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ORIGIN OF PARAUTOCHTHONOUS POLISH MOLDAVITES – A PALAEOGEOGRAPHICAL AND PETROGRAPHICAL STUDY

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Abstract: In this article, the most recent moldavite discoveries in Poland and their host sediments are characterised and discussed. They were discovered at Lasów, located about 8 km north of Zgorzelec (Poland) and Görlitz (Germany), about 700 m from the Polish-German border, close to the Lusatian Neisse (Nysa) River. The tektites were collected from Vistulian (Wiechselian) glacial age sand and gravel of a closed quarry pit, associated with the river terraces. In the Lasów area, the moldavite-bearing sediments are Pleistocene in age and represent Lusatian Neisse terrace deposits. They were redeposited from the upper part of the drainage basin of the Lusatian Neisse, probably washed out from the Miocene sediments that filled the Zittau Depression, the Berzdorf–Radomierzyce Depression, the Višňová Depression and the tectonically uplifted Izera Mts. and Działoszyn Depression. The erosion of Miocene deposit occured on a large scale in the uplifted foothills of the Upper Miocene Izera, Lusatia and Kaczawa complexes. The sediment cover was removed from the Działoszyn Depression. The drainage basin of the Lusatian Neisse is the area where moldavites were formed by the Nördlinger Ries impact. The source area of moldavite is the same for the Miocene deposits around Gozdnica, as well as for the Pleistocene sediments at Lasów.

Key words: Polish tektites, redeposition, river terrace, Miocene, Pleistocene, drainage basin.

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INTRODUCTION

Moldavites are a type of tektite produced by an impactor during the Miocene (14.74 ± 0.20 Ma) at Nördlinger-Ries, Germany (Buchner *et al*., 2013). The tektite population is scattered across the Czech Republic, Germany and Austria (Trnka and Houzar, 2002 and references therein). These impact glasses were produced by the melting of quartz sands, marls and carbonates, of the Cenozoic Obere Süßwasser Molasse (Meisel *et al*., 1997; Trnka and Houzar, 2002; Řanda *et al*., 2008; Skála *et al*., 2009; Magna *et al*., 2011; Žák *et al*., 2012) as well as the impactor itself. Fluvial transport was the main factor controlling moldavite distribution across the Bohemian Massif area and to the north (Bouška, 1964, 1988; Žebera, 1972; Rost *et al*., 1979; Bouška *et al*., 1999; Lange and Suhr, 1999; Brachaniec *et al*., 2014, 2015, 2016; Skála *et al*., 2016). This mode of transport also was common for other tektites (e.g., Jimenez-Martinez *et al*., 2015). Sporadic finds of moldavites outside the main sub-strewn fields were noticed at a few localities in the Czech Republic, e.g. at the Kobylisy sand pit in Prague (Žebera, 1972), at a sand pit near Jeviněves (Žák *et al*., 1999), or in the river terrace of the Berounka River near Skryje (Ložek and Žák, 2011). Likewise, parautochthonous moldavites were discovered in southwestern Poland (Brachaniec *et al*., 2014, 2015, 2016). Recent studies have demonstrated that some Polish moldavites are associated with Pleistocene fluvial sediments. This paper describes the new occurrence of parautochthonous moldavite-bearing gravel-clast suite in order to identify the provenance of the sediment.

LOCALITIES AND GEOLOGICAL SETTING

During field work in 2015, moldavites were found in a closed pit at Lasów (51°13′12.1"N,15°01′40.6"E; Lower Silesia, SW Poland). The sand and gravel pit is located 8 km north of Zgorzelec (Poland) and Görlitz (Germany), close to

