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Citation style: Brachaniec Tomasz. (2020). Moldavite finds in Middle Miocene (Langhian Stage) deposits of southwestern Poland. “Carnets de Geologie” (Vol. 20 (2020), s. 241-247), doi 10.2110/carnets.2020.2012

Carnets Geol. 20 (12)

E-ISSN 1634-0744
DOI 10.2110/carnets.2020.2012

Moldavite finds in Middle Miocene (Langhian Stage) deposits of southwestern Poland

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Abstract: Most of the Ries tektites (moldavites) were deposited in sediments clearly postdating the Ries crater formation. This suggests secondary deposition for these ejected glasses. Only a few sedimentary formations known to contain these tektites are of Middle Miocene age and coeval with the Ries event. One is the Poznańska Formation, which is exposed across southwestern Poland. These mud deposits formed in the Middle Miocene (Langhian Stage). New moldavites, described in this report were found in the Poznańska Formation and weigh from 0.851 to 0.907 g. The North Stanisław sandpit, where the tektite specimens were found, is located 490 km from the Ries structure. These finds agree with the numerical simulation modelling of the ejection of these moldavites up to 600 km away from the source crater.

Key-words:

- moldavite;
- tektite;
- distal ejectas;
- Ries crater;
- Middle Miocene;
- Poland

Citation: BRACHANIEC T. (2020).- Moldavite finds in Middle Miocene (Langhian Stage) deposits of southwestern Poland.- *Carnets Geol.*, Madrid, vol. 20, no. 12, p. 241-247.

Résumé : ***Découverte de moldavite dans des sédiments du Miocène moyen (Langhien) du sud-ouest de la Pologne.-*** La plupart des tectites de Ries (moldavites) se sont déposées dans des sédiments clairement postérieurs à la formation du cratère de Ries, ce qui suggère un dépôt secondaire de ces éjectas vitreux. Seules quelques formations sédimentaires connues pour livrer ces tectites sont d'âge miocène moyen et contemporaines de l'événement de Ries. L'une d'elle, la Formation Poznańska, affleure à travers la Pologne sud-occidentale. Ses dépôts argileux se sont formés au Miocène moyen (Langhien). Les nouvelles moldavites décrites dans cette note proviennent de la Formation Poznańska. Elles pèsent de 0,851 à 0,907 g. La sablière de Stanisław Nord, où ont été trouvées ces tectites, est située à 490 km de la structure de Ries. Ces découvertes s'accordent parfaitement avec les simulations numériques modélisant l'éjection de ces moldavites à plus de 600 km du cratère source.

Mots-clefs :

- moldavite ;
- tectite ;
- éjectas distaux ;
- cratère de Ries ;
- Miocène moyen ;
- Pologne

Introduction

In the geological record many impacts are recognised by multiple evidence, *e.g.*, craters, impactites, altered meteorite fragments, PGEs anomaly, tektites, shock minerals or cosmogenic components (RACKI *et al.*, 2011; GLASS and SIMONSON, 2012; SZOPA *et al.*, 2017a). Tektites and microtektites are shock-melted glassy droplets (KOEBERL, 1993; GLASS and SIMONSON, 2012; BRACHANIEC *et al.*, 2014a). The Central European tektites, known as moldavites, are related to the Ries crater, the diameter of which is approximately 24 km. Its age is estimated to be 14.81 ± 0.04 Ma (SCHMIEDER *et al.*, 2018). The tektites were produced as a result of melting of the Miocene molasse deposits (Upper Freshwater Molasse), which formed the target paleosurface at the time of impact, and which are mainly composed of quartz sands, carbonates, and clays (SKÁLA *et al.*, 2016; ŽÁK *et al.*, 2016; RODOVSKÁ *et al.*, 2016).

