

Fluorine and boron geochemistry of tektites, impact glasses, and target rocks

DIETMAR MATTHIES^{1,2} AND CHRISTIAN KOEBERL^{3*}

¹Mineralogisch-Petrographisches Institut, Universität München, Theresienstr. 41, D-8000 München 2, FRG

²Present address: Lehrstuhl für Forstliche Arbeitswissenschaft, Universität München,
 Hohenlindener Str.5, D-8000 München 80, FRG

³Institute of Geochemistry, University of Vienna, Dr.-Karl-Lueger-Ring 1, A-1010 Vienna, Austria

(Received 18 September 1990; accepted in revised form 3 December 1990)

Abstract—We have analyzed fluorine and boron in nine tektites from all four strewn fields, and in a suite of impact glasses and target rocks from the Zhamanshin and Darwin impact craters, as well as Libyan Desert Glass and Aouelloul impact glass samples. Fluorine and boron are useful indicators for the volatilization and temperature history of tektites and impact glasses. Tektites from different strewn fields show a limited range of F and B contents and have F/B ratios near unity. Most splash-form tektites have lower average F and B contents than Muong Nong type tektites, which is similar to the relation between irghizites and zhamanshinites. The F and B contents in target rocks from the Zhamanshin and Darwin impact craters are similar to normal terrestrial sediments. Fluorine in impact glasses and tektites is more depleted compared to their (known or inferred) target rocks than is boron, which is caused by the higher volatility of F. The F/B ratios therefore decrease with increasing temperature of formation (suggesting that irghizites were formed at a higher temperature than zhamanshinites, and Muong Nong type tektites at a lower temperature than splash-form tektites). Mixing of local country rocks together with partial loss of the volatiles F and B can reproduce the F and B contents of impact glasses.

INTRODUCTION

VOLATILE ELEMENTS ARE IMPORTANT as indicators of chemical processes during an impact. Impact glasses and tektites are known to have lower contents of most volatile elements (and water) when compared to their parent materials and other terrestrial upper crustal rocks (*e.g.*, Koeberl, 1986; Koeberl and Beran, 1988). This depletion is expected because of the high temperatures that lead to melting and quenching, or volatilization and recondensation, of country rocks during a hypervelocity impact. For studying relations between projectile and target, it is interesting to compare target rocks and impact glasses at known meteorite impact craters, as well as different types of tektites. For example, Muong Nong type tektites are enriched in many volatile elements when compared to normal splash-form tektites, but they still show a depletion if compared to their (inferred) precursor rocks of upper crustal (sedimentary?) composition (*e.g.*, Koeberl and Beran, 1988). In impact glasses, these elements indicate the degree of volatilization and the formation temperature (and the time spent at a certain temperature) of individual glasses. This is especially obvious if there are several different types of impact glasses at one crater (like at the Zhamanshin crater) that all differ in chemistry (indicating different precursor rocks), and if the glasses can be compared to actual parent rocks.

Fluorine and boron are diagnostic volatile elements that are rarely determined in impact glasses and tektites. This is mostly because of the rather extensive and time-consuming analyses that have to be performed, as these elements often have low abundances in geological materials and are usually difficult to determine with common (instrumental) multi-element methods (such as neutron activation analysis or XRF). The first determinations of fluorine contents of tektites and impact glasses were reported by Koeberl *et al.* (1983, 1984a) and Moore *et al.* (1984); these authors noted that the F abundances in these glasses are dissimilar to those of any volcanic glasses, and lower than

in terrestrial sedimentary rocks. Data on Muong Nong type indochinites were given by Koeberl *et al.* (1984b), who showed that they are enriched by a factor of about two compared to splash-form tektites of the same strewn field. Some F concentrations have been reported by Koeberl and Fredriksson (1986) for Zhamanshin crater impact glasses, but without comparison to target rocks.