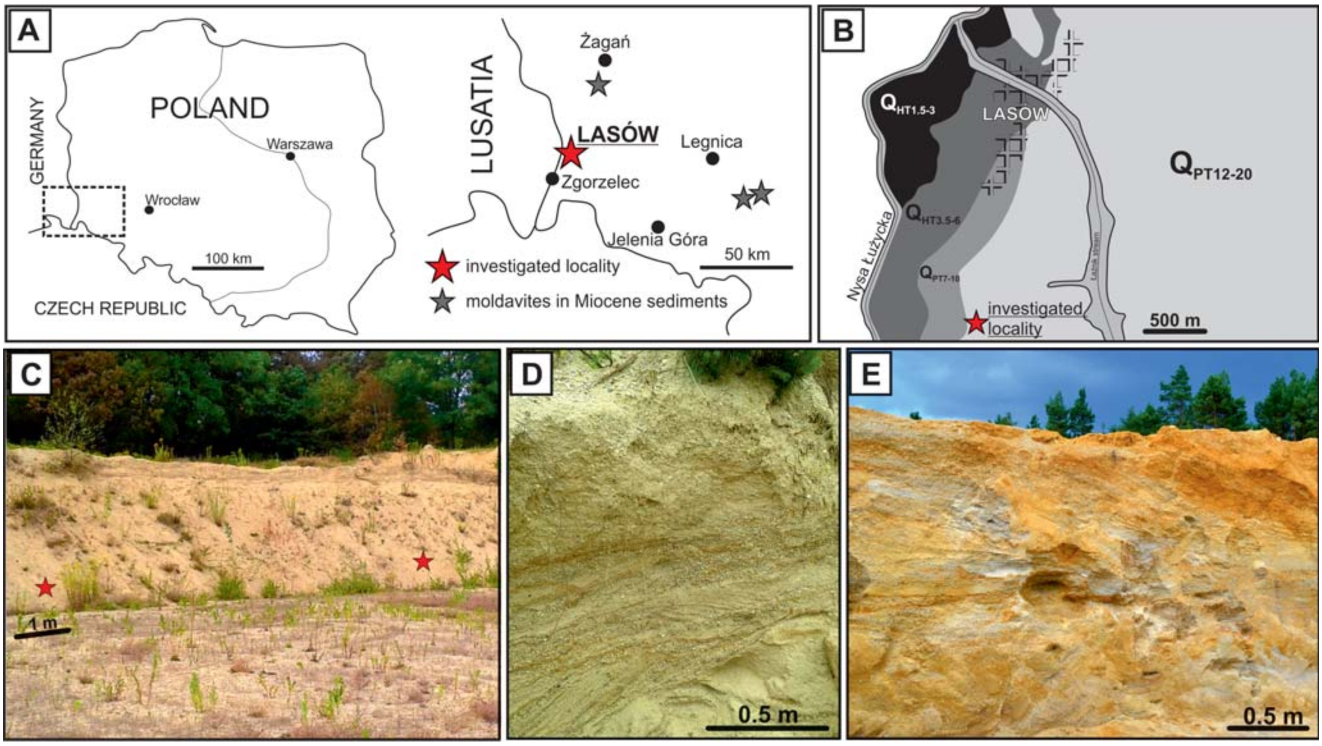

Fig. 1. **A**. Simplified map with location of the closed pit mine at Lasów. Distribution of Polish moldavites within Miocene sediments in southwestern Poland (Brachaniec *et al*., 2014, 2015, 2016) indicated as a grey asterisk. **B.** Simplified geology of study area. **C.** One of the four exploitation levels in the Lasów open-pit mine yielding moldavite. **D.** General view of the Pleistocene sands and gravels of the Lusatian Neisse fluvial terraces investigated. **E.** Overview of Miocene sands with gravels in the Gozdnica open pit. Notes: QPT12-20 – Investigated Pleistocene sand with clays and gravel terrace with a height of 12– 20 m above the Lusatian Neisse River level, QPT7-10 – Pleistocene sand and gravel terrace with height 7–10 m above the Lusatian Neisse River level, QHT3.5-6 – Holocene sand and gravel terrace with height 3.5–6 m above the Lusatian Neisse river level, QHT1.5-3 – Holocene clay with sand terrace with height 1.5–3 m above the Lusatian Neisse River level (modified from Badura *et al*., 2005).

the Polish-German border (ca. 700 m) along the Lusatian Neisse (Nysa Łużycka) River (Fig. 1A). The closed sand and gravel pit is located on a high fluvial terrace (+16 m above the river level).

The drainage basin of the Lusatian Neisse River (Fig. 2) is underlain by the southern and middle portions of the Lausitz-Izera-Karkonosze complex as far north as the city of Pieńsk. This block is composed of Karkonosze granitoids, Zawidow granodiorites, Rumburg granites, and the Izera granite-gneisses complex (Białek *et al*., 2014). Some metasedimentary and metavolcanic rocks underlie the northern part of the area and are represented by the Görlitz Slate Belt and the Kaczawa Metamorphic Belt (Mazur *et al*., 2010).

The E–W-oriented Nysa valley between Liberec and Zgorzelec (Fig. 2) separates the Zittau Depression from the Berzdorf–Radomierzyce Depression. Both depressions form the northern part of the Eger Graben (Badura and Aleksandrowski, 2013). These depressions are filled with volcanics and clastic sediments with three characteristic horizons of brown coal (Václ and Čadek, 1962; Kasiński, 2000; Standke, 2006). The depressions formed in the Oligocene and sediment accumulation ceased to occur in the Late Miocene.

Up to the end of Oligocene, the area north of Zgorzelec formed a wide lowland including the North Sudetic Synclinorium, which formed an important regional depocentre of sand, gravel, clay and silt (Fig. 3). Up to three horizons of brown coal are found in this basin. They are correlated with similar well-described sediments in numerous open-pit coal mines in the Lusatia area (Suhr *et al*., 1992; Standke, 2006; Tietz and Czaja, 2010) and show that sedimentation in the Polish part of the North Sudetic Synclinorium took place from the Late Oligocene up to the Middle Miocene. Moreover, some of previously published data indicate that the estimated age of some of the sediments is considered to be Late Miocene–Pliocene. However, the eastern and western parts of the Miocene–Pliocene complex differ from each other and cannot be directly correlated (Dyjor, 1966; Stachurska *et al*., 1971; Dyjor *et al*., 1998). Also the Gozdnica Formation stratigraphy (Stachurska *et al*., 1971), supposed to be Pliocene in age, is controversial, as recently was documented by Standke (2006) and also by Tietz and Czaja (2010).

Pliocene to Early Pleistocene gravels of the pre-Lusatian Neisse River crop out near Opolno Zdrój on a steep slope at ~60 m above the river level. The sediments occur there as an isolated river bed (Kasiński *et al*., 2003). The sediments comprise grains of quartz, 5–10 mm in size (89.2% by volume), feldspars and quartz-feldspar aggregates (7.2% by volume). Sporadic occurrences of isolated clasts of schist and gneiss were noted. Miocene gravels from the Zittau Depression display the same composition in all stratigraphic units. Similar sediments have been documented in the region NW of Zittau (Lange *et al*., 2009).

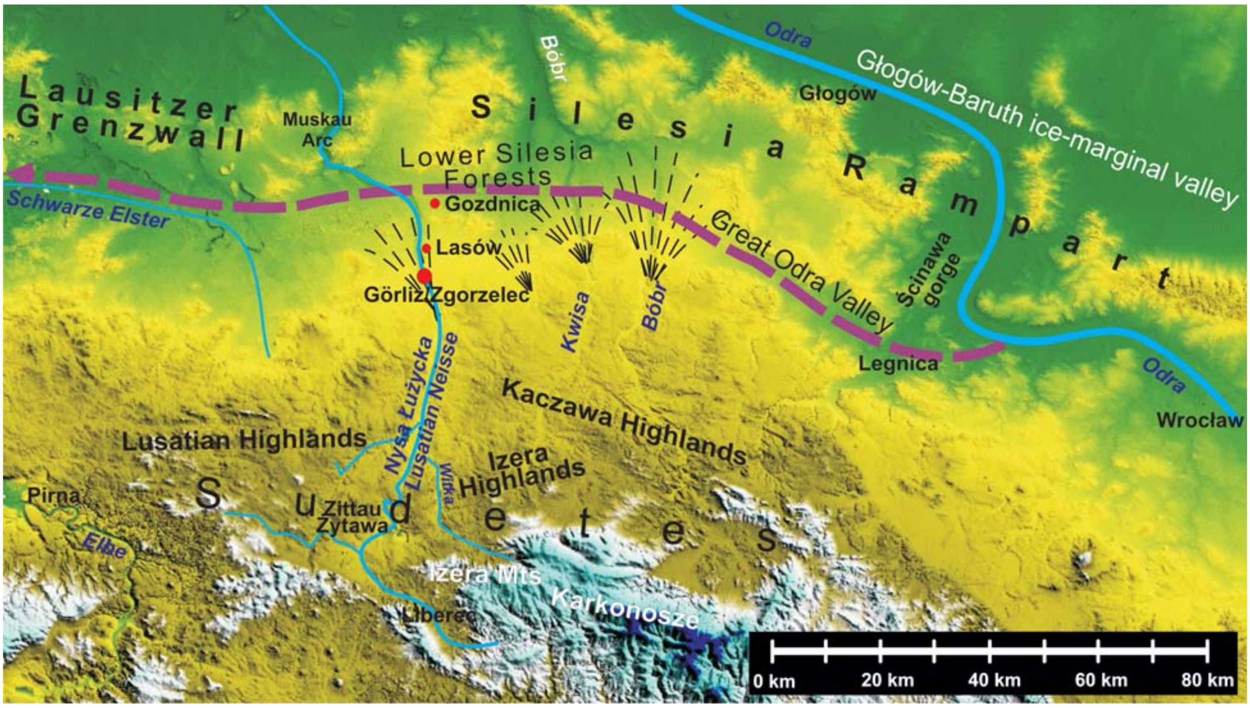

Fig. 2. Location of river fans extending from the Sudetes, which buried the abandoned channel at the end of Vistula glaciation (MIS 2) of the Great Odra Valley (*sensu* Badura *et al*., 2013). White-dark colour shows the area with long-lasting snow cover: white – 400 and 800 m a.s.l.; dark – above 800 m a.s.l.

