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An experimental model for the tektite fluvial transport based on the most distal Polish moldavite occurrences

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Abstract–Reworking and redeposition of tektites is a highly complex and multistage geological process including many factors. A tumbling experiment was therefore undertaken with the aim of estimating a distance of transport that such moldavites can withstand. Though the experiment probably did not accurately mimic natural conditions, our results proved that moldavites can withstand considerable transport only over a distance of a few kilometers. Observed abrasion of tektites was significant in the early stage of experimental transport; the rate of abrasion decreased correlatively with increasing distance of transport as usual. Overall, given the results obtained from this experimental study and their state of preservation described in the literature, it is very likely that Polish tektites were reworked and redeposited by rivers from the Sudetes Mountains. Based on the paleoreconstruction of river flows, it can be assumed that the Polish tektites originated from two independent sediment supply areas.

INTRODUCTION

Tektites are distal ejecta that can be found over a distance of more than 10 crater diameters (Glass and Simonson 2012). They are natural silica-rich glasses, from the melting of sediments, after impact, and are distributed over large areas where they are subject to many geological processes, leading to the so-called "age paradox" (McCall 2001). That is, the age of the tektite-bearing deposits differs widely from the age of the originating impact.

Reworking of impact ejecta has been documented from numerous impact sites (Simonson and Glass 2004; Buchner and Schmieder [2009] and literature cited therein). Since 1963, when radiometric methods for determining the age of deposits were elaborated (Gentner et al. 1963), it has been stated that two craters located in southern Germany, i.e., Steinheim (3.8 km in diameter) and Ries (24 km in diameter), and the Central European tektite strewn field, all resulted from a sole impact event dated from 14.93 to 15 Ma (Rocholl et al. 2017). This implies that their origin traces back to Middle Miocene. These craters were formed by the impact of a binary asteroid consisting of two fragments of different diameters, i.e., 1500 m (Ries) and 150 m (Steinheim; Stöffler et al. 2002). Moldavites were produced from the fluvial to lacustrine foreland basin deposits, as a product of melting mainly quartz sands, clay minerals, and carbonates (Meisel et al. 1997; Rodovská et al. 2016; Skála et al. 2016; Žák et al. 2016). At present, they represent distal ejecta, scattered over the territory of the Czech Republic (Trnka and Houzar 2002), Lausitz area in Germany (Lange 1996), Austria (Koeberl et al. 1988), and Poland (Brachaniec et al. 2014b, 2015, 2016; Brachaniec 2017; Szopa et al. 2017). Moldavites and "Tertiary" sediments in the surroundings of the Ries structure are characterized by a very high geochemical homogeneity (Rodovská et al. 2016; Skála et al. 2016; Žák et al. 2016).

In the case of impact ejecta, reworking and redeposition is complex, resulting from fluvial reworking, gravity flows, or glaciers. According to Buchner et al. (2003) and Buchner and Schmieder

(2009), fluvial transport played a significant role in the distribution of proximal and distal Ries ejecta. Due to moldavite reworking and redeposition, they occur in the various age sediments. Only the age of two Czech moldavites-bearing deposits, the Domanin Formation and the Moravian colluvio-fluvial clays with sandy gravels, is coeval to the Ries impact/moldavites formation (Ševčík et al. 2007; see also Skála et al. [2016] and references cited therein).

Some authors (Bouška et al. 1968; Cífka et al. 1971; Lange 1996; Žák 2009) question the possibility of a long transport (>several dozens of km) of tektites due to their fragile nature. According to Trnka and Houzar (2002), most moldavites had only been transported over a short distance (a few kilometers), although redeposition of distal impact glass over a long distance was also reported (Vamberková and Ševčík 1990). Based on paleogeographical reconstruction and from the Polish tektite size, Brachaniec et al. (2014b, 2015, 2016) concluded that they originated from Lusatia. In order to test this suggested long-distance moldavite transport, tumbling experiments were conducted. In particular, this paper intends to evaluate the distance of transport sufficient to provide complete tektite disintegration and subsequently to delineate the possible sediment supply areas of Polish moldavites.