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Published online in final form (pdf) on June 30, 2020
[Editor: Robert W. SCOTT; technical editor: Bruno GRANIER]

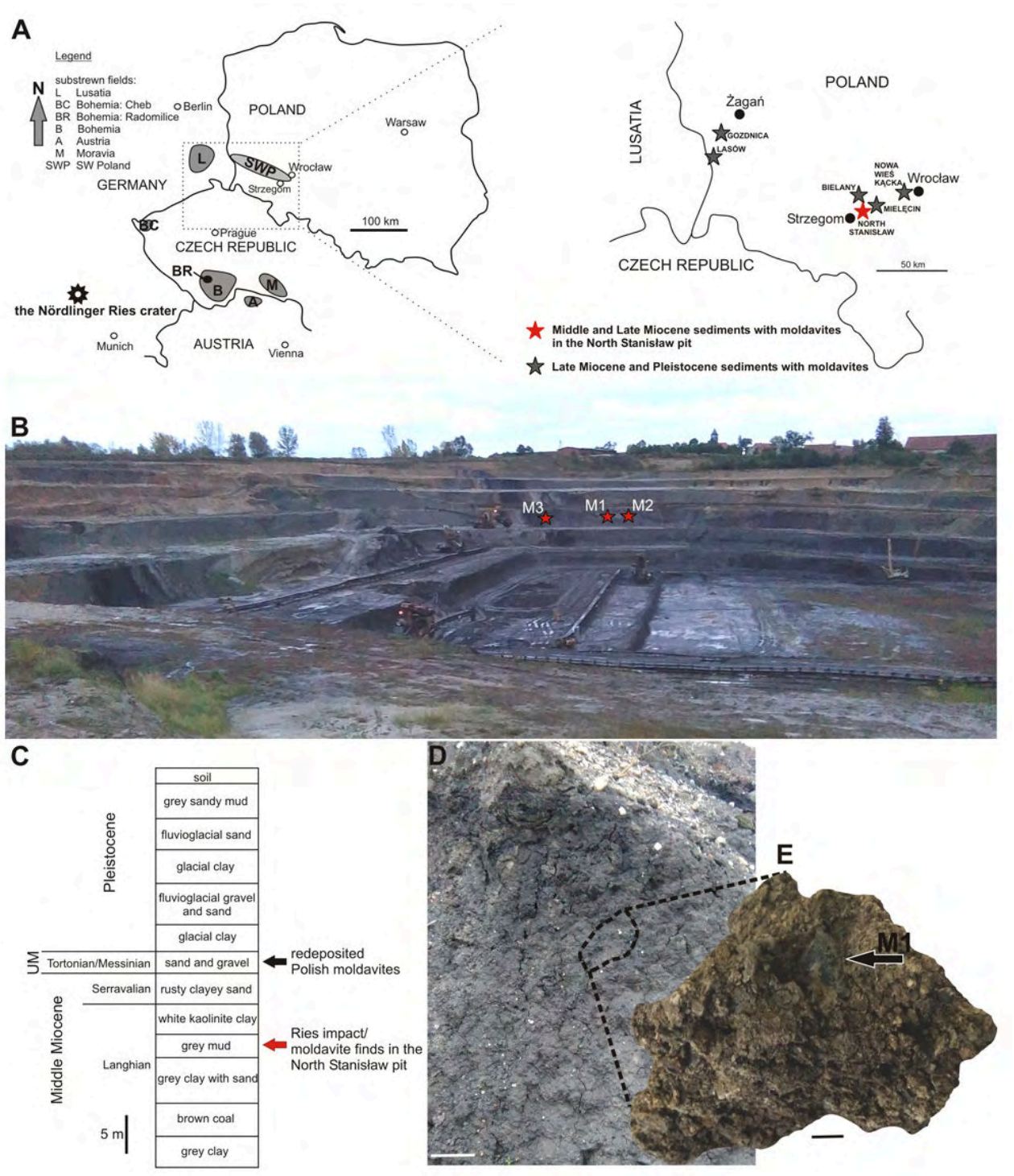

Figure 1: A. Schematic map of moldavite distribution across Central Europe. Substrewn fields are indicated according to Stöffler *et al.* (2002). **B.** Section of the North Stanisław pit where the investigated moldavite specimens were found. Lithological profile in this part of pit has *ca.* 60 m thickness. **C.** Simplified lithostratigraphic profile of the sediments visible in the North Stanisław mine. Lithostratigraphic data from Szynkiewicz (2011). UM - Upper Miocene. **D.** General view of the Poznańska Formation grey muds. Scale bar 10 cm. **E.** Moldavite specimen M1 pitting in its original position in the mud block. Scale bar 5 mm.