Boron concentrations in tektites have been reported by, *e.g.*, Preuss (1935), Mills (1968), and Taylor and Kaye (1969). The latter authors noted that, based on analyses of Henbury impact glass and Henbury target rocks, there does not seem to be a loss of B during the impact process, and that B abundances in australites are compatible with continental sediments. However, Chapman and Scheiber (1969) and Kluger and Koeberl (1985) showed that Muong Nong type tektites are enriched in B compared to splash-form tektites (thus Chapman and Scheiber [1969] designated the Muong Nong type tektites chemically as high Cu,B-tektites). No comparative data were available for other impact glass/target rock associations (some preliminary data from the present study were reported by Matthies *et al.*, 1989).

SAMPLES

Tektite Samples

Two thailandite samples (T8203, T8204; see, *e.g.*, Koeberl *et al.*, 1983, 1985) and two Muong Nong type tektites, MN 8302 (Koeberl *et al.*, 1984b,c,d) and F-16 (Glass and Koeberl, 1989), were analyzed from the Australasian strewn field. Two bediasites from the North American strewn field (B 8401, B 8402; Weinke and Koeberl, 1985), and one moldavite (T 8201; Koeberl *et al.*, 1983, 1985) from the moldavite strewn field were studied. From the rarely studied Ivory Coast tektite strewn field, two new samples from the Paris collection were analyzed within the framework of a larger consortium study of Ivory Coast tektites (Koeberl *et al.*, 1989). Two samples of Libyan Desert Glass (LYD 8501, LYD 8504; Koeberl, 1985), an enigmatic natural glass of probable impact origin found in the Western Egyptian

* To whom correspondence should be addressed.

Desert, were analyzed, as well as one sample of impact glass from the Aouelloul impact crater, Mauritania (I 8205; Koeberl *et al.*, 1983, 1985).

Zhamanshin Crater Samples

The Zhamanshin impact crater in Khazakhstan, USSR, is the source of several different types of impact glasses which have different chemical compositions and petrographic characteristics. They include irghizites (Si-rich, average SiO₂ content of 74 wt.%; small, tektite-like black homogeneous glasses of irregular shape [e.g., rope-form, droplets, wire-form]), Si-rich zhamanshinites (about 70–80 wt.% SiO₂; irregular, blocky shape, layered structure, similar to Muong Nong type tektites), and Si-poor zhamanshinites (about 40–60 wt.% SiO₂; irregular, chunky shape; often recrystallized; inhomogeneous; contain inclusions).

The crater has a rather complex geological setting: the bedrocks are comprised of Paleozoic metamorphic crystalline rocks, including Upper Paleozoic volcanic-sedimentary series, surface sediments, and some ultrabasic dikes. We have studied samples from different sources; target rock samples were supplied by D. D. Badjukov and M. A. Nazarov (Vernadsky Institute, USSR Academy of Sciences, Moscow) and included rocks from most target lithologies (shale, andesite, diabase, marble) and clay samples from a drill core. Impact glass (irghizite, Si-rich and Si-poor zhamanshinite) samples were partly supplied by E. Izokh (USSR Academy of Sciences, Novosibirsk). Some of the samples used in this study have previously been described by Koeberl and Fredriksson (1986) and Koeberl and Storzer (1988), who also give additional geochemical information.

Darwin Glass

Five Darwin glass samples and five different rocks (a quartzite and four shales) from the proposed target area in Tasmania have been analyzed. Four of the glass samples and the target rocks have been described in detail by Meisel *et al.* (1990). More information on glass sample I 8202 is given by Koeberl *et al.* (1983, 1984a, 1985). Samples from all three compositional groups of Darwin glass (A, B, C; after Meisel *et al.*, 1990) have been studied.

ANALYTICAL METHODS

After powdering in an agate mortar, a minimum of about 100 mg sample powder is placed in a platinum crucible and fused with Na₂CO₃ for about 30 minutes at 1000 °C. The soda fusion is preferred over pyrohydrolysis because at standard temperatures boron is not liberated quantitatively (Sauerer, 1986). The fusion cake is then dissolved with dilute HNO₃ and filtered into a polyethylene volumetric flask. One aliquot of the solution is then used for the potentiometric determination of fluorine. A buffer solution (TISAB) is added to the sample solution, and the electrochemical potential is measured with a fluoride-selective electrode. The fluorine concentration is then determined by the standard addition method using the Nernst equation.