GOZDNICA FORMATION

Tumbling experiments were conducted using sediments from the Gozdnica Formation (Fig. 1). These are alluvial deposits of the Sudetic Foreland probably deposited during the Pannonian (Mai and Wähnert 2000; Szynkiewicz 2011), though a Pliocene age cannot be completely excluded (Badura 2012; Kramarska et al. 2015). This formation is mainly represented by poorly sorted gravels and sands, rich in quartz, quartzite, feldspar, granite, and gneiss. Detailed description of these sediments with associated tektites can be found in Brachaniec et al. (2014b, 2015, 2016) and Szopa et al. (2017).

MATERIAL AND METHODS

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; see also Gorzelak and Salamon 2013; Gorzelak et al. 2013; Salamon et al. 2014).

An experiment ended after complete destruction of tumbled moldavites. A bulk sediment sample (5 kg) from the Miocene Gozdnica Formation was used. It contains about 3 kg of quartz gravels and 2 kg of coarse sand. The majority of gravels display a diameter ranging from 3 to 8 cm (1.5 kg), or are up to about 3 cm in diameter (1 kg). Large clasts (i.e., displaying more than 8 cm in diameter) are rare (0.5 kg). During the first cycle, inside the rotating barrel filled with these sediments, a specimen of moldavite (1.642 g in mass) was inserted. In the second cycle, another tektite was used (1.497 g in mass). In each cycle, the barrel was filled with 10 L of water.

Fig. 1. General view of typical Gozdnica Formation sediments outcropping in the Gozdnica sandpit. Pickaxe is for scale.

Tumbling speed (approximately 3 m s^{-1}, calculated from RPM) corresponds to ~10.8 km of transport distance per 1 h. These parameters for rivers in SW Poland were taken from Haładyj-Waszak (1981) and Meyer (1987). During the tumbling process, tektites were sieved and we documented their preservation and dimensions every 10 min, corresponding to 1.8 km of transport. After observation, we placed the tektites back in the tumbler. During the experiment, roundness and sphericity of moldavites were estimated and compared to Powers's (1953) patterns (Fig. 2).

