The Meteoritical Society

Meteoritics & Planetary Science 50, Nr 10, 1697–1702 (2015)
doi: 10.1111/maps.12504

A new discovery of parautochthonous moldavites in southwestern Poland, Central Europe

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(Received 06 March 2015; revision accepted 20 July 2015)

Abstract–Moldavites represent tektites derived from the Ries impact structure (~24 km diameter, ~15 Myr old) in southern Germany. Two new localities with parautochthonous moldavites in southwestern Poland were found. In these localities, fluvial sediments of the so-called Gozdnicka formation host the moldavites. Characteristic tektite features, especially bubbles and inclusions of lechatelierite, are reported. The moldavites' size distribution and their abraded shapes indicate that they were redeposited from the nearby Lusatia substrewn field.

INTRODUCTION

Moldavites are siliceous impact glasses which were produced by the high-temperature melting of the Tertiary ObereSüßwasser Molasse during the Nördlinger Ries impact in Germany (Horn et al. 1985; von Engelhardt et al. 1987; Meisel et al. 1997; Trnka and Houzar 2002; Řanda et al. 2008; Magna et al. 2011; Žák et al. 2012). This impact event has been dated at 14.74 ± 0.20 Ma (Buchner et al. 2013). Tektites ejected during the Ries impact had only been described from three substrewn fields in the Czech Republic, Germany, and Austria (Trnka and Houzar [2002] and citations therein) until Brachaniec et al. (2014) discovered a new site with distal Ries tektites (North Stanisław sandpit) near Strzegom in southwestern Poland. In this article, we report two new localities with moldavites in Poland.

LOCALITY AND GEOLOGICAL SETTINGS

We have discovered two new tektite occurrences in Poland. The first new locality is situated 7 km from the German border (Fig. 1A) in the Gozdnica sandpit, which lies about 400 km from the impact crater. The second new locality, the Mielęcin site, is situated 2.5 km east from the North Stanisław sandpit, where the first Polish moldavites were found (Brachaniec et al. 2014), and is ~150 km from the first new locality.

All previously documented Polish tektites—and those found here—have been found within the lower Upper Miocene sediments of the so-called Gozdnicka Formation (Pannonian age; Szynkiewicz 2011). Herein, the moldavite-bearing sediments are typical fluvial deposits but differ from those occurring in the North Stanisław sandpit. The sediments at the Gozdnica locality (Fig. 1B) are mainly composed of well-sorted yellow and orange sands with only sporadic white/gray layers or lenses of gravel. The gravel clasts range from <0.5 to 2 cm and are in most cases by slightly rounded quartz fragments (Fig. 1C). Partially fossilized wood represented by fragments of roots (up to several centimeters long) and tree trunks (<20 cm long) are present in the Gozdnica sandpit, but no clay was observed. Scattered clasts of weathered feldspars are also present. The maximum thickness of the formation in the Gozdnica sandpit is 9 m. The moldavites are randomly distributed through a zone 3 m thick in the upper part of the exposed section (Fig. 1C).

In Mielęcin, only 3 m of the Gozdnicka Formation are exposed (Fig. 1D) and they consist of well-sorted, light-yellow to gray sands that contain numerous, well-rounded gravel clasts, mainly composed of quartzite, granite, chert, and sandstones. In contrast to the Gozdnica sandpit, the strata exposed in the Mielęcin pit contain five gray clay lenses up to 2 cm in thick (Fig. 1E). No redeposited fossil wood was observed.