A second aliquot is used for the determination of boron with a spectrophotometrical method. The pH is adjusted to 1.0–1.5 with conc. HCl, and boron is extracted from the aqueous solution with ethylhexane-1,3-diol (EHD). After repeating the extraction, boron is extracted back with 0.5 N NaOH. After acidifying the solution with HCl, conc. H₂SO₄ and carmine reagent (carmine acid in conc. H₂SO₄) are added. The carmine complex develops fully within about one hour; the extinction is then measured at 610 nm. The methods were tested by analyzing international reference materials.

The reference materials were analyzed repeatedly to demonstrate precision and accuracy; the following contents have been obtained (in ppm;

values of individual determinations and averages with standard deviation): DTS-1 (USGS): fluorine: 16, 16, 18, 18, 21; ave.: 18 ± 2; boron: 10, 11, 11, 13, 14; ave.: 12 ± 1.6 (recommended values: 12 F, 10 B); BIR-1 (USGS): fluorine: 43, 44, 47, 50, 50; ave.: 47 ± 3.3; boron below detection limit (recommended values: 44 F, 0.3 B); AGV-1 (USGS): fluorine: 431, 440, 443, 459, 460; ave.: 447 ± 12.3; boron: 8, 10, 10, 11, 12; ave.: 10 ± 1.5 (recommended values: 435 F, 7.8 B). More details on the methods and a more extensive study of international reference samples are given by Hofstetter *et al.* (1991), Matthies and Troll (1990), Sauerer (1986), and references therein.

RESULTS AND DISCUSSION

The results of our analyses, together with F/B ratios (where applicable), are given in Tables 1–3. All tektites (Table 1) have rather low F and B abundances. North American tektites show the lowest average F abundances with 8 ppm, while the two Muong Nong type tektites from the Australasian strewn field have consistently higher abundances than all other tektite groups. Excluding Muong Nong types, the range of fluorine contents for tektites is 6–31 ppm. The abundances in Libyan Desert Glass and Aouelloul impact glass are similar to the lower limit for tektites with about 7 ppm F.

The F contents reported here are similar to the data given by Koeberl *et al.* (1983, 1984a) who report a range of 21–46 ppm for Australasian tektites, and Moore *et al.* (1984) who find a range of 12–40 ppm for tektites from three strewn fields (their lowest value of 12 ppm for a bediasite is in good agreement with our data). The higher abundances in Muong Nong type tektites are in agreement with earlier data by Koeberl *et al.* (1984b) and Koeberl and Beran (1988), who report a range of 56–127 ppm for 19 samples, and similar to the 230 ppm reported by Moore *et al.* (1984) for one sample. The present data for F (and B) in MN8302 is somewhat higher than the values given by Koeberl *et al.* (1984b), which might be due to sample inhomogeneity. On the other hand, Bailey (1986) finds considerably higher F contents for all tektite classes with a range of 78–285 ppm in normal tektites, and no distinction between splash-form and Muong Nong type tektites (range 124–312 ppm F for four samples). Bailey (pers. comm., 1990) now considers that his reported values may be too high due to laboratory contamination.

Boron abundances in tektites show a wider range, between 4 and 50 ppm. With the exception of one Ivory Coast tektite (which contains 50 ppm B, but has an anomalous F/B ratio of 0.4 compared to about 0.8–1.5 for other tektites), Muong Nong type tektites have higher B abundances. This is consistent with data by Mills (1968) who found a range of 6–53 ppm for tektites from all four strewn fields (with highest B contents in some indochinites, but apparently no distinction is made between splash-form and Muong Nong type) and Taylor and Kaye (1969) who report a range of 3–55 ppm for Australasian tektites and moldavites. Kluger and Koeberl (1985) found a range of 28–66 ppm B for 19 Muong Nong type tektites with an average of 48 ppm, compared to 27 ppm for splash forms (Taylor and Kaye, 1969), which is in good agreement with the present data.