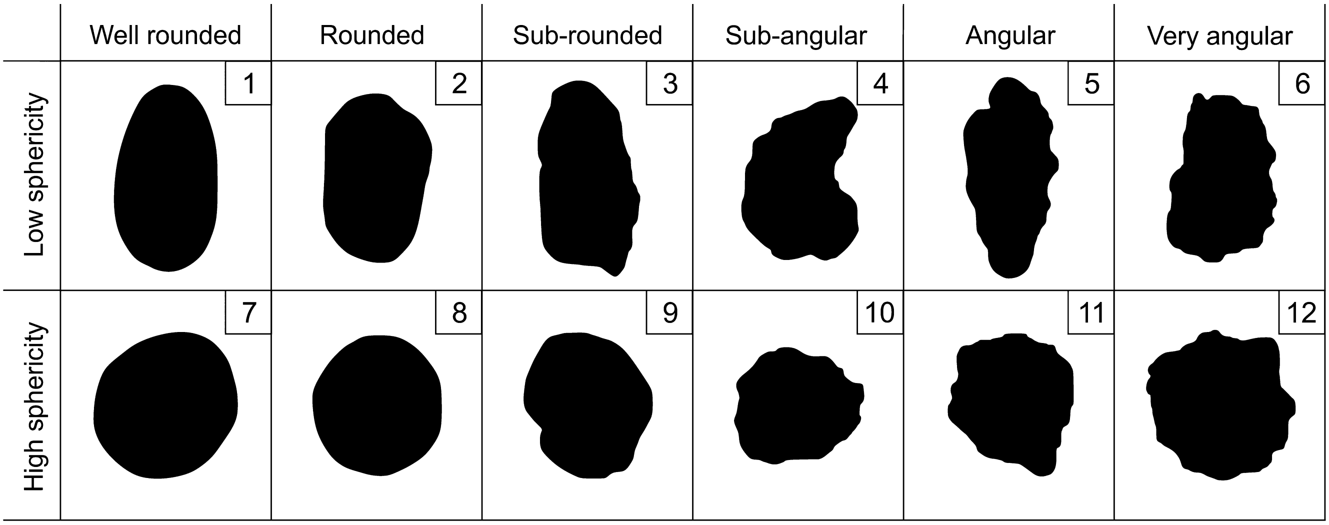

Fig. 2. Evaluation scale of roundness and sphericity of mineral grains (after Powers 1953).

RESULTS

Experimental cycles describing the precise effects of fluvial abrasion on each moldavite are presented below.

First Cycle (No. 1)

A moldavite specimen weighing 1.642 g with dimensions of 28 × 23 × 21 mm was used (Fig. 3A; Table 1). After 10 min of tumbling (i.e., a time equivalent to ~1.8 km), a weight loss of about 59% was recorded. At this stage, the edges of the moldavite specimen became noticeably more blunt and worn out. Subsequent observation after transport of 3.6 km recorded a further weight loss of ~18%. During this stage, the moldavite became more rounded. The surface of glass turned matte with abrasion signs. The last abrasion stage was registered after 5.4 km of transport. The surface of tektite was totally smooth. Between this distance and 7.2 km, the remaining moldavite fragment was totally destroyed.

Second Cycle (No. 2)

During this cycle only three abrasion stages were observed. A moldavite specimen weighing 1.497 g with dimensions 22 × 21 × 19 mm was used (Fig. 3B; Table 2). After ~1.8 km of transport, a weight loss of about 64% was recorded; this value is very similar to weight loss during first stage of first cycle. The shape of tektite became much more rounded. Subsequent observations documented less reduction in weight loss of moldavite. After 3.6 km of transport, tektite became rounded with many abrasion signs on the surface. This is the final stage before total glass destruction.

Tables 1 and 2 and Fig. 4 summarize each step of erosion of moldavite in both cycles.

DISCUSSION

Problematic Interpretation of Polyphasic Reworking of Moldavites

Polyphasic fluvial reworking of moldavites is commonly known from Czech and Lusatian sections (Bouška 1964, 1988; Žebera 1972; Lange 1996; Bouška et al. 1999). Sporadic reworked moldavite finds outside substrewn fields have been reported from many Czech sections, e.g., the Kobylisy sandpit in Prague (Žebera 1972) and the Berounka River (Ložek and Žák 2011). Localization of the moldavite source, as is the case of Lusatian finds, remains controversial due to their common fluvial reworking. According to Rost et al. (1979) and Bouška and Konta (1986), Lusatian moldavites have been reworked from the Czechian strewn field. On the other hand, Žebera (1967) suggested that they were ejected over the Lusatian area and subsequently transported in the aquatic environment only a short distance. The general chemical composition of all moldavites implies that they derive from the fluvial to lacustrine foreland basin deposits. Minor differences in chemical structure indicate local variability of source sediments (Rodovská et al. 2016; Skála et al. 2016; Žák et al. 2016). Based on the interpretation of chemical composition and the Miocene paleogeography, moldavites are thought to have fallen out on the Lusatian area and were subsequently reworked (Lange 1995, 1996).