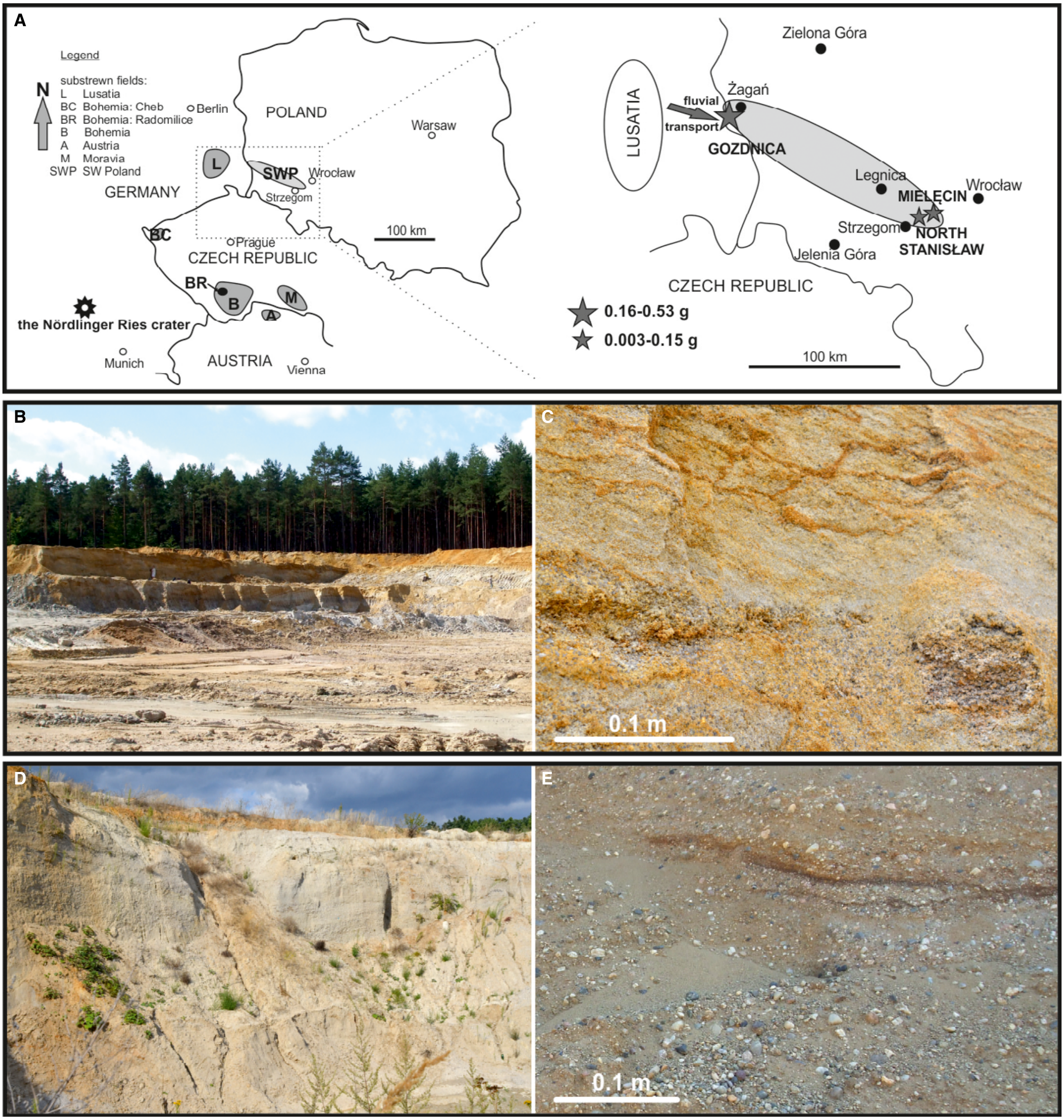

Fig. 1. A) Map of moldavite distribution in Central Europe with inferred direction of fluvial transport of tektites to SW Poland. The substrewn fields (excluding the Polish area) are marked following Stöffler et al. (2002). Size ranges of the Polish moldavites are taken from Brachaniec et al. (2014) and this study. B and C) A general view of the exposed wall of the Gozdnicka Formation in the west part of the Gozdnica sandpit and a close-up of sediments in the moldavite-bearing zone. D) General view of the Gozdnicka Formation in the Mielęcin quarry and a close-up of sediments in the moldavite-bearing zone (E).

METHODOLOGY

During the field sampling, 1 and 5 mm mesh sieves were used. Four moldavites were found after sieving of ~2.0 tons of the sediments from the Gozdnica sandpit. In the case of Mielęcin locality, two tektites were collected from approximately 1 ton of sieved sediment.

