THE ORIGIN OF TEKTITES: A GEOCHEMICAL DISCUSSION

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Abstract: Tektites are a group of natural glasses occurring in four different strewn fields on earth. They are generally small, brownish to black, partly transparent, spherically symmetric, and sometimes aerodynamically ablated. Strewn fields are geographically restricted areas on earth where tektites are found, usually in association with microtektites. Microtektites are spherules of up to about 1 mm in diameter and are retrieved from deep sea sediments. Recently microtektites have been found to co-occur with tektite fragments. Besides chemical, isotopical, and age arguments this gives final proof for a genetic relationship between tektites and microtektites. Chemically tektites are Si-rich glasses (SiO_2 between 65 and 85 wt%), not unlike some well known terrestrial impact glasses. The major element chemistry allows the distinction of tektites of different strewn fields, and the use of some geochemical diagrams allows the further distinction between different sub-strewn fields. Within one strewn field, we can distinguish between splash-form tektites (normal tektites) and so called Muong Nong tektites, which differ from normal tektites in respect to a higher volatile content and greater inhomogeneity, besides being of generally larger size. The trace element chemistry reveals a close similarity of tektites to terrestrial rocks, especially to surface sediments. No similarity with lunar rocks or terrestrial mantle derived rocks can be observed. Trace element ratios and rare earth element patterns are especially useful in further delineating the type of precursor rocks for tektite production. The study of isotopes, like Rb/Sr, Sm/Nd, or the lead isotopes, adds further credibility to the connection between tektites and upper crustal sediments. For two of the four strewn fields a clear connection, based on chemical, isotopical, and age considerations, between tektites and impact craters, has been established. This is the Ries crater and moldavite and the Bosumtwi crater and Ivory Coast tektite connection. The consideration of various theories of tektite origin in view of the known facts leads to the conclusion that only the production of tektites during an impact on earth is consistent with the data. Analogous studies of impact glasses associated with terrestrial impact craters (like the Zhamanshin crater) give a picture which is in accordance with the impact model for tektites. Some of these glasses show an enrichment of the platinum group and other cosmic fingerprint elements compared to the terrestrial sedimentary background, these elements being the only ones from the impacting body which may survive the impact. Tektite analyses point in the same direction, and it may be possible to get further clues on the nature of the projectile by studying these elements.

1. Introduction

Tektites are small pieces of natural glass, usually up to a few cm in size. The name has been created by Suess (1900) from the greek τήκτοσ, meaning molten. Tektites usually have no direct relationship with the bedrocks in which they are found. Their color ranges from gray or brown to black, some varieties are even green. This applies

for transmittent light, while in reflecting light they appear blackish. In thin section they are of homogeneous structure, and do not readily show any inclusions. When viewed in polarizing light, they reveal the presence of schlieren and often show indications of stress. Tektites can be divided in two major groups, microtektites, and tektites. Microtektites are small, usually less than 1 mm in diameter, and mostly spherical. They are found in deep sea sediments at specific layers. Tektites, usually found on land, can be divided in three subgroups. Splash-form tektites and aerodynamically ablated tektites (flanged buttons) together constitute the normal tektites and are sometimes only referred to as the splash-form tektites because of the common first phase of origin. The third variety is called Muong Nong type. Splash-form tektites (Fig. 1) form the majority of all known tektites. They occur in a variety of different forms, including spheres, droplets, dumbbells, etc. and distorted or fragmented versions of the above-mentioned shapes. These tektites show forms which occur by formation out of rotating or moving melts by cooling and solidification. Flanged buttons, on the other hand, have a core and are surrounded by concentric rings (ringwaves), which extend on one side of the button. These tektites show aerodynamic ablation (which is rarely shown by any other tektite variety) and occur in Australia. The aerodynamic ablation results from secondary heating and melting of already molten and solidified glasses during atmospheric passage.

Muong Nong type tektites are named after a locality on Laos in Indochina and are known as a subgroup of Indochina tektites. Their occurrence at other localities than Indochina has not yet been demonstrated in a convincing way. They are of irregular shape and of blocky, chunky appearance, and are generally much larger than normal tektites (up to several kg in weight). In addition, they are rather inhomogeneous and show layers of different color and chemistry (KOEBERL, 1985). They contain many relatively large bubbles with gas inclusions (JESSBERGER and GENTNER, 1972) and have crystalline inclusions like corundum, quartz, cristobalite, zircon, and chromite (GLASS and
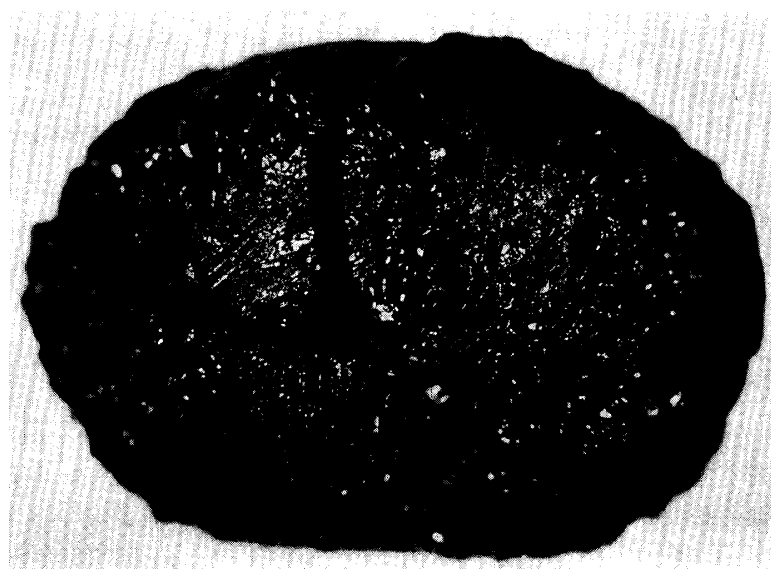

Fig. 1.   Splash-form philippinite (119 g, Natural History Museum, Vienna) showing the typical spherical form and surface features of tektites.

BARLOW, 1979). These inclusions are unique to Muong Nong types and do not occur in other tektite varieties. An important feature of Muong Nong tektites is their enrichment in volatile elements compared to splash form tektites. Elements like the halogens, boron, zinc, antimony, and others are enriched by considerable factors (MÜLLER and GENTNER, 1973; KOEBERL, 1986a).

Another important feature of tektites is their geographical distribution. They occur on earth in geographically restricted areas called strewn fields. At present four such strewn fields are known: the North American, the Czechoslovakian, the Ivory Coast, and the Australasian strewn fields (arranged in order of decreasing age). The Australasian strewn field is the largest, and the Ivory Coast and the Czechoslovakian strewn fields are the smallest. With the exception of the Czechoslovakian strewn field, all strewn fields are determined in size by using the microtektite distribution. The Australasian strewn field includes Indochina, the Philippines, Indonesia and Australia. In all these locations tektites have been found on land, but the overall extension of the strewn field was determined by the occurrence of microtektites found in deep sea sediments in that whole area. So far microtektites have only been found in deep sea sediments, and this may explain why the Czechoslovakian strewn field, which is completely surrounded by land, does not have microtektites. Some of the strewn fields may be subdivided in sub-strewn fields, and tektites from these sub-strewn fields carry different names. The Czechoslovakian tektites are generally called moldavites, and the two sub-strewn fields are named Moravian and Bohemian, after the geographical location. In the Australasian strewn field, there are varieties known as indochinites, australites, philippinites, etc., while the North American strewn field may be divided in bediasites (from Texas) and georgiaites (from Georgia), although recently some tektites have been recovered from other areas of the North American strewn field as well. These tektites found at Barbados and in drill cores will be mentioned later.

