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RELATIONSHIP BETWEEN THE ABRASION OF TEKTITE CLASTS AND THEIR HOST SEDIMENTARY FACIES, PLEISTOCENE, SW POLAND

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Abstract: This study reports on the occurrence of tektite clasts with a markedly different degree of abrasion in two different fluvial facies of the Pleistocene deposits of the Nysa Kłodzka river near Paczków, SW Poland. The question addressed by the study is whether the redeposited and differently abraded tektite glass clasts derive from different distances/sources, or whether their differing degree of abrasion relates to their different host sediment as the medium of river bedload transport. Laboratory tumbling experiments are used to estimate the progress of tektite abrasion with the distance travelled within a bedload sediment of the corresponding grain-size composition. The study concludes that there is a direct relationship between the abrasion degree of tektites and their host sediment facies, but it is not simple and straight forward, as a range of specific factors comes potentially into play. Their role is discussed and is recommended to be taken into account in an abrasion experiment design and in the interpretation of experimental results. The study suggests that the tektite clasts found near Paczków were transported over a distance of about 2–4 km and were derived from denudation of the nearby Bardzkie Mts.

Keywords: Moldavite, fluvial redeposition, sedimentary facies, abrasion, laboratory experiments, provenance.

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INTRODUCTION

Bolide impacts melt ground rocks, with some of the molten material ejected far from the source crater in the form of spherules, a few millimetres in size, and larger glass sherds up to a few centimetres called tektites (Koeberl, 1993; Glass and Simonson, 2012, 2013; Brachaniec *et al*., 2014a). Tektites, as classical impactites with shocked mineral signatures, have long attracted geological research, while raising awareness of their possible redeposition (Koeberl, 1994; Buchner and Schmieder, 2009; Jimenez-Martinez *et al*., 2015). Sediment erosion and redeposition played major role in the distribution of moldavite debris in Central Europe, including the area of Poland (Trnka and Houzar, 2002; Brachaniec *et al*., 2015, 2016; Brachaniec, 2017). Unlike the vast majority of tar-black or brownish-black tektites, moldavite is a translucent deep forest-green natural glass and is the only tektite variety suitable for cutting and faceting as a gem.

The present study is from SW Poland, where moldavites have thus far been documented in fluvial Miocene deposits and interpreted as redeposited distal ejecta from the Ries impact crater in adjacent Germany (Brachaniec *et al*., 2014b), and have also been found in the Pleistocene fluvial terrace deposits of the Nysa Łużycka (Lusatian Neisse) river (Szopa *et al*., 2017). The post-Palaeogene Central Europe was a terrestrial area with extensive river networks (Badura and Przybylski, 2004; Tockner *et al*., 2009), where erosion and large-scale redeposition of tektites was inevitable.

The inherent homogeneity of natural glass makes it impossible to prove tektites synchronicity and to identify the place of their origin (Rodovská *et al*., 2016; Skála *et al*., 2016; Žák *et al*., 2016). Likewise, the resedimentation by land surface processes render uncertain the potential supply areas of moldavites, while experimental tumbling showed that they are highly susceptible to fluvial abrasion (Brachaniec, 2018a, b). Therefore, little is known about the provenance or transport distance of moldavites found earlier in the Pleistocene deposits of the Nysa Łużycka (Lusatian Neisse) in Poland (Szopa *et al*., 2017), as they occur in a single sedimentary facies, whereas their degree of abrasion expectedly depends upon both distance and the mode of fluvial transportation. The present comparative study focuses on three tektites found in two different Pleistocene fluvial facies units of the Nysa Kłodzka river and differing in their degree of abrasion. The question addressed is whether there is a qualitative relationship between the degree of tektite abrasion and the type of host fluvial sediment, and hence transportation hydromechanics. In addition, an experimental tumbling was carried out using sediments of both facies units, to shed light on the intensity of abrasion in a particular transport mode and to assess the potential distance travelled by tektites from the source area.

