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Moldavites: a review

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Abstract. Moldavites from southern Bohemia, from western Moravia, from the Cheb Basin, from Lusatia (Germany), and from Waldviertel (Austria) are the only known European tektites. In the present paper, we briefly sum up the existing knowledge about their strewn fields and geology, about their properties, and their origin. The present survey should enable a detailed comparison with other groups of tektites and separation of primary differences from differences caused by earth history. The extent of moldavite occurrences is a result of intensive denudation and redeposition of the initial strewn field. All regions of moldavite occurrences are spatially associated with regional basins and depressions. The oldest moldavite-bearing sediments with very short-transported material are unsorted colluvio-fluvial gravelly sands and clays of Middle to Upper Miocene age. Fluvial transport of moldavites to more distant places determined their present distribution and led to a substantial lowering of their content in the sediments. Roughly 10^6 metric tons of moldavite matter (macrotektites) formed initially. Only about 1% of this mass has been preserved till the present. Most moldavites are splash-form moldavites. No ablation features were found on their surface. Muong Nong type moldavites occur sporadically but their amount could be much higher at the time of their formation. Micromoldavites were not found. Their preservation in the conditions of continental sediments over a time period of about 15 m.y. is not probable. It is, however, a question whether they were formed or not. Moldavites represent the most acid group of tektites with silica content of around 80 wt%. They are relatively rich in K_2O, too. On the other hand, they are characterized by low average contents of Al_2O_3, TiO_2, FeO and Na_2O. These low contents of TiO_2 and FeO lead to their higher translucency, similarly as in georgianites. In the same way as with other tektites, moldavites originated by fusion and ejection of porous target rocks during an oblique impact of a large meteorite. The impacting body – in the case of moldavites – was probably a chondrite 500–1000 m in diameter. Its impact also created the Ries crater at approximately 14.4–15.1 Ma.

Abstrakt. Vltavíny z nalezišť jižních Čech, západní Moravy, chebské pánve, Lužice (Německo) a Waldviertelu (Rakousko) představují jediné evropské tektity. V tomto příspěvku jsou stručně shrnuty dosavadní znalosti o dílčích pádových polích vltavínů, geologii jejich sedimentů, o vlastnostech vltavínů a jejich vzniku. Shrnutí poznatků umožňuje jejich detailnější porovnání s ostatními skupinami tektitů a odlišení primárních rozdílů od rozdílů vyvolaných pozemskou historií. Dnešní rozšíření vltavínů je výsledkem intenzivní denudace a redepozice původního pádového pole. Všechny regiony s výskyty vltavínů jsou prostorově spjaty s rozsáhlejšími geomorfologickými pánvemi a sníženinami. K nejstarším vltavínonosným sedimentům patří deluvio-fluviální písky a jíly středně až svrchně miocenního stáří. Současné rozšíření výskytů vltavínů výrazně ovlivnila síť vodních toků, které transportovaly vltavíny na větší vzdálenosti (většinou do 10 km). S délkou transportu podstatně klesal obsah vltavínů v sedimentech. Množství vltavínové hmoty v době vzniku odhadujeme minimálně na 10^6 t. Z ní se do současnosti zachovalo přibližně 1%. Převážná většina vltavínů jsou běžné tvarované vltavíny nebo jejich části. Nebyly na nich zjištěny žádné znaky ablace. Vltavíny typu Muong Nong se vyskytují sporadicky. Jejich původní množství však mohlo být výrazně vyšší. Mikrotektity v pádovém poli vltavínů nebyly zjištěny. Možnost jejich zachování v kontinentálních podmínkách po dobu přibližně 15 Ma je však nepatrná. Otázkou je, zda existovaly v době vzniku. Vltavíny jsou nejkyselejší skupinou tektitů s obsahy SiO_2 kolem 80 hmot.%. Relativně bohaté jsou rovněž na K_2O. Naopak jsou typické nízkými obsahy Al_2O_3, TiO_2, FeO a Na_2O. Právě nízké obsahy TiO_2 a FeO, podobně jako u georgianitů jsou příčinou jejich vyšší průsvitnosti proti ostatním tektitům. Vltavíny vznikly tavením a odmrštěním povrchových porézních terčových hornin (písky sladkovodní molasy) při šikmém impaktu velkého meteoritu v Riesu. Meteoritem byl zřejmě chondrit o průměru 500 až 1000 metrů. Stáří impaktu i vltavínů je 14.4–15.1 Ma.

Key words: tektite, moldavite, origin, physical properties, chemical composition, textures, Ries crater

Introduction

Tektites are natural glasses that are found in four geographically restricted areas, referred to as strewn fields (North American, Central European, Ivory Coast and Australasian). Central European tektites – moldavites – became the objects of researchers' interest as early as in the late 18th century. They were introduced to the scientific public for the first time in 1786 as "chrysolites" from Týn nad Vltavou in a lecture by professor Josef Mayer of Prague University, read at a meeting of the Bohemian Scientific Society (Mayer 1788). Zippe (1836) first used the term "moldavite". He derived it from the German name of the Vltava River (Moldau). The present Czech name "vltavín" first appeared in the daily press in 1891. The term gradually spread through the Czech professional literature (Bohatý 1990). Roughly 100 years after Mayer's report, Dvorský (1880) described a similar discovery from the locality of Kožichovice near Třebíč in Moravia. Suess (1900) published the first extensive monograph about moldavites and similar glasses from Australia and Billiton Island. For decades, his book was the main source of information about these glasses. Suess coined the term tektites (Greek τεκτοσ means "melted") for all similar glasses.

A significant progress in the scientific study of moldavites and tektites dates to 1960, in connection with the onset of cosmic research by means of space probes; this research activity continues practically till the present. In addition to a substantial expansion in the number of moldavite occurrences in South Bohemia and in Moravia, new areas were discovered in Lusatian region in Germany, in northern Austria and in some localities near Cheb in western Bohemia.

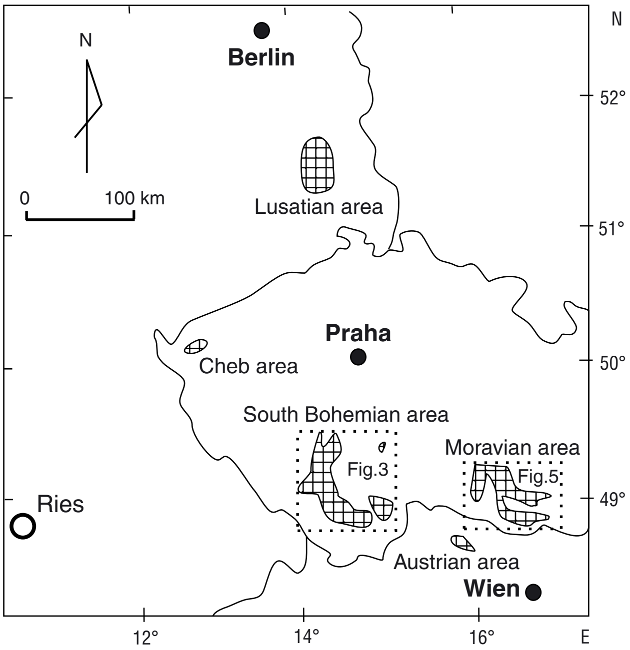

Fig. 1. A map of the moldavite strewn field in central Europe (with indicated positions of Figs 3 and 5).

A number of general surveys about moldavites were published in Czech. They include books by Rost *Vltavíny a tektity* [Moldavites and tektites], 1972, by Trnka and Houzar *Moravské vltavíny* [Moravian moldavites], 1991, and by Bouška *Tajemné vltavíny* [Mysterious moldavites], 1992. Bouška also published two books in English: *Moldavites* (together with Konta, 1986), which describes mostly South Bohemian moldavites, and *Moldavites – the Czech Tektites,* 1994, unfortunately a very poorly accessible book. Lange (1995) wrote a very detailed study about Lusatian moldavites (in German). There is also a number of papers about moldavite occurrences, geology of moldavite-bearing sediments, properties and origin of moldavites etc., published in Czech, only with English or German summaries (e.g. Proceedings on Moldavites Conferences II–VIII).

An overview of substrewn fields of moldavites

The deposits of moldavites are known from a few discrete regions (Fig. 1). The present boundaries and the size of substrewn fields are determined by the geological development of the whole territory and do not correspond to the distribution of moldavites at the time of their fall. In view of intensive denudation of a predominant part of the Bohemian Massif and adjacent regions, the present occurrences of moldavites are only relicts of the initial strewn field.

The nature of the original surface on which moldavites fell and where they were buried by sediments has never been identified reliably. Immediately after the moldavites fell on the earth's surface, they were transported to secondary deposits. The oldest moldavite-bearing sediments are colluvio-fluvial clays and sands, which are designated as sediments of the strewn field. In these sediments, moldavites were transported over very short distances. Streams were of decisive importance for the transport of moldavites to faraway places. A majority of moldavites connected with fluvial sediments is supposed to have been transported over a distance of about one to ten kilometres. However, with even longer transport of moldavites, the chances of their preservation substantially decrease.

Individual areas with moldavite occurrences partly differ in their geological evolution. Therefore, also the character and age of moldavite-bearing sediments can be different. Fig. 2 shows a comparison of stratigraphic positions of the main types of moldavite-bearing sediments from all substrewn fields. Moldavites from separate areas also differ in their properties (Table 1).

The richest accumulations of moldavites are usually found in deposits in strewn-field sediments. With a longer transport the concentration of moldavites strongly decreases. Sporadic finds of moldavites from places outside the main occurrences, e.g. Jindřichův Hradec, Chrášťany and Staré in České středohoří, Jeviněves (Bouška et al. 1999), Praha-Ďáblice (Žebera 1972) and Skryje near Beroun in Bohemia, Znětínek and Moravské Bránice in Moravia, can

Table 1. A comparison of some typical features of moldavites from individual substrewn fields.

Properties	Souhern Bohemia (except Radomilice area)	Radomilice area	Cheb area	Western Moravia	Lusatian area, Germany	Horn area, Austria
Predominant colour	bottle green (80%)	pale and bottle green (90%)	bottle green (80%)	olive green and brown (89%)	olive green and bottle green (71%)	bottle green
Number of found pieces	10 000,000	50,000	1,200	20,000	300	20
Maximum weight (g)	122	172	36	258	74	104
Muong Nong type	found	not found	not found	not found	not found	not found
Sphericity	lower	higher	lower	higher	higher	not determined
SiO_2 wt%	78.6	82.6	78.7	79.3	79.3	79.7
Al_2O_3 wt%	10.1	8.2	10.1	11.0	10.5	9.8
$\sum FeO$ wt%	1.62	1.18	1.62	2.26	1.84	1.54
CaO + MgO wt%	5.31	4.20	5.10	3.03	3.75	4.13
HCa / Mg types	found	not found	not found	not found	not found	not found
$\delta^{18}O$	11.29 ‰	11.42 ‰	not determined	11.13 ‰	not determined	not determined
Homogeneity	lower	higher	lower	higher	higher	not determined
Lechatelierite abundance	higher	lower	higher	lower	medium	not determined
Bubble abundance	higher	lower	higher	lower	lower	not determined
Crystalline inclusions	rare	rare	not found	not found	not found	not found
Strewn field sediments	found	not found	not found	found	not found	found (?)

