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Shape analysis of moldavites and their impact origin

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SUMMARY. 1666 moldavites from 19 localities in Bohemia and 617 moldavites from 10 localities in Moravia were measured to yield parameters L (length), B (breadth), and T (thickness). A digital computer was programmed to calculate values T/L, $(L-B)/(L-T)$, and $\sqrt[3]{T^2/LB}$ according to Sneed and Folk (1958) and values $q = B/L$, $p = T/B$, and $F = p/q$ according to Zingg (1935). Averages of large numbers of values characterize Bohemian and Moravian localities. Moldavites from most localities in Bohemia are often drop-like, flat or elongate with average values of $\sqrt[3]{T^2/LB}$ between 0·53 and 0·66 and F between 0·68 and 0·91. Moldavites from Moravia are frequently massive to spheroidal with average $\sqrt[3]{T^2/LB}$ in the range 0·60 to 0·75 and F between 0·87 and 1·08. Among the localities in Bohemia, four have moldavites with morphological features of Moravian moldavites. The data obtained permit an interpretation that localities of moldavites with low average sphericity contain less heated material. Less heated and thus more viscous glass could have flown along shorter trajectories (Bohemia). More heated glass was ejected to geographically more distant places (Moravia) or travelled along relatively long steeper trajectories (several localities in Bohemia).

MOLDAVITES from localities in Bohemia are mostly drop-like, flat or elongate, whereas moldavites from localities in Moravia are frequently massive to spheroidal. Among the moldavites in Bohemia, complete forms are rare, which can be explained by an easier breakage of flat or rod-like forms with a relatively low sphericity. Massive torspheroidal moldavites from Moravia yield more complete forms. Most fragments, irrespective of their present shape, indicate sphericity of the original forms, so that average values of a large number of measurements characterize individual localities.

Shape, colour, weight, and surface features of several thousand moldavites were described qualitatively by Bouška, Faul, and Naeser (1968). They concluded that 'Shapes of moldavites show significant differences among localities, but no trends appear, it is possible to state only that the moldavites from Moravia have mainly round shapes. Moldavites could not have been transported more than a few km by water, and the original strewn fields must have been very small.' Konta and Mráz (1969) studied the relationship between chemical composition, bulk density, and sphericity and hypothesized a relationship between sphericity of moldavites and viscosity of the hot glass and the magnitude of thermal energy liberated in different impact areas.

This study was aimed at exploiting the shape analysis of moldavites to verify the assumed mutual position of the source area (Ries Crater) and the strewn fields. Shape parameters of tektites such as sphericity, which have not been explored yet, were analysed quantitatively. The shape parameters of moldavites were expressed analogously to those of fragments used in petrology of coarse clastic sediments (Sneed and Folk, 1958; Zingg, 1935). In the course of a secondary relatively short transport by water with other clastic material, which took place in Upper Tertiary and Quaternary, the original sphericity of moldavites remained largely unaffected; the degree of roundness may have changed much, but it is just a function of surface quality (Konta, 1966).

Theoretical assumptions. Among other data, Barnes (1964, 1968) found statistically that moldavites from localities in Bohemia contain more lechatelierite and bubbles than do those from localities in Moravia. This proves that the material of Bohemian moldavites was less heated than that of Moravian moldavites. From the studies of Barnes and of Konta and Mráz (1969) it follows that the thermal energy causing homogenization of the glass was lower in most moldavites found in Bohemia than in those from Moravia. The more thermal energy affected the source material of tektites, the less viscous it became, the less lechatelierite and bubbles it contained; such glass assumed more massive to spherical forms than the less heated glass.

If we hypothesize an impact origin of moldavites, it is likely that the most heated silicate material was ejected from sites in the crater where most of the mass energy of the cosmic body was focused. The glass thus formed is expected to have been carried mainly to sites remote from the impact or, more exactly, is expected to have travelled along a longer trajectory than the less heated glass. Its viscosity being smaller, the solidified glass ought to have decidedly more massive and spherical forms than the less heated and more viscous glass.

Material studied. Moldavites from nineteen localities in Bohemia and ten localities in Moravia were selected for study (fig. 1). Table I summarizes the numbers of moldavites measured, their maximum, minimum, and average weights and data on average forms of moldavites expressed quantitatively by geometric parameters according to Sneed and Folk (1958) and Zingg (1935). From Bohemian localities 1666 moldavites were studied, mostly from the author's collection, the others being from another private collection. The localities were exploited systematically for many years, and every specimen, including the smallest fragments, was collected and considered. The Moravian moldavites studied (617 specimens) come mostly from several private collections; only a small part is from the author's collection. Most collections of the Moravian moldavites studied contain representative material from several localities collected during several decades. Some localities gave poor yields that are not quite suitable for statistical analysis. When considering the totals of Bohemian and Moravian localities, however, these localities do have some importance. An increase in the number of specimens from non-systematically accumulated collections might bias the statistical relations observed.