2. History

Tektites, as all natural glasses like obsidian, have attracted humans since a very long time. In the Austrian settlements of pre-stone age periods, moldavites have been used presumably for cultic purposes, and in Australia and the Philippines, tools are known to have been manufactured from tektite glass by man at a time of about 5000 B.C. In these times and later on, tektites have been subject to trade amongst tribes and cultures, not unlike obsidian (which was of immense importance to delineate the trade routes of early cultures). A good outline of the early use and the first descriptions of tektites as well as a history of the first theories of tektite origin is given by O'KEEFE (1976). The first scientific investigations led to the classification of tektites as obsidians, and thus of volcanic origin. Late in the last century, the idea was born that tektites are some kind of a meteorite. The features shown by some australites (the flanged buttons) were regarded as being the result of aerodynamic ablation. SUESS (1900) was convinced that tektites are of extraterrestrial origin and attributed most of the surface features of tektites to aerodynamic ablation after having studied tektite analogs in a crude version of a wind tunnel; a theory which we now know is not true, since only certain australites show the typical aerodynamic ablation features. At the same time,

a vigorous discussion was going on in Europe about whether to regard tektites as being of natural origin at all. The occurrence of moldavites in the center of an old glass making area in central Europe gave rise to the suggestion that moldavites have an artifical origin. Proponents of the natural glass hypothesis pointed out, however, that artifical glass may be distinguished from natural glass by a much lower Al_2O_3 and a higher alkali content, and a different viscosity. BERWERTH in 1917 pointed out that tektites have chemistry similar to sandstones, and proposed that they have been produced by an ancient culture by melting sandstones. After that time, no serious suggestion that tektites are artifical has been made any more, and the natural origin was generally accepted.

The acceptance of the natural origin of tektites, however, did not end the scientific debate, because now the process of tektite formation by natural means has to be agreed upon. Early investigators claimed that tektites are not considerably different from obsidian. An early suggestion by VERBEEK (1897) was the origin of tektites from lunar volcanoes, which would spit their analogues of obsidian material to the earth. Another idea was put forward by DUNN around 1911: that tektites formed from dust in a volcanic eruption after melting by lightning. The idea was later presented by others in a different form, starting with windblown dust. The 1920s and 1930s saw all kinds of fantastic theories, ranging from the production during the collision of meteorites with some unknown natural earth satellites over drying out and hardening of siliceous gels to the origin from melt ablation of large stony meteorites. The well known tektite and meteorite investigator A. LACROIX elaborated on an earlier theory that tektites are the product of the burn-up of light metal meteorites from a hypothetical parent body in the terrestrial atmosphere.

A suspected meteorite impact crater in Arabia and the glass found there led L. SPENCER to the theory that tektites have an analogous origin, namely being produced by a meteorite impact. Others objected to that view because the Wabar glasses are slaggy, inhomogeneous, and generally unlike tektites. SPENCER, on the other hand, tried to reinforce his view by the description of impact glass from the Henbury crater in Australia, which he stated to be more like tektites. The German researcher PREUSS found in 1935 after extensive chemical studies, that tektites, in respect of trace element chemistry, are much like terrestrial sedimentary rocks and suggested that they originated from these rocks after a strong heating period. This was interpreted as being in favor of the impact idea. Another type of impact idea was put forward by the renowned meteoriticist H. NININGER. He suggested that tektites originated by meteorite impacts on the moon, where material is molten and reaches the lunar escape velocity, and some debris presumably reaches the earth. Amongst other ideas for tektite origin at this time was the suggestion that they are fulgurites (glass which is produced by lightning striking the earth's surface) or that they are produced by the fall of antimatter.

During the 1950s and 1960s intensive research on tektites led to the elimination of most of the more obscure theories, leaving only two or three better formulated ideas, namely the origin on earth during meteorite impact, and the origin on the moon either from lunar volcanoes or also from impact. Geochemical arguments, especially from the studies performed by S. R. TAYLOR and co-workers, and early analyses of lunar

material more and more favored the terrestrial impact theory. In the course of the following paragraphs we will try to follow the arguments which today led to an almost general acceptance of this model.

3. Chemical Characteristics

3.1. Major element chemistry

A close examination of the major element chemistry of tektites leads to the conclusion that they are different from all other natural glass except some impact glasses (glass found to be directly associated with meteorite impact craters). As a group they are characterized by high silica content, ranging from approximately 65 to 85 wt%, and higher iron, but lower alkali content than igneous rocks of comparable silica content. The K_2O content is usually larger than the Na_2O content. The ratio $(FeO + MgO)/(Na_2O + K_2O)$ can be used to discriminate tektites from igneous rocks. Most tektites (like impact glasses) show an inverse variation of SiO_2 vs. other main constituents, like Al_2O_3, FeO, or TiO_2 or sums or ratios of them. Figure 2 gives the inverse relation between SiO_2 and Al_2O_3 for different tektites, while Fig. 3 shows the relationship between SiO_2 and the sum of FeO+MgO. Another valuable diagram is the plot of SiO_2 vs. the ratio $(FeO + MgO + CaO)/(K_2O + Na_2O)$, given in Fig. 4. Other main constituents sometimes exhibit significant correlations, an example being the positive correlation between TiO_2 and Al_2O_3, shown in Fig. 5.

These diagrams very often allow the distinction between tektites from different strewn fields. The chemistry of australites and bediasites, for example, is different enough to show up in these plots or even in tables. We have mentioned earlier that most strewn fields can be subdivided in sub-strewn fields, and the chemical distinction between tektites in sub-strewn fields is not as easy as between tektites of different fields. Table 1 gives the ranges of tektite compositions encountered among different varieties of tektites, divided in major and sub-strewn fields. It is clearly visible that there is
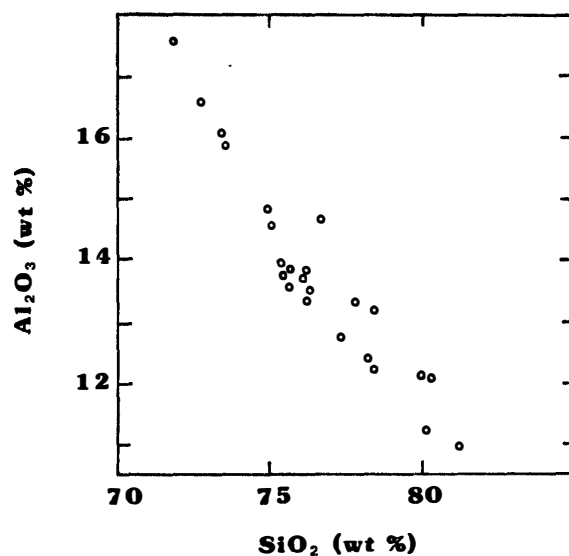

Fig. 2. Correlation diagram (Harker diagram) for the relationship SiO_2 vs. Al_2O_3 for bediasites. Data from CHAO (1963).
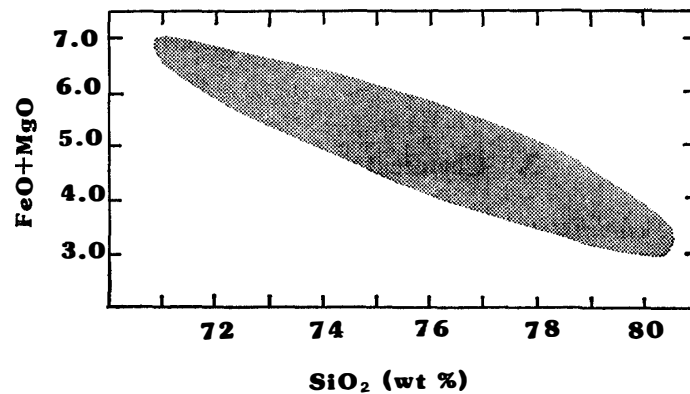
Fig. 3. Inverse correlation between the SiO₂ content and the sum
FeO+MgO. The shaded represents data for australites
and bediasites. After CHAO (1963).