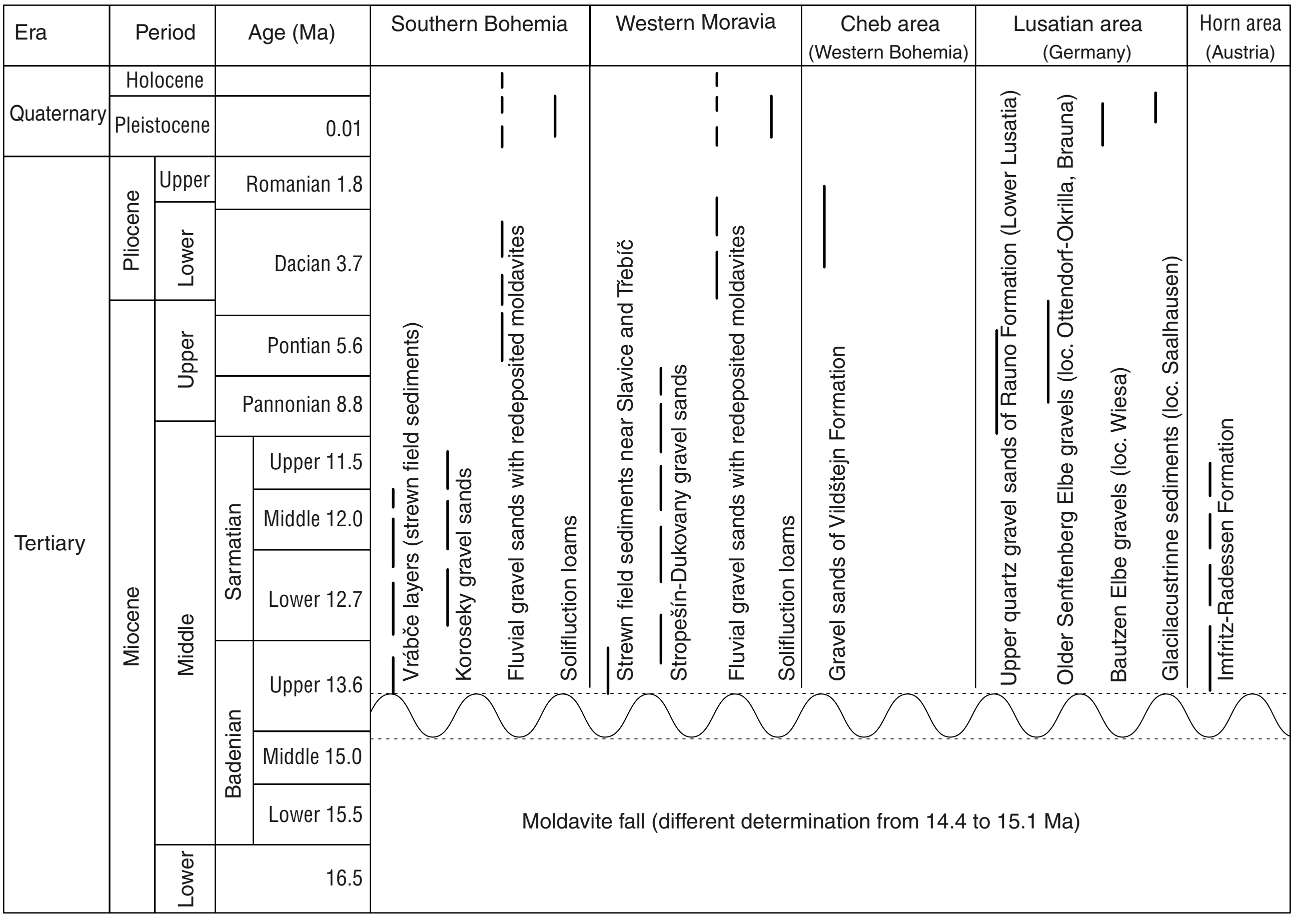

Fig. 2. Stratigraphic scale with a comparison of geological positions of moldavite-bearing sediments from individul substrewn fields.

represent pieces transported over a long distance or very small relicts of other, earlier substrewn fields. On the other hand, it is also possible that these data are not reliable.

Even the prehistoric man contributed, to a small extent, to the present-day distribution of moldavites. The oldest archaeological finds of moldavites are dated back to the Palaeolithic. Worked pieces of moldavites, associated with Paleolithic prehistoric remains, were found at the Gudenushöhle (Mousterien) and Willendorf (Aurignacien, Gravettien) in the Waldviertel in Austria (Koeberl et al. 1988). But worked moldavites are characteristic especially of Neolithic people in western Moravia. A polished disc-shaped moldavite was found in a small pot together with a sculpture of a bull's head in Skřípina fortifications (Červený and Fröhlich 1990, Vokáč 1999).

Southern Bohemia

The largest area of moldavite occurrences is the South Bohemian substrewn field. It covers the area of both Tertiary basins (České Budějovice and Třeboň Basin) and of the adjacent crystalline complex, to the west and the south of the basins. The deposits cover a total area of more than 2000 km^2. The area is defined by the connecting lines of the towns of Písek, Veselí nad Lužicí, České Velenice, Český Krumlov and Prachatice. The rough overview of the main moldavite deposits in Southern Bohemia is indicated in Fig. 3.

The character of moldavites is not the same in the whole area. Bouška (1997) has set aside the Radomilice area as a discrete part in the NW of the Budějovice Basin. Somewhat unusual are also the moldavites found near Horusice, which are, moreover, spatially separated from other localities of the South Bohemian substrewn field. Certain differences have also been found in the moldavites from the southern part of the Třeboň Basin. In spite of this, it is more logical to understand the whole South Bohemian area as a one substrewn field and to explain minor or major differences among the moldavites by the variability of the source material or by the variability of the conditions of their origin.

The South Bohemian moldavite-bearing sediments belong to several stratigraphic levels. The oldest ones, usually classified to the Middle Miocene, are marked as the Vrábče beds and Koroseky gravels and sands. These two groups of sediments of different facies lie close to, and pass into, each other. They were formed in different depositional environments in the neighbourhood of the shores of receding lakes (Žebera 1967, 1977).

The Vrábče beds are deposited on crystalline rocks or on the Middle Miocene sediments of the Mydlovary Formation. Most of the sediments are colluvio-fluvial sandy

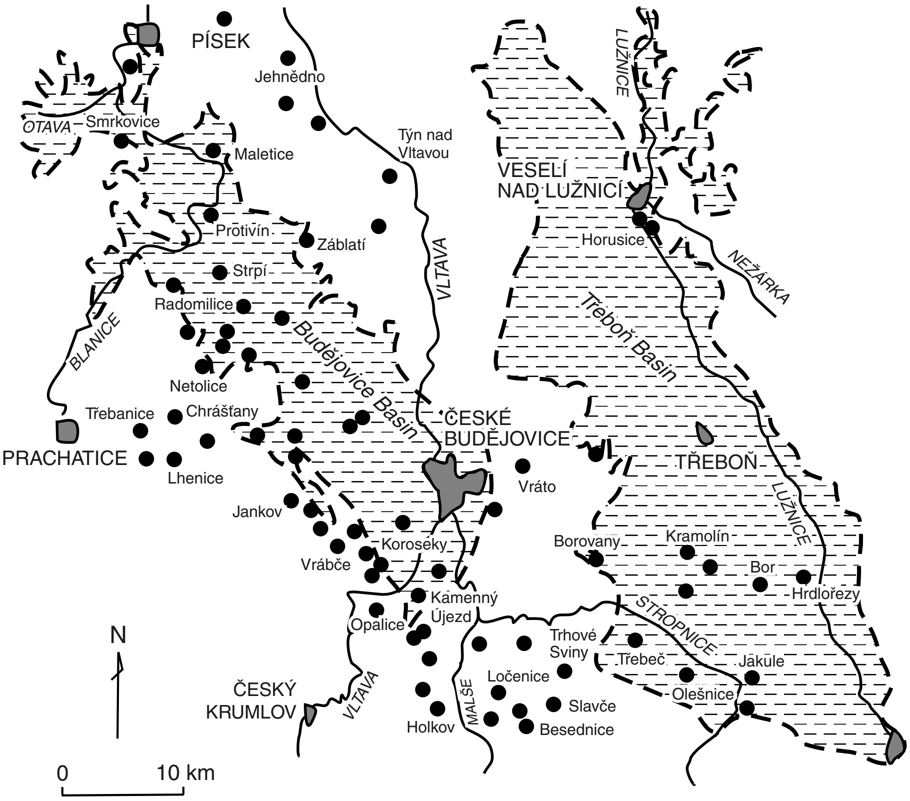

Fig. 3. Sketch map of moldavite localities in southern Bohemia (modified according to Bouška 1994).

clays and/or clayey sands with an admixture of angular psephitic material. They fill stream depressions, ravines or form dejection cones. The thickness of these sediments is usually several metres. The total length of transport of the moldavites from the place of their fall is estimated at about 1 km at the most. Therefore, the Vrábče beds are marked as strewn-field sediments.

Koroseky gravels and sands represent fluvial, fluviolacustrine to deltaic facies of the Vrábče beds, in which moldavites underwent a longer transport, usually of a few kilometres. The thickness of the sediments reaches about 25 m. The main component of these gravels and sands are quartz and feldspars. The usual size of pebbles is 1–2 cm, up to 10 cm at the most.

Later, some of the Middle Miocene sediments were destructed and the moldavites were redeposited into younger sediments. Therefore, we can find moldavites also in the Pliocene to Recent fluvial sediments and in the Pleistocene solifluction soils (Bouška 1972).

The character of moldavites is particularly connected with their geological history, in the same way as in other substrewn fields. The moldavites from the Vrábče beds are angular, with deep, well-preserved sculpture and low average weight. In the Koroseky gravels and sands, the moldavites were partially rounded and the number of pieces with flat pit sculpture increased. Moldavites, which underwent a longer transport in the Pliocene to Pleistocene ages obtained pebble-like shapes and their surface was abraded or only slightly corroded (finely enlarged fissures).

Southern part of the České Budějovice Basin and its surroundings

This is the area with the richest moldavite occurrences, where more than 99% of all moldavites were found. This is the reason why the majority of information about the physical, chemical and structural properties is based on the study of moldavites from this area.

The most important deposits are concentrated in the NW-SE strip along the western margin of the České Budějovice Basin. This strip stretches from Netolice to Besednice and is a few kilometres wide and more than 35 km long. Most occurrences are connected with the Vrábče beds and the Koroseky gravels and sands.

Relicts of the moldavite-bearing Vrábče beds can be found in whole length of the strip, mainly (from NW to SE) at Brusná, Dolní Chrášťany, Jankov, Kvítkovice, Habří, Lipí, Slavče (near České Budějovice), Vrábče (the locality of Nová Hospoda), Bukovec, Krasejovka, Besednice, Slavče (near Trhové Sviny) and Záluží. Moldavites in these sediments are deposited very irregularly. Extremely rich accumulations were found at Jankov, Vrábče and Slavče (near Trhové Sviny). It is estimated that approximately more than three tonnes of moldavites were dug out at the last mentioned locality.

