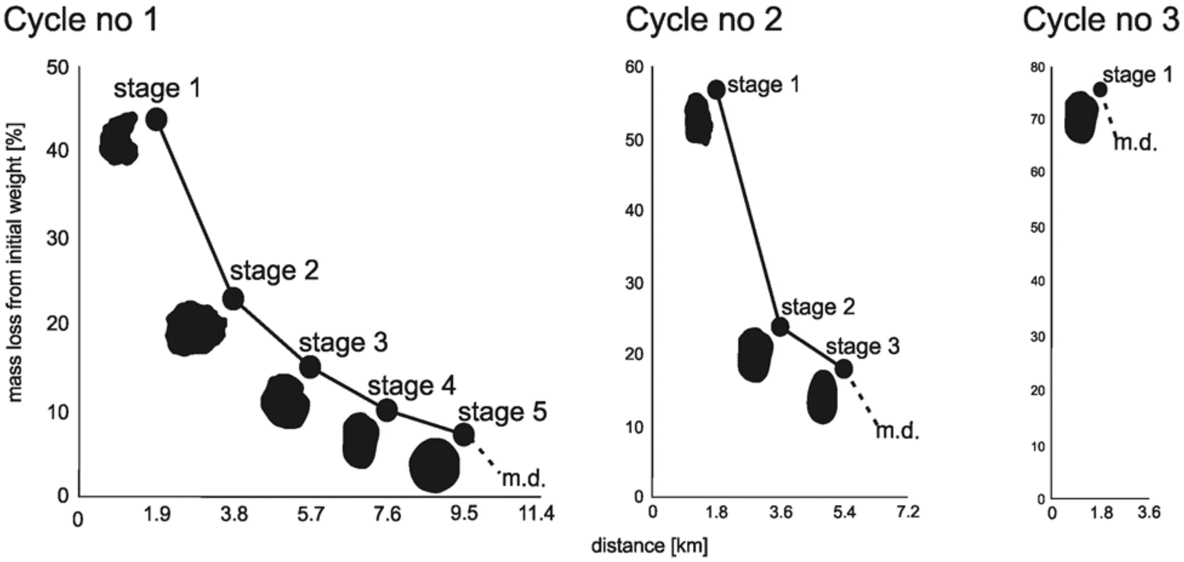

Figure 3: Diagram showing the relationship between weight loss (%) and reworking distance of tumbled moldavites during each cycle and stage. General type of glass shape is also shown. m.d. - moldavite destruction. See also Fig. 2 and Tables 2-4.

conditions. This makes the term 'supply areas' of Polish tektites debatable. According to Szopa *et al.* (2017) and Brachaniec (2018) moldavites from the Gozdnica and Lasów pits could successfully resist several tens of kilometers of transport (assuming their large initial size) and may most likely come from the Zittau area (Fig. 1). Results of presented cycles tend to support such an assertion. Tektites found in the Lusatian Neisse sediments could have theoretically withstood longer reworking than those from the Strzegom region, due to the higher sand fraction in the river sediments. A large amount of gravel in the river deposits undoubtedly limited the distance of tektite reworking in pits located between Wrocław and Strzegom (Fig. 1). Even assuming their large initial size, it seems impossible they could survive more than a few dozen kilometers of transport. As Brachaniec (2018) already suggested, they may most probably originate from the Strzegom Hills area. Despite the large amount of gravel in these deposits, this region, according to Grocholski (1977) and Kural (1979), was likely facilitating longer reworking of tektites due to the numerous depressions. It should also be kept in mind that the intense destruction of tektites in the Strzegom region is supported by the fact that the sharp-edged tektites found in the North Stanisław pit are most likely shards, separated from the main glass mass. According to Trnka and Houzar (2002), fragmentation of tektite glass is a final result of abrasion.

The cardinal question is the origin of the moldavites within the identified potential supply areas. The recent find of an entire moldavite in the North Stanisław pit within Middle Miocene mud (Brachaniec, nearing completion) most likely indicates that these tektites may have been ejected at a distance over 500 km from the Ries structure, as the numerical simulations of Stöffler *et al.* (2002) and Artemieva *et al.* (2013) have shown.

6. Summary

The present study reveals how difficult it is to determine the relationship between the weight loss of tektite glass, the type of sediment and the river velocity. Nevertheless both of these factors seem to play an important role in moldavite fluvial abrasion. However the experimental tumbling results at hand should be treated theoretically. Actually the moldavite transport does not only depend on the river velocity and the type of sediment, but also on many environmental factors that can not be reproduced in laboratory conditions. Various shapes of glass and mass, variable environmental energy over different reworking distances, and local sedimentary changes do contribute to the respective differential stages of fluvial abrasion, and to the duration of resistance to its reworking. Undoubtedly, given the experimental results, must come to the conclusion that abrasion of impact glass happens quickly, and that the tektites could not be transported over considerable distances. Theoretically, assuming favourable environmental conditions (mainly high amount of sand in deposits) and a large initial size, moldavite could endure tens of kilometers of reworking transport, making identification of their supply areas highly speculative.

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