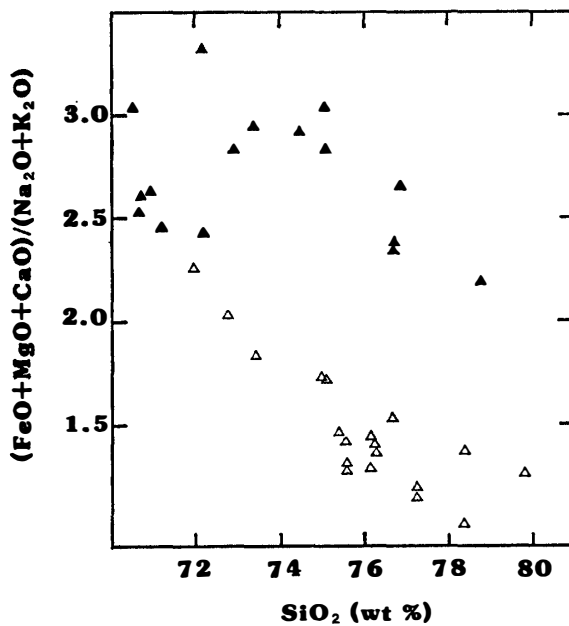Fig. 4. Inverse correlation between the silica
content and the sum FeO + MgO
+CaO/Na₂O+K₂O. Open triangles
represent bediasites, full triangles rep-
resent australites. After CHAO (1963).
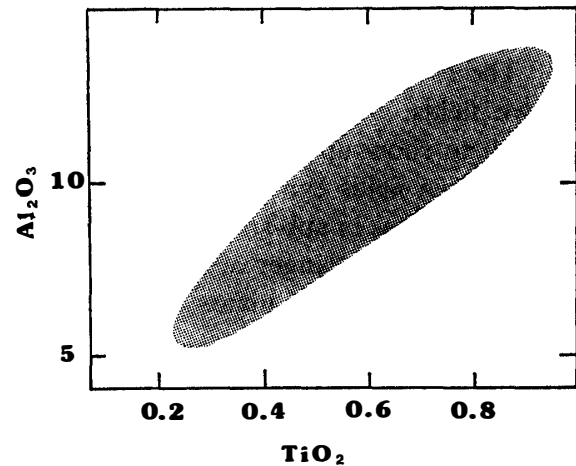
Fig. 5. Positive correlation between Al₂O₃ and
TiO₂. The shaded area represents the
field occupied by tektites. Data from
various sources (see e.g., KOEBERL,
1986b). Data in wt%.

an enormous variation in tektite chemistry, but also that some chemical features allow
the distinction between the groups. Ivory Coast tektites, for example, are distinguished
from other groups by having a K_2O/Na_2O ratio around unity, while that ratio for
other groups is usually significantly larger. The sodium-potassium ratio is, on the
other hand, useful for a distinction between tektites of different subgroups, like be-
diasites and georgiaites. Figure 6 gives a K_2O-Na_2O plot for these two tektite groups,
and it is clearly visible that they do not overlap. Thus a specimen can be ascribed as

Table 1.   *Ranges of major element composition in tektites from different strewn fields. All data in wt%. After* KOEBERL *(1986b). The numbers in paratheses indicate the number of analyses used for the range. All Fe as FeO.*

	Australasian tektites						
	Normal australites (3)	Normal philippinites (2)	Normal indochinites (2)	HAlaustralites (3)	LCaHAlphilippinites (5)	HCaautsralites (5)	HCaphilippinites (5)
SiO$_2$	70.4–72.4	71.2–71.6	72.9–73.3	66.9–68.5	67.2–69.2	68.9–79.7	68.6–74.9
Al$_2$O$_3$	12.9–14.3	13.0–13.4	13.1–13.5	15.4–16.1	15.2–17.7	9.3 –14.3	8.9 –11.0
FeO	4.67–4.97	4.55–5.12	4.47–4.49	5.27–5.43	4.87–5.87	3.57–4.75	3.87–4.55
MgO	2.16–2.23	2.33–2.42	2.00–2.04	2.44–2.60	2.45–3.15	1.31–2.53	1.87–2.43
CaO	2.94–3.48	3.31–3.34	2.17–2.41	3.18–3.83	1.37–2.37	1.83–5.48	4.34–9.77
K$_2$O	2.41–2.62	2.33–2.47	2.36–2.40	2.37–2.57	2.33–2.81	2.14–2.21	1.77–2.33
Na$_2$O	1.32–1.56	1.31–1.50	1.17–1.27	1.04–1.27	0.97–1.18	1.00–1.24	0.91–1.28
TiO$_2$	0.80–0.83	0.78–0.82	0.72–0.89	0.87–0.93	0.85–1.00	0.49–0.81	0.50–0.63

	Australasian tektites	North American tektites		Czechoslovakian tektites		
	HMgtektites (10)	Georgia tektites (9)	Bediasites (21)	Bohemia (61)	Moravia (21)	Ivory Coast tektites (15)
SiO$_2$	64.8–77.0	79.8–83.6	71.9–80.2	75.5–85.1	74.9–81.4	67.0–69.3
Al$_2$O$_3$	10.7–13.3	9.50–11.7	11.2–17.6	7.32–11.4	9.44–13.8	15.8–17.1
FeO	3.85–8.63	1.83–3.14	2.29–5.75	1.08–2.93	1.72–3.50	6.03–6.80
MgO	1.83–7.95	0.37–0.69	0.37–0.95	1.34–2.74	1.13–2.06	2.64–3.93
CaO	1.79–3.73	0.40–0.69	0.49–0.96	1.21–2.96	0.95–3.17	0.71–1.61
K$_2$O	1.34–2.56	1.00–1.53	1.20–1.84	0.20–0.89	0.40–1.08	1.54–2.44
Na$_2$O	0.62–1.38	2.22–2.51	1.60–2.43	2.23–3.81	2.83–3.81	1.70–2.07
TiO$_2$	0.66–0.77	0.42–0.60	0.59–1.05	0.24–0.74	0.31–1.40	0.52–0.60

