INTRODUCTION

Large impact craters are relatively rare in geological record on the Earth. All over the world only 164 crater structures are above 1 km in diameter and only 40 with more than 20 km in diameter (Earth Impact Database). The most notable features of such big impacts are significant pressure and temperature caused by extraterrestrial body fall. In some cases, impact may lead to glass production, which is named tektite. The distribution and chemical features of impact glasses are the most diagnostic features of the cosmic body impacts. Tektites are distal ejecta type deposits, next to three other impact melt products (Osinski 2003): (1) crystalline melt bodies in the impact structure, (2) glassy clasts in melt-bearing breccias or suevite, and (3) injection dykes in the crater. These different types of glasses form during the shock melting phase of target. Impact melt glasses resemble a terrestrial volcanic glass in appearance. There are three properties, which can be used to distinguish between the impact and terrestrial types of glasses: (1) the impact glass has a chemical composition of one lithology or mixture of different rock types that are present in the source basement (Dence 1971), (2) it is characterized by the presence of lechatelierite (Stöffler 1984), and (3) it has inclusions of shocked minerals (Engelhardt 1972). Characteristic shapes of tektites result from three stages of processes (Baker 1963): (1) the cooling of molten terrestrial material, (2) the flight of tektites through the atmosphere (however this stage did not occur in most of the tektites) and (3) emplacement on Earth’s surface, when geochemical processes, like redeposition or weathering, finally influence the morphology of tektites.

Up to now, only four tektite strewnfields are recognized (Koeberl 2007 and references therein): Central European, North American, Australasian and Ivory Coast. It seems that additional data on new tektites distribution areas are very important to better understand the impact geology.

New moldavites from SW Poland

TOMASZ BRACHANIEC, KRZYSZTOF SZOPA and ŁUKASZ KARWOWSKI

Department of Geochemistry, Mineralogy and Petrography; Faculty of Earth Science; University of Silesia; Będzińska Str. 60, PL-41-200 Sosnowiec, Poland.
E-mails: tomasz.brachaniec@o2.pl, krzysztof.szopa@us.edu.pl, lukasz.karwowski@us.edu.pl.

ABSTRACT:


Four newly discovered moldavites from the East and West Gozdnic a pits, SW Poland, are characterized. All specimens, including other four, reported earlier, are from Upper Miocene fluvial sediments of the Gozdnic a Formation. Their weight varies between 0.529 and 1.196 g. The moldavites are bottle green in colour and have bubbles and inclusions of lechatelierite. Low degree of corrosion suggests short river transport, apparently eastward from Lusatia.

Key words: Moldavites; Tektites; Ries; Fluvial transport; Miocene; Poland.
The European tektites (moldavites) became the subject of scientific research in the late 18th century. In the 1960s, it was confirmed that moldavites are distributed over three specific areas: the Czech Republic (Bohemia, Moravia and near Cheb), Lusatia (SE Germany) and northern Austria (Trnka and Houzar 2002, and references therein). Until now, these tektites have been the subject of numerous geochemical, sedimentological and physical investigations (e.g., Knobloch et al. 1981, 1983; Engelhardt et al. 1987, 2005; Koeberl et al. 1988; Lange 1995; Meisel et al. 1997; Stöffler et al. 2002; Skála and Čada 2003; Řanda et al. 2008; Buchner and Schmiede 2009; Žák et al. 2012; Glass and Simonson 2013). Moldavites source impact structure is the Nördlinger Ries crater in southern Germany. The crater is 24 km in diameter and is Miocene in age (14.74 ± 0.20 Ma; Buchner et al. 2013). The Ries crater, together with the smaller, Steinheim crater, situated c. 24 km west of it, were probably formed as a result of binary asteroid fall (Artemieva et al. 2002). These tektites were produced by a melting of the Upper Freshwater Molasse (Meisel et al. 1997; Trnka and Houzar 2002; Řanda et al. 2008; Magna et al. 2011; Žák et al. 2012), composed mainly of quartz sand with feldspars, carbonate lenses (dolomite) and clay layers. According to Artemieva et al. (2002) the total mass of created moldavites might be up to 10^10 kg. Brachaniec et al. (2014, 2015) described a new moldavite distribution area in SW Poland. In this paper, based on new finds, their size, shape and chemical features are presented and discussed.

LOCALITIES AND GEOLOGICAL SETTINGS

New specimens of moldavites were found in the East and West Gozdnica sandpits, near the town of Iłowa, in SW Poland. The West Gozdnica sandpit is situated c. 100 m to the west of the East Goydnica pit (Text-fig. 1A).