During the Late Miocene, the large, so-called Działoszyn Horst formed near the Zittau Depression (Kasiński and Panasiuk, 1987). Horst formation deeply modified the local drainage network and the course of the Lusatian Neisse River.

In the Działoszyn Horst, the remnants of Neogene sediments are characterized by thin brown coal horizons. Horst uplift led to a division of the northern part of the Eger Graben into two main depressions: the Zittau Depression and Višňová Depression. The Višňová Depression (Václ and Čadek, 1962) is cut by the Sméda River, which is an east bank tributary of the Lusatian Neisse River. The same valley was occupied during the Neogene by the Lusatian Neisse River, when the main trunk channel of the river was flowing northwards. The present channel of the Lusatian Neisse River was cut during the deglaciation of the Żytawa–Zgorzelec Depression.

The gravels and sand deposits of the four terrace horizons of the Lusatian Neisse in the study area have been discussed by numerous authors (Frydrychowicz and Frydrychowicz, 1957; Berezowska, 1968; Badura *et al*., 2005, 2013). The three main terrace levels are marked on Fig. 3, where two Holocene terrace levels have been merged into one level (Berger *et al*., 2002; Badura *et al*., 2005). In the Lasów area, the moldavite-bearing sediments are found in Pleistocene sands and gravels. These sediments represent the Lusatian Neisse terrace, situated ca. 12–20 m above river level (Fig. 1C). North of Zgorzelec, the river terrace is represented by an alluvial fan and in part follows the Wrocław–Magdeburg–Bremen ice-marginal valley (Geniser, 1955; Mol, 1997; Piwocki *et al*., 2004; Badura *et al*., 2013). This terrace level (including the fan) was formed at the end of the Vistulian glaciation (North Polish Glaciation; Cepek, 1965; Badura *et al*., 2005). By the Holocene, the terraces were separated by an erosion edge 10 m long (Berezowska, 1968). All three Holocene terraces are marked as a single horizon on the map (Fig. 3).

Sands and gravels of the upper river terraces (12–20 m above river level) are represented by coarse- and medium-grained sands with sporadic layers of fine-grained gravels (Fig. 1D). The main mineral components include quartz, fragments of glacial erratics, grey gneisses and granitoids, lydites and flints. The terrace sediment colour is yellowish to grey, locally changing into ivory or rust, and the sands are conspicuously layered. The sediments mostly were deposited horizontally, with the thickness varying from a few centimetres up to two metres.

A relic of Pleistocene middle terraces, 7–10 m high (Fig. 3), on the west riverbank can be found north of Görlitz. The grain-size distribution and colour are similar to those previously described. Holocene sediments in the study area are sands and gravels of the Lusatian Neisse terrace that can be found up to 6 m above the river level (Fig. 3). They are represented by coarse-grained quartz-rich gravels, mixed with yellowish, medium-grained sandy layers. The youngest sediments are Holocene alluvial soils (clays with sands) that make up the lowermost terrace level (1.5–3.0 m above river level).

The moldavite-bearing sediments in Lower Silesia, Poland (Figs 1A, 4; Brachaniec *et al*., 2014, 2015, 2016; Skála *et al.*, 2016) are Pannonian in age (Dyjor, 1966; Stachurska *et al*., 1971; Dyjor *et al*., 1992, 1998; Sadowska, 1992; Piwocki and Ziembińska-Tworzydło, 1997). The age of the Gozdnica Formation has been estimated on the basis of the