belonging to one of the two sub-fields on the basis of the Na$_2$O/K$_2$O plot. The question of the origin or history of specimens found outside of the traditional boundaries of the substrewn-fields may be addressed using such plots. An interesting example is the case of the Cuban tektite, which allegedly was found in Cuba, according to a scrap of paper found with the specimen at the collection of Columbia University. The specimen is definitely a tektite and its composition and age indicate that it is a North American tektite (GARLICK *et al.*, 1971); however, the finder of the tektite could not be located and therefore the place it was found could not be determined in detail. In the sodium-potassium diagram, the Cuban tektite plots between the two fields determined by the georgiaites and the bediasites, and thus there seems to be an indication that this specimen may in fact not belong to any of these subgroups, creating an own occurrence field. Another tektite was found in Massachusetts, at Martha's Vineyard, and it has also been identified as a North American tektite (KAYE *et al.*, 1961). The location in Massachusetts is distant from any other location of tektites in the North American field, and thus it would be of interest if the tektite was really recovered from the spot where it originally fell. In the sodium-potassium diagram, the tektite from Martha's Vineyard plots within the georgiaite field, and does not form a separate group. Recently
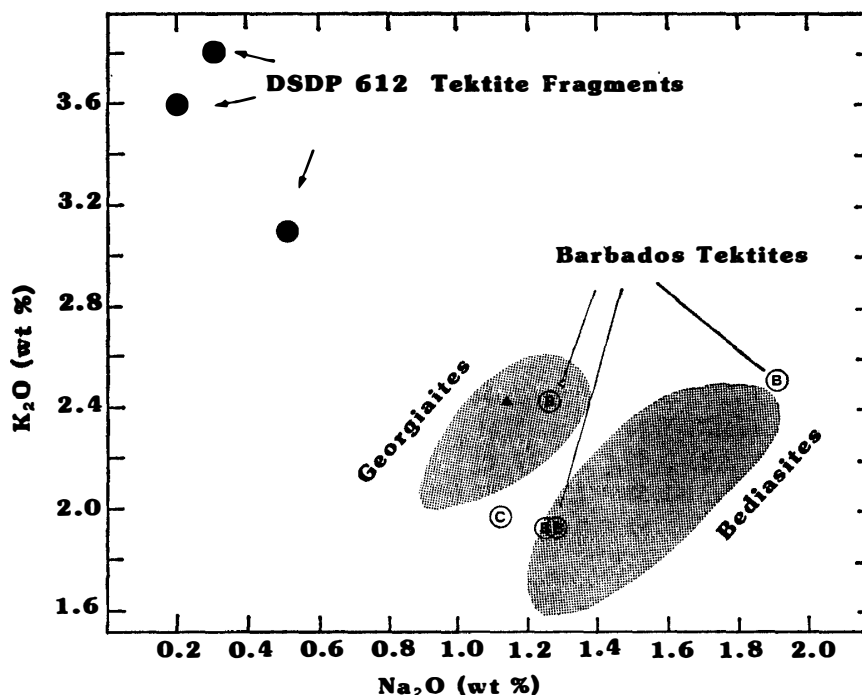
Fig. 6. Sodium-potassium diagram for tektites from the North American strewn field (*after* KING, *1968*). Bediasites and georgiaites occupy different areas in the diagram, which do not overlap. The triangle represents the tektite from Martha's Vineyard which falls in the Georgia tektite field. C denotes the Cuban tektite, which does not plot within any of the two main fields. The recently discovered tektites from Barbados are scattered over the whole bediasite/georgiaite area, while the DSDP 612 tektites plot into a completely different area of the diagram (*data from* KOEBERL *and* GLASS, *1988*). It seems as if there is an inverse correlation of K_2O vs. Na_2O over the whole strewn field.

new tektite specimens have been discovered outside the boundaries of the classical sub-strewn fields in North America. Usually the boundaries of the whole North American field have been determined using occurrences of microtektites recovered from deep sea sediments (from drill cores). Also in the past tektites and microtektites have not been found within one drill core. One reason may be the small statistical chance to accidently hit a tektite resting on the seafloor, while microtektites are spread out in layers. But with the discovery of microtektites and tektite fragments in the same deep sea sediment layer at Barbados (on land!) the situation has changed dramatically (GLASS *et al.*, 1984; SANFILIPPO *et al.*, 1985). For the first time a real physical connection between microtektites and tektites has been demonstrated, a connection which previously was only inferred from chemistry, age, and isotopic considerations. Now it has been shown that all the conclusions drawn on this basis are valid. More recently a layer of tektite fragments and microtektites, probably associated with impact ejecta, has been found in late Eocene sediments from Deep Sea Drilling Project (DSDP) Site 612 on the continental slope off New Jersey (THEIN, 1987; KELLER *et al.*, 1987). The composition and the age of this tektite debris suggest that it also belongs to the North American strewn field (KELLER *et al.*, 1987; KOEBERL and GLASS, 1986, 1988).

In the sodium-potassium diagram, these newly found tektites plot in an interesting area. First, the Barbados tektites and the DSDP 612 tektites can easily be identified in the plot. Second, the Barbados tektites plot very close to the bediasite field. And third, the DSDP 612 tektites occupy a completely different part of the diagram, which is mainly due to their extremely low sodium contents. The sodium content of these tektites is much lower than the average value for the other North American tektites. Table 2 gives some analyses of Barbados and DSDP 612 tektites, and some comparison data. Bediasites and georgiaites rarely have K_2O contents >2.6 wt%. The tektite fragments from DSDP 612, however, generally have K_2O contents >2.6 wt%. Together with the low sodium this results in very high K_2O/Na_2O ratios (>5). Compared with the two main tektite groups, the DSDP 612 tektites have sodium-potassium ratios which are closer to georgiaites than to bediasites. Together with other arguments (trace elements, isotopes) this leads to the conclusion that there are other sub-strewn fields present in the North American field, and that the extension of the strewn field is really as large as inferred from the microtektite distributions.

An examination of the same plot (or of the sodium-potassium ratios) for tektites from the Czechoslovakian strewn field leads to the conclusion that Moravian and

Table 2.   Major element analyses for tektite fragments recovered from Barbados and DSDP Site 612, together with comparison data for bediasites, georgiaites, and the tektites from Cuba and Martha's Vineyard. The numbers given in parentheses represent the number of specimens used to give the range or calculate an average. All data in wt%. After KOEBERL and GLASS (1988).

	Barbados				DSDP Site 612	
	Tektite fragments				Tektite fragments	
	Selected analyses			Range (18)	Selected analyses	
SiO₂	77.4	79.5	82.0	76.9 –85.6	72.3	74.2
Al₂O₃	13.5	12.1	10.3	7.97–14.8	15.1	14.0
FeO*	3.98	3.45	2.48	1.37– 3.98	4.8	4.5
MgO	0.64	0.58	0.48	0.13– 1.13	1.2	1.1
CaO	0.54	0.57	0.65	0.52– 0.87	0.85	0.9
Na₂O	1.26	1.29	1.23	1.15– 1.52	0.3	0.2
K₂O	1.94	1.93	2.42	1.73– 2.54	3.8	3.6
TiO₂	0.71	0.59	0.41	0.40– 0.71	0.85	0.77

	DSDP Site 612		Average bediasite (21)	Average georgiaite (8)	Martha's Vineyard tektite	Cuban tektite
	Tektite fragments					
	Selected analyses	Range (8)				
SiO₂	77.6	71.9 –77.8	76.37	81.5	80.5	74.8
Al₂O₃	13.1	13.0 –15.1	13.78	10.71	11.2	15.
FeO*	2.8	2.7 – 5.0	3.98	2.50	2.69	4.4
MgO	0.7	0.7 – 1.4	0.63	0.55	0.69	0.7
CaO	1.0	0.8 – 1.0	0.65	0.51	0.69	1.2
Na₂O	0.5	0.2 – 0.6	1.54	1.19	1.00	1.1
K₂O	3.1	3.0 – 3.8	2.08	2.39	2.37	2.0
TiO₂	0.56	0.55– 0.85	0.76	0.49	0.53	0.8

* All Fe as FeO.