Not many comparison data for material from the Zhamanshin impact crater (Table 2) are available. Koeberl and Fredriksson (1986) found 61 ppm F for an irghizite, and 67–81 ppm F for three Si-rich zhamanshinites. The Si-rich zhamanshinite USNM 6014 was analyzed twice in the present work (70, 94 ppm; average 82 ppm) as well as by Koeberl and Fredriksson (1986),

TABLE 1. Fluorine and boron concentrations in tektites and related glasses.

Sample number	F (ppm)	B (ppm)	F/B-ratio
Australasian tektites			
T8203 (Thailandite)	20	17	1.2
T8204 (Thailandite)	6	4	1.5
MN 8302 (Muong Nong type)	169	44	3.8
MN F-16 (Muong Nong type)	57	44	1.3
North American tektites			
B 8401 (Bediasite)	8	<5	—
B 8402 (Bediasite)	8	10	0.8
Moldavites			
T 8201	31	n.d.	—
Ivory Coast tektites			
IVC 2069	23	20	1.2
IVC 3395	22	50	0.4
Libyan Desert Glass			
LYD 8501	7	7	1.0
LYD 8504	8	<5	—
Aouelloul impact glass			
I 8205	7	n.d.	—

For more information on the samples, and comparison data, see text.
n.d. = not determined.

yielding 72 ppm, which is considered to be in good agreement. (Note, however, that this zhamanshinite has the lowest F concentration of all samples in Table 2; therefore, by pure chance, the data reported by Koeberl and Fredriksson [1986] seem to represent the glasses with the lowest F abundances.) No other F data (for Si-poor zhamanshinites and target rocks) are available, and no B data have been reported in the literature at all.

Results for Darwin glass samples and possible target rocks are given in Table 3. In the glass, F shows a range of 15–33 ppm, while the range for B is 9–13 ppm. Koeberl *et al.* (1984a) reported 30 ppm F for one Darwin glass sample, and Mills (1968) found 25 ppm B for another Darwin glass sample, while Taylor and Kaye (1969) give a range of 20–46 ppm B for 12 Darwin glass samples. Compared to these earlier analyses, our B contents are rather low, but consistent with the abundances in the target rocks.

A general observation is that the abundances of both B and (especially) F are much lower in tektites (and impact glasses) than in their inferred target rocks (*i.e.*, normal terrestrial upper crustal rocks). Furthermore, the F contents of tektites are lower than those in Zhamanshin glasses and Darwin glasses. There is a clear connection between F abundances and the glass type: the glasses that seem to have had a higher temperature origin have lower F contents. Muong Nong type tektites have higher average F (and B) abundances than splash-form tektites, and zhamanshinites (which are similar to Muong Nong type tektites) have higher abundances than irghizites.

The abundances found in target rocks are consistent with literature data on comparable rocks. Wedepohl (1978) lists 180–450 ppm F for sandstones, and 290–800 ppm F for shales, with no distinct difference between continental and marine sediments. However, a much wider range is possible for all rock types if more diverse samples are taken into account, but the average value remains virtually unchanged. Matthies and Troll

TABLE 2. Fluorine and boron concentrations in target rocks and impact glasses of the Zhamanshin impact crater.

Sample	F (ppm)	B (ppm)	F/B-ratio	
Irghizite	102	33	3.1	
Si-rich zhamanshinites				
Zh 30a	273	55	5.0	
I 8201	289	59	4.9	
20/2	237	52	4.6	
Zh 57/2b	101	n.d.	—	
USNM 6014	82	n.d.	—	
Si-poor zhamanshinites				
m 43a	244	146	1.7	
m 43b	232	84	2.8	
m 45E	281	76	3.7	
Zh 3	188	n.d.	—	
Zh 63/3	197	78	2.5	
Target rocks				
Zh ZSK1	Neogene clay	643	74	8.7
Zh ZSK8	Neogene clay	772	132	5.8
Zh ZSK22	Paleogene clay	766	119	6.4
Zh DB6	shale	707	15	47.1
Zh DB7	Proterozoic shale	130	25	5.2
Zh DB9	shale	305	7	43.6
Zh 2DB1	andesitic conglomerate	348	41	8.5
Zh 5DB1	diabase	225	7	32.1
Zh 5DB3	Proterozoic marble	66	4	16.5

For sample provenance and comparison data, see text.
n.d. = not determined.