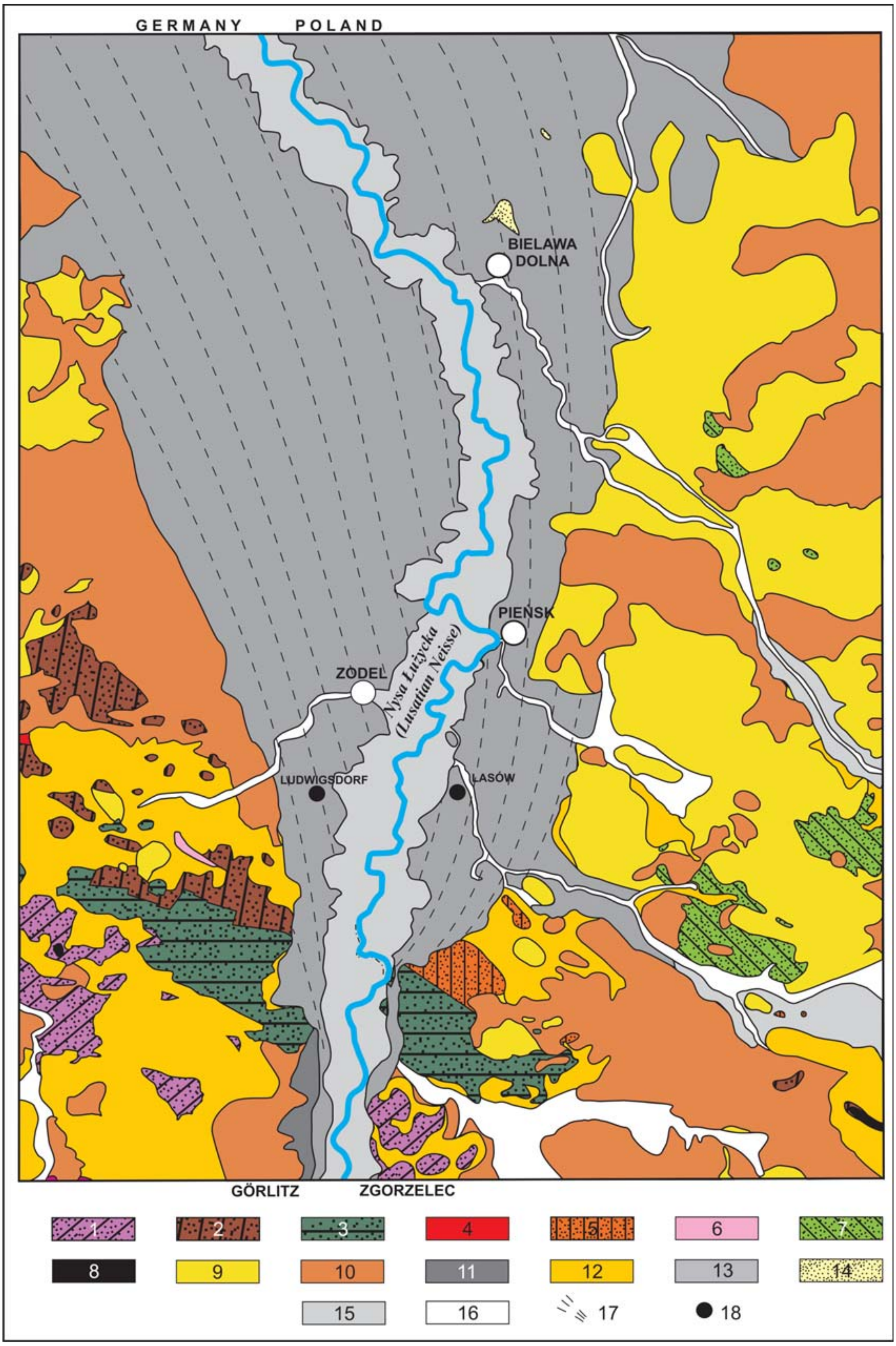

Fig. 3. Simplified geological sketch of the Lasów area. 1. Neoproterozoic–Lower Cambrian the Zawidów granodiorite; 2. Cambrian–Devonian slates, quartzites and diabases, cherts, greywackes; 3. Lower Carboniferous contact between metamorphosed greywackes and slates (=hornfelses), greywackes and slates; 4. Carboniferous–Permian biotite-monzogranites; 5. Permian anhydrite, sandstones and conglomerates; 6. Lower Triassic sandstones and siltstones; 7. Upper Cretaceous sandstones and siltstones; 8. Oligocene–Miocene basaltoid rocks and extrusive rocks; 9. Middle and Upper Miocene sand, silt, clay and silcretes; 10. Pleistocene till and glaciofluvial sediments; 11. Upper river terraces; 12. Weischelian Glaciation loess; 13. Middle terraces/alluvial fan; 14. Holocene aeolian sands; 15. Lower terraces; 16. Alluvial deposits; 17. Structural lines on the alluvial fan; 18. Main outcrops.

sediments at their type locality by Stachurska *et al*. (1971) and Dyjor *et al*. (1992). The sediment distribution and their age were discussed by Badura and Przybylski (2004). According to Badura and Przybylski (2004), Dyjor *et al*. (1992) assigned a Neogene age to the sand- and gravel-rich sediments, which lie on sediments of the Gozdnica Formation. Many kilometres northwards, fine-grained sand and silt predominate. Estimating the direct stratigraphic age of the Gozdnica Formation is very difficult, so its formation range is estimated as ranging from Late Miocene and Pre-Pleistocene (Badura, 2012). The same broad interval applies to the moldavite-bearing alluvial sediments at Jaroszów and Mielęcin (Brachaniec *et al*., 2014). The main problem concerns the Pannonian age of the sediments at Gozdnica (Stachurska *et al*., 1971; Dyjor *et al*., 1992). Their geological position indicates a Middle Miocene age (Standke, 2006). The sediments may be overlying the second and third brown coal horizons, which are used as a regional stratigraphic benchmark. In the Gozdnica area, where the third brown coal horizon was examined, sediments yielding moldavites (Fig. 1E) are 12–14 Ma old. Moreover, Eckelmann and Lange (2013) assigned a Neogene age to the same sediments at Gozdnica. However, photographs presented by Eckelmann and Lange (2013) clearly indicate the Pleistocene character of these sediments, and their connection with the Breslau–Magdeburg–Bremen Urstromtal (ice-marginal) valley. This structure is an inselberg in the Great Odra Valley (Fig. 2).

METHODS

During field work, two pieces of moldavite were recovered from a new locality at Lasów. Fifty kilograms of terrace and Pleistocene sediments were collected for the purpose of petrographic analyses. The fraction 4–10 mm in size was washed for clast identification using sieves. The clasts were classified according to their provenance area. The clast separation allowed the authors to distinguish Scandinavian glacial erratics, clasts from the Fennoscandian Peninsula, and clasts from the Sudetes. Quartz as a widely distributed component was extracted separately as an independent group (the 1st type). Characteristic dove-blue quartz from the Rumburg granites and sharp-edged quartz-feldspar aggregates were included within the rocks of the Sudetic group. The same group also yielded Permian volcanites and jasper (the 2nd quartz type). Thin sections were prepared for all clast types.

One moldavite from Lasów was used for LA-ICP-MS trace element analysis. All moldavite REE data were acquired using a Photon Machines Analyte Exite 193 nm ArF Excimer laser-ablation system with a Helex 2-volume ablation cell, coupled to an Agilent 7900 ICPMS, at Trinity College Dublin; 0.5 l/min He carrier gas was fed into the large outer sample chamber and 0.2 l/min He carrier gas was fed into the small inner volume (the 'cup') where ablation occurs. A small volume of N_2 (ca. 6 ml/min), to enhance signal sensitivity and reduce oxide formation, and 0.76 l/min Ar nebulizer gas were then introduced into the sample-gas mixture via an in-house smoothing device. The 14 isotopes (with the respective dwell times in milliseconds in parentheses) acquired were: ^{139}La[5], ^{140}Ce[5], ^{141}Pr[5], ^{146}Nd[5], ^{147}Sm[8], ^{153}Eu[10], ^{157}Gd[10], ^{159}Tb[10], ^{163}Dy[10], ^{165}Ho[10], ^{166}Er[10], ^{169}Tm[10], ^{172}Yb[10], ^{175}Lu[15], with a total duty cycle of 389.5 ms. A 130 μm laser spot, a 10 Hz laser repetition rate and a fluence of 3.5 J/cm^2 were employed, with a 28-second ablation period and a 10-second washout, the last 7 seconds of which were used for the baseline determination. The raw isotope data were reduced, using the "Trace Elements" data reduction scheme of the freeware IOLITE package of Paton *et al.* (2011). User-defined time intervals were established for the baseline correction procedure to calculate session-wide baseline-corrected values for each isotope. NIST612 standard glass was used as the primary standard. Sample-standard bracketing was then applied to account for long-term (session-wide) drift in isotopic or elemental ratios.