More significant occurrences of the Koroseky gravels and sands with moldavites are known from the localities of Žitná, Třebanice, Lhenice, Koroseky, Vrábče, Záhorčice, Holkov, Ločenice, Chlum nad Malší (Fig. 4), Nesměň and Dobrkovská Lhotka. In younger fluvial sediments the moldavites are less frequent. These sediments were found to the east of other localities towards to basin centre, e.g. the Pliocene occurrences near Kamenný Újezd or Quaternary sandy gravels at Rožnov near České Budějovice. The upper parts of older moldavite-bearing sediments were redeposited by solifluction in the Pleistocene age.

Radomilice area

Moldavites with specific characteristics were found at a few localities in the northern part of the České Budějovice Basin (localities of Radomilice, Strpí, Záblatí, Záblatíčko, Dubenec, Březí and others). These moldavites are relatively rich in SiO_2 (the average content is 83%), part of them are typically light green coloured, they have a relatively the low content of lechatelierite and bubbles, a

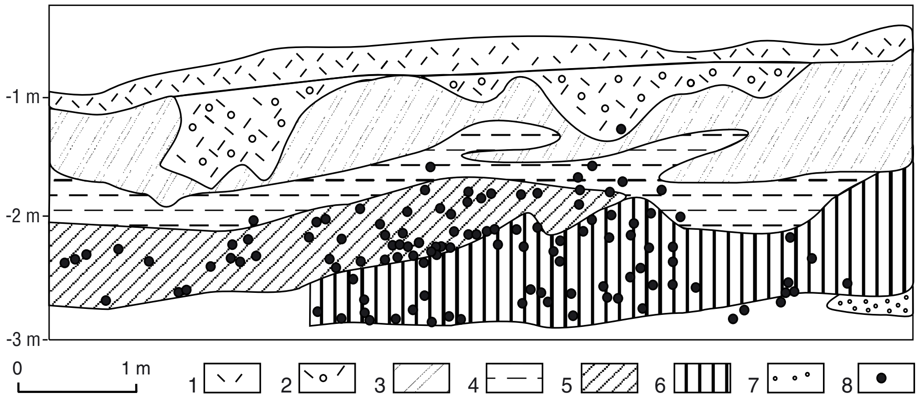

Fig. 4. A section of moldavite-bearing sediments of the Koroseky type in the sand-pit near Chlum nad Malší, southern Bohemia (according to Žebera in Vrána et al. 1984).
1 – topsoil, 2 – slightly humic grey gravelly sand, 3 – rusty brown gravelly sand, 4 – rusty brown limonite-rich gravelly sand, 5 – greyish white gravelly sand, 6 – rusty yellow gravelly sand with limonite aggregates, 7 – greyish white fine-grained sand, 8 – position of moldavites

high sphericity and a high average weight (Bouška 1997). The majority of South Bohemian moldavites with the weight over 100 g come exactly from these localities. Therefore, this area used to be delimited as a discrete substrewn field.

Oval moldavites with abraded surface are connected with the Quaternary alluvial-fan gravels and sands (Mindel-Riss, Schovánek et al. 1981). As indicated by sporadic finds of well-preserved moldavites at many localities in this area, we may speculate about the existence of relicts of the Koroseky gravels and sands in their footwall. This would be in agreement with the description of the finds of moldavites in a section in rusty brown gravels near Radomilice (Woldřich 1888). Deeply sculptured and well-preserved moldavites even prevail at some localities.

To the north of the Radomilice area, very poor occurrences of moldavites are scattered near Protivín, Maletice, Týn nad Vltavou, Písek, Jehnědno, Podolsko, Červená and others. Absolute lack of data on these moldavites does not permit any considerations about their similarity with other occurrences.

Třeboň Basin

Most localities in the Třeboň Basin are situated in its southwestern part. Several thousands of moldavites are estimated to come from this area. At the localities of Bor and Jakule, the moldavites are connected with coarse-grained clayey gravelly sands rich in quartz and feldspars, which probably represent Middle Miocene sediments (Koroseky gravels and sands). Clayey sands usually form their footwall. The character of the moldavites is in agreement with the character of the sediments. The moldavites are angular tiny fragments, usually with the weight under 3 grams. The primary shapes are usually drops. The most corroded are green-brown to brown moldavites but bottle green or olive-green moldavites generally prevail.

Moldavites from Borovany occur at two stratigraphically different levels. The older gravels and sands lie in the hangingwall of the Mydlovary Formation and are designated as the Domanín Formation – probably an equivalent to the Vrábče beds (Vrána et al. 1983). The younger level is found inside the Ledenice Formation of Pliocene age and is formed by coarse-grained rusty-brown sands.

Gravels with subangular quartz pebbles are younger, Pliocene to Pleistocene in age. Slightly water-abraded moldavites with higher weight (often exceeding 20 g) were found near Hrdlořezy. Individual, longer-transported moldavites come from the Holocene sediments of the Lužnice River, e.g. near Majdalena (Vamberová and Ševčík 1990).

Anomalous moldavite concentration (more than 1,000 pieces) was found in gravel and sand deposits at the Horusice locality near Veselí nad Lužnicí, at the northeastern margin of the Třeboň Basin. The moldavites come from a basal gravel bed 1 m in thickness. Subangular pebbles of varicoloured quartz, less frequently of gneiss, granite and amphibolite, are the main constituents of the gravels. The moldavites are light green, bottle green, olive green to brown green and their weight is usually 5–20 g. The moldavite sculpture is deep or slightly worn. The chemical data and physical properties of the moldavites prove the primary high variability of the local part of the substrewn field. These moldavites are not a mixture of pieces transported from various areas, as it was claimed by Bouška and Ševčík (1990). Some other localities with rare moldavites are known from the gravels of the Lužnice River, from the surrounding of Veselí nad Lužnicí (Žebera 1977).

Cheb Basin (western Bohemia)

The first moldavites from the Cheb Basin came from the gravelly shore of the Jesenice reservoir (Okrouhlá near Cheb – Bouška et al. 1995). But the main present-day deposit is the gravel pit of the TEKAZ Cheb company, not far from Dřenice, where the moldavite-bearing sediments have been well exposed. Some sporadic pieces were found also at other localities in the near surroundings.

In the bottom of the sandpit, sediments of the Middle Miocene Cypris Formation are recovered. Moldavite-bearing sediments are Pliocene in age and belong to the Vildštejn Formation. These are fluvio-lacustrine, poorly sorted gravels and sands, rich in quartz and often containing clasts of kaolinized feldspars, granite, gneiss, quartzite and phyllite. The presence of alternating beds of coarse and fine material, lenticular beds and the frequent interfingering and cross bedding indicate a rapid sedimentation (Bouška et al. 1995).

The gravels also include pebbles of andalusite and other heavy minerals such as ilmenite, tourmaline, diop-

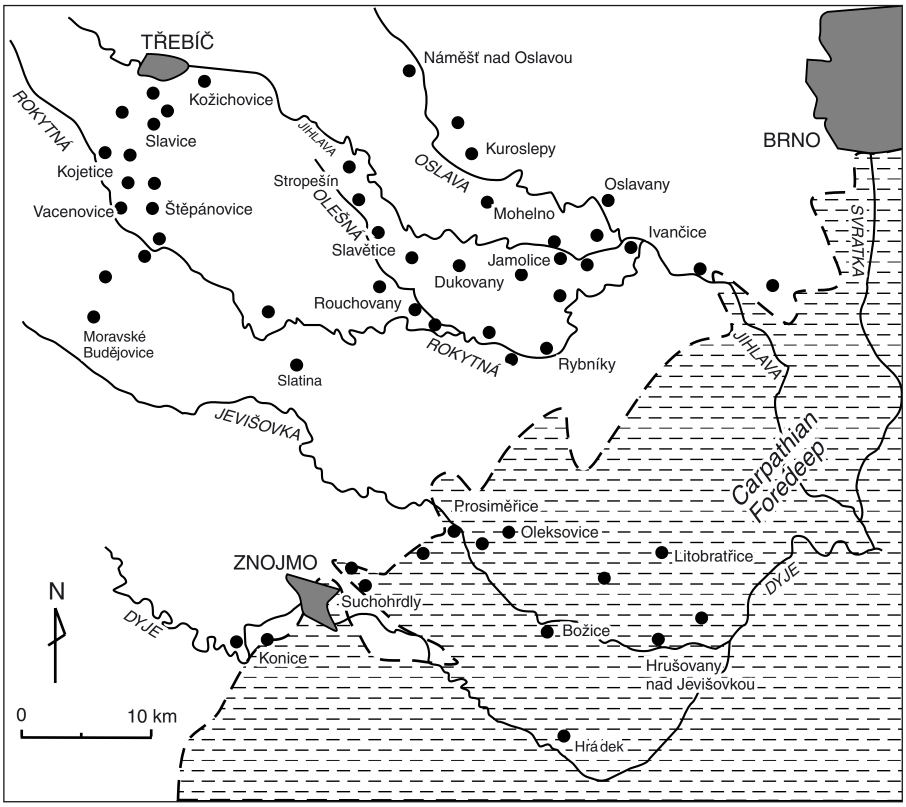

Fig. 5. Sketch map of moldavite localities in western Moravia.

side, garnet, zircon and anatase. In the gravel pit, moldavites were found in a bed at the depth of 17–22 metres (445–450 m above sea level). The bed is overlain with black Mn-bearing sandy gravels (Čada et al. 1998).

It can be assumed that the Cheb moldavites form a small substrewn field or that streams brought them down from the area SE of the Cheb Basin. The extent of the substrewn field of the Cheb moldavites can be determined by the observation of the so-called green clay beneath the Vildštejn Formation and by the study of Neogene relicts in the Cheb–Domažlice Graben and in the surroundings of Schirnding in Germany (Kopecký and Václ 1999).

Altogether more than 1,200 moldavites were found at the locality near Cheb. The moldavites are flat in shape, almost rounded, with shallow and rarely deep sculpture. The weight is 2–6 g on average but the weight of the largest moldavite is 36 g. Chemical analyses and colours of the Cheb moldavites correspond to those of the moldavites from the South Bohemian area (Bouška et al. 1995).

Western Moravia

The Moravian substrewn field is the second most extensive area of moldavite occurrences after the South Bohemian moldavite area. The total amount of recovered pieces is estimated at about 20,000. The occurrences of moldavites are located, with some exceptions (e.g. Moravské Bránice, Houzar and Šrein 1998), in an area delimited by Třebíč, Moravské Budějovice, Znojmo, Hrušovany nad Jevišovkou, Ivančice and Náměšť nad Oslavou.

The northern and northeastern limits of the area are defined by tectonic structures (Rejl 1980). The western boundary is probably controlled by denudation, lying at the altitude of around 500 m above sea level. The southern and the eastern boundaries are determined by the possibility of fluvial transport of the moldavites from the places of their dropping. The majority of Moravian moldavite deposits have a narrow spatial connection with streams of the Oslava, Jihlava, Rokytná, Jevišovka and Dyje rivers. The distribution of moldavite deposits in Moravia is shown in Fig. 5.