Measurements and calculations. Each moldavite was weighed with an accuracy of $\pm 0{\cdot}001$ g, and its length (L), breadth (B), and thickness (T) was measured with a contact rule. The measurements were performed in the same fashion as with pebbles (cf. Krumbein, 1941). The only difference was that both breadth (B) and thickness (T) were measured at mid-length. For each moldavite were calculated values T/L, $(L-B)/(L-T)$, and the maximum projection sphericity $\sqrt[3]{T^2/LB}$ according to Sneed and Folk (1958). Following Zingg (1935) $q = B/L$, $p = T/B$, and sphericity $F = p/q$

were calculated. All these values were calculated on a British-made ICT 1904 digital computer at the State Bank of Czechoslovakia in Praha. Averages for each of the 29 localities studied and for all moldavites from Bohemia and Moravia were also calculated (see Table I).

Graphical representation. Variation of shape of moldavites from the 29 localities is summarized in triangular diagrams (fig. 2). Each point represents one moldavite. The overwhelming majority of moldavites from Bohemia are represented by fragments,

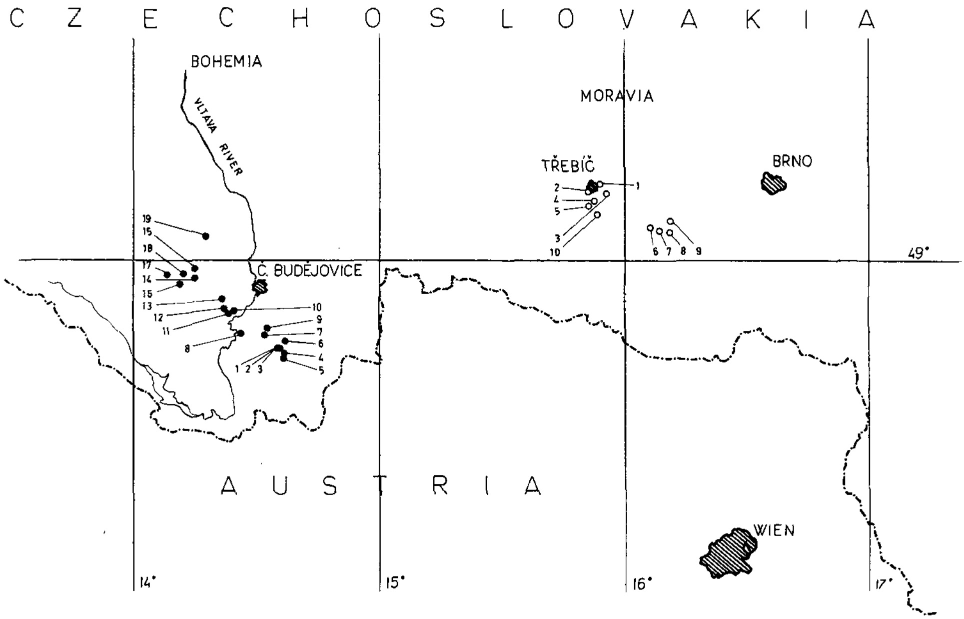


FIG. 1. Map showing the positions of 19 moldavite localities studied in Bohemia and 10 in Moravia.

whole forms being exceptional. The size of points or crosses showing whole forms among Bohemian moldavites has been doubled. In Moravian localities, whole forms are frequent and doubling the point sizes would cause confusion in the figures and therefore all points are the same size. Some diagrams summarize two or three localities, if the localities yielded fewer moldavites. In triangular diagrams according to Sneed and Folk (1958) the parameters $\sqrt[3]{T^2/LB}$ and T/L are characteristic for the shape analysis of moldavites; $(L-B)/(L-T)$ is not so characteristic for different localities. In square diagrams according to Zingg (1935) the values $F = p/q$ and $p = T/B$ are characteristic for the shape analysis of moldavites, $q = B/L$ is not. This follows particularly from the last two graphs (figs. 3 and 4), where solid circles represent averages for individual localities in Bohemia and open circles for those in Moravia.