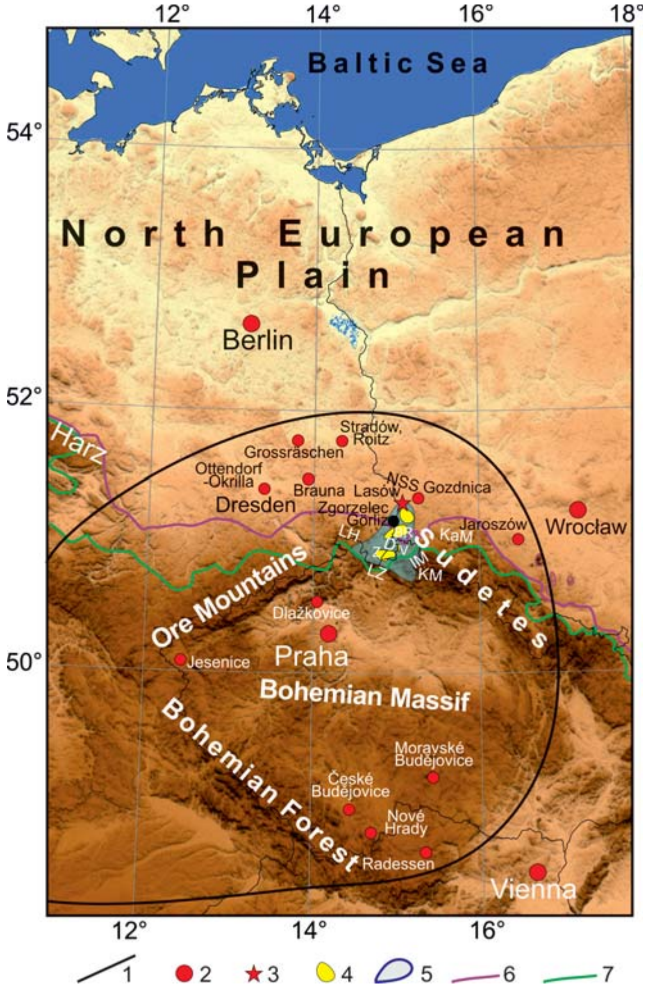

Fig. 4. Map showing moldavite distribution and drainage basin for the Lusatian Neisse River. 1. Moldavite distribution area in the Bohemian Massive, Lusatia and Lower Silesia; 2. Polish sites with moldavites; 3. Lasów; 4. Drainage basin for the Lusatian Neisse; 5. Main Neogene sedimentation basins; 6. The Elster glacier maximum (MIS 12); 7. The Drente glacier maximum (MIS 6). Abbreviations: IM – Izera Mts, LH – Lusatian Highlands, LZ – Lausitz Mt., KM – Karkonosze Mts, KaM – Kaczawa Mts, BR – Berzdorf–Radomierzyce graben, V – Višniova graben, Z – Żytawa/Zittau graben, D – Działoszyn horst, NSS – North Sudetic Synclinorium.

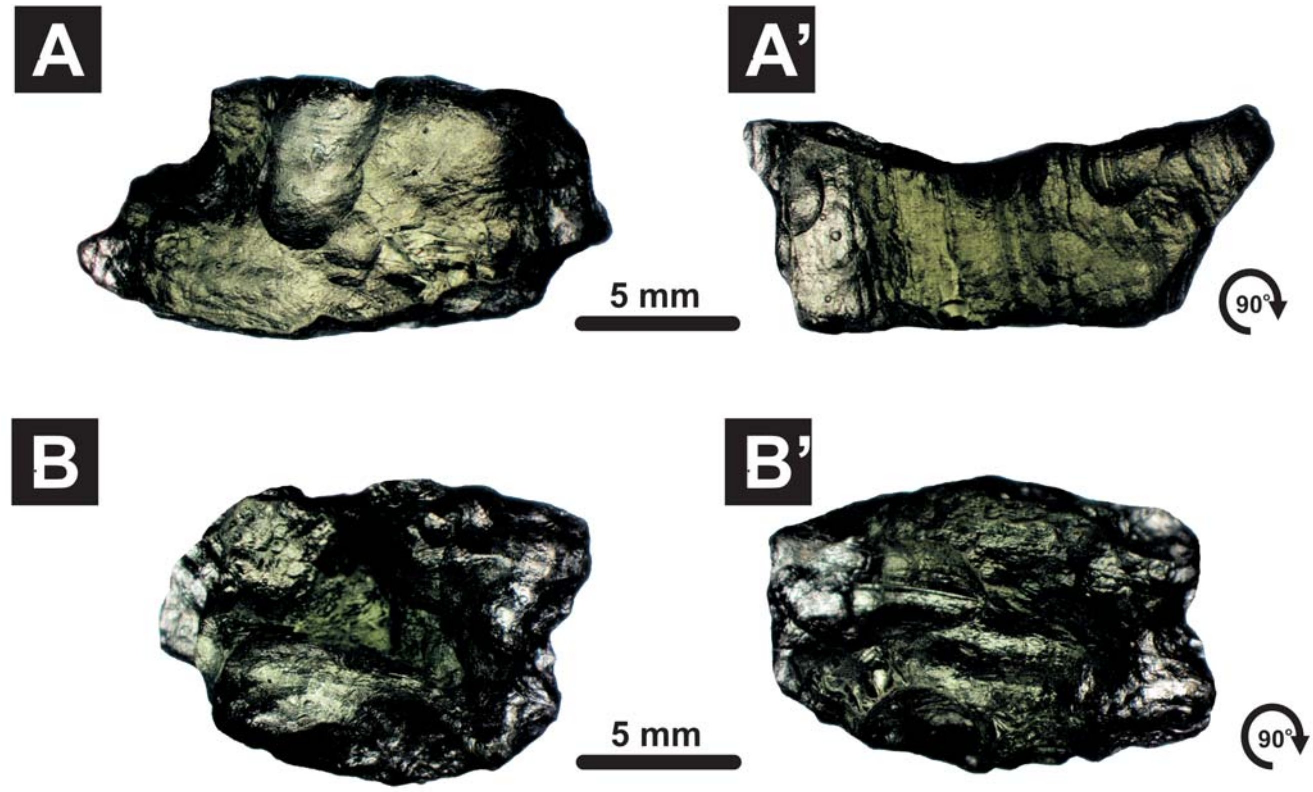

Fig. 5. Close-ups of Polish moldavites from the Lasów open-pit mine. Macroscopic and microscopic features of investigated material are given in Table 1.