Moldavite occurrences can be subdivided into several groups according to the origin, petrographic composition and the age of the moldavite-bearing sediments. The oldest sediments are the Middle-Upper Miocene colluvio-fluvial sand-dominated sediments with gravel admixture (sediments of the strewn field). They were discovered only at the localities of Slavice and Třebíč in the northernmost part of the Moravian moldavite area. The sediments contain material transported over short distances, which originated from eluvia of granosyenite (the Třebíč massif), and – to a lesser degree – also from the surrounding rocks (aplites, ferruginous sandstones, cherts and others). The thickness of the sediments is below 2 metres. The sediments fill a local depression in the weathered underlying rocks. Moldavites from these sites have deeply pitted surface.

Fluvial sandy gravels lying farther to the south (Štěpánovice, Kojetice, Jaroměřice nad Rokytnou) or to the southeast near Rouchovany are approximately of the same age and show signs of longer transport. In all cases, these gravels have a small thickness, are poorly sorted and represent sediments of short local streams, which were redeposited into quaternary loams. The ratio between the primary and the redeposited sediments is demonstrated by the ratio of preserved and water-abraded moldavites.

Absolutely different are the fluvial terrace gravelly sands along the Jihlava River from the area between Stropešín and Dukovany. They include subangular moldavites with deeply corroded surface. These sediments were deposited in the distal part of a braided river (Fig. 6). Their thickness exceeds 20 metres. The sedimentation was rapid and episodic. Two populations of quartz pebbles were distinguished in the psephitic material. The shape indexes of moldavites are closer to less rounded quartz population originated in alluvial environment. The sediments are reddish in colour and highly mature. They are composed of quartz, subordinate quartzite, granulite, pegmatite, and chert and other rocks from both near and faraway surroundings. The heavy mineral assemblage comprises mostly ilmenite, tourmaline, andalusite and zircon (Nehyba 1992). Sediments are not positively dated, but most often they are considered to be of Miocene age. We found sediments of similar character at the localities of Kožichovice, Mohelno and Náměšť nad Oslavou. There is a noticeable admixture of redeposited marine sediments along the Oslava River (Houzar et al. 1997).

Flat rounded moldavites come from the deposits at Suchohrdly and Kuchařovice near Znojmo. Their shallow sculpture was formed by widening of fissures on a strongly rounded surface. These moldavites are linked with reddish coloured, fluvial, coarse-grained sandy gravels, which are composed of pebbles of quartz, less of granitoids, gneiss, quartzite and amphibolite. These sediments are considered to be of Pliocene age.

The locality of Konice near Znojmo yielded only one exceptional moldavite. Its colour is bottle-green and its chemical composition is similar to that of the South Bohemian or Austrian moldavites (Houzar et al. 1993). The Konice moldavite and a moldavite from Podmolí (Šobes) indicate that the moldavite occurrences extend to the southwest of Znojmo (Trnka and Houzar 1991, Šmerda 1997, 2000).

The youngest fluvial moldavite-bearing sediments are Pleistocene in age, developed along the present-day streams of the Jihlava River (between Jamolice and Ivančice – Mrázek and Rejl 1976, Mrázek et al. 1997), the Oslava River (Náměšť, Kuroslepy), the Rokytná River (Slatina) and the Jevišovka River (to the east of Znojmo – Oleksovice, Prosiměřice, Božice etc., Mrázek 1976). The relative height above the present-day streams is 20–100 m. In most instances the moldavite-bearing sediments are coarse-grained gravels dominated by quartz and local rock fragments. Plentiful pebbles of fossilized wood have been reported from the localities around Znojmo. All these deposits are characterized by pebble-shaped moldavites with water-abraded or particularly slightly corroded surface (enlarged fissures) and by the general paucity of moldavites.

Quaternary colluvial loams are the youngest moldavite-bearing sediments, in addition to the Pleistocene terrace gravels. They developed above older sediments with moldavites, by the reworking of which they originated.

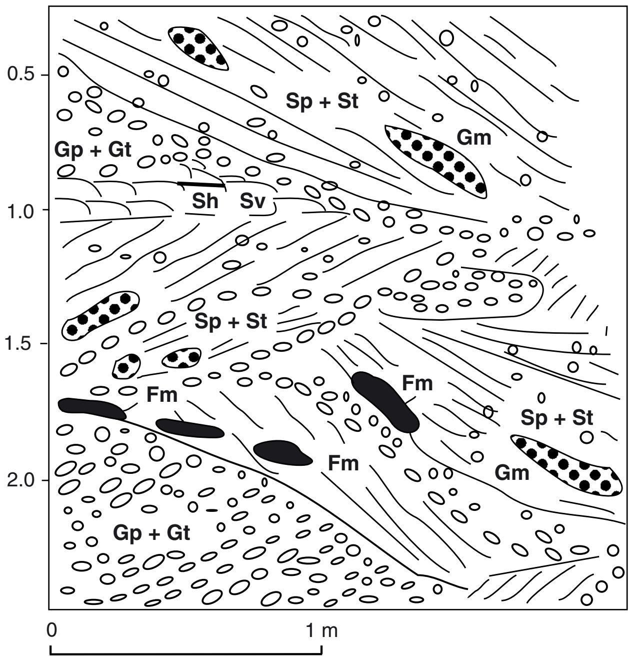

Fig. 6. Schematic vertical succession of moldavite-bearing sediments in Moravia (Slavětice sand-pit, Nehyba 1992).
Gm – massive gravel, Gt – trough cross-bedded gravel, Gp – planar cross-bedded gravel, Fm – massive mud, fine sand, silt, Sp – planar cross-bedded sand, St – trough cross-bedded sand, Sh – horizontally laminated sand, Sv – ripple-bedded sand

Lusatia, Germany

Since 1967, more than 300 finds of moldavites have been registered in Lusatia (Rost et al. 1979, Lange and Wagner 1992, Lange and Suhr 1999). They occur in the area of about 1300 km^2, northeast of Dresden (e.g. locality of Ottendorf-Okrila, Brauna, Gottschdorf, Buchwäldchen, Wiesa, Grossgrabe).

Moldavites have been found in different geological units. Fluvial sandy gravels – Older Senftenberg Elbe Gravels and/or Rauno Formation – indicate characteristic rapid and turbulent sedimentation with clay lenses and rare occurrences of flora. They consist of quartz, quartzite, lydite, agate, silicified wood, and of heavy minerals (tourmaline, staurolite, rutile, sillimanite, andalusite and zircon). The composition of the gravels, including the flora typical of warm climate, indicates a Miocene rather than a Pliocene age. These observations are supported by the high maturity of these sediments compared to the Pliocene sediments in southern Bohemia.

Fluvial sediments of Bautzen Elbe Gravels of Lower Pleistocene age consist of higher amounts of unstable components (pebbles: basalts, phonolite, greywacke; heavy minerals: epidote and amphibole) and, together with the glacio-fluvial moldavite-bearing sediments, show many features of a cold climate (Lange 1996).

The study of Lusatian moldavites suggests that their origin cannot bee explained by fluvial transport from the South Bohemian strewn fields. The physical and chemical characteristics of the Lusatian moldavites (e.g. the similarity to the Moravian tektites), together with the palaeogeographical and stratigraphical position of the moldavite-bearing sediments, suggest an independent substrewn field for the Lusatian moldavites within the moldavite strewn fields (Lange 1995, 1996).

Lusatian moldavites are mainly olive green in colour, with rounded appearance and sculpture of shallow pits. They are rather of Moravian type. The shape and the frequency of bubbles are halfway between the Bohemian and Moravian moldavites.

Horn area, Austria

Moldavites were also found in northern Austria in the Horn area (localities Eggenburg, Altenburg, Radessen, Mahrersdorf – Suess 1914, Koeberl et al. 1988), not far from the moldavite deposits close to Znojmo in Moravia. Yet earlier, Sigmund (1912) reported a moldavite from Stainz near Graz, southeastern Austria. However, Koeberl (1986a) suggested that this one was hauled by prehistoric human there. Two of the archaeological discoveries were mentioned above.

The deposits near Horn yielded about twenty moldavites. Most of them come from the gravel-pit near Altenburg. The moldavite-bearing sediments are fluvial gravels and sands overlying the St. Marein-Freischling Formation, which probably corresponds to the Mydlovary Formation in southern Bohemia. Two larger moldavites from Radessen were found in a thin gravel bed overlying the crystalline basement. These gravels belong to the so-called Irnfritz-Radessen Formation that is most probably of Miocene age.

All Austrian moldavites, with the exception of one sample, show more or less deep sculpture and are angular in shape. The largest of them come from Eggenburg (104 g) and Radessen (46.4 g). The colour and chemical composition of most Austrian moldavites appear to be closely associated with the South Bohemian moldavites, while the Radessen sample seems to be related to the Moravian group. The geological setting, the chemical compositions and the physical properties of Austrian moldavites indicate that they belong to an independent substrewn field (Koeberl et al. 1988). They show a wider range in chemical composition and their colour scale is similar to the moldavites from the Třeboň Basin.

Total mass of moldavites

About 75 years ago, Hanuš (1928) estimated the total amount of fallen moldavites at 20 million pieces and their weight at 100 metric tons. As indicated by both organized and illegal mining, the present estimates are 10–20 million collected pieces with a total weight of 30–60 metric tons.

In a similar way, the present-day approximation of the total weight of moldavites at the time of their formation and today is different. According to Bouška and Rost (1968) about 3,000 metric tons of moldavites fell on the Earth but only 275 tons remained after the “geological windstorm”. These values are much lower compared to the estimates for other groups of tektites. If we consider the extent of the moldavite-bearing sediments, of the geological progress of the area and the rate of moldavite destruction, we can make a rough estimate that the Ries impact produced at least 10^6 metric tons of moldavites (splash form and Muong Nong type), from which only 10^4 tons have been preserved until today. These values are not compatible with the data for other groups of tektites, because researchers combine the weight of macrotektites and microtektites.

Shape of moldavites

The present-day shape of tektites is not only the result of their formation in the time of their origin but distinctly reflects also the effect of later processes. Therefore, Baker (1963) divided the evolution of shapes into three stages. First of all, the separate bodies of tektites were formed and cooled. In the second, so-called ablation phase, the shapes were changed by melting of front solid parts during the flight of tektites through the atmosphere. This phase, however, did not take place in most of the tektites. In the third phase, after falling on Earth’s surface, various geological processes finished the morphology of the tektites.

Primary shapes

Depending on the conditions of their origin, different primary types of tektites were formed. They are: (i) splash-form tektites, (ii) Muong Nong-type tektites and (iii) microtektites.

The most common group are the splash-form tektites. The initial shapes of all splash-form tektites were drops, which originated in the separation of bigger mass of tektite melt by shearing flow. Other shapes of splash-form tektites are the result of transformation of some parts of the original plastic drops by rotation (Trnka and Houzar 1991, Trnka 1999).