In the natural environment many conditions play a role in fluvial reworking. Miocene fluvial sands from

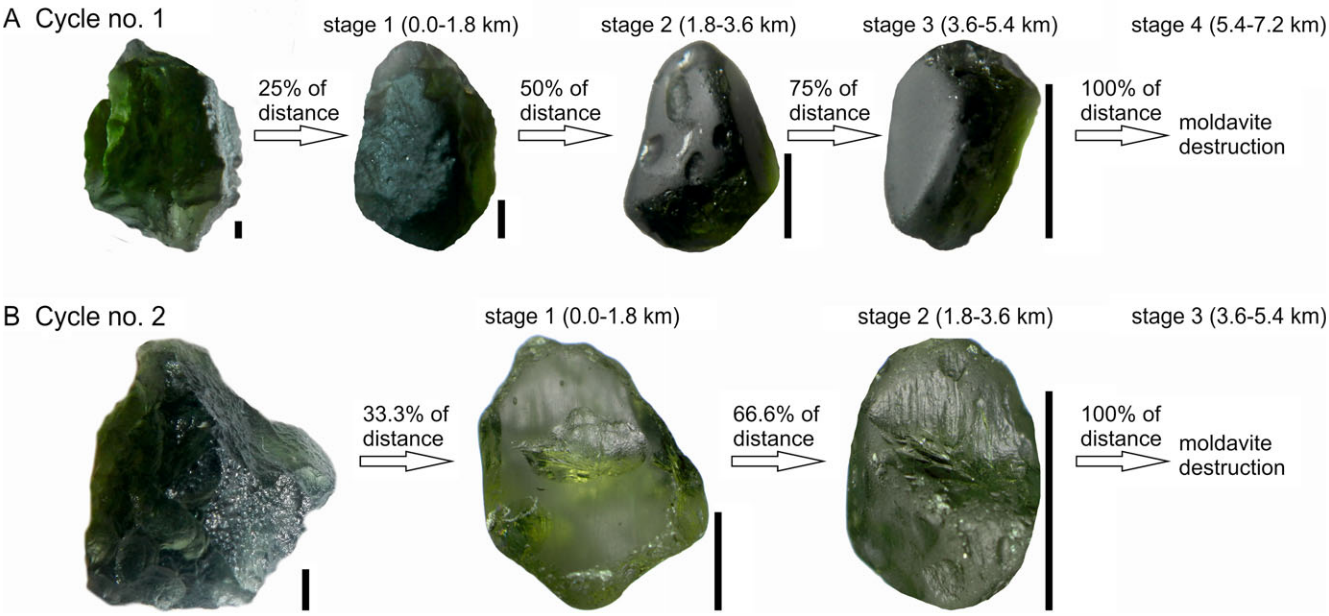

Fig. 3. Diagram showing the stages of abrasion of moldavites during two cycles (see also Tables 1 and 2). Scale bar = 2 mm.

Table 1. Progressive steps in abrasion of moldavite during cycle no. 1 (for an explanation, see text and Fig. 3A).

Distance (km)	Mass (g)	Dimensions–length × width × height (mm)	Weight loss (g)	Mass loss from initial weight (%)
Primary moldavite	1.642	28 × 23 × 21	0	0.000
0–1.8	0.668	10 × 8 × 8	0.974	59.318
1.8–3.6	0.371	5 × 4 × 4	0.297	18.088
3.6–5.4	0.114	3 × 2 × 2	0.257	15.652

Table 2. Progressive steps in abrasion of moldavite during cycle no. 2 (for an explanations, see text and Fig. 3B).

Distance (km)	Mass (g)	Dimensions–length × width × height (mm)	Weight loss (g)	Mass loss from initial weight (%)
Primary moldavite	1.497	22 × 21 × 19	0	0.000
0–1.8	0.536	8 × 6 × 5	0.961	64.195
1.8–3.6	0.087	2 × 2 × 2	0.449	29.993

Lusatia and SW Poland contain admixtures of gravel. Consequently, gravelly sands were used as a proxy for these fluvial sediments in the experiment. The results of this study quantify the relationships between the weight loss of moldavites and the distance they are transported as a function of the type of sediment involved.