LOCALITY AND GEOLOGICAL SETTING

The study area is located in the fore-Sudetic part of the Nysa Kłodzka river valley, near the city of Paczków, SW Poland, ca. 72 km south of Wrocław and ca. 70 km southwest of Opole (Fig. 1A). The whole area of the fore-Sudetic part of the Nysa Kłodzka valley is covered mainly with Pleistocene deposits. They form a fluvial terrace system corresponding to the river four main levels (Fig. 1B; Przybylski, 1998): the Upper Terrace, 20–32 m above the present-day river level); the Middle Terrace, 10–17 m above the river level; and two Lower Terraces, 1.5–8 m above the river level. Under the Pleistocene sediments are Miocene sandy gravels with clays as well as Cretaceous marls and clayey shales (Przybylski, 1998).

The pre-Nysa Kłodzka deposits are composed mainly by Sudetic rocks: Permian rhyolites and tuffites of the Intra-Sudetic Depression, gneisses of the Śnieżnik Massif and Bystrzyckie Mountains, and mudstones and lydites of the Bardzkie Mts (Badura and Przybylski, 2004). The investigated profile near the town of Paczków is in the Upper Terrace deposits with an estimated thickness of 4 m (Fig. 1C).

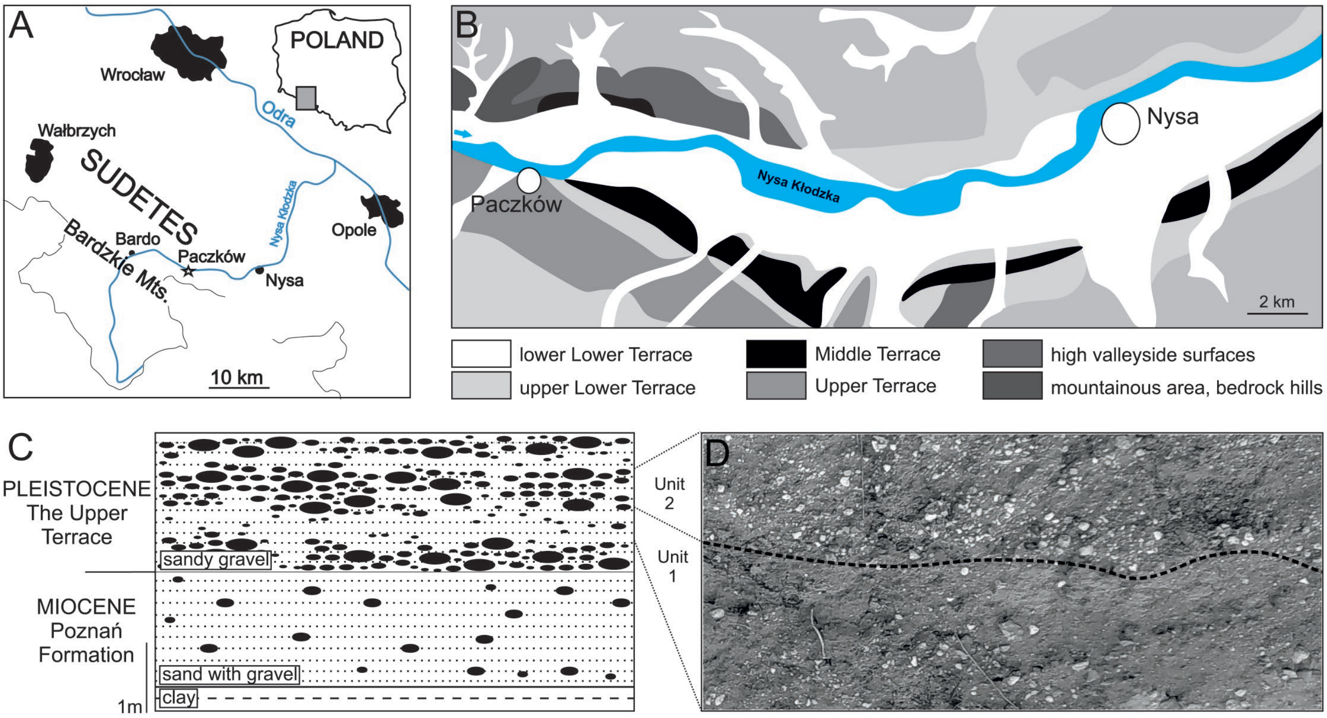

Fig. 1. Study area location. **A.** Schematic map of the Nysa Kłodzka river course in SW Poland with location of the studied outcrop section near Paczków. **B.** Geological setting of the study area (modified from Przybylski, 1998) with indicated fluvial terraces of the Nysa Kłodzka river valley. **C.** Lithostratigraphic profile of the deposits exposed near Paczków. **D.** Outcrop photograph of the moldavite-bearing facies units 1 and 2.

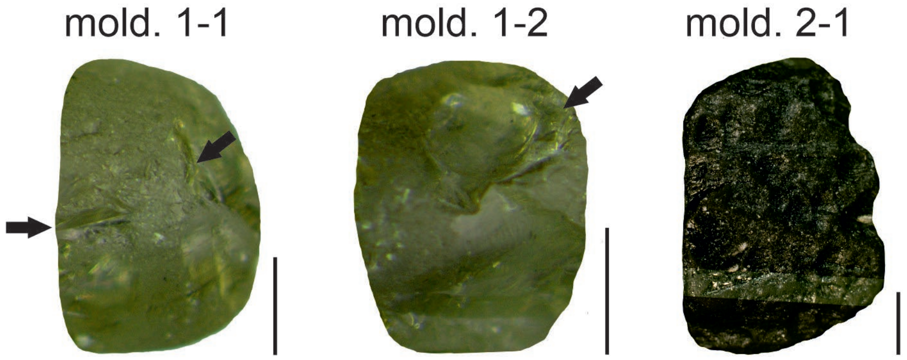