Most moldavites belong to this type. The most usual shape of splash-form moldavites is a drop (Konta 1980), elongated, flattened, bent or spirally curved to a different degree. Lenticular shapes (discs), three-axial ellipsoids, sphere-like bodies and dumb-bells are frequent, too. Discs have sometimes thickened edges.

Statistics from measurements of moldavites show (Konta and Mráz 1969, Konta 1971a, b) that moldavites from southern Bohemia are much more anisometric in comparison with the moldavites from Moravia. This means that specimens of South Bohemian drops are more elongated and more flattened than the ones from Moravia, and the same also holds for other shapes.

Layered tektites without total internal stress, which usually form bigger irregular angular pieces, are designated as Muong Nong type tektites (Lacroix 1935). They have characteristic shimmering structure, higher content of bubbles and foamy lechatelierite. Some of the bubbles are irregular in shape. A broad range of crystalline phases has been found in tektites of this type. In the view of chemical composition they are rich in volatile components (H_2O, F, B, S, Cl, Cu, Zn, Sb and others – for example, Koeberl 1988), slightly acid (Schnetzler 1992) and they have higher Fe^{III}/Fe^{II} ratio than the splash-form tektites.

Muong Nong type of tektites in typical forms and with all the above mentioned features are common only in Asia (indochinites). According to Rost (1966), only one big moldavite found near Lhenice in southern Bohemia is regarded as a Muong Nong type of tektite, thanks to its morphological features and to the absence of total internal stress. Koeberl (1986b) considers the occurrence of Muong Nong type a rarity among moldavites on the basis of their chemical composition and the absence of crystalline phases. Lower contents of volatiles and the presence of baddeleyite lead later to the establishment of only a few other moldavites of this type by Glass et al. (1989) and Meisel et al. (1989,1993).

On the other hand, Barnes (1969) supposed a more frequent occurrence of the Muong Nong type among moldavites based on the study of their internal structure. The difference between Barnes's conclusions and the conclusions of other authors follows from their preference of different features for the distinction between the Muong Nong type and the splash form and also from their different understanding of this term. There is no sharp boundary between these two types. Izokh and An (1983) and Schnetzler (1992) described tektites with transitional properties. Structural features show that these tektites occur also among moldavites (Trnka 1997a).

Higher heterogeneity, porosity and cracking of Muong Nong type tektites caused their relatively lower chemical and especially mechanical durability. The known finds of Muong Nong type moldavites come from localities with very short transport of material. These facts may indicate a possible destruction of most of the Muong Nong moldavites during their geological history.

Essential parts of original shapes of Muong Nong type of tektites are preserved only very exceptionally in Indochina. From them it is possible to deduce that these tektites had originally the shape of spoon-like bent drops with the weight attaining 100 kg. It seems evident that they went through airborne transport together with the splash-forms. The Muong Nong tektites show evident traces of flight through the atmosphere, but their deformations are of primitive character (Futrell 1987, Trnka 1994, 1997a).

Microtektites come close to splash-form tektites because of their total morphology but their size usually does not exceed 1 mm. The small size of microtektites permitted substantial use of forces of surface stress of melt, which resulted in the appearance of predominantly spherule shapes. Drops, dumb-bells and other shapes are less frequent. Microtektites have been found only in marine sediments.

Microtektites are known from all tektite strewn fields except for the moldavite fields. It is not possible to consider microparticles of moldavite glass as microtektites, because the microparticles originated by breaking off from the usual moldavites in sediment. In the conditions of continental sediment accumulation, however, there is only a theoretical possibility that they could be preserved for approximately 15 Ma.

Ablation

Only some splash-form tektites, namely some australites and javanites, have provable signs of ablation, which originated during their long flight through the atmosphere at speed exceeding 5 km s^{-1} (Chapman and Larsson 1963). Melting and evaporation of the glass on the front side of tektites occurred during the ablation, and the melting glass was ripped off to the edge. This is why the shapes have either characteristic rims along the cores or ablation peripheral edges.

Chao (1964), Rost (1972) and Soukeník (1971) have described the impact of ablation on the moldavites. They explained the rarity of ablation features in moldavites by their later removal during the transport, chemical corrosion and so on. The morphological similarity between their samples and some australites is very high. Shapes similar to ablation shapes can originate also by chipping of the flat fragment from the moldavite surface. This happens mainly in bigger pieces with strong internal stress.

According to Soukeník (1971), the majority of moldavites with presupposed signs of ablation come from localities in the Třebíč area in Moravia and are very heavy. This is in direct contrast with australites, where the ablation shape is well developed just on the smallest pieces. Moreover, the shape of moldavites is much more similar to indochinites and philippinites, which do not show any ablation features, than to australites. No other phenomena were observed in moldavites, which have a direct connection with the origin of ablation. Therefore, it is probable that no conditions, which would bring about ablation, were present during the flight of moldavites. The cases described earlier are the consequence of shattering.

Development of shape of moldavites after their fall

Tektites went through a marked change of their shape on the Earth's surface, which was caused by mechanical or chemical effects of various factors: breaking and cracking of tektites was very substantial and lead to the origin of fragmental or splinter shapes. It happened not only during the dropping and geological transport but also spontaneously in sediments due to the influence of internal stress.

Unbroken drops, discs, dumb-bells and other shapes are very rare among moldavites, representing less than 1% of all pieces (Konta 1980).

A specific feature of tektites and in the same way also of moldavites is the surface sculpture (sometimes called "sculptation") formed by pits, grooves and other disparities. Because of Suess's accurate study (1900), an opinion survived for a long time that the sculpture was formed due to aerodynamical effect on plastic tektites. The main support for this opinion was the radial or generally regular arrangement of sculpture elements. Later, proofs were gathered on the sculpture formation by chemical corrosion in sediments (in moldavites e.g. Rost 1972, Trnka 1980).

Unevenness of chemical corrosion, leading to the appearance of sculpture elements, is conditioned mainly by the properties of the moldavites, although the all-round character of sculpture is influenced by the co-operation of many internal and external factors. From this point of view, Trnka (1988, 1997b) regarded the effect of stresses of various origin the most important.

The influence of stress on chemical corrosion of glass, thoroughly discussed in glass literature (for example Scholze 1977), is based on the existence of surface microfissures, which originated in tektites mainly during their transport in sedimentary environment and/or during the temperature changes in the last phase of their origin.

Similarly as in other materials, the mechanical strength of the tektite glass was reduced by the internal and external stresses. The glass fatigue leads to gradual growth of fissures. The fissures propagated preferentially along the course of various inclusions, which substantially decrease the strength of glass. The orientation of the fissures was related to general shape of the tektite and to its texture. The reactions between the attacking solution and tektite glass were the strongest in places where the stress was secondarily concentrated, that means on the peaks of fissures. At these places, the structure of glass is more reactive. La Marche et al. (1984) proved experimentally the higher rate of chemical corrosion along the cracks in tektites.

The total appearance of sculpture and the rate of its formation was influenced also by many other factors: geological history of tektites, duration of corrosion, climatic conditions, the character of sediments and sedimentary solutions, and finally by the chemical composition, the texture and the heterogeneity of the tektite etc. Their effects were commented upon, in addition to the already mentioned publications, by Barkatt et al. (1984), Glass (1984, 1986), Konta (1988) and others.

Rost (1972) estimated that a layer 2–7 mm in thickness was removed by chemical corrosion from the surface of moldavites. Knobloch et al. (1980) estimated this at a minimum of 2.5–4.5 mm. Some observations on moldavites from Besednice (southern Bohemia) show even higher rates of loss of mass. That means that pieces about 1 cm in size had only minimum odds to be preserved to the present day.

In addition to chemical corrosion, the moldavite morphology was also distinctly influenced by mechanical abrasion. Abrasion of small particles of moldavite glass during the sedimentary movement leads to the removal of the original surface of moldavites and later also to the removal of sculpture. A decrease in the moldavite weight during transport could distinctly exceed the loss of mass due to chemical corrosion. It could happen that the sculpture was totally wiped away during movement on slopes hundreds of metres long.

Physical properties

Mass

The mass of the splash-form tektites comes to the same values (hundreds of grams) in all tektite groups and does not exceed 1 kg. This value agrees to the calculation of Centolanzi (1969) of the maximum mass of a tektite sphere, which, during the cooling by radiation, does fragment spontaneously. If we take into account the substantial mass losses of moldavites during the time about 15 Ma, we can suppose that the initial mass of the largest moldavites is close to this value.

Depending on the conditions of origin and on the geological history, both the maximum and the average mass of moldavites differ. Relatively largest are the moldavites from western Moravia today and the smallest are from southern Bohemia. The largest moldavite comes from Slavice in Moravia, with its mass being 258.5 g.

Colour

Most tektites are dark to black in incident light. The brown or green colour of their glass is usually visible only in very thin parts. Moldavites are an exception because they are more translucent. Higher translucency of moldavite glass makes it possible to observe the colour differences among them and the relationship between the colour of moldavites and their chemical composition.

The colour scale of moldavites ranges gradually from pale green to brown. The main colouring components are Fe^{II}, Fe^{III} and perhaps also Mn^{II}. Their content increases in the direction to brown moldavites (Bouška and Povondra 1964, Bouška and Cílek 1992), together with the ratio of Fe^{III}/Fe^{II} (Bouška et al. 1982). Deviation from this scale is found in the so-called "poisonous" green moldavites (HCa/Mg moldavites). Their colour can be explained by a slightly higher content of Ni, in combination with a high content of alkaline earths (CaO, MgO) and a low content of K_2O (Bouška et al. 1990a).

Some other components, which have low or no colouring capability, control the effect of colouring elements themselves. The colouring influence of Fe^{III} in glass substantially increases with the increasing content of Ti and Mn (Volf 1978). The relatively low content of titanium, nearly half content, in moldavites, rare georgianites, bediasites from Muldoon (and also in urengoites) is in all probability the cause of their higher translucency in comparison with other tektites.

In the South Bohemian substrewn field, bottle green and light green moldavites prevail, with the proportion of more than 80%. In the Radomilice area, very pale green pieces can be also found in addition to these colours. Colour shades of the rare moldavites from the Cheb Basin and from Austria come close to South Bohemian moldavites (Čada et al. 1998, Koeberl at al. 1988). Moravian and Lusatian localities are dominated by olive green to brown moldavites: over 90% in Moravia, and approximately 70% in the Lusatian region.

Rare specimens of moldavites are composed of two differently coloured parts with a sharp boundary. They originated by collision of molten moldavites before their impact on the Earth's surface. More than fifty moldavites of this type were found in the South Bohemian area and about ten in Moravia (Bouška at al. 1982, Trnka and Houzar 1991).

Stress

All splash-form tektites have strong internal stress. Cooperation of several partial components of various origin determines the resultant stress. The main component is overall stress, which was formed by cooling of tektites as a result of temperature differences between surface and internal parts.

Stress intensity increases with the rate of cooling, with the size of the tektite and with the temperature of formation. Later cracking of the pieces and/or removal of surface parts by mechanical or chemical corrosion lead to a substantial reduction in stress intensity. Centolanzi (1969) indicates the reduction of the stress intensity by 80% at half decrease in the diameter of the tektite sphere.