Bohemian tektites cannot be distinguished on the basis of their sodium-potassium ratio, which is in both cases close to 0.15. Thus it is evident that the same method cannot be used for all tektite fields in the same way. For the moldavites another method has proven to be useful, namely the use of oxide ratio plots. These plots allow the distinction between different sub-fields (see Fig. 7) and have been used to gain information about the precursor rocks of the moldavites (DELANO and LINDSLEY, 1982). The interpretation of the trend, on which both tektites groups seem to plot, as a mixing line, has, however, to be taken with care. Strictly speaking, the method would work only if there is no correlation between the elements plotted against each other, like Al and Ti, or Mg and Ca. Since we have seen earlier that especially the correlation between Ti and Al is very good, the results given by DELANO and LINDSLEY (1982) for the composition of the precursor material have to be viewed with extreme care. But the fact that some kind of a mixing trend is also visible in plots of non-correlated elements (upper part of Fig. 7), although in a much fuzzier way, gives some evidence for the presence of a real effect. Quantitative conclusions, however, seem not to be possible at this time. The plots are useful, on the other hand, for the assignment of a specimen of unknown origin to a certain subgroup. KOEBERL (1986c) has used these plots, amongst other data, for showing that a moldavite specimen found far from the original strewn field in Styria (Austria) is in fact a dislocated Bohemian tektite. The dislocation was probably due to prehistoric trade.

If the same kind of plot is used for other tektite fields, like the Australasian tektites,
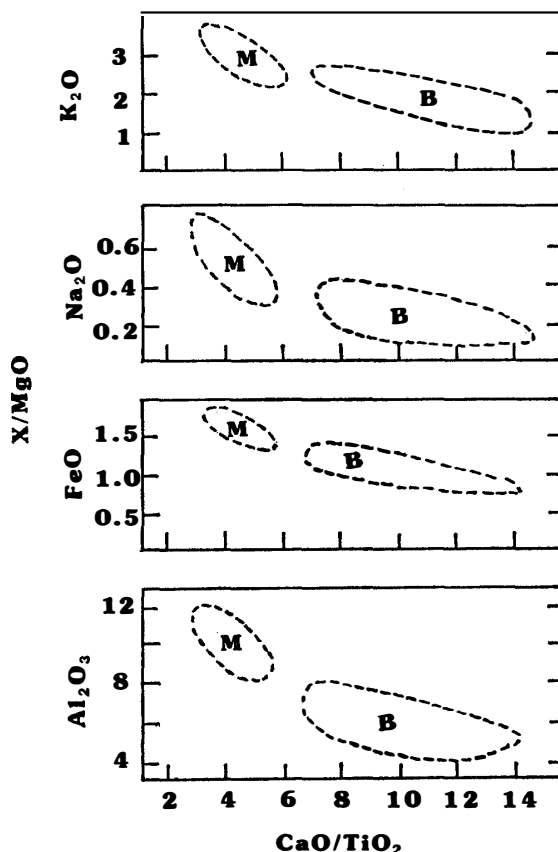

Fig. 7. Oxide ratio plot for moldavites (after DELANO and LINDSLEY, 1982). The Bohemian (B) and the Moravian (M) subgroups of the moldavites plot in different parts of the diagrams.

they grow more complex. DELANO *et al.* (1982) used this approach and demonstrated that there is not a consistent or bimodal mixing trend, as it seems to be for moldavites. All the tektite groups show different trends. The problem is complicated by the fact that DELANO *et al.* (1982) used mainly the Al_2O_3/MgO *vs.* CaO/TiO_2 plot to draw their conclusions, and again the correlation problem arises. Based on other ratios, with non-correlated elements, it is possible to show different group trends, like for the HCa philippinites and the HCa australites, which vary from group to group. This may be indicative of the incorporation of various amounts of several different precursor materials. One component (probably shale) seems to be the same in all tektite groups. It is most interesting to construct such diagrams also for major *vs.* trace elements, especially if plotting volatiles against lithophile refractories.

3.2. Microtektites

Microtektites are microscopic tektites with diameters of generally less than 1 mm which are found in deep sea sediments. They have been identified as tektite-like material based on their chemistry, shape, petrographic characteristics, isotopic signature, and age. Their association with the known tektite strewn fields is based on the geographical location as well as on other characteristics, as mentioned above. Microtektites have been recovered from deep-sea sediment cores from throughout the Indian Ocean, the Pacific Ocean (western part), and the Philippine Sea, and thus belong to the Australasian strewn field. Ivory Coast microtektites have been found in the eastern equatorial Atlantic Ocean mainly south and southwest of the tektite localities on land. North American microtektites have been found in the Caribbean Sea, the Gulf of Mexico, and along the east coast of the U.S. So far no microtektites have been reported from the Czechoslovakian strewn field, although some authors have suggested that bentonites may be corroded microtektites (STORZER and GENTNER, 1970). However, GRAUP *et al.* (1981) have shown that bentonites are not associated with the moldavite strewn field.

The fact that microtektites have not been found on land (in surface deposits other than deep sea sediments) may be due to several reasons. Microtektites would be hard to find on land because of their small size. Also, no systematic search for microtektites on land has so far been undertaken. Tektites and microtektites on land would most probably be separated by various transport mechanisms, since tektites are usually not found in the places where they fell. Tektites are found in much younger terrestrial sediments than what is indicated by their radiogenic age of formation, indicating that tektites are (naturally) transported. In addition, microtektites would most probably not survive under land conditions because of etching and solution effects, which have been shown to take place for tektites.

Some of the microtektite layers are associated with other terrestrial effects. The Australasian microtektite layer is associated with the Brunhes-Matuyama reversal of the earth's geomagnetic field, while the Ivory Coast microtektites are associated with the Jaramillo event (GLASS *et al.*, 1979). The North American microtektite layer has so far not been tied to any geomagnetic event, but is closely associated with the Eocene-Oligocene boundary (GLASS *et al.*, 1979), which is in turn associated with an iridium anomaly and a layer of clinopyroxene spherules (KELLER *et al.*, 1987; D'HONDT *et al.*, 1987). The association between the microtektite layer and the clinopyroxene layer is

still in question (KELLER *et al.*, 1987; GLASS, 1987). The Ir anomaly does not occur in the same layer as the microtektites, but shows a slight offset, thus we cannot be certain about a physical connection between the iridium anomaly (the "Eocene-Oligocene-event") and the microtektite forming event.

The presence of a worldwide strewn field of spheres associated with the Cretaceous-Tertiary boundary event has been shown by SMIT and ROMEIN (1985). They used the term microtektites in connection with these spherules to indicate possible similarities between the microtektites found in the known tektite strewn fields and these materials. This would also include a reference to the alleged impact origin of the spherules. Later investigations have shown that these spherules are hollow, variable in composition, and often replaced by secondary minerals, following the metastable glass. Thus the term microtektites should not be applied for these K-T spherules. A model for the origin of the K-T spherules not using an impact glass-like scenario but a scenario similar to flyash condensation in volcanic-like clouds was proposed by BOHOR and TRIPLEHORN

Table 3. Major element data for microtektites from the Australasian field.
All data in wt% and all Fe as FeO.