Fig. 3 shows that the average values for individual localities in Bohemia fall in a field bounded by values T/L 0·32 to 0·47, $\sqrt[3]{T^2/LB}$ 0·53 to 0·66, and $(L-B)/(L-T)$

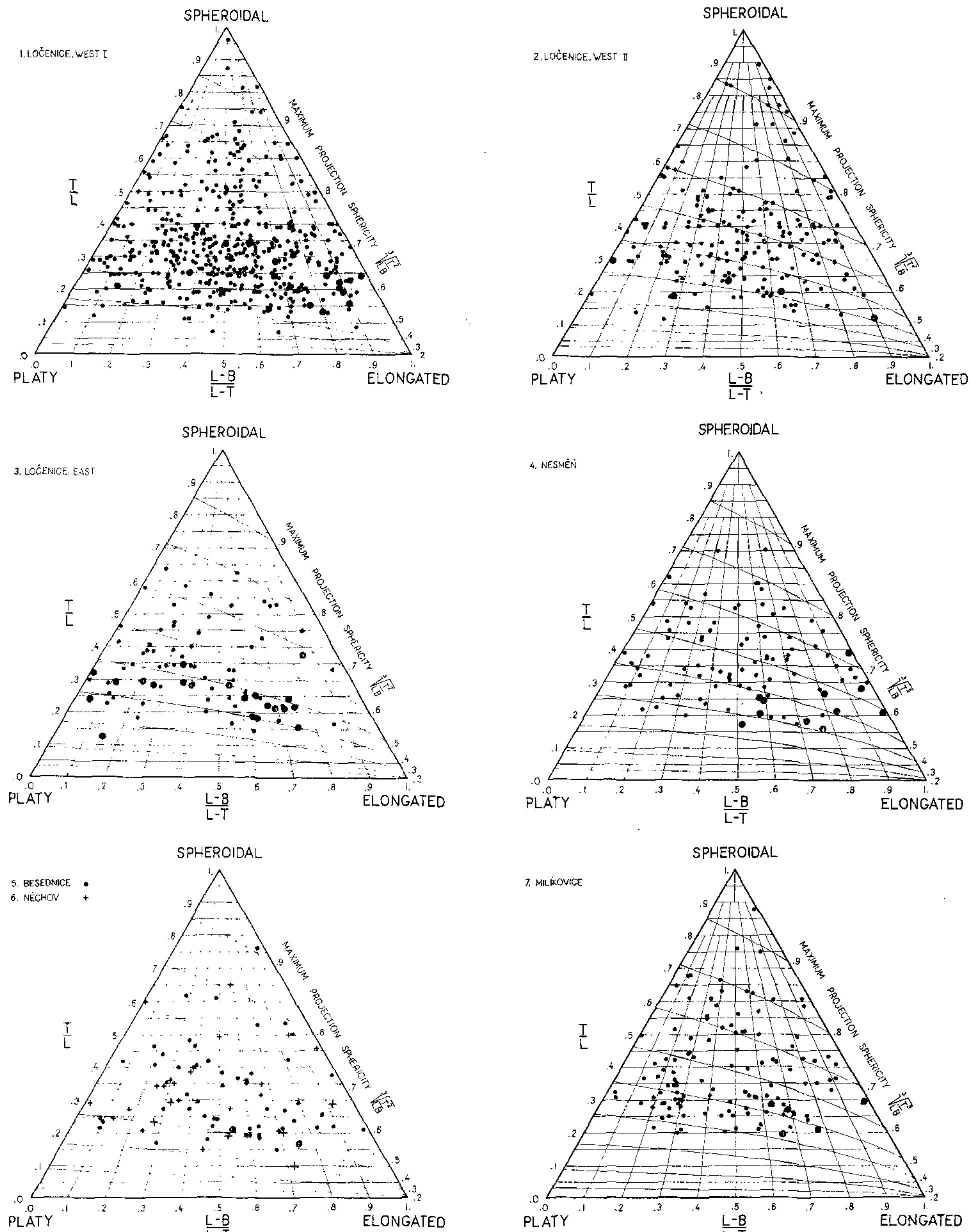
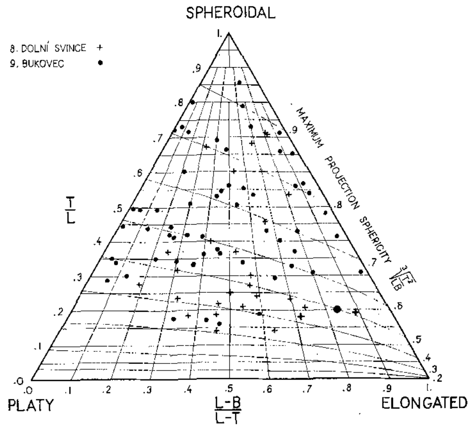
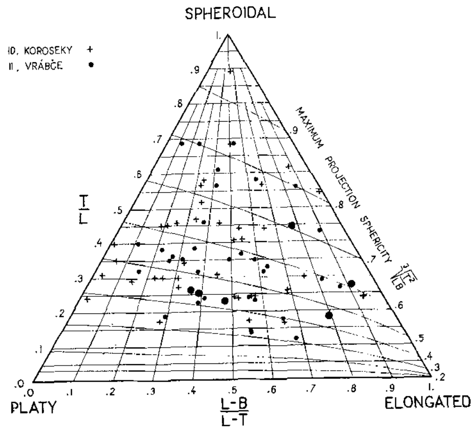
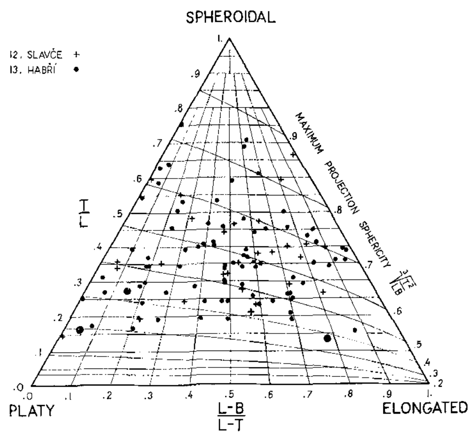
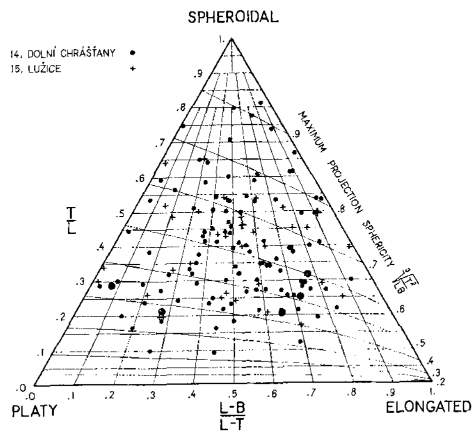