The intensity of overall internal stress is locally increased or decreased by stresses that formed on the boundary of chemically different parts, through the influence of their different thermal expansibility. It may be a boundary between lechatelierite particles and the matrix or between individual fibres of fluidal structure.

The strain is connected with the hardening of tektites on the one side and also with the capability of spontaneous breaking on the other side. With regularly spaced strain, the tensile strength increased. However, the stress is usually not regular and the centre, sometimes of tensile stress, is close to the surface. In these cases spontaneous cracking of tectites is frequent.

Barnes (1969) surveyed the relative intensity of stress in moldavites on the basis of distinctiveness of birefringence. He viewed separately the overall stress and stress among strips of fluidal structure. Moravian moldavites have statistically higher intensity of overall stress than Bohemian ones as a result of their higher average size. The stress in fluidal structure increases with SiO_2 content, which positively influences the viscosity and therefore decreases the possibility of diffusion. So, it is lower on average in Moravian moldavites.

Other physical properties

The refractive index and the density reflect the chemical composition of moldavites. It is possible to calculate their values from chemical analyses. Both values decrease mainly with the increasing SiO_2 content, and increase with the increasing CaO content. The refractive index and the density data for each group of moldavites are shown in Table 2.

Viscosity of tektites is also in close relationship to the chemical composition. Its value, especially at higher temperatures, increases mainly with the increasing SiO_2 and Al_2O_3 contents and decreases with the alkalies. The viscosity, together with temperature, undoubtedly influenced the formation of shape.

Chemical composition

The characteristic feature of all tektites is their specific and rather uniform chemical composition (except for some microtektites), in which they differ from other glasses of natural and artificial origin. The affinity with some sediments follows already from the main oxide contents (the high $Al_2O_3/K_2O + Na_2O$ ratio, the high content of CaO and MgO). Bouška (1968) described the affinity between the sediments and moldavites.

Also, the contents and the ratios of trace elements indicate that (i) moldavites differ from meteorites, lunar rocks and terrestrial igneous rocks and that (ii) they are close to clay- and sand-dominated sediments (for example, the distribution of REE, the ratios of Zr/Hf, K/U, Th/U, K/Rb and others – Bouška 1992). No indication of contamination by meteoritic material was found whatsoever.

In spite of the generally close chemical composition of tektites coming from various places on the Earth, certain differences can be also found between them. The moldavites form the most acid group of tektites, with SiO_2 contents about 80 wt%. They are also relatively rich in K_2O. On the other hand, they have very low average contents of Al_2O_3, TiO_2, FeO and Na_2O. North American tektites are the nearest to moldavites, especially the georgianites, which are very close to moldavites from many points of view as well (Bouška et al. 1990b, Koeberl 1990).

Minor differences exist even among moldavites. Table 2 shows the average moldavite compositions from various parts of strewn fields. The fluctuation of individual oxide contents can be explained by variable contents of three essential mineral components in the parental rock, i.e. quartz, clay minerals and carbonates (Delano et al. 1988 – see below). From this point of view, the source material of the Bohemian moldavites was relatively rich in carbonates, while it was clay minerals in the Moravian moldavites and quartz in moldavites of the Radomilice group.

Most chemical analyses show the overall composition of the moldavites. The inhomogeneity of individual pieces, which is obvious also from the existence of fluidal texture, is caused by local fluctuations in chemical composition. The extent of these fluctuations approximately corresponds to differences among various moldavites (Cílek et al. 1992). Engelhardt et al. (1987) determined the following variation in the chemical composition of a moldavite from Ločenice (southern Bohemia) from 20 point analyses on a line 0.27 mm long: SiO_2 78.6–82.7 wt%, CaO 1.8–2.7 wt%, MgO 1.3–1.8 wt%, FeO 1.15–1.67 wt%, Na_2O 0.30–0.45 wt%, K_2O 3.5–3.9 wt%.

The extremely low content of most volatile components is characteristic of all tektites. The results of Beran and Koeberl (1997) show that the tektites have water content ranging from 0.002 to 0.030 wt%, and moldavites themselves from 0.006–0.010 wt%. These results show that tektites are in general the driest natural material.

During moldavite formation, vaporization of a high proportion of rare gases, halides, sulphur, carbon and nitrogen from the source occurred (Moore et al. 1984, Bailey 1986, Matsuda et al. 1993, Meisel et al. 1997 and others.). A distinct decrease also occurred in less volatile components, for example As, Sb, Cu, P.

The valence of elements in tektites indicates reducing conditions of their formation. This is evidenced primarily by the Fe^{III}/Fe^{II} ratio. The $Fe^{III}/\sum Fe$ ratio is 0.13 in the Moravian moldavites, 0.17 in the South Bohemian moldavites and 0.25 in the Radomilice moldavites. In other tektites, the Fe^{III} content is even lower, reaching almost zero (for

Table 2. The chemical compositions, the refractive index and the density of moldavites from individual substrewn fields.

	Southern Bohemia n = 43		Radomilice area n = 3		Cheb area n = 4		Western Moravia n = 46		Lusatian area n = 15		Austrian area n = 7	
	range	average	range	average	range	average	range	average	range	average	range	average
SiO_2	71.90–81.00	78.60	80.00–84.70	82.60	78.46–79.89	78.97	74.91–83.10	79.28	77.20–84.10	79.30	78.10–85.10	79.73
TiO_2	0.23–0.50	0.31	0.24–0.29	0.26	0.28–0.40	0.33	0.30–0.72	0.42	0.26–0.42	0.34	0.24–0.35	0.30
Al_2O_3	8.96–12.70	10.10	7.27–9.36	8.22	8.38–10.13	9.17	9.27–13.18	11.01	8.94–11.80	10.50	8.10–10.60	9.81
Fe_2O_3							0.09–0.72	0.33 (17)				
FeO							1.32–3.28	2.07 (17)				
FeO^{tot}	1.28–2.86	1.62	1.00–1.41	1.18	1.34–1.86	1.54	1.40–3.50	2.26	1.32–2.51	1.84	1.02–1.78	1.54
MnO	0.05–0.20	0.09	0.05–0.07	0.06	0.12–0.25	0.22	0.02–0.13	0.13 (18)	0.03–0.11	0.06	0.03–0.08	0.06
MgO	1.52–3.73	2.33	1.60–2.26	1.91	1.86–2.75	2.34	0.88–2.11	1.39	1.06–2.73	1.75	1.10–2.03	1.72
CaO	2.05–4.48	2.98	1.80–2.82	2.29	2.36–4.56	3.60	0.61–3.17	1.64	0.93–3.85	2.00	1.46–3.30	2.41
Na_2O	0.25–0.60	0.42	0.19–0.32	0.24	0.31–0.59	0.41	0.27–1.08	0.57	0.28–0.70	0.47	0.19–0.49	0.39
K_2O	2.88–3.77	3.40	2.20–2.97	2.53	2.61–3.85	3.24	2.60–3.81	3.38	3.06–3.75	3.46	2.62–3.90	3.49
P_2O_5							0.01–0.03	0.02 (4)				
refractive index	1.487–1.502	1.494	1.481–1.491	1.486		1.490	1.485–1.492	1.489	1.481–1.495	1.490		
density	2.33–2.44	2.36	2.32–2.37	2.34		2.36	2.33–2.37	2.35	2.31–2.38	2.35		
References	Lange (1995)		Lange (1995)		Bouška et al. (1995), Skála and Čada (2002)		Lange (1995), Trnka and Houzar (1991)		Lange (1995)		Koeberl et al. (1988)	

example, Fudali et al. 1987). On the other hand, this content is higher in tektites of the Muong Nong type (Koeberl et al. 1985).

Substantial reduction of source rocks was also confirmed by magnetic spherules with a core from pure iron (Kleinmann 1969) or by probable occurrence of metallic silicon in a moldavite found near Chlum in southern Bohemia (Cílek 1985). The intensity of reduction reflects a high temperature of formation and a low partial pressure O_2.

The study of isotopes is of essential importance for our knowledge of tektites. This study enabled not only the determination of tektite age but also helped with the problems of their genesis. The most common method for age determination is the $^{40}K/^{40}Ar$ method, which shows the time of the last remelting. Short-time remelting does not change the ratios of isotopes of $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Cr$ and therefore they can lead to the search for the source material of tektites. The data about ratios of strontium isotopes in various types of rocks in the Ries area (Horn et al. 1985) show that the only possible source of moldavites are sands of freshwater molasse. The ratio of isotopes $^{18}O/^{16}O$ is higher in the moldavites than in the mentioned sediments. This discrepancy was explained by Engelhardt et al. (1987): the oxygen released from water combined with the oxygen of the moldavites.

When unprotected bodies travel through space, their surface is bombarded with cosmic radiation. This leads to the formation of radioactive isotopes $^{26}A1$, ^{10}Be and ^{14}C. These isotopes cannot be found in moldavites because of their half-life. Neither the estimated values for the Australasian tektites and Ivory Coast tektites show that they travelled through the outer space (for example Tera et al. 1983).

Internal structure

Tektites are very homogeneous compared to other natural glasses. They differ from the impact glasses, obsidians and fulgurites in almost total absence of unmelted mineral grains and crystallites. This fact gives evidence not only for the high temperature of their origin but also for a very rapid solidification (Wosinski et al. 1967).

Fluidal arrangement is the basic attribute of the tektite texture (Fig. 7), and small bubbles, lechatelierite and schlieren are common in tektite glass. Crystalline inclusions of various origin are sporadic.

Lechatelierite

Lechatelierite is a common inclusion in tektites. Barnes (1969) and mainly Knobloch et al. (1981, 1983, 1988, 1997 and others) studied their abundance, morphology, arrangement and the chemical composition in moldavites. Lechatelierite sometimes forms isometric particles, or has the shape of long flat fibres as a result of shearing flow. Isometric shapes are not bigger than 1 mm in size. The width and the thickness of flat fibres usually reach dimensions from hundredths to a few tenths of millimetre (the proportion of both sizes is 1.4–4.5), their length of max. a few centimetres.

The arrangement of elongated lechatelierites is conformable with the fluidal structure. Longer fibres can have a multiple S-shape. The amount of lechatelierite depends on the temperature conditions of origin. Higher temperature caused a lower abundance of lechatelierite in Moravian, Radomilice and Lusatian moldavites (Barnes 1969, Konta 1971a, Lange 1995).

Lechatelierite in moldavites is formed by very pure silica. Chemical analyses show SiO_2 contents of above 99.0 wt% (Knobloch 1997). Kinnunen (1990) obtained the same results from a study of lechatelierite in indochinites.

