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

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Résumé : Découverte de moldavite dans des sédiments du Miocène moyen (Langhien) du sud-ouest de la Pologne.- La plupart des tektites 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 tektites 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 tektites, 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-clés : • moldavite ; • tektite ; • 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).
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: Miełęcin (Brachaniec et al., 2015), Lasów and Gozdna (Brachaniec et al., 2015, 2016; Szopa et al., 2017b), as well as in Nova Wieś Kącka (Brachaniec, 2017). In total 30 tektites were found, which supports Poland as the fourth European country where moldavite sub-strewn 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 re-worked 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 Stanislaw 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 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 Stanislaw sandpit, near Stryzem 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 (HALUSZCZAK, 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; HALUSZCZAK, 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 Stanislaw 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 strewn fields in Central Europe.

**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 Stanislaw (this study)          |
|                                        | East Gozdica (BRACHANIEC et al., 2016)|
|                                        | Miełęcin (BRACHANIEC et al., 2015)    |
|                                        | North Stanislaw (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  |
| **Al₂O₃ | 10.93 | 10.71 | 11.01 | 10.87 | 10.91 | 10.5 | 11.01 | 9.81  |
| **FeO**<sub>total</sub> | 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 |
| **Na₂O | 0.40 | 0.49 | 0.51 | 0.57 | 0.52 | 0.47 | 0.57 | 0.39 |
| **K₂O | 3.27 | 3.36 | 3.58 | 3.21 | 3.33 | 3.46 | 3.38 | 3.49 |
| **P₂O₅ | 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 Gozdnic 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
streams flowed across Central Europe. BUCHNER et al. (2003) and BUCHNER and SCHMIEDEK (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 (TRNIKÁ and HOUZÁR, 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-Rassen 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 Stanislaw 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.

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