Fig. 2. Moldavite specimens from the Paczków outcrop section (Fig. 1C). Specimens 1-1 and 1-2 are from Unit 1; arrows indicate glass chip-off scars. Specimen 2-1 is from Unit 2. Scale bar is 5 mm.

Exposed at the base are mainly grey clays, overlain by a unit of quartz sand with gravel. These two units are part of the Middle Miocene Poznań Formation (Przybylski, 1998). The upper unit, with a thickness of 1.7 m, is laterally overlain by Pleistocene fluvial deposits, ca. 2 m thick, composed of alternating sand, pebbly sand and gravel. In the middle part of the Pleistocene deposits, the study focused on moldavite-bearing two different facies units, each about 0.5 m thick. Unit 1 is pebbly sand, whereas Unit 2 is a sandy pebble gravel (Fig. 1D). Two moldavite specimens were found in Unit 1 (specimens 1-1 and 1-2, Fig. 2) and one specimen in Unit 2 (specimen 2-1, Fig. 2). The exact age of the Upper Terrace deposits has been long debated, with the most plausible scenario that these sediments formed during the Saalian (Odranian) glaciation (Czerwonka and Krzyszkowski, 1992; Badura *et al.*, 1998, 2007; Krzyszkowski *et al.*, 1998; Krzyszkowski and Biernat, 1998; Przybylski, 1998; Przybylski *et al.*, 1998).

METHODOLOGY

The laboratory experiment was run using bulk sediment samples from both facies units contained moldavite clasts (Fig. 1D). From each unit, a 20-kg sediment sample was analysed in the laboratory to determine the grain-size percentage of sand and gravel, with the gravel divided into three size classes: up to ca. 3 cm, 3–8 cm and more than 8 cm. On this basis, a 5-kg sediment sample for each abrasion cycle was assembled (Table 1) and thrown into the tumbling barrel filled with 10 litres of tap water.