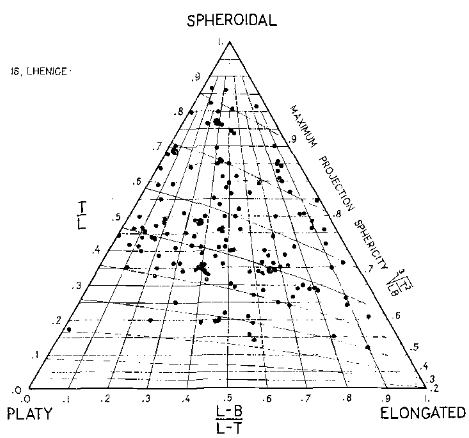
FIG. 2. A graphical plot of shape parameters for 2283 moldavites from 19 localities in Bohemia and 10 localities in Moravia (18 triangular diagrams).

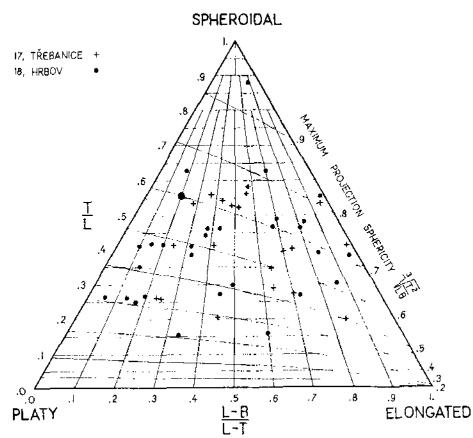

SPHEROIDAL
8. DOLNÍ SVINCE +
9. BUKOVEC •
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED

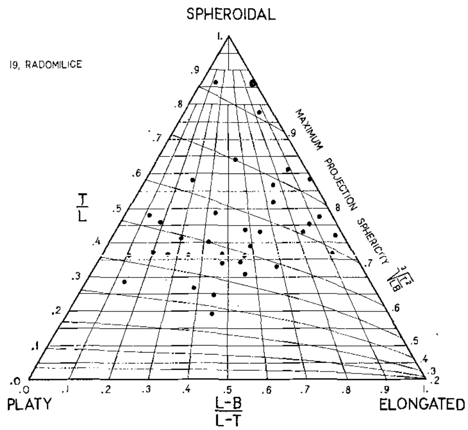

SPHEROIDAL
10. KOROSEKY +
11. VRÁBČE •
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED

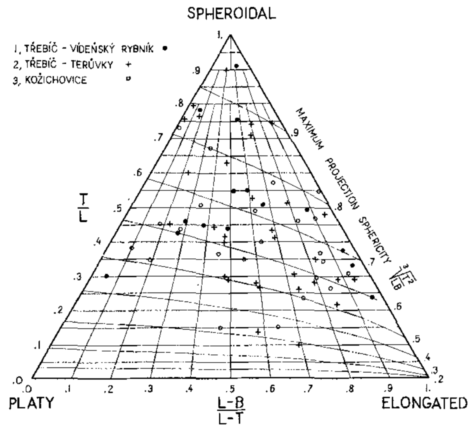

SPHEROIDAL
12. SLAVČE +
13. HABŘÍ •
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED

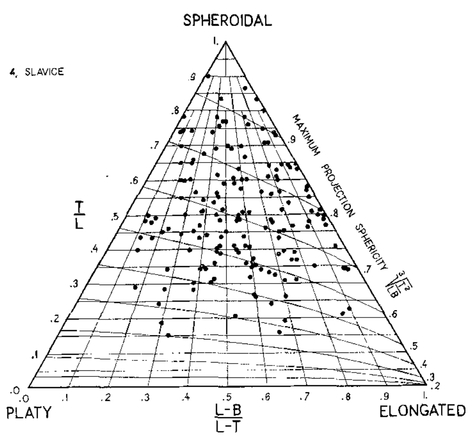

SPHEROIDAL
14. DOLNÍ CHRÁŠŤANY •
15. LUŽICE +
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED

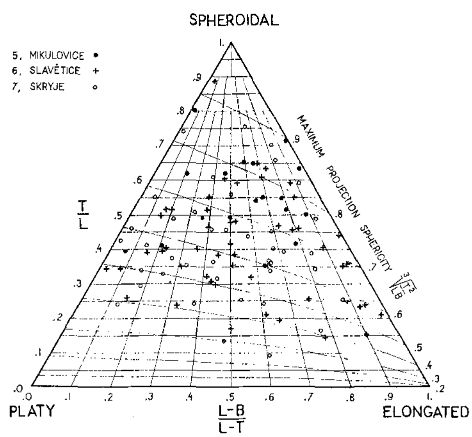

SPHEROIDAL
16. LHENICE ·
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED

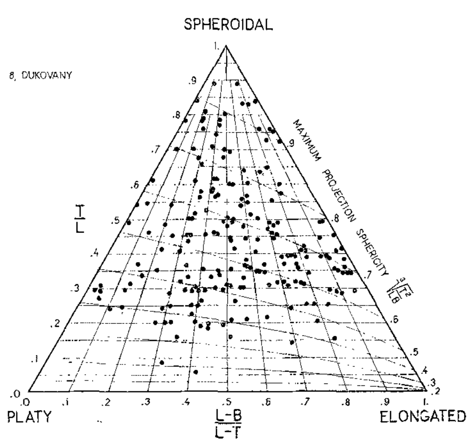

SPHEROIDAL
17. TŘEBANICE +
18. HRBOV •
T/L
MAXIMUM PROJECTION SPHERICITY
PLATY
L-B/L-T
ELONGATED


SPHEROIDAL
19, RADOMILICE
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED


SPHEROIDAL
1, TŘEBÍČ - VÍDEŇSKÝ RYBNÍK •
2, TŘEBÍČ - TERŮVKY +
3, KOŽICHOVICE
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED


SPHEROIDAL
4, SLAVICE
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED


SPHEROIDAL
5, MIKULOVICE •
6, SLAVĚTICE +
7, SKRYJE ∘
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED


SPHEROIDAL
8, DUKOVANY
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED

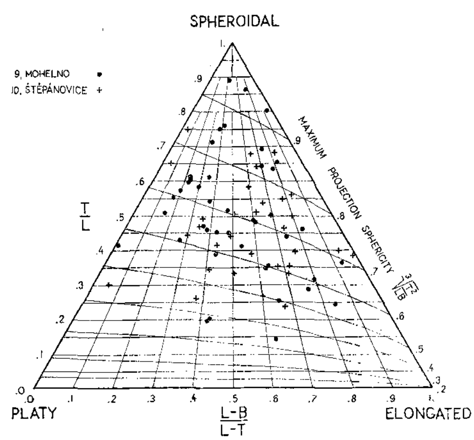
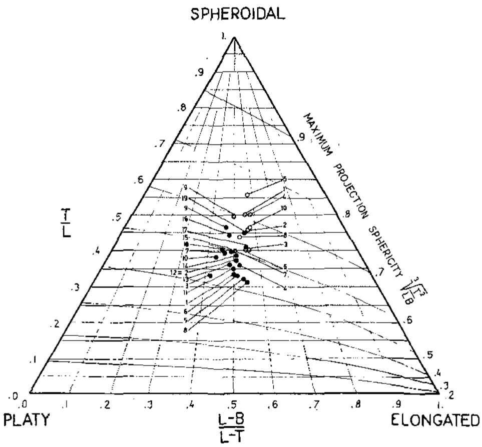