The East Gozdnica sandpit

In this open pit mine (Text-fig. 1B), sand and gravel are exploited as a preliminary substratum for grout production and clay sediments for the local ceramic factories. The exposed Neogene sequence is c. 30 m thick. The oldest sediments are represented by muds with coal detritus of the Mużakowa Formation and are overlain by the “Henryk” brown coal layer (Dyjorek et al. 1992, 1998; Piwocki et al. 2004; Żelaźniewicz et al. 2011). The coal layer is followed by the Poznań Formation, which is represented by grey, green, blue and white loam, mud and clay. The youngest sediments are fluvial sands with gravel of the Gozdnica Formation, which yielded the moldavites. The gravel of the Gozdnica Formation is composed mostly of quartz with sharp edges, with grains between 0.5 and 5 cm in diameter. The sand is mainly yellow to grey in colour. Sporadically the Gozdnica Formation contains clay lenses and fossilized wood. The repeated changes in the sedimentary conditions of the formation are visible; coarse and poorly sorted sands with gravel embedded within fine-grained sand and sandy silt indicate low-energy sedimentation, presumably in river meanders (Stachurska et al. 1971). The Gozdnica Formation is dated to the Late Miocene – Pannonian (Stachurska et al. 1971; Dyjorek et al. 1992, 1998; Sadowska 1992; Piwocki and Ziembińska-Tworzydło 1997; Szykiewicz 2011). According to Baraniecka (1991) this formation can be correlated to uppermost Pliocene sands of the Różce borehole.

The West Gozdnica sandpit

The West Gozdnica pit mine has been abandoned for more than ten years. The bottom of the pit was flooded, thus the lowermost part of the sequence is no longer exposed; only the Poznań and Gozdnica formations are still accessible. The total thickness of the accessible sequence is c. 25 m.

METHODOLOGY

During the field works, 3 and 5 mm sieves were used. In the East Gozdnica sandpit, after sieving c. 1.5 tones of the sediments, three moldavites were found. In case of the West Gozdnica sandpit, one tektite from c. 0.5 tone of sieved sediment was collected. The tektite morphologies were studied under 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 were conducted in the Inter-Institutional Laboratory of Microanalyses of Minerals and Synthetic Substances, Warsaw, using CAMECA SX-100 electron microprobe. The analytical conditions were: acceleration voltage 15 kV, beam current 20 nA, counting time 4s for peak and background, beam diameter 1 mm. The studied material is stored in the Museum of the Faculty of Earth Sciences, University of Silesia, number WNOZ/Mt/89.

RESULTS

All found moldavites were chaotically distributed in the sediments of the Gozdnica Formation. From the East
Gozdnica pit, three tektites were collected (Text-fig. 2). Their weight varies from 0.529 to 1.196 g. The largest moldavite is 3 cm long and 1 cm wide (Text-fig. 2A). All specimens display green bottle colour and are complete. Only one tektite (Text-fig. 2B) reveals slight corrosion marks. Two tektites are elongated, that is typical for the autochthonous material. Moldavites contain bubbles, which are spherical in shape; their diameters vary from 10 to 250 µm (Text-fig. 3 A). One tektite (Text-fig. 2A) contains a bubble that is 9 mm long, which is the largest bubble observed among Polish moldavites.

In the BSE images, many lechatelierite inclusions were noted (Text-fig. 3B). Their length varies from 20 to 300 µm. The single moldavite from the West Gozdnica pit weights 0.685 g (Text-fig. 2D, Table 1). The largest bubble in its glass is up to 4 mm long. From among all the new moldavites, this specimen contains the most numerous and irregular lechatelierite inclusions (Text-fig. 3B).

No other mineral inclusions were detected. The most typical features of the studied moldavites are listed in Table 1. EMP data show that the new Polish moldavites from the Eastern (A-C) and Western (D) Gozdnica pit mines. The biggest bubble, on specimen A, is arrowed. A – sample EG1, B – sample EG2, C – sample EG3, D – sample WG1. See Table 1 for characteristics set. Scale bars are 5 mm.
ish moldavites are characterized by SiO₂ content ranging from 77.34 to 78.46 wt% which is slightly higher than moldavites from other Polish sections (Brachaniec et al. 2015). The content of other main elements (Al, Fe, Mg, Ca) is similar in all specimens. The chemical variation of investigated tektites falls in the range of all known moldavites, as described by Trnka and Houzar (2002). The chemical composition of investigated moldavites is presented in Table 2.
DISCUSSION