Moldavite clasts from the Czech Republic were used to simulate glass abrasion by river bedload of differing grain-size compositions. The moldavite clasts used were angular, with a high sphericity. The rotation speed of the barrel in each cycle was the same, corresponding to the average flow velocity of the Nysa Kłodzka river, estimated at 4.5 km/h (Haładyj-Waszak, 1975, 1978, 1980). In each laboratory cycle, the tumbling experiment was stopped every 27 minutes, which approximated the river's mean bedload transport distance of ca. 2 km. Once removed from the barrel, tektites were sieved off and their state of abrasion (roundness and size) was compared with that of the primary clasts. The tektite clasts were then put back into the barrel for the next tumbling step. The experiment cycles continued until complete destruction of the moldavite clasts. The tumbling experiments were conducted at the Faculty of Earth Sciences of the University of Silesia, using a rotating barrel LPM-20 (Glass GmbH & Co., KG Spezialmaschinen).

Table 1

Grain-size composition of sediment samples used in the laboratory tumbling experiments on moldavite clast abrasion. Cycle 1 simulated bedload transport for Unit 1 and cycle 2 for Unit 2

Laboratory experiment cycles	Sediment grain-size composition			
	Sand	Gravel size		
		≥3 cm	3–8 cm	>8 cm
Cycle 1 (Unit 1)	2.3 kg (46%)	0.7 kg (14%)	1.6 kg (32%)	0.4 kg (8%)
Cycle 2 (Unit 2)	0.6 kg (12%)	1.3 kg (26%)	2.4 kg (48%)	0.7 kg (14%)

RESULTS

Description of sedimentary facies

Moldavite clasts were found in two different facies units of the Pleistocene fluvial deposits in the Upper Terrace (Fig. 1C, D). Unit 1 consists chiefly of pebbly sand, whereas Unit 2 consists of a sandy pebble gravel with an admixture of small cobbles. Their grain-size composition is reflected in the simulated sediment grain-size mixtures (Table 1). Sand is quartzose, with minor accessory grains of amphibole, pyroxene, biotite and garnet. The gravel fraction is similarly composed mainly of quartz, with subordinate clasts of quartz porphyries, mudstones and sandstones.

Description of moldavite specimens

The moldavite specimens found in these Pleistocene deposits are shown in Figure 2 and are characterized briefly in the present section.

Specimen 1-1 (Unit 1)

This moldavite clast was 13 × 10 × 8 mm in size and weighed 0.722 g. It had the characteristic bottle-green colour of moldavites, but very light and transparent. According to the Powers (1953) scale, the clast was rounded and had a low sphericity. The glass surface showed abrasion scratches, but was relatively smooth, compared to specimen 2-1.

Specimen 1-2 (Unit 1)

This second specimen of moldavite was 11 × 8 × 7 mm in size and weighed 0.643 g. It also was rounded, with a low sphericity and a light bottle-green transparent colour. The glass surface bore less abrasion scratches, compared to specimen 1-1, but showed a major chip-off scar.

Specimen 2-1 (Unit 2)

This tektite specimen differed significantly from the others. It was much larger, 21×14×10 mm in size, and weighed 1.289 g; was sub-angular with a low sphericity; and had a much darker bottle-green colour. It had a matt and heavily worn off surface, with partially preserved circular grain-impact abrasion pits.

The tumbling experiment results

Two independent cycles of moldavite clast abrasion were conducted by experimental tumbling, with cycle 1 simulating bedload transport for Unit 1 and cycle 2 for Unit 2 (Table 1). Two different moldavite specimens from the Czech Republic were sacrificed for this purpose. The experimental results are described in the present section.

Experiment cycle 1

The sediment composition used in cycle 1 was as specified in Table 1. The moldavite clast used was angular, with a rough surface and high sphericity, and an initial weight of 1.148 g. The observed progress in this clast abrasion is shown in Figure 3A and summarized in Table 2.

After step 1, simulating about 2 km of bedload transport, the tektite clast lost 40 wt.% of its initial mass and became subrounded, while its surface became much smoother, with the edges blunt and with characteristic signs of abrasion. Despite its volume loss, the glass was not yet transparent. In step 2, simulating transport by another 2 km – to a distance 4 km, the moldavite clast lost another nearly 21 wt.% of its mass, became rounded and acquired an almost completely smooth surface, while the glass became transparent. In step 3, simulating transport to 6 km, the tektite clast became well-rounded and acquired an even smoother surface, while its weight decreased to 0.456 g, that is ca. 40 wt.% of the initial mass.