In the summer of 2013, the first Polish moldavites were discovered in the North Stanisław sandpit, SW Poland (Brachaniec *et al.*, 2014b). In the following years tektites were also found in the following sections: Mielęcin (Brachaniec *et al.*, 2015), Lasów and Gozdnica (Brachaniec *et al.*, 2015, 2016; Szopa *et al.*, 2017b), as well as in Nowa Wieś Kącka (Brachaniec, 2017). In total 30 tektites were found, which supports Poland as the fourth European country where moldavite substrewn fields lie (Fig. 1.A). However, it should be mentioned that all tektites were found in Upper

Miocene and Pleistocene deposits, therefore, it appears likely that those tektites have been reworked from older strata and redeposited.

In this report three Polish moldavites equals to Ries event are described. In the second half of 2017, during amber exploration, one moldavite was discovered in Middle Miocene muds exposed in the North Stanisław pit. The other two tektites were discovered from the same deposits in 2018. The age of this formation and its features suggest that tektites found in this unit might occur in *in-situ* position and/or were transported only a short distance in a fluvial environment.

Location and geological setting

The moldavites were found in the open North Stanisław sandpit, near Strzegom in Lower Silesia, southwestern Poland (Fig. 1.A-B). In the investigated area, below the Cenozoic deposits is a Paleozoic epimetamorphic complex of phyllite and shales, some 50-70 m thick (HAŁUSZCZAK, 2011). In the lithostratigraphic profile (Fig. 1.C) the oldest unit of the Miocene is represented by a *ca.* 5 m-thick grey kaolinite clay bed. Above it lay two units of brown coal, which in turn are overlain by grey muds with sand and clays of the Poznańska Formation that contained the three moldavites at hand (Fig. 1.D-E). These deposits are *ca.* 3 m thick. Micropaleontological analysis estimated the age of this formation to be Middle Miocene - Langhian Stage (DYJOR *et al.*, 1992; SŁODKOWSKA, 2002; HAŁUSZCZAK, 2011; SZYNKIEWICZ, 2011). The Poznańska Formation is overlain by characteristic white kaolinite clays and rusty clayey sands. The youngest Neogene deposits are the Tortonian/Messinian stage moldavite-bearing sandy gravels of the Gozdnica Formation (BRACHANIEC *et al.*, 2014b, 2015).

Methodology

Three moldavites were recovered from Middle Miocene sediments. The glass was found deeply embedded in the mud (Fig. 1.E). From this context, its redeposition from overlying deposits appeared unlikely. Each moldavite specimen was mounted on a 25 mm-diameter epoxy resin plug, then ground and polished to expose the glass. Lechatelierite inclusions were imaged by scanning electron microscopy on a FET Philips 30 electron microscope (15 kV and 1 nA) at the Faculty of Natural 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. 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 Polish moldavites are stored at the Museum of the Faculty of Natural Sciences, University of Silesia, under registration number WNOZ/Mt/88.

Results

Three moldavites were collected in total from the Middle Miocene mud from the North Stanisław pit (Fig. 2). Their masses are very similar and range from 0.851 to 0.907 g (Table 1). Their shapes are angular (specimens M1 and M2) and sub-angular (specimen M3). All tektites are likely complete, and not cracked. Surfaces of tektites M1 and M2 have a relatively deep sculpturing and seem to be not or very slightly corroded. Additionally, all three specimens have sharp edges. Only the surface of moldavite M3 is smoother than M1 and M2. The specimens display the characteristic green colour of moldavite. The investigated glass contains spherical bubbles 10-200 μm diameter (Fig. 3.A). Backscattered electron images reveal many lechatelierite inclusions, with dimensions from 50 to 600 μm (Fig. 3.B). Electron microprobe data show that the new Polish moldavite specimens are characterized by an average SiO_2 concentration of ~79 wt%, which is slightly higher than that of the Polish moldavites analyzed previously (Table 2). On the other hand, the main elemental concentrations, Al, Fe, Mg, Ca, are similar to those of the moldavites from other substrewn fields in Central Europe.

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

Table 1: Characteristics of moldavites from the Poznańska formation. B = bubbles, L = lechatelierite. * = low, ** = high, *** = very high.