SPHEROIDAL
9, MOHELNO •
10, ŠTĚPÁNOVICE +
MAXIMUM PROJECTION SPHERICITY
T/L
PLATY
L-B/L-T
ELONGATED

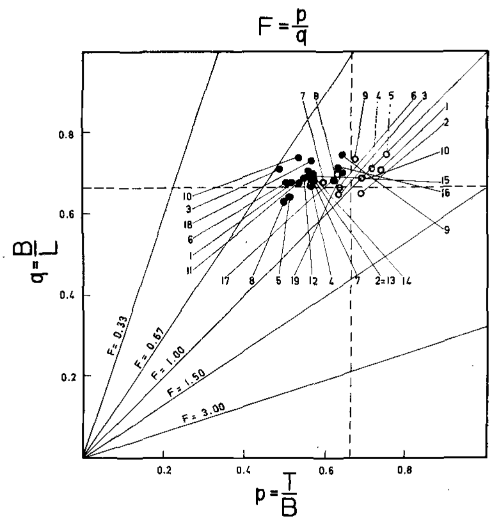
TABLE I. *Number of moldavites studied, their maximum, minimum, and average weight, and data on shapes of moldavites quantitatively expressed by various geometric parameters for 29 localities*

Locality	Number of moldavites	Weight, grams Max.	Min.	Ave.	Shape average values acc. to Sneed and Folk T/L	$(L-B)/(L-T)$	$\sqrt[3]{T^2/LB}$	Shape values acc. to Sneed and Folk for moldavites over 5 grams T/L	$(L-B)/(L-T)$	$\sqrt[3]{T^2/LB}$	Average shape values acc. to Zingg $q = B/L$	$p = T/B$	$F = p/q$	Shape values acc. to Zingg for moldavites over 5 grams $q = B/L$	$p = T/B$	$F = p/q$	Number of moldavites over 5 grams
BOHEMIA																	
1. Ločenice, west I	459	46·531	0·191	3·759	0·34	0·50	0·54	0·34	0·41	0·54	0·67	0·52	0·78	0·70	0·50	0·72	102
2. Ločenice, west II	181	27·436	0·136	3·856	0·37	0·51	0·58	0·37	0·38	0·56	0·69	0·55	0·80	0·77	0·50	0·65	40
3. Ločenice, east	80	16·398	0·467	3·578	0·33	0·42	0·53	0·36	0·35	0·55	0·71	0·48	0·68	0·77	0·49	0·64	19
4. Nesmeň	91	12·227	0·224	3·203	0·36	0·52	0·58	0·37	0·52	0·58	0·66	0·57	0·86	0·65	0·57	0·88	17
5. Besednice	57	13·175	0·335	2·705	0·32	0·53	0·54	0·31	0·47	0·52	0·64	0·52	0·81	0·66	0·46	0·70	7
6. Něchov	25	11·285	0·625	4·709	0·33	0·51	0·54	0·31	0·48	0·53	0·67	0·51	0·76	0·68	0·49	0·72	9
7. Milíkovice	120	30·344	0·451	6·834	0·39	0·47	0·59	0·37	0·47	0·57	0·71	0·56	0·79	0·71	0·53	0·75	63
8. Dolní Svince	27	22·336	0·684	4·733	0·32	0·55	0·53	0·29	0·56	0·52	0·63	0·50	0·79	0·59	0·50	0·85	8
9. Bukovec	59	26·848	0·069	6·135	0·47	0·47	0·66	0·47	0·46	0·66	0·75	0·64	0·85	0·75	0·64	0·85	23
10. Koroseky	38	13·553	0·904	3·984	0·38	0·43	0·58	0·47	0·47	0·66	0·74	0·53	0·72	0·75	0·63	0·84	10
11. Vrábče	40	11·689	0·475	3·468	0·35	0·50	0·56	0·34	0·59	0·57	0·67	0·53	0·79	0·61	0·59	0·97	9
12. Slavče	28	13·859	0·690	4·583	0·37	0·51	0·58	0·34	0·54	0·56	0·69	0·56	0·81	0·67	0·55	0·82	9
13. Habří	82	31·581	0·467	5·332	0·36	0·48	0·57	0·33	0·38	0·53	0·69	0·55	0·80	0·75	0·48	0·64	30
14. Dolní Chrášťany	108	20·810	0·600	5·011	0·39	0·52	0·59	0·34	0·51	0·55	0·68	0·57	0·84	0·66	0·53	0·80	43
15. Lužice	35	13·239	0·242	3·268	0·39	0·49	0·60	0·42	0·42	0·61	0·70	0·57	0·81	0·75	0·57	0·76	7
16. Lhenice	148	34·554	0·339	5·651	0·44	0·48	0·65	0·43	0·51	0·64	0·72	0·63	0·88	0·70	0·62	0·89	52
17. Třebanice	20	11·164	0·361	4·741	0·41	0·55	0·62	0·44	0·57	0·65	0·68	0·62	0·91	0·68	0·66	0·97	9
18. Hrbov	31	27·856	0·296	4·872	0·40	0·46	0·60	0·41	0·39	0·60	0·73	0·57	0·78	0·78	0·56	0·72	10