	Selected analyses							Range	Average	Bottle-green microtektites selected analyses			high ave.	low ave.
SiO$_2$	67.9	67.1	72.1	64.2	62.6	59.2	75.9	49.6–77.0	72.0	59.7	48.1	61.0	74.2	68.6 50.5
A$_2$lO$_3$	15.2	15.4	13.8	11.0	19.3	22.1	7.5	7.5–22.1	13.6	11.7	11.3	16.3	10.5	12.6 16.7
FeO	5.7	5.4	4.7	9.6	5.3	3.5	5.4	3.0– 8.1	4.9	7.7	5.5	4.73	3.79	6.00 4.53
MgO	2.7	4.0	2.3	7.2	3.1	5.8	3.4	1.9–17.1	2.4	14.6	27.3	11.4	3.47	6.94 20.7
CaO	2.9	2.6	2.4	3.3	2.2	4.5	1.4	1.0– 5.8	3.6	3.9	5.3	3.16	1.35	2.55 4.81
Na$_2$O	1.7	1.2	1.2	1.8	1.3	0.7	1.7	0.2– 2.8	1.9	1.2	0.5	0.28	0.73	0.59 0.05
K$_2$O	3.2	2.7	3.0	1.5	3.1	0.3	2.6	0.1– 3.7	0.6	0.6	0.1	0.41	2.11	1.21 0.04
TiO$_2$	0.8	0.9	0.8	0.6	1.0	—	0.5	0.5– 1.0	0.8	0.7	—	1.06	0.70	0.80 0.86

Data sources: CASSIDY *et al.* (1969); GLASS (1972, 1982). In the bottle-green microtektite columns the terms high and low average denote two different groups of bottle-green microtektites (one with SiO$_2$ between 48 and 54%, and the other one with SiO$_2$ between 65 and 74%, low and high thus referring to the SiO$_2$ content).

Table 4. Major element data for microtektites from the North American strewn field.
All data in wt% and all Fe as FeO.

	Selected analyses						Range	Average	Selected analyses Barbados microtekt.			DSDP 612 microtekt.		
SiO$_2$	75.7	73.0	71.1	67.9	65.7	64.4	64.4–75.9	70.7	79.5	79.1	77.4	71.4	73.4	75.4
Al$_2$O$_3$	13.1	14.1	14.6	16.0	17.5	16.7	13.1–17.5	15.4	12.5	12.1	12.9	15.4	14.5	13.2
FeO	3.83	4.67	4.62	6.64	6.40	6.79	2.73–6.79	5.00	2.35	2.42	3.02	5.18	5.00	4.19
MgO	0.82	1.06	2.05	2.30	1.92	2.87	0.78–2.87	1.77	0.74	0.92	0.80	1.15	1.14	1.02
CaO	1.01	1.22	2.07	1.68	1.24	2.49	0.92–2.49	1.61	0.79	0.74	0.75	1.13	0.74	0.99
Na$_2$O	0.77	0.75	1.04	1.31	1.49	1.48	0.63–1.52	1.05	1.17	1.24	1.23	1.47	0.57	0.78
K$_2$O	2.72	2.57	2.85	3.81	3.96	3.70	2.16–3.96	3.02	2.49	2.71	2.73	2.95	3.61	3.02
TiO$_2$	0.62	0.78	0.86	0.86	0.99	0.90	0.52–0.99	0.80	0.62	0.43	0.69	0.87	1.01	0.71

Data sources: GLASS *et al.* (1973) and KOEBERL and GLASS (1988).

(1987) and BOHOR (1987). Thus, so far no real microtektites or tektites have been found to be associated with the K-T boundary.

The chemistry of microtektites is very similar to the chemistry of tektites in the adjacent strewn fields. However, microtektites from each strewn field have compositions extending to much lower SiO_2 contents than tektites from the same strewn field. Some microtektites have SiO_2 abundances of even less than 50 wt%. Usually microtektites of such a low silica content belong to the enigmatic group of bottle-green microtektites, which are transparent, pale green, and very often badly corroded. One interesting characteristic of these bottle-green microtektites is their high MgO content, ranging up to 24 wt%. There have been numerous major element studies of microtektites from all strewn fields, and some characteristic results are given in Table 3, for microtektites from the Australasian strewn field. Table 4 gives major element analyses for microtektites from the North American strewn field, including data on the newly discovered microtektites from Barbados and DSDP Site 612. The microtektites (as well as the tektite fragments, Fig. 8) from Barbados and DSDP Site 612 have generally major oxide compositions similar to North American tektites and microtektites. Like them they have rather low CaO and MgO contents. The tektite fragments from Barbados are relatively rich in silica and thus similar to the tektites from Georgia, while the microtektites have a much wider range in composition which overlaps with bediasites as well as with Georgia tektites. The DSDP 612 samples have a lower SiO_2 content than the Barbados samples, but the microtektites do not have as low Na_2O contents at the tektite fragments (cf. Table 2). Their overall chemical composition is more closely related to other microtektites from the same strewn field than the composition of the

Fig. 8.   Tektite fragment recovered from DSDP Site 612 off the coast of New Jersey, on the continental slope, weighing about 30 mg. Numerous fragments have been found in a layer also containing microtektites and impact ejecta (shocked quartz and other shocked materials). They belong to the North American strewn field.

Table 5.   Major element data for microtektites from the Ivory Coast strewn field.
All data in wt % and all Fe as FeO.

	Selected analyses					Range	Aver-age	Bottle-green microtektites selected analyzes				average
SiO_2	66.2	64.2	67.4	62.4	68.2	62.4 –68.2	64.7	48.6	51.4	53.1	53.6	51.8
Al_2O_3	15.0	14.0	15.1	15.5	16.1	12.8 –17.3	15.1	20.3	16.0	14.1	14.9	15.7
FeO	6.2	6.8	6.0	8.7	7.9	5.70– 8.61	6.9	9.45	10.5	10.1	9.83	9.53
MgO	4.3	5.4	3.7	7.7	2.0	2.01– 7.69	6.3	16.9	20.0	20.0	17.4	18.1
CaO	1.5	1.3	1.6	1.8	0.2	0.22– 1.82	1.7	3.53	2.75	2.70	2.09	3.27
Na_2O	2.0	1.7	2.1	1.4	1.4	1.41– 2.30	1.6	0.63	0.40	0.73	0.47	0.52
K_2O	1.8	1.5	1.7	1.0	2.9	1.12– 2.87	1.6	0.33	0.12	0.30	0.19	0.23
TiO_2	0.9	0.5	0·5	0.7	0.8	0.45– 0.93	0.7	0.54	0.50	0.48	0.50	0.61

Data sources: GLASS (1969, 1972).

tektite fragments is related with bediasites or georgiaites (KOEBERL and GLASS, 1988).

Table 5 gives the major element compositions of microtektites from the Ivory Coast strewn field, also including bottle-green microtektites. It is clearly visible that the average microtektites and the average bottle-green microtektites from the Ivory Coast strewn field are very different in composition. It is interesting to note that the characteristical sodium-potassium ratio of the Ivory Coast tektites (see Table 2) also shows up in the microtektite analyses, and that the effect seems to be even more pronounced in the bottle-green microtektites.

3.3. Muong Nong type tektites

Muong Nong type tektites are a subgroup of the indochnites, occurring within the

Fig. 9.   Microphoto of a section of Muong Nong type tektite MN 8304.
The light and dark layer, flow structures, and bubbles, all of which
are typical for Muong Nong tektites, are clearly visible.   Width
of the picture is 5 mm.

Table 6.   Major element data for Muong Nong type indochinites, averaged from 19 samples.   Also given are data for a light and a dark layer within one of the Muong Nong tektite samples.   It can be seen that there is a considerable difference between the layers.   All data in wt %, all Fe as FeO.   After KOEBERL (1986b).