In the subsequent tumbling step, the moldavite clast was totally pulverized, which meant its destruction at a transport distance between 6 and 8 km.

Experiment cycle 2

The sediment composition used in cycle 2 was as specified in Table 1, imitating Unit 2. The moldavite clast used was similar – angular, with a rough surface and high sphericity, and with an initial weight of 1.895 g. The observed progress in this clast abrasion is shown in Figure 3B and summarized in Table 3.

In the first step of abrasive tumbling in this cycle, simulating bedload transport to a distance of about 2 km, the moldavite clast lost ca. 70% of its initial weight, while becoming rounded and transparent. Its surface showed numerous traces of intense abrasion. The clast was then totally pulverized in step 2, which meant its destruction at a transport distance between 2 and 4 km.

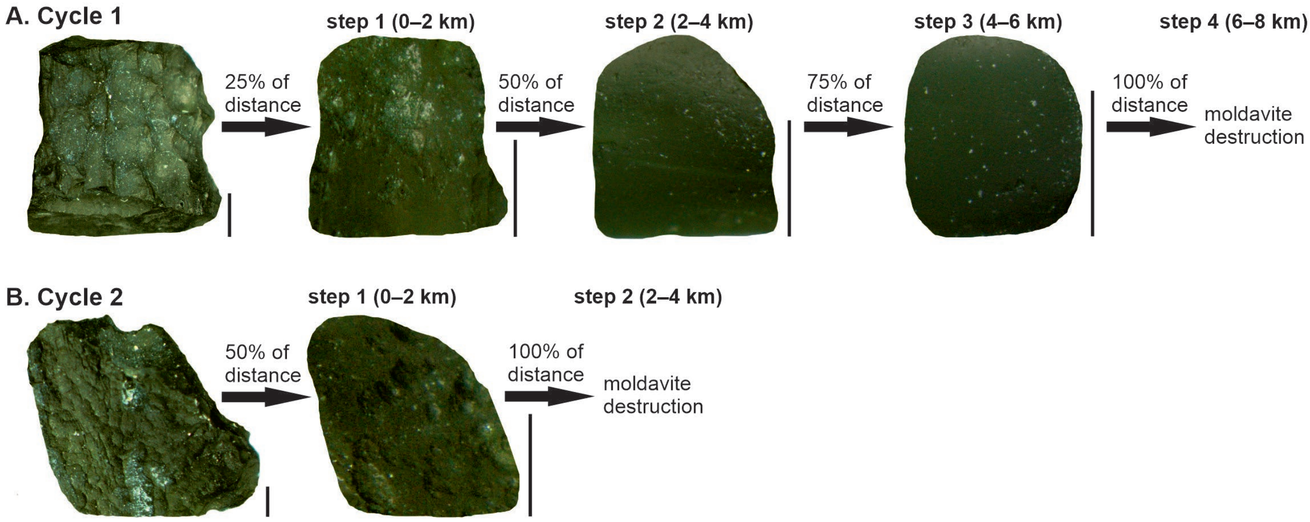

Fig. 3. Photographic illustration of the progressive abrasion of moldavites clast in the laboratory tumbling experiments. **A.** Experiment cycle 1 (see Table 2). **B.** Experiment cycle 2 (see Table 3). The respective bedload sediment used is as specified in Table 1. The distance %-value pertains to the moldavite clast's survival distance in particular bedload transport conditions. Scale bar is 5 mm.