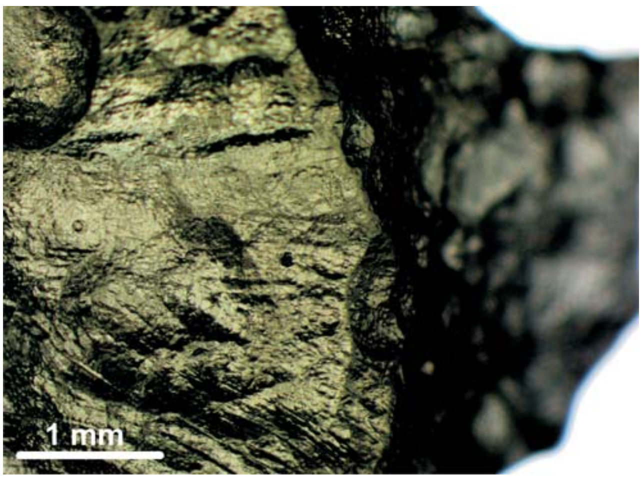

Fig. 6. Slightly corroded surface of moldavite A (see Fig. 5 and Table 1) from Pleistocene sediments of Lasów open pit-mine. Optical microscope image.

Table 1

Characteristics of Polish moldavites found in Pleistocene deposits

Sample	Mass (g)	Shape	Surface	Colour	Features
A	0.405	elongated	low corrosion	bottle green	B * L***
B	0.445	ellipsoidal	low corrosion	bottle green	B ** L **

B – bubbles; L – lechatelierite; * – low rich, ** – rich, *** – very rich

The tektites described in this paper are stored in the Museum of the Faculty of Earth Sciences, University of Silesia, under registration/catalogue number WNOZ/Mt/90.

RESULTS

Description of moldavites

The first moldavite was found in the sieve residues of some 800 kg of sediments and the second one in the next 600 kg. Figure 1C shows the localities of the new moldavite discoveries at Lasów. Both moldavite fragments display a typical bottle-green colour (Fig. 5). Their weight is ~0.8 g. They are similar in size to moldavites from the Miocene sediments in the Gozdnica pit (Brachaniec *et al*., 2015, 2016) and much bigger than those from Mielęcin and Jaroszów (Brachaniec *et al*., 2014; Skála *et al.*, 2016).

One specimen (A) includes numerous bubbles, but displays no lachatelierite, unlike specimen B. Both tektites show a slightly corroded surface (Fig. 6). Sample A displays an elongated shape, unlike the more irregular sample B (Fig. 5). All characteristics of the described tektites are listed in Table 1. Characteristic features of the Polish tektites from Miocene sediments are the degree of corrosion and the ellipsoidal/elongated shape (see details in Brachaniec *et al*., 2014, 2015, 2016; Skála *et al.*, 2016).

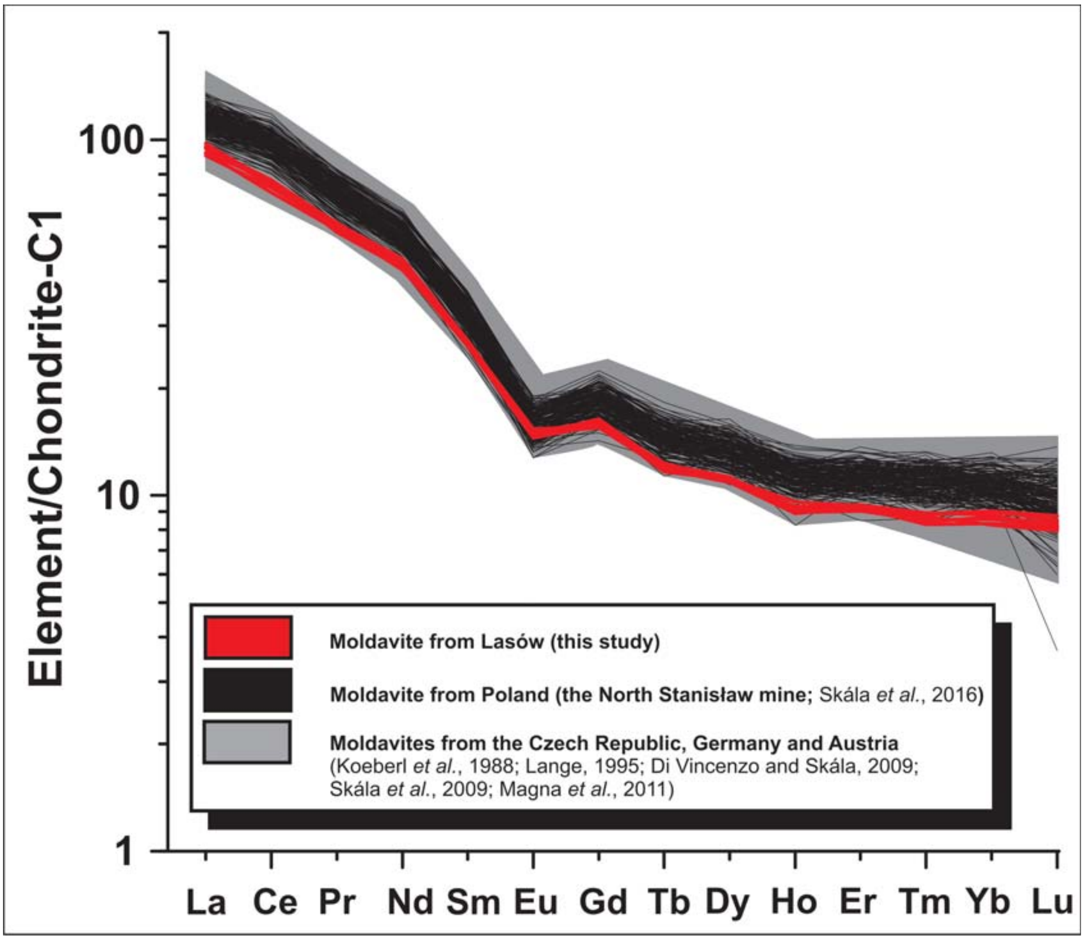

Fig. 7. The CI-chondrite normalized REE distribution in tektites. The distributions of the rare earth elements in moldavites from all known sub-strewn fields are given for comparison (data from: Koeberl *et al.*, 1988; Lange 1995; Di Vincenzo and Skála, 2009; Skála *et al.*, 2009, 2016; Magna *et al.*, 2011).

REEs characterisation of moldavites

The moldavite specimen from Lasów is characterised by REE patterns typical (Fig. 7) for all moldavites, where LREE dominates over HREE ($(La/Yb)_N$ = 10.01–11.49; Table 2). The LREE/HREE ratios range from 4.70 to 5.06. Chondrite-normalized REE patterns of the specimen overlap with those of other sub-strewn fields, though the Lasów specimens plot in the lower part of all the CI-normalized REE ranges for Moravian, Lusatian, Austrian and Polish (Miocene) moldavites. The sample from Lasów is characterised by weak REE fractionation ($(Ce/Yb)_N$ = 8.12–9.04), negative Eu anomalies (Eu/Eu* = 0.28–0.30) and positive Ce anomalies (Ce/Ce* = 7.59–8.20).