	Muong Nong tektite average	MN8319 dark layer	MN8319 light layer
SiO_2	78.30± 1.58	80.44	76.38
Al_2O_3	10.18±1.01	9.33	12.40
FeO	3.75±0.36	3.25	4.38
MgO	1.43±0.13	1.35	1.71
CaO	1.21±0.15	1.26	1.33
K_2O	2.41±0.11	2.49	2.62
Na_2O	0.92±0.09	1.25	0.91
TiO_2	0.63±0.05	0.57	0.66

Australasian strewn field.   In contrast to normal tektites, they have a different shape, size, and chemistry (see Section 1).   Amongst the more important features is the occurrence of colored layers (Fig. 9).   These layers have different widths but are typically not much wider than a few mm.   Table 6 gives the average chemical composition of Muong Nong type indochinites, as averaged from 19 samples.   Also included are typical analyses of dark and light layers, showing that there is indeed a remarkable chemical difference between these layers (WEINKE and KOEBERL, 1984).   The layering, which is a rather large-scale phenomenon and ordered, is not to be confused with schlieren, which are quite common in tektites and are also sometimes associated with slight chemical differences (ENGELHARDT et al., 1987).   The question about the nature of the color has not yet been solved, although it seems likely that some oxidation state changes may be involved.   The chemistry of the layers yields a rather surprising result, since all the possible coloring elements are depleted in the dark layers.

3.4.   High Na-K australites

These glasses are very interesting, since they have a very unusual chemical composition when compared to other tektites.   They have higher CaO abundances than most of the other groups (except HCa philippinites and australites), and have a very unusual sodium/potassium ratio.   The sodium abundances considerably higher than the potassium abundances, with Na_2O/K_2O ratios between 3 and 4, which is completely unusual for tektites.   Table 7 gives the chemical compositions of eight HNa,K-australites as analyzed by CHAPMAN and SCHEIBER (1969), and comparison with Table 1 or 2 clearly shows the significance of the compositional variation.   For comparison reasons, also a terrestrial andesite is tabulated, the composition of which is very close to the australite compositions.   The trace element content is, however, grossly different (CHAPMAN and SCHEIBER, 1969).   In view of the andesite-like composition one is tempted to ascribe an igneous origin to the HNa, K-australites.   The oxygen isotopes are rather different from terrestrial andesitic compositions and are closer to normal Australasian tektite numbers (TAYLOR and EPSTEIN, 1969).   Age determinations (STORZER and MÜLLER-

Table 7.   Major element data for eight HNa,K-australite samples.   All data in wt%,
all Fe as FeO.   Data from CHAPMAN and SCHEIBER (1969).

	AN87	AN245	AN318	AN325	AN327	AN370	AN371	AN372	Average (8 samples)	Terrestrial andesite
SiO_2	62.2	63.9	63.4	63.4	63.3	63.9	63.4	63.1	63.3 ±0.5	62.1
Al_2O_3	15.8	15.8	16.9	16.8	16.4	16.5	16.9	17.1	16.5 ±0.5	16.5
FeO	6.88	5.94	5.67	5.67	5.93	5.58	5.92	5.54	5.89±0.43	6.05
MgO	4.68	3.67	3.81	3.69	3.85	3.60	3.79	3.57	3.83±0.36	3.99
CaO	5.81	6.00	4.52	4.49	4.49	4.52	4.49	4.61	4.87±0.64	6.56
Na_2O	2.78	2.75	3.64	3.84	3.91	3.83	3.53	3.80	3.51±0.48	2.58
K_2O	0.90	1.02	1.10	1.08	1.12	1.07	1.01	1.08	1.07±0.07	1.27
TiO_2	0.58	0.54	0.58	0.58	0.59	0.65	0.53	0.60	0.58±0.04	0.67

SOHNIUS, 1986) have shown that these tektites are probably as old as 11 Ma, which would make them considerably older than the other Australasian tektites (which have an age of about 750000 years).   Sections of HNa,K-australites show less structure and abundant bubbles and lechatelierite inclusions.   CHAPMAN and SCHEIBER (1969), however, conclude that they are real tektites.   If this conclusion is true, even in spite of the new age data, we are dealing with a second event in the area, predating the major Australasian tektite event by more than 10 Ma.   No new trace element data or isotope data are available for these samples at the time of writing, although it would be highly desirable to collect further data on the HNa,K-australites.   At present the author is not convinced that they are real tektites, and that the term "australites" should be used. As far as the finding locations are concerned, all the samples (9) recovered so far are from the same area in Australia (at four different localities).   Any relationship with Ivory Coast tektites, as suggested by CHAPMAN and SCHEIBER (1969), is irrelevant in view of the new age data.

3.5.   Trace elements

Recently, trace elements in tektites have found more consideration than before, a development which reflects the improvement in analytical methods and instrumentation.   Until less than a decade ago, the only strewn field that was reasonably well analyzed, mainly due to the efforts of S.R. TAYLOR and co-workers, was the Australasian strewn field (see e.g. TAYLOR, 1962, 1966, 1973; TAYLOR and KAYE, 1969; TAYLOR and McLENNAN, 1979; TAYLOR and SACHS, 1964).   Recently the situation has improved for other strewn fields, except for the Ivory Coast strewn field, where due to sample number limitations no new data are available.   Like some major elements, trace elements can be used not only for the characterization of tektites from one strewn field or for the subdivision in different sub-strewn fields, but also for the determination of the type of the source rocks of tektites.   Table 8 gives trace element data for a number of selected samples from different strewn fields, together with microtektite data.   It can be seen that in the most cases the microtektite and the tektite data are in good agreement. Data for microtektites are sparse, even today, since the analysis of single microtektites is a rather complicated procedure (typical microtektite weights are in the 10–100 μg range).   Also here it would be heighly desirable to gain new data.   In the case of the

Table 8. Data for selected trace elements in samples from different strewn fields, compared with microtektites from the same strewn fields. All data in ppm; from: KOEBERL (1986b), FREY et al. (1970), FREY (1977), and KOEBERL and GLASS (1988).

| | Average australite | Australasian microtektites | North American tektite | | | | Ivory Coast tektites | microtekt. |
			bediasite	georgiaite	Barbados tektite	microtekt.		
Sc	13	11.9	9.2	6.9	9.9	4.6	17	15
Cr	72	81	26	22	110	50	327	230
Mn	670	820	252	—	258	495	500	600
Co	25	9.9	9.1	6.7	20	20	21	51
As	—	—	1	<0.7	1	2.5	—	—
Rb	80	66	73	66	84	<130	69	70
Zr	264	—	152	160	<400	<600	116	—
Sb	0.06	—	0.05	<0.1	<2	<2.5	—	—
Cs	5.7	2.3	1.33	1.0	11	6	2.9	2.3
Ba	356	530	450	620	<800	<1000	830	650
Hf	7.1	6.4	5.1	4.7	7.1	3	3.8	—
Ta	1.2	2.4	0.70	—	2	—	—	—
Th	13.7	14.5	6.8	4.9	6.8	4	2.9	3.8

bottle-green microtektites, the situation is even gloomier. FREY (1977) analyzed a composite of 16 bottle-green microtektites from the Australasian strewn field (to obtain a higher sample weight) for four trace elements and two rare earth elements. One of the important results of this study was that Cr is in the 1000 ppm region (the other elements analyzed are Sc, Mn, Co, Sm, and Eu). The lack of other trace element data and the lack of further studies (this remained the only analysis!) precludes any quantitative conclusion. Thus trace elements have not yet contributed to solve the question about the origin of the bottle-green microtektites, although they would be very helpful.