Destruction patterns of the original shape of moldavite at different stages of reworking are very similar in both cycles. The results of the said experiment indicate that moldavites are not resistant to fluvial abrasion. As inferred from the paleogeography of the studied area, newly formed moldavites probably fell into the rivers. They display a typical "tektite shape" and are relatively large and heavy (even up about a dozen grams). Unfortunately, due to the lack of available in situ preserved moldavites deposited soon after their fall, moldavites from the Moravian substrewn field were used (types 5–6 and 11–12 of Powers classification; Fig. 2). Admittedly, though such specimens lost their primary shape due to some reworking, their state of preservation is fair. All newly formed tektites have regular shape (Baldwin et al. 2015) with high or low sphericity (types 1–2 or 7–8 of Powers classification). In general, four stages of moldavites fluvial abrasion can be distinguished:

Stage 1. Tektite reveals rounding of edges, which corresponds to types 3–4 and 9–10 of Powers classification. This step appears to be the most important in the whole reworking due to the strongest abrasion, mass loss (reaching up to about

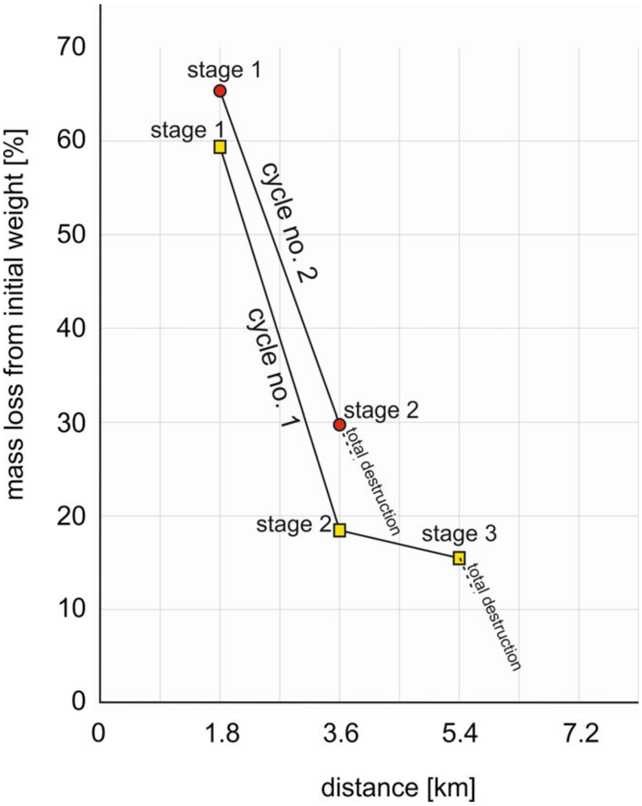

Fig. 4. Diagram showing the relationship between weight loss (%) and reworking distance of tumbled moldavites. See also Fig. 3; Tables 1 and 2.

64% of the initial weight), and partial obliteration of glass shape. However, it seems that in some cases the primary shape may be reproduced approximately. This significant mass loss is connected with initial tektite shape. In contrast to quartz sand and pebbles (7 on the Mohs scale), tektites typically display a lower hardness of about 5–6 on the Mohs scale (Simmons and Ahsian 2007). Tektite surface may be transparent but also matte. This stage ranges over the first 1.8 km of reworking.

Stage 2. This stage covers about 25–66.6% of the total distance of transport. Tektite is rounded in shape (types 2 and 8 of Powers classification). At this moment, determination of the original shape of moldavite is impossible. Tektite surface is much more matte than in stage 1. It may also present strong abrasion signs.

Stage 3. After transport of about 66.6–100% of the total distance, the shape of the moldavite becomes oval (types 1 and 7 of Powers classification) and its surface is matte. The glass becomes fully nontransparent.

Stage 4. Total moldavite destruction.