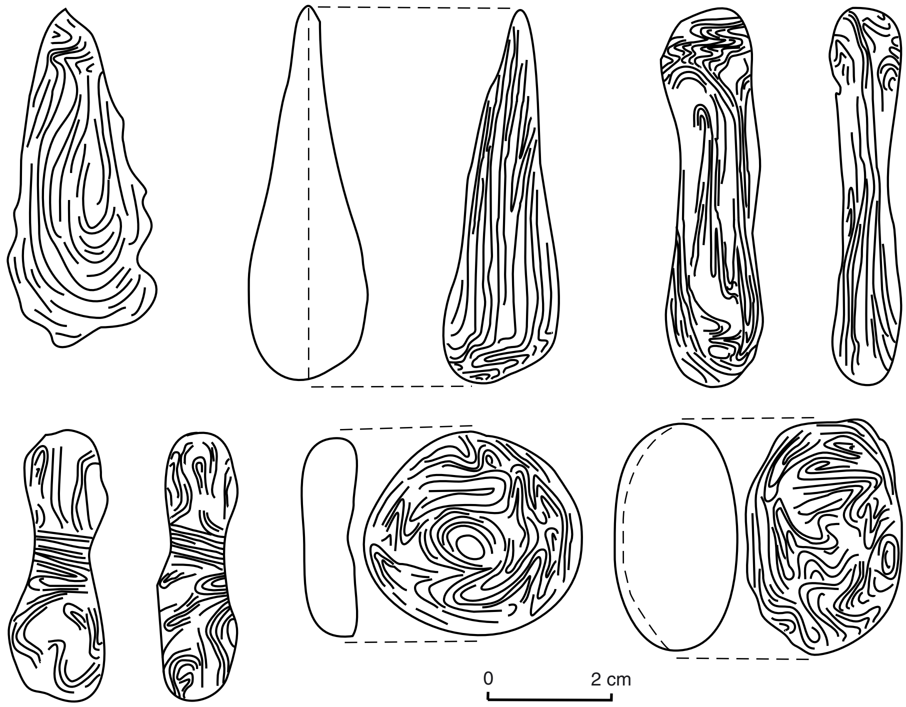

Fig. 7. Arrangement of fluidal texture in various shapes of moldavites and tektites.

The origin of lechatelierite in tektites is usually explained by fusion of quartz grains of source rocks. Quartz inclusions in lechatelierite can support this idea. They were described from samples of moldavite and bediasite (Barnes 1969, Glass et al. 1986). Conversely, Kinnunen (1990) supposed the origin of lechatelierite from biogenic CT-opal on the basis of a chemical and a petrographic study of their inclusions in indochinites.

Lechatelierite resistance against chemical corrosion is substantially higher than in the surrounding matrix. Therefore, lechatelierite inclusions often protrude from the sculptured surface. Only rarely were moldavites found in which lechatelierite fibres "bridge over" furrows of surface sculpture. A detailed search revealed that lechatelierite particles separated by etching could be found in adjacent moldavite-bearing sediments.

Schlieren

In addition to lechatelierite, other types of glassy inclusions also occur in tektites. They used to be marked as schlieren or by specific designations such as "fingers", "rays" or "lenticles" in some cases. The differences in refractive indexes between these bodies and the glass in matrix are higher, by one to two orders of magnitude, than their fluctuation in the matrix itself. This corresponds with higher deviations in the chemical composition. If the classification of Rost (1972) is followed, according to which all glassy inclusions with the refractive index under 1.470 (that means with SiO_2 content above 92%) are regarded lechatelierite, then schlieren are not very frequent.

In comparison with the glass matrix, schlieren can be divided into two groups: acid and basic. Acid schlieren are usually similar to lechatelierite in their shape and size. Certain varieties in shape are "fingers", which are characteristic mainly for australites but were also found in moldavites (Barnes 1963, Chao 1963). Chemical analysis of this inclusion in a moldavite from Mikulovice (western Moravia) showed an increase in SiO_2 against the overall composition (+2.7 wt%) and a decrease in Al_2O_3 (–1.4 wt%), FeO (–0.7 wt%) and K_2O (–0.5 wt%). Basic schlieren are less frequent and may have a finger-like shape, too. An analysis of a dark schlier from a moldavite from Něchov (southern Bohemia) proved a lower content of SiO_2 (–6.4 wt%) relative to the matrix, while the contents of Al_2O_3, FeO and CaO were higher (Barnes 1969).

Long, narrow basic inclusions, forming radiating clusters around bubbles, were found in sporadic cases by Barnes (1969) that marked them as "rayed bubbles". These inclusions in a moldavite from Lhenice (southern Bohemia) contain less SiO_2 (–9.2 wt%) and K_2O (–1.0 wt%) but more of CaO (+10.2 wt%), Al_2O_3 (+0.9 wt%) and FeO (+0.7 wt%) than the matrix. There is an idea that these inclusions originated during an explosion of a zeolite or calcareous nodule in parent sediment during the moldavite origin.

Bubbles

All tektites contain bubbles. The bubbles are associated both with the glass in matrix and with lechatelierite. Their number in splash-form tektites represents usually about 0.1% of the overall volume. The volume of bubbles in Muong Nong type tektites is several times higher (usually 0.5–2.0% in indochinites). The most usual bubble dimensions are 0.0X to 0.X mm and very rarely exceed 1 cm. On

Plate I

1. Fissures on the surface of a moldavite widened by chemical corrosion, Besednice (S Bohemia); 2. A moldavite enclosed in a concretion of ferruginous sandstone, Slávče near Trhové Sviny (S Bohemia); 3. A spirally curved moldavite from Chlum nad Malší (S Bohemia); 4. A deeply sculptured moldavite from Besednice (S Bohemia); 5. A pitted sculptured moldavite from the Koroseky gravels and sands, Vrábče sand-pit (S Bohemia); 6. An opened bubble in a moldavite, Záluží (S Bohemia); 7. A spontaneously "in situ" fractured moldavite under influence of internal stress. The fractured surface is also slightly corroded, Chlum nad Malší (S Bohemia); 8. A Muong Nong type moldavite from strewn-field sediments, Jankov (S Bohemia); 9. A dark brown Muong Nong type moldavite from Slávče near Trhové Sviny (S Bohemia); 10. Moldavites from Dřenice, Cheb Basin (W Bohemia); 11. A pebble-shaped moldavite with a typical sculpture of slightly widened fissures, Litobratřice (W Moravia); 12. Angular moldavites from strewn-field sediments, Slavice (W Moravia); 13. A moldavite with two types of sculpture (thin part – pitted, thick part – strong cuts), Slavice (W Moravia). All photos scale 1 : 1.

Plate II

14. A drop-like moldavite from Slávče near Trhové Sviny (S Bohemia); 15. A dumb-bell moldavite from Slávče near Trhové Sviny (S Bohemia); 16. An ellipsoid-like moldavite from Chlum nad Malší (S Bohemia); 17. Typical moldavites from W Moravia (left – Třebíč-Terůvky, middle – Štěpánovice, right – Kožichovice). All photos scale 1 : 1.

the other hand, the surface of some moldavites reveals noticeable parts of open bubbles up to a few centimetres large.

The shape of the bubbles in the matrix is either spherical or elongated and flattened at the same time. The elongation corresponds to the direction of flow of tektite melts at high viscosity. The extreme cases of bubble elongation are the so-called "channels", which occur mainly in the South Bohemian moldavites. Irregular, angular to "spiny" bubbles are common only in some Muong Nong type tektites (Barnes 1963).

A variable amount of comparatively small spherical bubbles occurs in lechatelierites. In the Muong Nong type tektites, they can accumulate to such a degree that lechatelierite particles acquire a foamy character. Some South Bohemian moldavites contain foamy lechatelierite, while no foamy lechatelierite was found in the Moravian moldavites.

All bubbles in tektites need not be of the same origin. The sources of most of them were gases, which were included in the parent rock. This is evident from the fact that the number of bubbles decreased when the temperature of origin rose (Barnes 1969, Konta and Mráz 1969). Additional possible evidence is (i) the absence of a relationship between the size of the bubbles and the size of the tektites, (ii) the abundance of bubbles in lechatelierite and (iii) their dispersal in the whole tektite volume.

Chao (1963) and Dolgov et al. (1969) regarded the bubbles a result of internal stress effective in the cooling period. Only some of the central bubbles in large tektites can belong to these so-called vacuum bubbles.

Angular bubbles in the Muong Nong type tektites are considered closed pores of the original rocks. The high viscosity of melt prevented their rounding (Barnes 1963). Angular bubbles are rare in normal tektites. They originated in the final stages of tektite formation, for example, when two parts of a tektite joined together. These cases are common among the moldavites in southern Bohemia. We can also find a specimen among the Moravian moldavites from Slavice, described – probably incorrectly – as a Muong Nong type moldavite by Barnes (1969).

Statistical differences in the shape and the abundance of bubbles exist among moldavites from individual substrewn fields. Moravian moldavites and the ones from the Radomilice area are poorer in bubbles when compared with other South Bohemian moldavites. The former also have less elongated bubbles, in accordance with more isometric shapes.

Crystalline inclusions

Crystalline inclusions form only rare components in tektites but have a substantial significance for the resolution of genetic problems. According to their origin, we can divide them into (i) unmelted rests of parental rocks (zircon, rutile, chromite, monazite, quartz), (ii) products of recrystallization and dissociation of original minerals (coesite, baddeleyite, corundum, cristobalite), (iii) products of exsolution formed by melting and solidification (magnetite, Fe-Ni spherules with a mixture of schreibersite and troilite, hematite, crystals of iron-nickel alloys, chalcopyrite) and finally (iv) devitrified parts (cristobalite).

The most varied range of crystalline inclusions was found in the Moung Nong type indochinites, which confirms that the source rock melted at a relatively low temperature. Data about the finds of crystalline phases in moldavites are rare and were obtained only from the South Bohemian moldavites. Kleinnman (1969) described microscopic magnetite spherules, which sometimes have a native iron core or an admixture of wüstite. The average amount of these spherules is 2–5 in one moldavite. The origin of magnetite spherules is explained by the crystallisation in melt under conditions of strong reduction. Mineeva et al. (1984) found small hematite particles (X 10^{-9} m). Quartz has been found only in one case in a moldavite from Radomilice (Barnes 1969). The quartz forms irregular broken grains of a size of several hundredths of millimetre, which are surrounded by lechatelierite. The occurrence of coesite (Weiskirchner 1962) and baddeleyite (Glass et al. 1989) in South Bohemian moldavites is also an exception.

The origin of moldavites

Today, most researchers accept the theory that moldavites, and in the same way also other tektites, are the product of terrestrial impact and represent melted target rocks ejected during crater formation. The first to present this theory was Spencer (1933). His theory was strongly supported by Cohen (1963), who assigned the Ries crater in Germany to moldavites and the Bosumtwi crater in Ghana to Ivory Coast tektites. The credibility of impact theory was then confirmed by the identical age of the tektites in question and of the respective craters. Later on, the parent crater to North American tektite strewn field was found. At present, the only source place still unknown is that for the Australasian tektites.

Not all impacts result in the formation of tektites. According to David (1972) and Stöffler et al. (2002), tektites appear only with the oblique impact of the cosmic body. This is supported by the fact that tektites are today found in only one direction from the parent crater. Another indispensable condition is the effect of strongly compressed air in front of the impacting body on the surface horizons (Remo and Sforza 1977, Delano and Lindsley 1982). The compressed atmosphere ejected material immediately before the crater-forming explosion. This condition makes it impossible for tektites to appear on the Moon and on other atmosphere-poor planets.