19. Radomilice	37	33·138	1·145	8·871	0·45	0·55	0·65	0·46	0·61	0·67	0·71	0·64	0·90	0·68	0·68	1·00	23
BOHEMIA	1666	46·531	0·069	4·502	0·37	0·50	0·58	0·37	0·46	0·58	0·69	0·55	0·80	0·71	0·55	0·77	490
MORAVIA																	
1. Třebíc—Vídenský rybník	15	53·150	4·400	18·987	0·50	0·56	0·71	0·51	0·55	0·71	0·71	0·74	1·04	0·72	0·74	1·03	13
2. Třebíc—Terůvky	32	71·000	4·500	14·956	0·46	0·57	0·67	0·47	0·58	0·67	0·65	0·69	1·08	0·65	0·69	1·08	30
3. Kožichovice	22	81·250	1·200	18·995	0·40	0·56	0·62	0·43	0·57	0·66	0·65	0·63	0·97	0·66	0·67	1.02	18
4. Slavice	165	115·170	1·750	20·661	0·50	0·58	0·71	0·50	0·57	0·70	0·71	0·71	1·00	0·72	0·71	0·99	135
5. Mikulovice	18	56·850	9·850	31·561	0·56	0·57	0·75	0·56	0·57	0·75	0·75	0·75	1·00	0·75	0·75	1·00	18
6. Slavětice	51	29·100	0·950	10·534	0·40	0·55	0·62	0·41	0·57	0·63	0·66	0·63	0·95	0·65	0·64	0·98	37
7. Skryje	42	22·400	0·550	5·294	0·40	0·51	0·60	0·41	0·60	0·63	0·68	0·59	0·87	0·65	0·65	1·00	17
8. Dukovany	198	73·500	0·700	11·213	0·44	0·53	0·64	0·45	0·54	0·65	0·70	0·63	0·90	0·70	0·65	0·93	144
9. Mohelno	42	88·450	1·250	16·331	0·50	0·51	0·69	0·50	0·51	0·68	0·74	0·67	0·91	0·75	0·67	0·89	33
10. Štěpánovice	32	48·650	5·900	21·761	0·47	0·58	0·68	0·47	0·58	0·68	0·69	0·69	1·00	0·69	0·69	1·00	32
MORAVIA	617	115·170	0·550	15·430	0·48	0·55	0·67	0·49	0·56	0·68	0·70	0·67	0·96	0·71	0·68	0·96	477

0·42 to 0·55. The average values for localities in Moravia fall in a field bounded by values T/L 0·40 to 0·56, $\sqrt[3]{T^2/LB}$ 0·60 to 0·75, and $(L-B)/(L-T)$ 0·51 to 0·58. In fig. 4 the field of Bohemian localities is bounded by $p = T/B$ 0·48 to 0·64, $F = p/q$ 0·68 to 0·91, and $q = B/L$ 0·63 to 0·75, while the field of Moravian localities is bounded by p 0·59 to 0·75, F 0·87 to 1·08, and q 0·65 to 0·75.

The centres of gravity of experimental points in triangular graphs for Bohemian localities 1 to 8, 10 to 15, and 18 lie decidedly lower that those for localities 9, 16, 17, and 19. The centres of gravity of Moravian localities lie toward a higher maximum projection sphericity. An exception is locality 7 at Skryje.





FIGS. 3 and 4: FIG. 3 (left). A graphical plot of average shape parameters according to the method of Sneed and Folk (1958) for moldavites from 19 localities in Bohemia (solid circles) and 10 localities in Moravia (open circles). FIG. 4 (right). A graphical plot of average shape parameters according to the method of Zingg (1935) for moldavites from 19 localities in Bohemia (solid circles) and 10 localities in Moravia (open circles).