Distal impact glass might have been redeposited multiple times by a river; its flow energy might have been also changing, depending on land relief, climatic period, etc. Tumbling experiments, in turn, were conducted to simulate constant transportation under moderate energy conditions. The results clearly indicate that the weight loss of moldavite is significant in the early phase of the experiment. This is probably due to the primal irregular shape of moldavite prone to abrasion. Subsequently, the percentage rate of weight loss decreases stepwise with the increased rounding of moldavite. In the final step, when the moldavite gets fully rounded, the rate of erosion is strongly reduced. Undoubtedly, the distance of transport of moldavites depends on their initial size; the larger they were, the longer distance they can withstand. The shape of moldavite also seems important; their irregular projections are rapidly abraded in the early phase of transport, resulting in significant weight loss and rounding.

Moldavites are usually deeply sculptured. Moldavites often display surface flow line sculpturing, grooves, furrows, and pits. They can also display some sharp edges. All these features are typical of tektite glasses, in relation to their formation, deposition, and/or reworking. Tektite sculpture is related to the climatic conditions, geological history of glass, chemical composition, and many processes, e.g., devitrification (Barnes and Russell 1966; Wosinski et al. 1967; Glass 1984, 1986; Konta 1988; French 1998; Trnka and Houzar 2002; Brachaniec et al. 2014a). Additionally, much of the sculpturing of their surfaces is attributed to etching and dissolution by ground water and soil acids (Scholze 1977; Koeberl 1986; Barnes 1990; McCall 2001; Trnka and Houzar 2002; Langbroek 2015). According to Knobloch et al. (1980), even 4.5 mm of glass can be removed by chemical corrosion. Therefore, it remains very difficult to distinguish which process generated a specific type of sculpturing. Lange (1995) attributed a lack of surface sculpturing to fluvial transport for some moldavites from Lusatia. Flow line structures run on the entire tektite glass so they might have been formed during glass formation. Bubbles can be also connected to gas content in silica melt.

Miocene Paleogeography of the SW Poland Area

The distribution area of Polish moldavites is located between the Czechian substrewn fields and the Lusatian area. Brachaniec et al. (2014b, 2015, 2016) suggested that Polish moldavites came from Lusatia and cannot have originated from the Czechian substrewn fields due to the Sudetes Mountains that separate the southern and northern substrewn fields. These mountains uplifted in the late Miocene as a high topographic unit at the border of the Bohemian Massif. According to Badura