Two selected moldavites from each locality in Poland were mounted in 25 mm diameter epoxy resin pucks, then grounded and polished to expose their

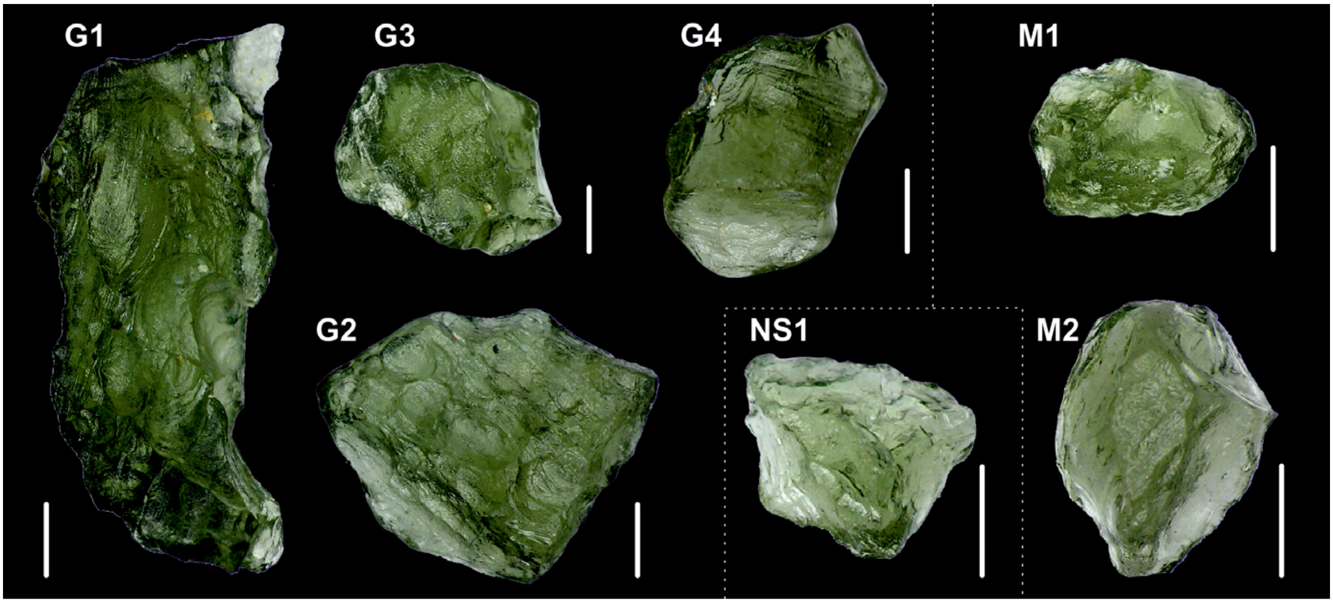

Fig. 2. Polish moldavites from the two new localities showing typical shapes and sizes. Macroscopic and microscopic features are given in Table 1. Scale bar is 2 mm.

interiors. The tektites' morphologies were imaged by scanning electron microscopy on a FET Philips 30 electron microscope (15 kV and 1 nA) at the Faculty of Earth Sciences, University of Silesia, Sosnowiec, Poland.

Microprobe analyses of main elements of the moldavites were done in the Inter-Institutional Laboratory of Microanalyses of Minerals and Synthetic Substances, Warsaw, using a CAMECA SX-100 electron microprobe. The analytical conditions were: acceleration voltage: 15 kV, beam current: 20 nA, counting time: 4 s for peak and background, and beam diameter: 1 μm.

The selected tektite subsamples were thoroughly crushed and ground to powder (generally 10–5 μm size fraction). XRD measurements were carried out using a PANalytical X'Pert Pro MPD 3040/60 diffractometer (2 Theta range 5–70°, step size 0.01°, step time 300 s) and measured using a Cu Kα radiation with an X'Celerator strip detector. The crystallinity parameter was calculated using High Score+ software and NIST respirable Alpha Quartz mixed with amorphous silicate glass. The analyses were carried out at the Faculty of Earth Science in the University of Silesia, Sosnowiec.

The studied material is stored at the Museum of the Faculty of Earth Sciences, University of Silesia, number WNOZ/Mt/88.

RESULTS

Seven tektites were collected in total from three quarries (Gozdnica, Mielęcin, and North Stanisław) in Poland (Fig. 2). The largest ones were collected from the Gozdnica quarry. Their masses range from 0.15 to 0.53 g. Their shape is ellipsoidal rather than elongated. Their average size is approximately 1 cm. The largest moldavite is 1.6 cm long and 0.7 cm wide (Fig. 2 sample G1). One sample from Gozdnica (G2) is likely complete, and not cracked. The largest specimen (G1) is broken and shows conchoidal fracture on one side. All edges of the other specimens from Gozdnica are sharp.