Petrography of the Pleistocene upper terraces

The petrographical characteristics of the gravels from the sand-pit at Lasów were based on the mean of two samples (Table 3). The clast suite was used to determine the source area of these moldavite-bearing sediments. From the first sample, Lasów 1 (Table 3), 620 clasts of 4 to 10 mm in size were separated. The characteristic feature of this sample is the high degree of weathering. More than 51% of the clast population was represented by quartz; the rest of the lithoclasts were gneisses (~8%), schists (~5%) and Vendian as well as Palaeozoic greywackes (~6%). The Scandinavian rocks are represented by resistant gneisses and Jotnian and Dalarne quartzites and rhyolites. All altered rhyolites were considered as redeposited Permian clasts that can be found between Zgorzelec and Lasów.

In general, all clasts are poorly rounded. Quartz and quartz-feldspar aggregates might have come from altered residual granites and gneisses, as well as from localized erosion of the numerous Miocene gravel-rich layers. This indicates short transport distances during the Miocene.

The second sample, Lasów 2, is characterised by fine pebbles. 50% of the clasts are represented by quartz including dove-blue type (Rumburg quartz). Sudetic material represents 46.3% of the whole sample (Table 3, Fig. 8). K-feldspars are strongly weathered and similar to those from altered porphyries or rhyolite. The main difference is the absence of empty pores in the volcanic glass. Only a single clast of Cretaceous sandstone from the Lusatia Mountains (Hradka near Nisou) was found. A flint clast from radiolarites within phyllites from the metamorphic cover of the Kaczawskie Mountains also was noted.

Table 2

REE content and selected petrological indicators of moldavites from Lasów

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	$(La/Yb)_n$	$(Ce/Yb)_n$	Ce/Ce^*	Eu/Eu^*	Σ_{LREE}	Σ_{HRRE}
#1	17.97	35.70	4.14	16.28	3.22	0.68	2.58	0.36	2.24	0.42	1.21	0.17	1.18	0.17	10.55	8.15	7.59	0.28	265.30	55.28
#2	18.55	37.50	4.19	16.19	3.31	0.72	2.56	0.36	2.24	0.42	1.21	0.18	1.12	0.16	11.49	9.04	7.86	0.30	272.34	55.00
#3	19.04	38.10	4.33	16.91	3.25	0.71	2.61	0.35	2.24	0.42	1.20	0.17	1.16	0.17	11.38	8.86	7.88	0.29	278.29	55.04
#4	18.61	38.70	4.31	17.42	3.34	0.70	2.65	0.37	2.25	0.43	1.24	0.18	1.19	0.16	10.79	8.73	8.08	0.29	279.06	56.42
#5	18.46	37.50	4.16	16.64	3.31	0.70	2.54	0.36	2.20	0.41	1.22	0.17	1.13	0.16	11.32	8.95	7.88	0.29	272.12	54.64
#6	18.66	37.90	4.25	16.80	3.32	0.69	2.61	0.37	2.22	0.42	1.22	0.17	1.17	0.17	11.06	8.74	7.92	0.28	275.38	55.91
#7	17.64	36.80	4.20	16.81	3.33	0.69	2.68	0.37	2.25	0.44	1.24	0.18	1.22	0.17	10.01	8.12	7.87	0.28	269.01	57.09
#8	17.96	38.50	4.08	16.41	3.25	0.70	2.55	0.37	2.28	0.43	1.25	0.18	1.22	0.18	10.18	8.49	8.20	0.29	270.02	57.26
Average	18.36	37.59	4.21	16.68	3.29	0.70	2.60	0.36	2.24	0.42	1.22	0.17	1.17	0.17	10.84	8.63	7.91	0.29	272.69	55.83
Minimum	17.64	35.70	4.08	16.19	3.22	0.68	2.54	0.35	2.20	0.41	1.20	0.17	1.12	0.16	10.01	8.12	7.59	0.28	265.30	54.64
Maximum	19.04	38.70	4.33	17.42	3.34	0.72	2.68	0.37	2.28	0.44	1.25	0.18	1.22	0.18	11.49	9.04	8.20	0.30	279.06	57.26

Table 3

Petrographic analysis of grain size 4–10 mm from Lasów

Province	Petrographic type	Lasów 1			Lasów 2		
		Amount	% of total	% in province	Amount	% of total	% in province
Indefinable	Quartz (monocr.)	315	50.8	50.8	667	51.4	51.4
Sudetic	Feldspar	9	1.5		41	3.2	
	Quartz "dove-blue" (Rumburg)	0.0	0.0		31	2.4	
	Gneiss	49	7.9		50	3.9	
	Quartz-feldspar aggregate	18	2.9		26	2.0	
	Granitoid/Granodiorite	24	3.9		99	7.6	
	Jasper	3	0.5		6	0.5	
	Rhyolite and ignimbrite	31	5.0	47.7	57	4.4	46.3
	Lydite	30	4.8		74	5.7	
	Mica & quartz-mica schist	34	5.5		76	5.9	
	Greywacke	35	5.6		59	4.5	
	Chert	24	3.9		13	1.0	
	Diabases and amphibolite	4	0.6		15	1.2	
	Quartz (polycr.) & mylonite	32	5.2		46	3.5	
	Quartz-hematite vein	3	0.5		6	0.5	
	Sandstone (Upper Cretaceous)	0.0	0.0		1	0.1	
	Hematite	0.0	0.0		1	0.1	
	Flint	0.0	0.0		1	0.1	
Fennoscandian and Baltic	Gneiss and granitoid	2	0.3		12	0.9	
	Rhyolite	1	0.2	1.1	5	0.4	1.8
	Dalarna and Jotnia quartzite	3	0.5		5	0.4	
	Red quartz-feldspar aggregate	1	0.2		0.0	0.0	
Weathered	Ferruginous concretion	1	0.2	0.3	6	0.5	0.5
	Undefined	1	0.2			0.0	
TOTAL		620	100.0	100.0	1297	100.0	100.0

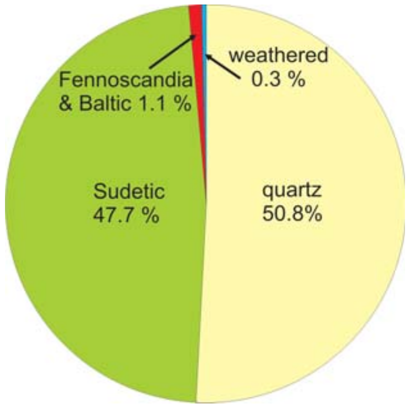

Fig. 8. Graphical illustration of the petrographical analyses of grain size (4–10 mm) in Lasów 1 (see also Table 3).