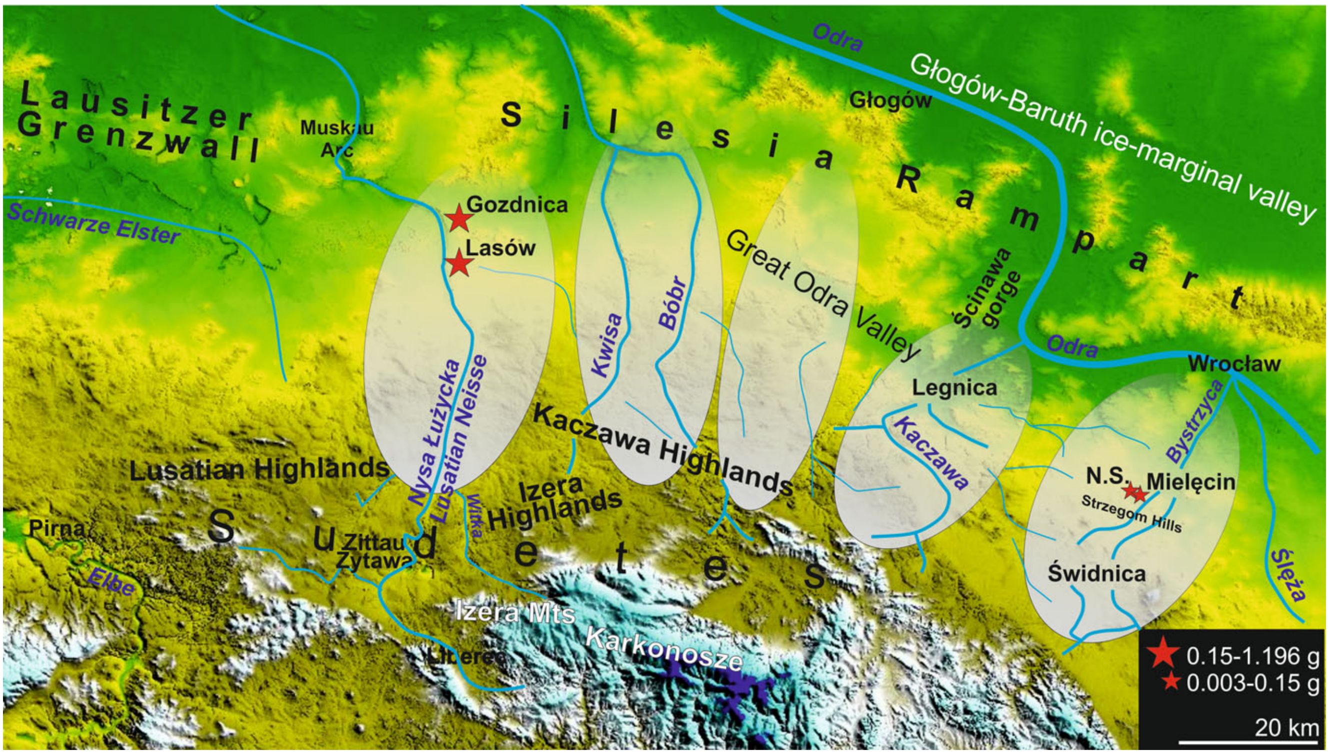

Fig. 5. Miocene paleogeographic map with schematic main river flows and their catchment areas range (modified after Badura and Przybylski 2004; Szopa et al. 2017). Moldavite distribution in SW Poland is also shown with their sizes.

and Przybylski (2004), during the Miocene, many rivers and streams flowed on the Silesian-Lusatian Lowlands (Fig. 5). In such environments, extensive reworking of moldavites took place, such that the present moldavite substrewn fields are only relicts of their initial distribution areas (Trnka and Houzar 2002).

The results obtained from this experiment are only a broad approximation of natural processes because, as stressed above, they involved constant rates of abrasion. Environmental flow energy is always changing. Specifically, in the moldavite-bearing area in Poland, low-energy river backswamps and meanders likely prevailed. Herein, moldavites could have been deposited without any further transport. Such a situation likely applies to the Strzegom Hills (near the North Stanisław and Mielęcin pits) close to the Bystrzyca paleoriver system. Additionally, the area of the Fore-Sudetic Block shows numerous depressions where sand, gravel, and clay were deposited (Grocholski 1977; Kural 1979). In the Lower Silesia, the average flow velocity in main rivers is 3 m s^{-1} (Haładyj-Waszak 1981; Meyer 1987), so this parameter was included in the experiment. Only locally, in the elevated area, the river flow might have been slightly faster. The Gozdnica Formation is mainly represented by fluvial sand and a substantial amount of gravel; therefore a postdepositional erosion origin of the sculpturing of moldavite glass is most likely. Pebble-like shapes of moldavites with abraded and matte surfaces observed during the final steps of the tumbling experiment are very similar to those derived from the Pleistocene deposits of Lusatia (Lange 1996).