The smallest tektites, weighing 0.02–0.08 g, were found in the Mielęcin quarry (Fig. 2 samples M1 and M2, respectively). They are much more rounded than specimens from the Stanisław sandpit that have been described previously (Brachaniec et al. 2014). All of the Polish moldavites are mostly ellipsoidal in shape, except one specimen (sample G1), which is elongated as in the case of the tektites from the Czech Republic. Typically, the largest bodies from Gozdnica are a much darker green in color (except sample G3) than the smaller specimens from the Stanisław or Mielęcin localities. They also possess less corroded surfaces. Some of the moldavites investigated also contained bubbles, which are regular in shape and vary in size from 15 to 500 μm (Fig. 3A). The only clearly resolvable inclusions in the studied material consist of lechatelierite (amorphous SiO_2), which occurs as both elongated (20–500 μm long) and irregular inclusions (Fig. 3B).

Summaries of the macroscopic and microscopic morphological characteristics and chemical composition based on EMPA of the studied tektites are presented in Tables 1 and 2, respectively.

EMP data show that the SiO_2 content of the new Polish moldavites range from 76.28 to 78.31 wt%, which is low as compared to the moldavites from the

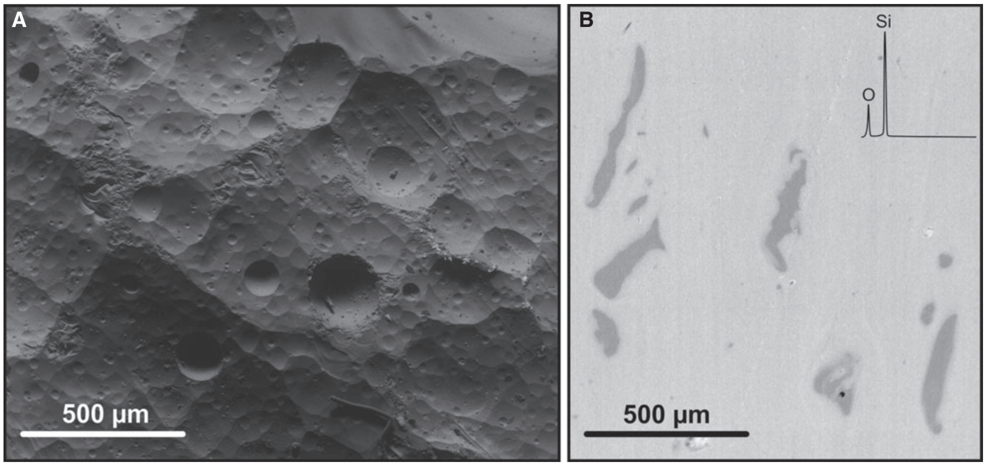

Fig. 3. A) BSE image of the surface of G2 moldavite. B) Elongated lechatelierite inclusions in G1 sample, determined to be pure silica by the EDS method.

Table 1. Characteristics of Polish moldavites, as shown in Figs. 2 and 3.

Sample	Mass (g)	Shape	Surface	Color	Features
G1	0.53	Elongated	Low corrosion	Bottle green	B***L**
G2	0.36	Ellipsoidal	Low corrosion	Bottle green	B***L*
G3	0.21	Ellipsoidal	Low corrosion	Light bottle green	B**L*
G4	0.15	Ellipsoidal	Corroded	Bottle green	B**L**
M1	0.05	Ellipsoidal	Strongly corroded	Light bottle green	B*L*
M2	0.08	Ellipsoidal	Strongly corroded	Light bottle green	B*L*
NS1	0.02	Ellipsoidal	Strongly corroded	Light bottle green	B*L*

G = Gozdnica quarry; M = Mielęcin quarry; NS = North Stanisław quarry; B = bubbles; L = lechatelierite; * = rare; ** = abundant; *** = very abundant.

Table 2. Average chemical composition based on EMP of moldavites from Poland and Lusatia (average wt% from n samples).