(1990) have studied the fluorine chemistry of marine sediments and found that fine silt and clay fractions contribute the largest fraction of fluorine in the sediments. Most igneous rocks have F concentrations that are at least as high as sediments. Granites show an average of about 800 ppm F, alkalic rocks about 1000 ppm, and ultramafic rocks about 100 ppm (Wedepohl, 1978). Meteorites and lunar rocks, on the other hand, show rather low F contents; mare basalt samples range from about 27–78 ppm, highland samples cluster around 40 ppm (Wänke *et al.*, 1975; Meyer *et al.*, 1975), but some higher values around 200 ppm have been found too (Jovanovic and Reed, 1974). Some lunar volcanic glasses (*e.g.*, Apollo 15 green glass) show surface en-

TABLE 3. Fluorine and boron concentrations in Darwin glasses and Darwin crater target rocks.

Sample	F (ppm)	B (ppm)	F/B-ratio
Darwin glass			
DG 8705 (A)	26	12	2.2
DG 8707 (B)	32	9	3.6
DG 8711 (A)	27	10	2.7
DG 8713 (C)	33	n.d.	—
I 8202	15	13	1.2
Target rocks			
Quartzite	423	35	12.1
Shale DG B1	769	n.d.	—
Shale DG B2	738	64	11.5
Shale DG C1	431	n.d.	—
Shale DG C2	389	19	20.5

Letters in () give the Darwin glass group classification after Meisel *et al.* (1990).

n.d. = not determined.

richments of F (Meyer *et al.*, 1975), which may in part be due to contamination (Goldberg *et al.*, 1975).

Boron concentrations in impact glasses and target rocks are comparable to normal terrestrial rock ranges; igneous rocks have an average B content of 10 ppm, continental sedimentary rocks of 85 ppm, with marine sediments having a considerably (by a factor of up to 10) higher abundance (Wedepohl, 1978). Abundances in lunar rocks are not well studied, but glasses from different lithologies show a range of about 1–24 ppm B (Meyer, 1978).

Muong Nong type tektites generally have higher F/B ratios than splash-form tektites (which, using additional data from Koeberl *et al.*, 1984b and Kluger and Koeberl, 1985, show an average F/B ratio of 2.9, compared to about 1.4 for splash-form tektites; but there is still some overlap between the two groups). The ratios for both groups are much lower than the ones for most possible target rocks, which indicates that during the impact fluorine is more depleted than boron. The relation of the degree of fluorine depletion with impactite type seems to indicate a connection with temperature history—the higher the temperature (and the longer the melt remains at the high temperature), the more F is released, while boron shows a less prominent depletion. Fluorine is thus easier volatilized than B, which is consistent with experience from pyrohydrolysis (Sauerer, 1986; Matthies and Troll, 1990). Water contents in Muong Nong type/splash-form tektites show a behavior that is very similar to F (Koeberl and Beran, 1988). The low F and B contents in Libyan Desert Glass and Aouelloul impact glass are most probably due to low contents in the precursor materials.

The complicated geological setting of the Zhamanshin crater makes it difficult to model the impact glass compositions from the target rocks. It is obvious that the irghizite shows the lowest F and B contents, in agreement with the assumption that it was subjected to the highest temperatures. Si-poor zhamanshinites have lower F/B ratios than Si-rich zhamanshinites, which is in agreement with the observation that the andesitic target rocks (which are possible precursor rocks for the former glasses) have lower ratios than shales. Because of the relatively high B contents in some zhamanshinites it is possible that there are some target rocks that contain more B.

The rocks from the Darwin glass area show F and B contents that are similar to the Zhamanshin target rocks; however, the contents in the Darwin glasses are lower than in the zhamanshinites. This is consistent with the greater chemical homogeneity (and possibly higher formation temperature) of the Darwin glasses. Assuming a target rock mixture such as the one proposed by Meisel *et al.* (1990), F in Darwin glass is at about 5% of the target rock level, whereas B is depleted to only about 20–25% of the original abundance. The F/B ratio is similar to that in Muong Nong type tektites. This indicates similar depletion processes for all impact glasses.