Sample	Mass (g)	Dimensions (mm)	Shape	Surface	Color	Features
M1	0.851	14x11x5	angular	primary sculpturing?	green	B** L*
M2	0.874	15x9x4	angular	primary sculpturing?	green	B* L**
M3	0.907	16x9x5	sub-angular	low corroded	light green	B* L***

Table 2: Major element composition (average wt%) of moldavites from different locations, based on electron microprobe analyses.

	moldavites from Middle Miocene deposits	moldavites from Late Miocene deposits						
	North Stanisław (this study)	East Gozdnica (Brachaniec *et al.*, 2016)	Mielęcin (Brachaniec *et al.*, 2015)	North Stanisław (Brachaniec *et al.*, 2015)	Nowa Wieś Kącka (Brachaniec, 2017)	Lusatia (Lange, 1996)	Moravian (Skála and Čada, 2003)	Austria (Koeberl *et al.*, 1988)
SiO_2	78.83	77.34	78.31	76.28	77.28	79.3	79.28	79.73
TiO_2	0.21	0.24	0.27	0.12	0.19	0.34	0.42	0.30
Al_2O_3	10.93	10.71	11.01	10.87	10.91	10.5	11.01	9.81
FeO_{total}	1.91	1.88	1.89	1.92	1.83	1.84	2.26	1.54
MnO	0.03	0.04	0.01	0.02	0.04	0.06	0.13	0.06
MgO	1.73	1.75	1.78	1.75	1.74	1.75	1.39	1.72
CaO	2.05	2.20	2.08	2.12	2.14	2.00	1.64	2.41
Na_2O	0.40	0.49	0.51	0.57	0.52	0.47	0.57	0.39
K_2O	3.27	3.36	3.58	3.21	3.33	3.46	3.38	3.49
P_2O_5	0.05	0.07	0.05	0.07	0.06	-	0.02	-
TOTAL	99.41	98.06	99.49	96.93	98.04	99.72	100.1	99.45

Figure 2: Morphology and size of moldavites from the Middle Miocene deposits. Scale bar 5 mm.

Discussion

Moldavites are found in sediments of various ages. In the Czech Republic three deposits contain moldavites (Trnka and Houzar, 2002; Ševčík *et al.*, 2007; Skála *et al.*, 2016, and references therein):
1) Miocene fluvial sandy gravels and clays,
2) Pliocene fluvial deposits (mainly Koroseky Sandy Gravel, Vildštejn Formation and Zdlby Group deposits), and
3) Pleistocene river terrace sediments (mainly sandy gravels).

In the Lusatian area of Germany tektites are mostly restricted to the Upper Miocene (Tortonian/Messinian) units: Older Senftenberg Elbe Gravels and Upper Gravel Sands (Lange, 1996; Trnka and Houzar, 2002). In Austria (the Horn region), moldavites have been discovered in two units (Koeberl *et al.*, 1988; Trnka and Houzar, 2002): the Messern Sands and Clays deposits of Serravallian and Tortonian age (Middle/Upper Miocene), and the Irnfritz–Radessen Sands and Gravels Formation of Tortonian/Messinian (Upper Miocene age). In the Polish substrewn field, moldavites are hosted in fluvial sandy gravels of the Gozdnica Formation (Tortonian/Messinian) and in Pleistocene river terrace sediments (*e.g.*, Brachaniec *et al.*, 2015; Szopa *et al.*, 2017b, 2019). Most of the moldavites occur in sediments younger than the Ries impact, thus indicating their reworking and redeposition (Trnka and Houzar, 2002). According to Badura and Przybylski (2004), during the Miocene, many rivers and