Origin of the Polish moldavites

According to Brachaniec et al. (2014, 2015) Polish moldavites are parautochthonous. They were found in fluviatile sediments, c. 10 Ma in age (Szyndzielski et al., 2011), whereas the Ries event is dated as c. 14.8 Ma (Buchner et al. 2013). The large size and evidence of only minor corrosion are indicative of rather short transport. It seems that moldavites described in this paper confirm this hypothesis. Investigated tektites from two sections near Gozdniczka are similar in size to those found in 2014. In contrast, much smaller specimens (0.003–0.15 g) were noted in the North Stanisław and Mielęcin pits (Brachaniec et al. 2014, 2015). Additionally, the degree of corrosion is similar. In our opinion, a characteristic elongated moldavite with non-eroded edges could not have been transported over long distance. Probably, it was associated with small quantity of gravel, content of which increases to the east. Parautochthonous origin of material is also confirmed by chaotic distribution in sediments because the Czech autochthonous tektites occur in well-defined moldavite horizons. According to Žebera (1972) and Bouška (1964) the moldavites outside the main strewn fields constitute redeposited material. The mechanism of moldavite fluvial reworking over a distance of a tenth of a kilometre is known from the Czech strewn field (Bouška 1964) and Lusatia (Lange 1996). Fluvial redeposition has also shaped a tektite glass (see discussion in Trnka and Houzar 2002). The only possible source area of Polish moldavites is the Lusatian region, from where large rivers were flowing eastward (Badura and Przybylski 2004). In the Late Miocene, the Sudetes were uplifted, which effectively limited the river-flow from the south. Additionally, the area of the Fore-Sudetic Block, north of the mountains (Groczyński 1977; Kurál 1979), contained numerous depressions and meanders, where accumulation of sands, gravel and clays took place. The Gozdniczka Formation originated on the Sudetic Foreland as alluvial deposits during the Pannonian (Piwocki and Ziembińska-Tworzydło 1997). These sediments were deposited before the first Scandinavian ice-sheet advanced onto the older fluvial lacustrine-marine deposits of the Poznań Formation (Badura and Przybylski 2004). They represent most probably the distal alluvial cone of pre-Nysa Łużycka river (Dyjor et al. 1992, 1998).

Bubbles and lechatelierite

The Polish moldavites contain numerous bubbles and inclusions of lechatelierite and the surfaces of investigated tektites are slightly corroded. This is indicative of a short transport and redeposition but also rules out extensive interaction with humic substances in the soil, which rapidly destroys glass surfaces (Koeberl et al. 1988). According to Suess (1951) and Chao (1963) the bubbles are a result of internal gas pressure during tektite cooling in environment where the external pressure was very low. Elongated bubbles, such as inclusions of lechatelierite in glass, correspond to the direction of flow in tektite melts. In glass, several mechanisms of bubble formation may be involved. A single tektite sample may contain several populations of bubbles formed by different mechanisms and containing gases of different compositions and pressures (Jessberger and Gentner 1972; see also discussion by Zak et al. 2012).

The lechatelierite forms as a result of melting of a terrestrial quartz grains in a high pressure during impact, and allows to distinguish between an impact glass and a terrestrial volcanic glass. The temperature necessary to lechatelierite formation is above 1713°C (Stöffler 1984), that is far above the normal terrestrial igneous processes. The elongated inclusions of the lechatelierite observed in investigated tektites are indicative of rapid and irregular glass flow during an early formation stage (Koeberl et al. 1988). The amount of lechatelierite depends on the temperature conditions of origin. Higher temperature caused a lower abundance of lechatelierite in the Czech and German moldavites (Barnes 1969; Lange 1995). Lechatelierite in moldavites is represented by almost pure silica, consistent with previous studies by Knobloch (1997) and Brachaniec et al. (2015). Other mineral inclusions are not present in the samples.

Chemical composition

The chemical composition of all impact glasses including tektites is a result of melting and sometimes mixing of molten source rocks (Magna et al. 2011). The moldavites are the most acidic group of tektites, with SiO2 contents c. 80 wt% (Engelhardt et al. 1987; Trnka and Houzar 2002). EMPA data show (Table 2) that the investigated moldavites have relatively high content of SiO2 and low content of Fe. The moldavites from Lusatia have in average higher SiO2 content (79.3 wt%) than Polish specimens but the concentrations of other main elements (Al, Fe, Mg, Ca) is similar with only minor differences (see details in Lange 1995). In summary, it is possible that Polish and Lusatian moldavites, despite the fact that they come from the same strewn field, could have formed from lithologically different parts of the Upper Freshwater Molasse. According to Engelhardt et al. (2005) and Randa et al. (2008), the similarity of the major element contents in tektite glasses indicates very similar, but not necessarily identical source deposits. The Upper Freshwater Molasse, the source of
moldavites, contain many lenses of carbonates and clays, which may account for the observed changes in moldavite compositions. Randa et al. (2008) claimed that tektites with similar Mg and Ca contents are evidence of a carbonate origin, whereas high content of Al originates from clay components. Based on average chemical composition, it may be tentatively suggested that the Polish parautochthonous moldavites were formed from quartz sands with a slightly higher content of carbonates and clays than autochthonous specimens from Lusatia. The chemical composition (EMPA) of the moldavites and the total sum of measured features (%wt. oxides; that is changing from −97.5 to −99.5) might indicate that the potential water content in the studied moldavites is up to 2.0 %.

CONCLUSIONS

Although experimental data indicate the probability of tektite occurrences c. 500 km from the Ries crater (Stöffler et al. 2002), Polish autochthonous moldavites have not been detected yet. Characteristic features for tektites, such as bubbles and lechatelierite inclusions, confirm their impact origin. The sedimentary characteristics of the Gozdnica Formation and the Middle/Late Miocene palaeogeography of the studied area, clearly suggest the fluvial transport of Polish tektites from the Lusatin strewn field. Low degree of corrosion confirms short transport of the investigated glass.

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