CONCLUSIONS

From the present new analyses of fluorine and boron contents in tektites, impact glasses, and target rocks, we can draw the following conclusions:

(1) Tektites from different strewn fields have a limited range of F and B contents (compared to sedimentary rocks); the F/B ratios in tektites are near unity.

(2) Muong Nong type tektites have mostly higher average F

and B contents and F/B ratios than splash-form tektites (about 2.9 vs. 1.4, respectively).

(3) Target rocks at the Zhamanshin and Darwin impact craters have F and B abundances that are well within the range of other upper crustal terrestrial rocks.

(4) Within the group of Zhamanshin glasses, the one irghizite that we measured has the lowest F and B content and a lower F/B ratio than the Si-rich zhamanshinites; this is similar to the relation between splash-form and Muong Nong type tektites.

(5) Fluorine in impact glasses and tektites shows a larger depletion compared to their (in the case of tektites, inferred) target rocks than boron; this is in accordance with the higher volatility of F. The F/B ratio therefore decreases with increasing temperature of formation.

(6) The F and B chemistry of the impact glasses studied here can be reproduced by mixing local country rocks (at Zhamanshin: clays, shales, andesites, quartzites; at Darwin: shales and quartzites) and by partial loss of volatiles from these country rocks during an impact.

Acknowledgements—We are grateful to D. D. Badjukov, M. A. Nazarov (Vernadsky Institute, USSR Academy of Sciences, Moscow), E. Izokh (USSR Academy of Sciences, Novosibirsk), and D. Futrell (Whittier, CA) for most of the Zhamanshin samples. We also thank J. Bailey, B. P. Glass, O. K. Manuel, and C. C. Schnetzler for helpful reviews and comments on the manuscript.

Editorial handling: B. P. Glass.

REFERENCES

- BAILEY, J. C. (1986) Fluorine and chlorine contents of tektites. *Meteoritics* **21**, 295–301.
- CHAPMAN D. R. AND SCHEIBER L. C. (1969) Chemical investigation of Australasian tektites. *J. Geophys. Res.* **74**, 6737–6776.
- GLASS B. P. AND KOEBERL C. (1989) Trace element study of high- and low-refractive index Muong Nong-type tektites from Indochina. *Meteoritics* **24**, 143–146.
- GOLDBERG R. H., BURNETT D. S. AND TOMBRELLO T. A. (1975) Fluorine surface films on lunar samples: Evidence for both lunar and terrestrial origins. *Proc. Lunar Sci. Conf.* **6th**, 2189–2200.
- HOFSTETTER A., TROLL G. AND MATTHIES D. (1991) Trace determination of fluorine, boron, and chlorine from a single sodium carbonate fusion of small geological sample masses. *Analyst*, in press.
- JOVANOVIC S. AND REED G. W. (1974) Labile and non-labile element relationships among Apollo 17 samples. *Proc. Lunar Sci. Conf.* **5th**, 1685–1701.
- KLUGER F. AND KOEBERL C. (1985) Determination of boron at low abundance levels in geological materials with a tetrafluoroborate-selective electrode. *Analyt. Chim. Acta* **175**, 127–134.
- KOEBERL C. (1985) Trace element chemistry of Libyan Desert Glass. *Meteoritics* **20**, 686.
- KOEBERL C. (1986) Geochemistry of tektites and impact glasses. *Ann. Rev. Earth Planet. Sci.* **14**, 323–350.
- KOEBERL C. AND BERAN A. (1988) Water content of tektites and impact glasses and related chemical studies. *Proc. Lunar Planet. Sci. Conf.* **18th**, 403–408.
- KOEBERL C. AND FREDRIKSSON K. (1986) Impact glasses from Zhamanshin crater (USSR): Chemical composition and discussion of origin. *Earth Planet. Sci. Lett.* **78**, 80–88.
- KOEBERL C. AND STORZER D. (1988) Chemical composition and fission track age of Zhamanshin crater glass. *Proc. 2nd Intern. Conf. Natural Glasses, Prague*, 207–213.
- KOEBERL C., KIESL W., KLUGER F. AND WEINKE H. H. (1983) The determination of fluorine in tektites and impactites (abstract). *Lunar Planet. Sci.* **14**, 381–382.
- KOEBERL C., KIESL W., KLUGER F. AND WEINKE H. H. (1984a) A comparison between terrestrial impact glasses and lunar volcanic glasses: The case of fluorine. *J. Non-cryst. Solids* **67**, 637–648.