Discussion of results. The shape analysis of moldavites shows that the experimental points representing averages for Bohemian localities in the summarizing triangular diagram (fig. 3) have perceptibly lower values of maximum projection sphericity and T/L ratio than do points for moldavites from Moravian localities. Average values of $(L-B)/(L-T)$ are slightly lower for Bohemian than for Moravian localities. The distinction is even more sensitive if we use the method of shape analysis according to Zingg (1935). In fig. 4, points representing average values for moldavites from Bohemian localities exhibit conspicuously low sphericity F and value p as compared to moldavites from most Moravian localities.

Points in both summarizing diagrams (figs. 3 and 4) do not outline two separated fields for Bohemian and Moravian localities, but two slightly overlapping fields. The triangular graph of fig. 3 shows that four of the Bohemian localities, namely Bukovec

(9), Lhenice (16), Třebanice (17), and Radomilice (19), have moldavites with characteristic shape features of localities in Moravia. Also in the summarizing square plot of fig. 4, the points representing average shapes of moldavites in those four Bohemian localities lie at the periphery of the field of Moravian localities. It should be noted that moldavites from these four localities, three of which lie in the northernmost part of the strewn field, exhibit also other features of Moravian moldavites. These are low lechatelierite content or even its absence (particularly in localities 17 and 19), lower abundance of bubbles and lower bulk density (not published as yet). Conversely, among the Moravian localities, Skryje (7) has moldavites with average geometric parameters close to values for Bohemian localities.

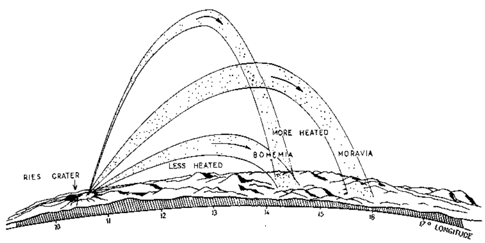


FIG. 5. A concept about the ejection of a less heated tektite material to most localities in Bohemia and of a more heated tektite material to localities in Moravia and some localities in Bohemia.

From the data obtained follows a hitherto unreported fact that the maximum projection sphericity $\sqrt[3]{T^2/LB}$ and sphericity F for moldavites from localities in Bohemia have averages distinctly lower than do moldavites from localities in Moravia. Localities of moldavites with lower average sphericity and higher average abundance of lechatelierite and bubbles and with a higher bulk density contain tektite material ejected from a place of impact where the smaller mass energy of a cosmic body was transformed into a smaller thermal energy. These places with smaller mass energy and thus also smaller thermal energy yielded a less heated and more viscous silicate glass. Such a glass may have flown over a relatively shorter trajectory and during solidifying gave rise to less spherical shapes of most localities in Bohemia. The more heated glass, which occurs in Moravian and a few Bohemian localities (nos. 9, 16, 17, 19), was ejected either into places geographically more remote (Moravia) or along relatively long steeper trajectories (the four above localities in Bohemia). It is also possible that some localities in Bohemia contain both the more and the less heated moldavites. Fig. 5 illustrates the concept about the ejection and longer trajectories of more heated moldavites from Moravian and several Bohemian localities and shorter less steep trajectories of moldavites from most Bohemian localities. The location of the Ries meteorite crater in Bavaria appears to be most suitable to account for both the location of moldavite localities in Bohemia and Moravia and their source and terrestrial origin.

In logical agreement with the above conclusion is the remarkable fact that localities of moldavites with the biggest average sphericity (in Moravia) have also a substantially higher average weight of moldavites. Locality 7, Skryje, has the lowest sphericity among the Moravian localities and also a conspicuously low average weight of moldavites. Of the four localities in Bohemia with biggest average sphericity (nos. 9, 16, 17, 19) three have a relatively high average weight (nos. 9, 16, 19). In all four the average weight of moldavites exceeds the average of all 19 Bohemian localities (see table I).

Table I also shows that the average values of both sphericities calculated from all specimens, small fragments included, differ only a little from values calculated for moldavites whose weight exceeds 5 grams. Only in a few localities, where there are many small fragments, are the differences bigger.

Quantitative shape analysis of tektites has not been performed in any other tektite area. It is likely that a regionally based statistic analysis of tektite shapes (expressed in terms of geometric parameters), when applied to localities in Australia, southeast Asia, in the U.S.A., or elsewhere, might, together with other quantitative data (Konta and Mráz, 1969), aid in determining the sites of impact craters and in constructing an image of trajectories of the silicate substance ejected.

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