	Locality			
	Poland			Germany
Element (wt%)	Gozdnica sandpit $n = 12$	Mielęcin quarry $n = 8$	North Stanisław sandpit $n = 10$	Lusatian area* $n = 15$
SiO_2	76.28	78.31	76.28	79.3
TiO_2	0.31	0.27	0.12	0.34
Al_2O_3	10.52	11.01	10.87	10.5
FeO_{total}	1.98	1.89	1.92	1.84
MnO	0.02	0.01	0.02	0.06
MgO	1.8	1.78	1.75	1.75
CaO	2.1	2.08	2.12	2
Na_2O	0.51	0.51	0.57	0.47
K_2O	3.6	3.58	3.21	3.46
P_2O_5	0.04	0.05	0.07	—
TOTAL	97.16	99.49	96.93	99.72

*Data from Lange (1995).

Lusatia area (Table 2). The SiO_2 content of the Lusatian moldavites is in the range from 78.10 to 85.10 wt%. The compositional range of the Polish tektites, however, is in the same range as all known Ries tektites (see Trnka and Houzar 2002).

For comparative purposes, Czech and Polish moldavites were analyzed using XRD (Fig. 4). Both specimens revealed a similar mineralogy. The amorphous halo, observed in the range from 8.6 to 40.8°2Θ, reached the maximum intensity at 22.1°2Θ and

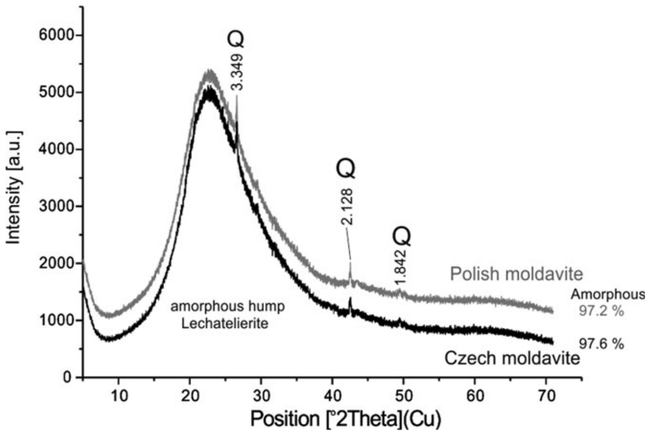

Fig. 4. XRD patterns of moldavite samples from the Czech Republic and Poland (the Gozdnica sandpit). Small quartz reflection "Q" occurring on amorphous glass hump is visible.

was characterized by FWHM (full width at half maximum) of 6.47°2Θ. On the amorphous hump, low intensity reflections are visible, calculated as the d_{hkl} values [Å]: 3.349, 2.128, and 1.842. These reflections show a good fit to the quartz standards. The crystallinity parameters for the Polish and the Czech moldavites are about 2.8% and 2.6%, respectively.

DISCUSSION

It has been argued that following the Ries impact, moldavites were deposited in Middle Miocene (14.8 Ma) sediments (Buchner et al. 2013). The Gozdnicka Formation, in which the new Ries tektites were found, is, however, Upper Miocene in age (Pannonian, approximately 10 Ma) (Szynkiewicz 2011). This strongly suggests that all 16 tektites discovered so far in Poland (seven described in this paper and nine by Brachaniec et al. 2014) are parautochthonous. Žebera (1972) and Bouška et al. (1999) mentioned that sporadic moldavite findings may represent redeposited material. Indeed, Gozdnicka Formation is represented by typical fluvial sediments.

During the Middle Miocene, transgression of the North Sea into Lusatia took place. As a result, a rise of the groundwater level of the Sudetic, especially north-western river valleys occurred. The subsequent marine regression terminated phytogenic accumulation and fostered intensive erosion upon higher situated areas. Downstream-located valley segments became occupied by silts, fine-grained sands, and even organic sediments. Depending on highly changeable local conditions, well-sorted sands or angular clasts cemented by kaolin–smectite–illite clays were deposited.

As mentioned above, the Late Miocene river system was strongly developed. This situation allowed long-distance transport and distribution of tektites. From the Middle to Late Miocene, the main river valley of this region was the Nysa Kłodzka River that used to flow toward the east (Badura and Przybylski 2004).

During the Late Miocene, the Sudetes formed a well-marked high topographic unit at the margin of the Bohemian Massif. The Fore-Sudetic Block was already separated from the Sudetes (Fig. 5A; Grocholski 1977; Kural 1979). Some large rivers bypassed both troughs and their northern surroundings. At the boundary between the Sudetes and the Lusatia Mts. (including the Gozdnica area), strong subsidence occurred (Kasiński 2000). Uplift of the Strzegom Hills (near Stanisław and Mielęcin), which were situated on the eastern most edge of the river system, was not strong enough to block the northern-directed outflow of local, small rivers (e.g., Strzegomka, Bystrzyca rivers).