When comparing both Lasów samples with the gravel petrography from the Zodel area (Wolf and Schubert, 1991), situated on the west part of the Lusatian Neisse, a significant difference can be noted in the smaller number of crystals (~20%), while clasts from granites and feldspars can reach up to 80%. What is striking is the lack of distinction of the broadly defined Izera-Lusatia gneiss, including the Rumburg quartz with a characteristic dove-blue colour of quartz. The amounts of Fenno-Scandinavian clasts are similar, and do not exceed 1.3% (Table 3).

DISCUSSION

The Ries impact event is dated at ~14.8 Ma (Buchner *et al*., 2013). This implies that all Polish moldavites found in younger deposits are parautochthonous. The moldavites exhibit trace-element characteristics typical of this kind of tektite (Table 2; Fig. 7). The Miocene deposits and Pleistocene terraces of the Lusatian Neisse are the result of fluvial depositional processes and confirm the alluvial recycling of moldavite clasts by a river in the Western Sudetes.

On the basis of the gravel petrography, the dominant clasts in the moldavite-bearing sediments are quartz and quartz-feldspar aggregates. Sub-rounded to angular clasts indicate their connection with weathered and exhumed granitoids, as well as gneisses of the drainage basin of the Lusatian Neisse. The small quantity of Vendian or Palaeozoic (Table 3) rocks and of Permian volcanics and Cretaceous sandstones from the North Sudetic Synclinorium in the Lasów area precludes recognition of this terrain as the source area for the moldavites investigated.

The present-day morphology of the drainage basin of the Lusatian Neisse River originated after the Pliocene and the Early Pleistocene uplift. This structure, transverse to the Eger Graben, was formed finally in the Early Miocene (Coubal *et al*., 2015). It precludes the presence of a large drainage basin of the Lusatian Neisse (Figs 2, 4) in the south, as was proposed previously by Suhr (2003).

The occurrence of moldavites in Miocene sediments at Gozdnica and in Pleistocene sediments at Lasów indicates that the mountainous source areas had been gradually uplifted. Meanwhile, subsidence occurred in the Eger Graben and the North Sudetic Synclinorium. The scarcity of moldavites in Poland may indicate their connection with the weathered Middle Miocene sediments, cropping out on both sides of the Żytawa–Zgorzelec Depression, the Berzdorf–Radomierzyce Depression and the Działoszyn area, where only scarce relics of the Miocene sedimentary cover are preserved.

Subsequently, the drainage basin of the Lusatian Neisse was covered by up to 500 m of deposits during the Elster Glacial (MIS 12; Fig. 4) and once more up to 200–250 m during the Drente Glacial (MIS 6). Therefore, the erosion of the Miocene sediments was limited in both time and space.

According to Bouška (1972, 1997, 1998), tektites might be hosted in younger fluvial and glacial deposits through multiple recycling events. A similar situation was observed in the case of the Holocene sediments of the Czech Republic rivers (see details in Mrázek and Rejl, 1976; Bouška and Lange, 1999), Pleistocene sediments in southern Bohemia, western Moravia, Lusatia and Austrian strewn fields (Lange *et al*., 1995; Bouška and Lange, 1999; Trnka and Houzar, 2002). The Czech Pleistocene sediments containing moldavites are represented by coarse-grained gravels with quartz. In Germany (Lusatia), the same sediments are mainly pebbles of basalts, phonolites, and of greywackes forming the Elbe Gravel Formation (Lange *et al*., 1995; Lange, 1996; Bouška and Lange, 1999). The presence of Permian fossilized tree trunks, lydites, and cherts from the Barrandian area indicates a wide source area for moldavites. Theoretically, they might have been transported even from České Budějovice in the Czech Republic to Lusatia in Germany.

Moldavites, occurring in glacial terraces at Lasów, are evidence of recycling from the Lusatia area. The drainage basin may be subdivided into two parts, depending on the structural setting where the moldavite tektites fell 14.8 Ma ago. The first comprises the western parts of Karkonosze, Izera and Lusatia mountains. The second area comprises the northern part of the Eger Graben and the wide valleys oriented parallel to the structure. According to Žebera (1972), Lange (1995, 1996), Trnka and Houzar (2002), and Buchner and Schmieder (2009), the brittle character of moldavite glass effectively constrains the duration of fluvial transport. Bouška *et al*. (1968), Cífka *et al*. (1971), and Žák (2009) similarly claimed that the fluvial transport of tektites was of short duration. Both Miocene and Pleistocene moldavites have slightly eroded surfaces. Sediments delivering a limited number of pebble-like moldavites thus indicate rather brief fluvial transport. Despite the multiple recycling events in the Pleistocene tektites investigated, they display a water-abraded/slightly corroded surface, and ellipsoidal shapes (Trnka and Houzar, 2002; Buchner and Schmieder, 2009; Skála *et al.*, 2016). Investigating fluvially transported moldavites from Lusatia, Lange (1995) did not notice this characteristic erosional feature on the moldavite surfaces.

Brachaniec *et al.* (2014, 2015, 2016) demonstrated that Polish moldavites from Mielęcin, Jaroszów and Gozdnica were recycled from Lusatia. Skála *et al.* (2016) suggested that the Lusatia region may not have been a suitable source area. In the light of this study, it might be supposed that the Polish parautochthonous tektites originated from the upper part of the drainage basin of the Lusatian Neisse (Fig. 4). They were probably eroded from the Miocene sediments that filled such structures as: the Zittau Depression, the Berzdorf–Radomierzyce Depression, the Višňová Depression and the tectonically uplifted Działoszyn Graben.

CONCLUSIONS

The presence of moldavites in the Middle Miocene alluvial sediments at Gozdnica, ~25 km NNE from Lasów, indicates that the pre-Lusatian Neisse (Nysa) River sediments originated from the same source area, the Western Sudetes, during the last 14 Myr. Erosion of these Miocene deposits is clearly evidenced on a large scale in the uplifted foothills of the Upper Miocene Izera, Lusatia and Kaczawa complexes. The sediment cover, estimated to be 100 m thick, was removed from the Działoszyn Depression. The drainage basin of the Lusatian Neisse is the source area, where moldavites fell to the surface after the Nördlinger Ries impact. Subsequently, the supply area of moldavites in the Miocene deposits around Gozdnica and the Pleistocene sediments at Lasów was the same. More finds of new tektite samples are required for better characterization and determination of the source area and a potentially new sub-strewn field for Polish moldavites.

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