Table 2

Successive steps of moldavite progressive abrasion during experimental cycle 1 (see also Table 1 and Figs 3A, 4A)

Tumbling experiment steps	Simulated transport distance (km)	Moldavite grain changes			
		Weight (g)	Dimensions (mm)	Weight loss (g)	Weight loss fraction (%)
Initial conditions		1.148	18×16×14	-----	------
1	0–2	0.687	11×9×8	0.461	40.233
2	2–4	0.545	9×7×6	0.142	20.783
3	4–6	0.456	7×6×6	0.089	16.417
4	6–8	Moldavite grain pulverized			

Table 3

Successive steps of moldavite progressive abrasion during experimental cycle 2 (see also Table 1 and Figs 3B, 4B)

Tumbling experiment steps	Simulated transport distance (km)	Moldavite grain changes			
		Weight (g)	Dimensions (mm)	Weight loss (g)	Weight loss fraction (%)
Initial conditions		1.895	31×25×22	-----	------
1	0–2	0.572	10×8×7	1.323	69.825
2	2–4	Moldavite grain pulverized			

DISCUSSION

The present study of the Pleistocene fluvial deposits in the Upper Terrace of the Nysa Kłodzka river, SW Poland, had found – in same outcrop near Paczków – specimens of moldavite differing markedly in their degree of abrasion and hosted by different sediment facies. The source of moldavites in the region's Pleistocene is unknown, taking into account their transportation and redeposition by fluvial drainage. Since tektites are highly sensitive to abrasion, the following key question arose: Might these differing moldavite clasts derive from different distances/sources, or perhaps their differing degree of abrasion relates to the difference in their host sediment as a bedload transport medium? This issue was addressed herein by an experimental tumbling study on the rate of tektite glass abrasion, using typical moldavite specimens and sediment grain-size mixtures resembling closely those of the two host facies in the outcrop section.

The moldavite specimens 1-1 and 1-2 from Unit 1 (Fig. 2) resembled in their shape and surface sculpturing the laboratory moldavite clast after its 2nd step of abrasion in the experimental cycle 1. Tektites with a comparable state of abrasion were described from the Pleistocene deposits of Lusatia (Lange, 1996) and western Bohemia (Trnka and Houzar, 2002). The laboratory tektite clast after the 3rd step of cycle 1 appeared much more rounded and had a considerably smoother surface. It would thus appear that the moldavite specimens 1-1 and 1-2 travelled only about half of their destructive transport distance and might have originally weighed between 1.3–1.6 g. The experiment confirms that the moldavites were redeposited by fluvial transport, but their source was apparently no farther than around 2–4 km away (Table 2), which would explain also why moldavite finds in the Pleistocene deposits in the region are not particularly rare.

It is further worth pointing out that the initial mass and shape of moldavite clast have a significant effect on the duration of the clast survival in river bedload transport (see also Brachaniec, 2018a). First, it will take a longer transport for a larger clast to be totally destroyed by abrasion. Second, as the clast becomes better rounded – its abrasive frictional interaction with the host bedload sediment grains decreases, which extends its survival and potential transport distance (Fig. 4A).

The moldavite specimen 2-1, from Unit 2, seemed to represent an abrasion state intermediate between that of a primary glass sherd and that formed after the 1st step of the experimental cycle 2. On the one hand, its surface was too grated for a primary tektite, while its shape was still too irregular as for a complete step 1 of abrasive transport. However, it should be kept in mind that the sediment hosting specimen 2-1 is considerably coarser-grained (cf. Table 1), which may imply a significantly higher flow power and transport velocity. This moldavite specimen may have thus been effectively transported over a similar distance as those in Unit 1, but its transportation rate was much faster and did not inflict the degree of abrasion expected from the constant-speed tumbling experiment. Assuming that specimen 2-1, similarly as specimens 1-1 and 1-2 at the same locality, was deposited about halfway of its survival travel distance, its original weight may have been about 2.5–2.6 g. However, this estimate may not be quite correct, as the faster-transported tektites will expectedly have a lower rate of abrasion and longer survival distances.

The experimental study suggests the following three main phases of moldavite clast abrasion in fluvial bedload transport:

Moldavite clasts, depending on their hosting sediment load, lose a major part (40–70%) of their mass after having travelled about 30% of their survival transport distance. The clasts become subrounded (cf. step 1 of experiment cycle 1) and their surfaces smoother, while showing clear abrasion marks.