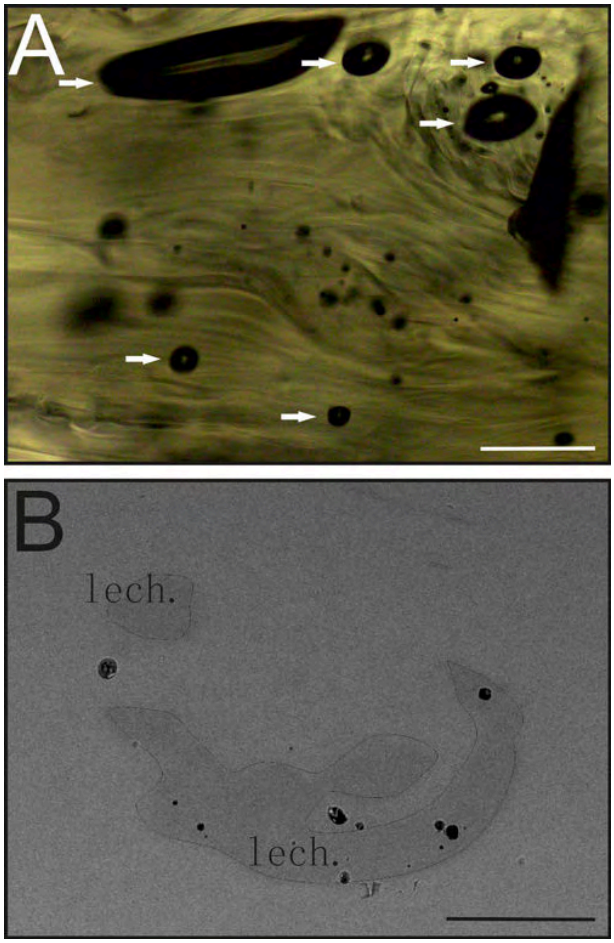

Figure 3: Characteristic features of moldavites. **A.** Bubbles in tektite glass. Scale bar 100 µm. **B.** Lechatelierite (lech.) inclusions. Scale bar 100 µm.

streams flowed across Central Europe. BUCHNER *et al.* (2003) and BUCHNER and SCHMIEDER (2009) claimed that fluvial transport played a significant role in the distribution of the proximal and distal Ries ejecta.

Moldavite-bearing deposits coeval with the Ries impact are relatively rare; up to now only three formations are a similar age to those of the moldavites formation (TRNKA and HOUZAR, 2002; ŠEVČÍK *et al.*, 2007): the Vrábče layers (Domanin Formation) in southern Bohemia, colluvio-fluvial clays with sandy gravels near Slavice and Třebíč in western Moravia, and probably the Imfritz-Radessen Formation in the Horn area (Austria). Numerical modeling simulations showed that moldavites might have been ejected up to 600 km away from the source crater (ARTEMIEVA *et al.*, 2013). Results of numerical modeling conducted by STÖFFLER *et al.* (2002) and ARTEMIEVA *et al.* (2013) show that Ries distal ejecta could have been ejected over distances of several hundred kilometres, possibly even above Earth's escape velocity of 11 km/s (N. ARTEMIEVA – personal communication). The most distal reworked moldavites were found *ca.* 510 km from the Ries crater (BRACHANIEC, 2017), but fluvial transport made it challenging to reliably estimate the original extent of the dispersal area of all redeposited tektites. Generally, tektites could survive hundreds of km by fluvial transport (HURTIG, 2019), not as previously thought, a dozen or so at most (VAMBEROVÁ and ŠEVČÍK, 1990; BRACHANIEC, 2018a, 2018b, 2019a, 2019b). The discovery of moldavites in the Middle Miocene deposits in SW Poland is consistent with modeling (STÖFFLER *et al.*, 2002; ARTEMIEVA *et al.*, 2013). The North Stanisław pit lies 490 km away from the Ries crater. Miocene paleogeography of SW Poland and the lithology of Badenian deposits indicate that the new moldavite specimens were probably deposited in a river environment (see PIWOCKI *et al.*, 2004). Specimens M1 and M2 have deep sculpturing on their surface. This feature and sharp edges of glass may indicate rapid burial in river deposits or reworking only short distance. Additionally, the sculpturing of specimen M3 surely indicates fluvial abrasion. Generally, the duration of abrasion depends on the environmental energy and type of deposits, but it can be assumed that tektites with sharp edges indicate brief reworking. Lechatelierite inclusions and bubbles both validate the impact origin of the glass, as well as its chemical composition, which is consistent with previously studied moldavite samples.

Summary

The three moldavites described in this report were found in sediments coeval with the age of the Ries impact. The finds are in accordance with the numerical simulations that show that these tektites were ejected up to 600 km from the crater. Typical features of moldavites were observed in two specimens (M1 and M2) such as irregular shape and deep ornamentation, which may indicate that they were found in *in-situ*. M3 specimen has slight traces of abrasion and was undoubtedly subjected to fluvial reworking and certainly for only a short distance, as evidenced by its non-rounded edges.

Acknowledgments

The author would like to thank Tadeusz PRZYLIBSKI, who provided detailed review of the manuscript as well as Bruno GRANIER and Robert SCOTT for careful editorial handling. The author also thanks Natalia ARTEMIEVA for consultations, and Krzysztof SZOPA for preparing the photo documentation of the material. Kamil RUDZKI is thanked for his field work, as well as Bruno FERRÉ for language corrections.

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