We suggest that river transport from Lusatia (Fig. 5B) over tens of kilometers' distance was the main mechanism that controlled the tektites, deposition in Gozdnica quarry, and other Polish sections (Fig. 5C). The investigated sediments contain the largest tektites yet found in Poland and are characterized by minor content of gravels, in contrast to similar sediments in other previously found two sections with tektites in Poland (Figs. 1B and 1C). This situation may explain why the moldavites from the Gozdnica area are very similar in size to the tektites from the Lusatian area. The tektites from Gozdnica are slightly cracked or broken and are less abraded (i.e., have sharper edges) compared to those from the North Stanisław and Mielęcin sandpits. This is consistent with a shorter distance of transport and/or minimal recycling. In the case of moldavites from the most distal part (the Stanisław and Mielęcin area), their small and comparable size as well as high degree of abrasion suggest rather long fluvial transport (Fig. 5D).

CONCLUSIONS

1. The new findings of moldavites come from two localities in Poland where sediments of the so-called Gozdnicka Formation are exposed.
2. The newly found moldavites from Poland represent additional findings of the distal most Ries tektites.
3. All investigated tektites are parautochthonous. Their occurrence suggests that they were fluvially transported from the Lusatian area.
4. The tektites differ in size at each locality. The largest one (> 0.9 cm) was found closer to the Lusatian area, whereas smaller ones (< 0.3 cm) were found at a greater paleodistance, consistent with fluvial dispersal to the SE.

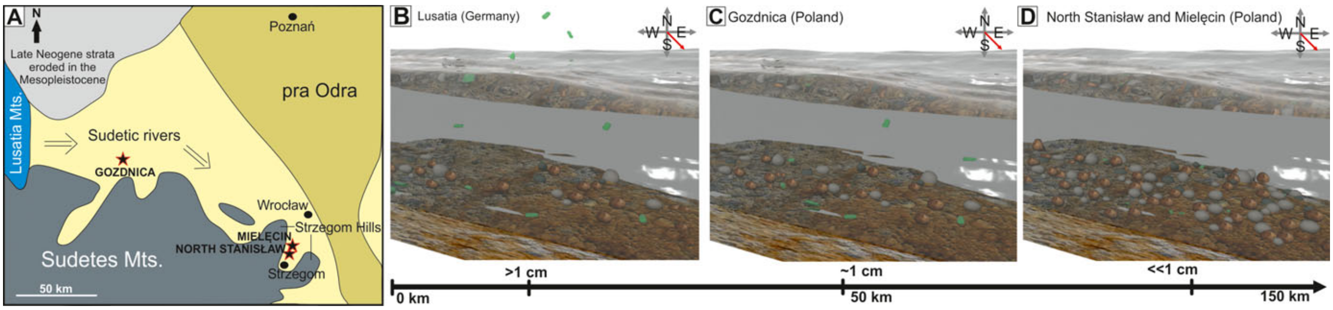

Fig. 5. A) Scheme showing distribution of fluvial deposits of the Upper Miocene (modified after Badura and Przybylski 2004) with a schematic reconstruction of the redeposition from the Lusatian area in Germany to SW Poland. B) After falling on the Lusatian area, some of the tektites were transported by the river. C) After transport of no more than a few kilometers, some moldavites (mostly with their original sizes preserved) were deposited in the Gozdnica area. D) Other tektites were transported even further to the SE, abraded to a higher degree, and finally deposited in the North Stanisław and Mielęcin sediments as smaller pieces.

Acknowledgments—This project was financially supported by NCN grant No 2014/13/N/ST10/04921. The authors thank Andrzej Muszyński (Adam Mickiewicz University in Poznań, Poland) and Bruce Simonson (Oberlin College, USA) who provided detailed and useful reviews of the manuscript as well as Gordon Osinski for careful editorial handling. We thank Tomasz Krzykawski (University of Silesia) and Zbigniew Bzowski (GIG, Katowice) for XRD consultation. We also thank Beata and Marek Woźniak for their help during the field work.

Editorial Handling—Dr. Gordon Osinski

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