The mass-loss rate of moldavite clasts decreases in the next 30–50% of the survival transport distance, as the clast roundness increases and renders them less abrasive. The original shape of clasts becomes impossible to reconstruct, while grain impact pits are more visible (cf. step 2 of experiment cycle 1 and step 1 of experiment cycle 2).

After having travelled 50–75% of their survival transport distance, the moldavite grains are considerably smaller and well rounded, and acquire smooth surfaces (cf. step 3 in experiment cycle 1). Afterwards, they become increasingly destroyed by abrasion and eventually pulverized.

The study points further to the impact of the tektite-carrying river bedload, with its grain-size range, transport speed and mineral composition as important factors. First, a gravel-rich bedload sediment might be expected to exert greater internal clast abrasion, but some of the relatively small tek-

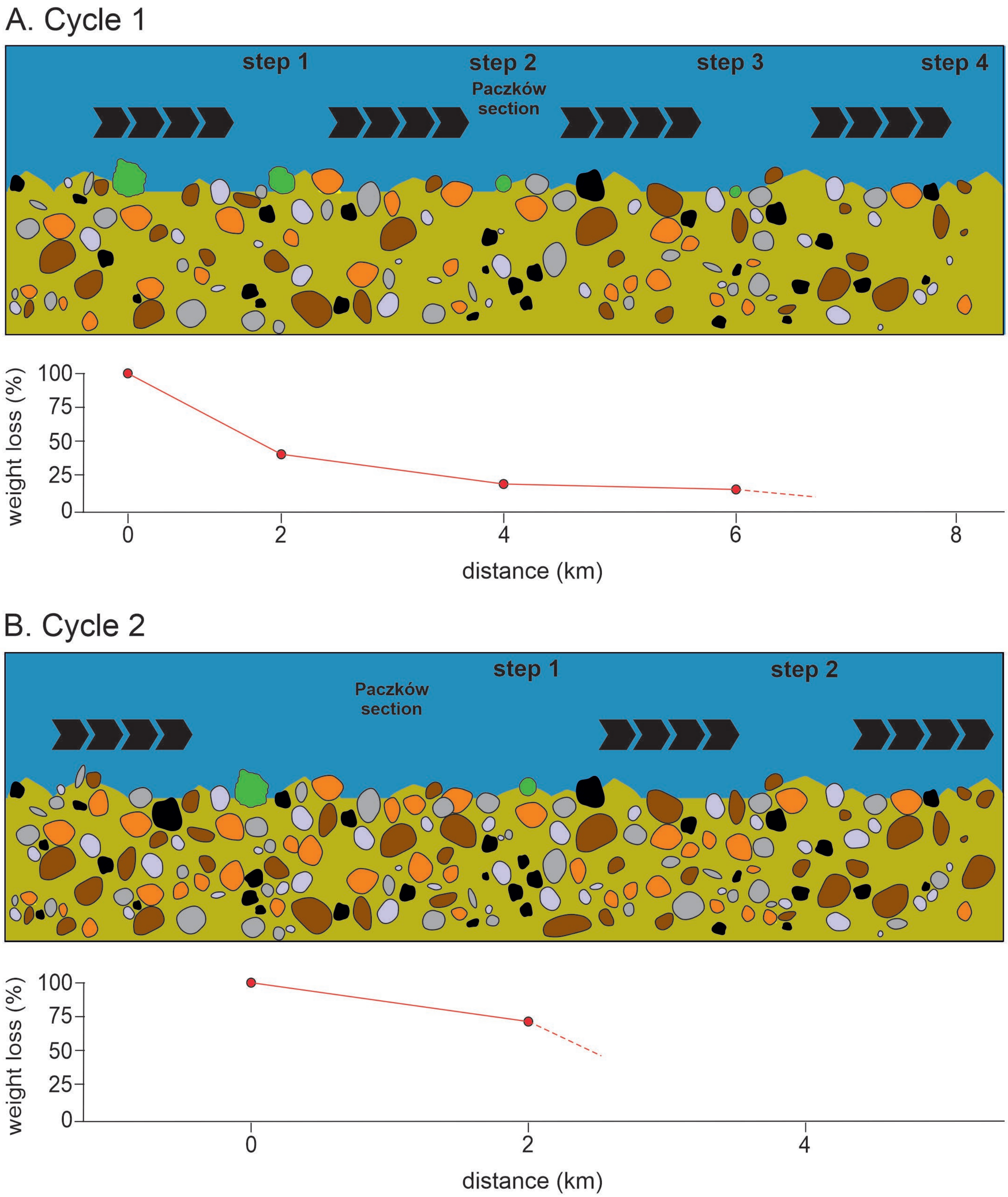

Fig. 4. Schematic presentation (tektite clasts in green) and quantitative clast weight-loss data of the moldavite clast abrasion in the laboratory tumbling experiments. **A.** Experiment cycle 1 (see Table 2). **B.** Experiment cycle 2 (see Table 3). The simulated bedload grain-size composition in each cycle is as specified in Table 1. For the visible abrasion progress in each case, see Figure 3.

tite grains may escape rapid abrasion by being carried by chance mainly within the interstitial spaces between large colliding clasts (cf. experiment cycle 2). On the other hand, the spatial rate of tektite abrasion appears to be lower when the transporting bedload is sandy. For example, a laboratory simulation for the first-discovered occurrence of tektites in the Polish Pleistocene, at the Lasów site (Szopa *et al*., 2017), suggested that they could have been theoretically transported over several dozen kilometres owing to the high sand content in the Nusa Łużycka's (Lusatian Neisse's) bedload (Brachaniec, 2018a, b). Second, a coarser-grained bedload will likely be carried by a faster flow, which may render the effective spatial rate of tektite-grain abrasion significantly lower than expected to a given travelled distance (cf. experiment cycles 1 and 2). Third, the hardness of tektite clasts is in the range of 5 to 6 in the Mohs scale (Simmons and Ahsian, 2007), while quartz debris, as in the present case, has a hardness of 7. The more quartz clasts are carried in the river bedload, the more abrasive