Supply Areas of Polish Moldavites

The experimental results presented here indicate that moldavites are not likely to survive lengthy transport in river systems. Thus, the hypothesis formulated by Szopa et al. (2017), suggesting that the Polish tektites from the Gozdnica pit originated from the upper part of the drainage basin of the Lusatian Neisse (Żytawa and Bogatynia area), is likely (Fig. 5). It is worth mentioning that moldavites from the Lasów pit are very similar in size to those from Gozdnica (Szopa et al. 2017). These two sections are located within the alluvial accumulation area of the Nysa Łużycka River. Assuming that moldavites were likely primarily deposited within the graben of Żytawa, they must have been transported over a distance of dozen kilometers. However, it should be kept in mind that these are purely theoretical predictions assuming constant physical disturbance, and without considering the many changeable factors occurring in the wild. Noticeably from the preservation of their typical “tektite” shape and relatively sharp edges (e.g., EG1 in Brachaniec et al. 2016; and sample G1 in

Brachaniec et al. 2015), it seems that some Polish tektites were subject to very short transport, perhaps only over a distance of a several hundred meters.

Moldavites in the final steps of tumbling, as well as those found in the field in North Stanisław and Mielęcin, are very small and lightweight. It is clear that both the total weight and the abundance of tektites decrease with longer redeposition. Noticeably, small tektites are usually overlooked and consequently not discussed any further in publications. According to Vamberková and Ševčík (1990), among 900 moldavites from the Bor sandpit near Suchdol nad Lužnicí, about 35% of them weigh <1 g. The shape of these smaller Polish moldavites is generally angular, in contrast to larger specimens displaying characteristic rounding. According to Trnka and Houzar (2002), during the last stages of fluvial abrasion, microfragmentation took place as a result of the destruction of a larger tektite due to its weakened structure. Konta (1980) stated that unbroken moldavites represent <1% of all reworked European tektites.

As shown in this study, it seems unlikely that tektites transported fluvially over a long distance could have preserved angular edges. Furthermore, moldavites found in Mielęcin and North Stanisław are very small, suggesting that they had been separated earlier from the main glass mass. Assuming the redeposited nature of moldavites from these Polish sections, it is impossible to determine their original shape and weight, and thus identification of their source area still remains tricky.

Looking at the paleogeography of the discussed area during the middle and late Miocene, it appears likely that the tektites from North Stanisław and Mielęcin were derived from a different area than those from Gozdnica, perhaps from the Bystrzyca River (Fig. 5). This interpretation seems currently most parsimonious, although one must bear in mind that an extensive network of local rivers and streams possibly existed in this area at that time. It seems probable that these moldavites were initially eroded from the sediments of the Strzegom Hills, then transported with gravel at the river bottom, which led to their fragmentation, and were finally buried within the sediments of the river meanders. Given the considerable distance (about 500 km) of the Polish finding locations from the Ries crater, the origin of moldavites in that area is still puzzling. However, the hypothesis of Stöffler et al. (2002) that moldavites reached this distance ballistically cannot be completely excluded.

SUMMARY

This study is concentrated on reworking moldavites, so it is undoubtedly indispensable to knowing geological and paleogeographical data from the investigated area. Undoubtedly, time and distance are two of the most important conditions in the reworking of moldavites. Unfortunately, it is not possible to exactly determine how far the rivers have transported tektites. Certainly, it was not a single, consistent process. During transport, moldavites, due to their lower density relative to the average density of river deposits, had to be permanently immobilized in river sediments, and later redeposited, depending on environmental energy. Though tumbling experimental conditions may not necessarily accurately mimic natural processes, the results of our experiments clearly show that moldavites cannot withstand considerable fluvial physical disturbance and transport. Due to the shorter distance of reworking, it can be assumed that the moldavites from the Miocene sedimentary succession near the Polish–German border come from the upper part of the Lusatian Neisse and are associated with the alluvial accumulation of the Lusatian Neisse River.

Undoubtedly, restoration of a number of processes affecting the tektite distribution is extremely difficult and highly speculative. Given that river transport was the main mechanism controlling moldavite distribution, paleoenvironmental and paleogeographic contexts should be deeply assessed. Moldavites from the North Stanisław and Mielęcin pits are likely connected to the alluvial accumulation of the Bystrzyca River, though their sediment supply area is still unknown. To determine the source area of these tektites, additional findings and further observations of their surface features are needed.

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