Dietz (1984) stressed that tektites are formed only during strong impacts, which create craters at least 10 km in diameter. The chemical composition of target rocks probably plays a certain role, because it strongly influences the character of the melted product and the possibility of glass formation. The proof of this is the relatively small variability of the chemical composition of tektites.

We may sum up the claims of many authors and present a probable explanation of the origin of tektites. A relatively large meteorite, at least hundreds of metres in diameter, penetrated the Earth's atmosphere at almost the original speed (11 to 72 km s^{-1}) and struck the Earth's surface at a sharp angle. An extreme compression of air occurred on the front part of the meteorite. The compressed air flung away non-solid surface rocks in one direction. The following explosion formed a crater and impactites.

According to Kalenda and Pecina (1997, 1999), the total melting of the ejected material occurred during the first phase of the impact, as a consequence of friction in the atmosphere. The adiabatic process distinctly influenced the origin of tektites from fluid phase (David 1973, 1988).

The origin of various primary tektite forms (the Muong Nong type, splash-form tektites and microtektites) is the result of the same process and it reflects strong temporal and spatial changes in the physical conditions. The origin of the Muong Nong type of tektites required low initial speed of ejection, and the end of the adiabatic process at temperatures about the point of softening or lower. Conversely, with microtektites this moment happened at temperatures at least by 1000 K higher (Trnka 1992).

Solidification of splash-form tektites took place according to gas pressure in bubbles at the height of at least 20 to 40 km above Earth's surface (Rost 1972, Matsuda et al. 1993, 2001), with the Muong Nong type tektites solidification occurred at a lower height. The rate of cooling of tektite melt depended on the type of cooling. This rate was the highest in the period dominated by adiabatic expansion; Feldman et al. (1983) estimated this rate at 70–100 Ks^{-1}. With Muong Nong type tektites, the adiabatic cooling was completed at temperatures near to the annealing range. During the solidification of splash-form tektites, their surface was cooled by radiation at a rate of about 10 Ks^{-1}. The inside of the tektites was cooled by conduction and its rate was about 10 times lower (Wilding et al. 1996). The tektites reached the Earth's surface already in a solid state.

The Ries impact crater, which is genetically associated with moldavites, is located about 120 km east of Stuttgart in Germany. It forms a morphologically marked depression with the outer diameter of 25 km. Its age is identical with the age of the moldavites (e.g. Storzer et al. 1995). According to several independent determinations (K/Ar, $^{40}Ar/^{39}Ar$, fission-track), this age most often ranges from 14.2 to 15.2 Ma. The latest $^{40}Ar/^{39}Ar$ data (Staudacher et al. 1982, Laurenzi, Bigazzi 2001, Schwarz, Lippolt 2002) determine the moldavite age in a narrow interval of 14.3 to 14.5 Ma. This age is slightly younger (by about 0.3–0.4 Ma) than the age suggested by earlier K/Ar determinations (Storzer et al. 1995). Relatively oldest age was obtained from fission-track data (Bigazzi, De Michele 1996, Bouška et al. 2000).

The cause of the origin of the Ries crater was the impact of a stone meteorite. Morgan et al. (1977) considered that it was aubrite because of the very low enrichment of impact glasses by Ir, Os and Ni. On the other hand, El Goresy and Chao (1977) supposed that it was the impact of a carbonaceous chondrite because of the chemical composition of metallic veinlets in the impact glasses. Pernička et al. (1987) and Schmidt and Pernicka (1994) inclined to the opinion that it was a chondrite. Preuss (1964) estimated the diameter of the meteorite at 500 to 1000 m, Engelhardt and Graup (1984) at 1000 m.

According to the Stöffler et al. (2002), the meteorite at Ries impacted the Earth surface at the velocity of 20 km s^{-1} and at an angle of 30° to 45°. The angle of dispersion of the moldavite matter was 50°, which corresponds to the present distribution of moldavites.

Cohen's application of the impact theory on the moldavites led to the search for chemically similar rocks in the Ries area. It was soon realized that there was a distinct difference in the composition of the crystalline rocks and of the Mesozoic sediments on one side and of the moldavites on the other side. According to Engelhardt (1967), the only possible source of moldavites in the Ries area are the Tertiary sands of the Upper Freshwater Molasse – UFM (Fig. 8). This opinion was supported by a detailed geochemical study (Luft 1983, Engelhardt et al. 1987, Koeberl et al. 1985, Delano et al. 1988 and others).

Delano et al. (1988) obtained very convincing results about the petrographic composition of the source sediments. They separated the elements contained in the moldavites on the basis of correlative relationships into three groups, which correspond to three mineral components of sand-dominated sediments (Fig. 9). These groups are: a) Si (quartz), b) Al, Fe, K, Na, Ti (clay minerals), c) Ca, Mg, Mn (carbonates). Meisel et al. (1997) also explained the basic chemical differences between moldavites by petrographic variation of these components in source material.

Moldavites and the sands of UFM are chemically very similar but not identical. Some of the differences (for example, lower contents of Ca, Mg, Sr and higher contents of Fe, Ti and P in sands) can be explained by the variability of sands or by later influence of weathering processes. However, other differences make us think about a partial change in the sand chemistry during its change to moldavites.

Selective volatilization is the only evident mechanism of change in the chemical composition of the source material. This process led to a distinct lowering of the most volatile components (H_2O, N, S, B, P, halides and noble gases, As, Sb, Cu and so on – Fig. 10) as was already mentioned in the chapter about chemical composition. Some studies on indochinites and australites show a particular loss of alkalies. Taylor (1961) compared the chemical composition of rims and of the cores of button australites and found that ablation caused lowering of alkalies content at their edges for 5–20 wt%. Ridenour (1986) supposed a loss of alkalies from the positive correlation between their contents and the weight of whole pieces of indochinites.

It is generally valid that the loss of volatiles from melt depends on the boiling point of the applicative component, on the external pressure, on the size of free surface and on the surface temperature. In the opinion of Knobloch and Kučera (1992), the main degassing came about under relatively low temperatures in the early stage of tektite development.

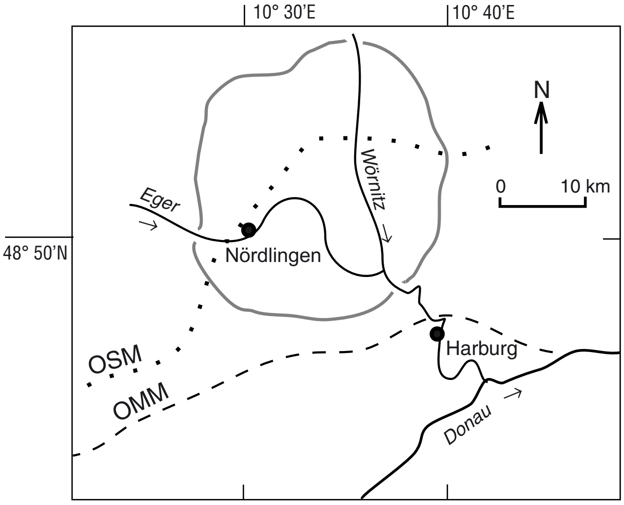

Fig. 8. Former extension of UFM sediments (moldavite source material) within the Ries Crater, Germany (modified according to Hüttner and Schmidt-Kaler 1999); (OSM = UFM = Upper Freshwater Molasse).

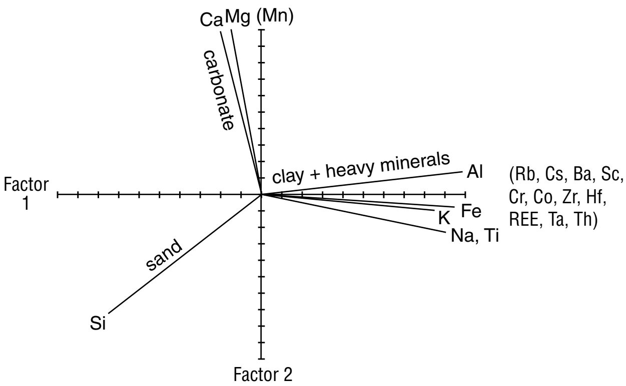

Fig. 9. Factor analysis of moldavites demonstrating the composition of the source rock (Bouška 1994).

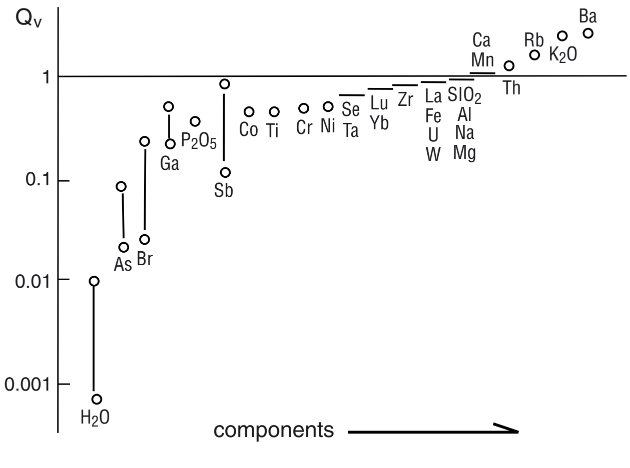

Fig. 10. A comparison of element concentrations in the moldavites and in the sands of UFM from Ries on the basis of Q_v parameter of contents of individual components (according to Knobloch and Kučera 1992).

Conclusions

Moldavites represent a group of tektites subjected to a number of relatively detailed studies. On the other hand, moldavites have been strongly influenced by their geological development. They are found in several discrete regions: southern Bohemia, western Moravia, the Cheb Basin, Lusatia in Germany, and Waldviertel in Austria. Only a few moldavites were found outside these regions.

The extent of moldavite occurrences is a result of intensive denudation and redeposition of the initial strewn field by surface streams. All regions of moldavite occurrences are spatially connected with regional basins and depressions. The oldest moldavite-bearing sediments with very short-transported material are unsorted colluvio-fluvial gravelly sands and clays of Middle to Upper Miocene age. They occur especially in the South Bohemian substrewn field. In Moravia and perhaps in Austria, they are rare. Fluvial transport of moldavites to more distant places determined the present distribution of moldavite occurrences and led to a substantial lowering of their content in the sediments.

Roughly 10^6 metric tons of moldavite matter (macrotektites) formed at the time of their formation. Only about 1% of this matter has been preserved till the present.

Most moldavites are splash-form moldavites. No ablation features were found on their surface. Muong Nong type moldavites occur sporadically. It is possible that in the time of origin their amount was higher. Micromoldavites were not found. Their preservation in the conditions of continental sediments over about 15 million years is not probable. It is a question whether they were formed or not.

Moldavites represent the most acid group of tektites, with silica content around 80 wt%. They are relatively rich in K_2O, too. On the other hand, they are characterized by low average contents of Al_2O_3, TiO_2, FeO and Na_2O. These low contents of TiO_2 and FeO are responsible for their higher translucency, similarly as in georgianites.

In the same way as with other tektites, moldavites originated by the fusion and ejection of surface rocks during an oblique impact of a large meteorite. The impact body in the case of moldavite formation was probably a chondrite 500–1000 m in diameter. Its impact, dating to 14.4–15.1 Ma, created also the Ries crater.

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