the transport of tektite clasts is expected to be. The moldavite-bearing Pliocene and earlier Miocene fluvial deposits in SW Poland are quartz-dominated, and hence their potential for long-transport tektite preservation was quite low. Finally, the fluctuations of river flow energy must be taken into account, as the river – in relation with its sediment facies deposited at a particular site – may deliver tektite clasts with a differing degree of abrasion.

On the account of the Pleistocene regional palaeogeography and fluvial drainage pattern in the study area and the experimental assessments of tektite transport distance, it is suggested that the moldavites clasts in the present case were probably derived from the nearby Bardzkie Mts (Fig. 1A). This mountain range is recognized as the provenance area for metamorphic mudstone and lydite clasts in the Pleistocene fluvial deposits of the Nysa Kłodzka palaeovalley (Badura and Przybylski, 2004).

CONCLUSIONS

The study indicates that the fluvial abrasion of tektite clasts is a process controlled by several factors, including the grain-size range, transport velocity and mineral composition of a river bedload. The survival transport distance of tektites appears to be longest in cases of a sandy bedload, which is less abrasive and generally means slower rivers. However, tektite clast abrasion is not instantaneous. Fast-flowing rivers tend to carry a coarser and more abrasive bedload, but may transfer tektites over comparably long distances before a destructive amount of abrasion is reached. There is thus a direct relationship between the abrasion degree of tektites and their host sediment facies, although it is not quite simple and straight forward.

Laboratory tumbling experiments are a useful and valid means of assessing the transport distance of tektites, provided that the experiment is carefully designed and its results are considered with all the potential controlling factors in mind. The bedload transport rate of a river is not necessarily steady, and even a sandy bedload can be episodically transported at an accelerated speed. Furthermore, the small tektite clasts in fast-flowing and gravelly rivers may be lifted into suspension and thereby escape a steady-state bedload abrasion. In short, the more realistic is a tumbling experiment design, the more reliable are its results as a predictive tool for the tektite abrasion and transport distance.

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