- KOEBERL C., KLUGER F., KIESL W. AND WEINKE H. H. (1984b) Geochemistry of Muong Nong type tektites I: Fluorine and bromine (abstract). *Lunar Planet. Sci.* **15**, 445-446.
- KOEBERL C., BERNER R. AND KLUGER F. (1984c) Geochemistry of Muong Nong type tektites II: Lithium, beryllium, and boron (abstract). *Lunar Planet. Sci.* **15**, 441-442.
- KOEBERL C., KLUGER F. AND KIESL W. (1984d) Geochemistry of Muong Nong type tektites IV: Selected trace element correlations. *Proc. Lunar Planet. Sci. Conf.*, **15th**, C351-C357.
- KOEBERL C., KLUGER F. AND KIESL W. (1985) Rare earth element abundances in some impact glasses and tektites and potential parent materials. *Chem. Erde* **44**, 107-121.
- KOEBERL C., BOTTOMLEY R. J., GLASS B. P., STORZER D. AND YORK D. (1989) Geochemistry and age of Ivory Coast tektites. *Meteoritics* **24**, 287.
- MATTHIES D. AND TROLL G. (1990) Distribution of fluorine in recent marine sediments related to petrographic composition: Bransfield Strait and Northwestern Weddell Sea, Antarctica. *Marine Geology* **91**, 313-324.
- MATTHIES D., SAUERER A. AND KOEBERL C. (1989) Volatile element geochemistry of target rocks and impact glasses at the Zhamanshin crater (USSR) and other impact craters. *Meteoritics* **24**, 300.
- MEISEL T., KOEBERL C. AND FORD R. J. (1990) Geochemistry of Darwin impact glass and target rocks. *Geochim. Cosmochim. Acta* **54**, 1463-1474.
- MEYER C. (1978) Ion microprobe analyses of aluminous lunar glasses: A test of the "rock type" hypothesis. *Proc. Lunar Planet. Sci. Conf.* **9th**, 1551-1570.
- MEYER C., MCKAY D. S., ANDERSON D. H. AND BUTLER P. (1975) The source of sublimates on the Apollo 15 green and Apollo 17 orange glass samples. *Proc. Lunar Sci. Conf.* **6th**, 1673-1699.
- MILLS A. A. (1968) Boron in tektites. In: *Origin and Distribution of the Elements* (ed. L. H. Ahrens), pp. 521-531. Pergamon Press, New York.
- MOORE C. B., CANEPA J. A. AND LEWIS C. F. (1984) Volatile non-metallic elements in tektites. *J. Non-cryst. Solids* **67**, 345-348.
- PREUSS E. (1935) Spektralanalytische Untersuchung der Tektite. *Chem. Erde* **9**, 365-416.
- SAUERER A. (1986) Bor in Gesteinen, Mineralen und Verwitterungsprodukten des Bayerischen Waldes. Ph.D. thesis, Univ. Munich. 137 pp.
- TAYLOR S. R. AND KAYE M. (1969) Genetic significance of the chemical composition of tektites: A review. *Geochim. Cosmochim. Acta* **33**, 1083-1100.
- WÄNKE H., PALME H., BADDENHAUSEN H., DREIBUS G., JAGOUTZ E., KRUSE H., PALME C., SPETTEL B., TESCHKE F. AND THACKER R. (1975) New data on the chemistry of lunar samples: Primary matter in the lunar highlands and the bulk composition of the moon. *Proc. Lunar Sci. Conf.* **6th**, 1313-1340.
- WEDEPOHL K. H. (1978) *Handbook of Geochemistry, Vol. II-1*. Springer-Verlag.
- WEINKE H. H. AND KOEBERL C. (1985) Trace elements in two bediasite tektites. *Meteoritics* **20**, 783.