More complete data on trace elements in tektites from all groups has been compiled by KOEBERL (1986b), so we will limit our discussion here to some general observations. Like in the case of major elements, plots of elemental ratios are very instructive in the case of trace elements. KOEBERL et al. (1986) have shown, using numerous elemental ratio plots (like K/Sc, K/Rb, K/Ba, Rb/Zr, Ba/Rb, and others), that all tektite groups plot on or near the respective ratio for terrestrial upper crustal rocks, and in no case near any lunar ratio. The usage of plots of volatile vs. refractory elements or of two incompatible elements is especially rewarding. Figure 10 gives one example of the various elemental ratio diagrams: the Th/Sm relationship. It is clearly visible that tektites cluster around the terrestrial ratio. Another famous example is the plot K vs. K/U, given in Fig. 11. This plot has long since been used to show the terrestrial provenance of tektites (e.g. GENTNER and MÜLLER, 1975). Meteorites, the moon, the earth, and other planets form distinctive fields in that diagram, and tektites clearly plot in the terrestrial field. Again this is an argument in favor of a terrestrial origin of tektites, and not compatible with a lunar origin, or an origin even outside of the earth-moon system (which is mentioned sometimes). It is also not in support of a mantle origin for tektites (see below). Other trace element ratios, like Th/Sc, or La/Sc, are
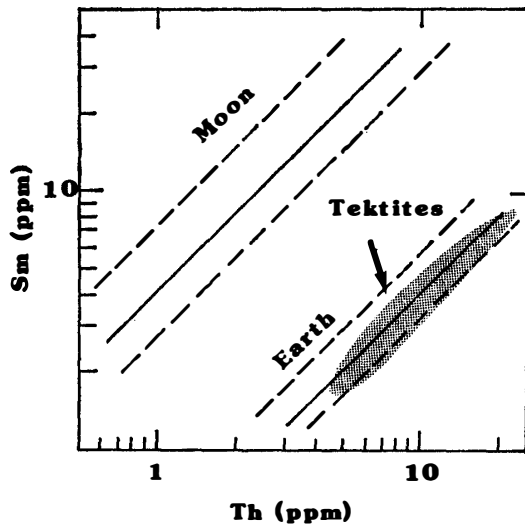
Fig. 10. Relationship between Th and Sm for tektites. The lunar and terrestrial ratios have been computed by using most available analyses for the moon and upper crustal rocks in the case of the earth. Standard deviations of the mean ratios are also plotted (broken lines). It is clearly evident that the tektites (shaded area) are indistiguishable from the terrestrial ratio and do not come close the lunar ratio. After KOEBERL et al. (1986).
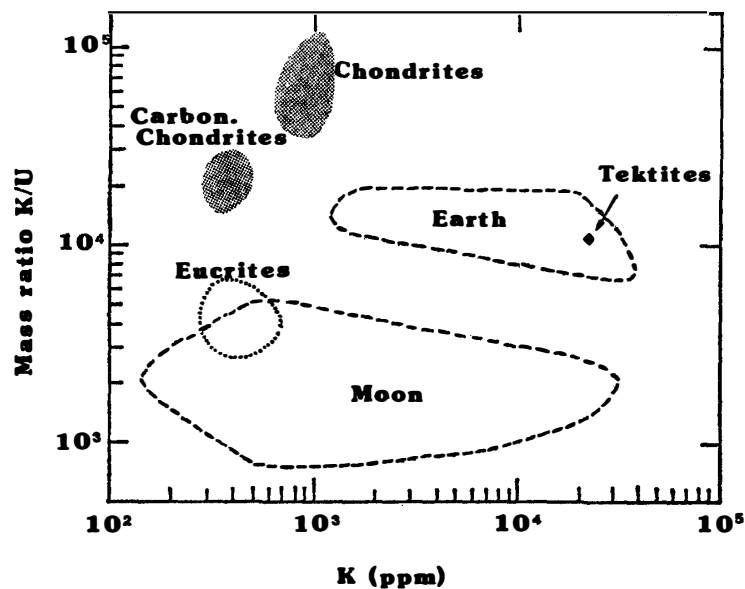

Fig. 11. Potassium vs. potassium over uranium diagram, showing the characteristic ratios for different bodies in the solar system (after GENTNER and MÜLLER, 1975). Tektites plot in the terrestrial field, close to granitic rocks.

very useful. They demonstrate clearly the upper crustal origin of the tektite source rocks, since tektites have a typical upper crustal ratio, while lower crustal ratios, oceanic crustal ratios, or mantle ratios are completely different.

The rare earth elements (REE) are also an extremely useful group of elements, since they behave very similar in geochemical cycles, although the slight differences in REE distributions between different phases in some processes allows their extensive use for genetic conclusions. Several authors have discussed the importance of REE patterns in respect to tektites (see *e.g.* KOEBERL *et al.*, 1985, TAYLOR and McLENNAN, 1979). Usually tektites are plotted in chondrite normalized REE diagrams, and one of the
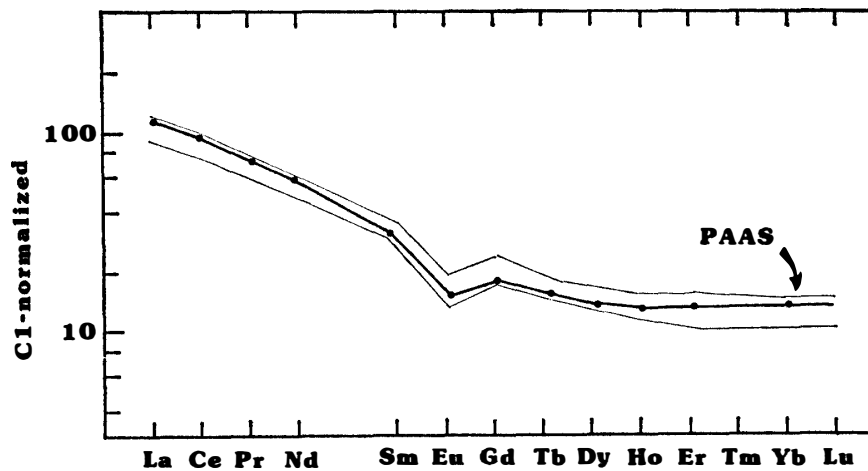
Fig. 12.   Rare earth element patterns for Australasian tektites and the post-Archean
average sediment.   The thin lines show the range of REE patterns for
Australasian tektites, and the solid line represents the PAAS, which plots
completely inside the tektite area.   This demonstrates the close relation-
ship between tektites and upper crustal sediments (after TAYLOR and
MCLENNAN, 1979).

first observations is that they fall within a very tight grouping in such a diagram, which means that the patterns of all tektites are very similar.   Furthermore, the La/Lu ratio (or the LREE/HREE ratio) is a good indicator of composition because this ratio typically changes with type and composition of rocks.   The ratio encountered in tektites (close to 10) is again typical of the upper crust (upper crustal sediments), and shows no similarity to ratios depicted by the lower crust, the mantle, or lunar rocks.   Figure 12 shows that the range of australite REE patterns is indistinguishable from the Post-Archean Average Sediment (PAAS), suggesting a very close correlation between tektites and similar sediments (TAYLOR and MCLENNAN, 1979).

Another interesting factor is the negative Eu anomaly, which is caused by geochemical differentiation processes in the precursor materials, and which is characteristic of post-Archean sediments.   Also, lunar rocks (except KREEP) rarely show a negative Eu anomaly, associated with the typical LREE/HREE ratio observed in tektites and terrestrial sediments.   The extent of the Eu anomaly varies between different tektite groups, but is essentially in the same order of magnitude.   A more thorough discussion of REE in tektite research is given by KOEBERL (1987) and TAYLOR and MCLENNAN (1979).   The conclusion here is that all REE data are in exclusive agreement with terrestrial upper crustal post-Archean rocks as precursor material,

Trace elements and especially REE are, of course, useful in comparison studies of tektites, microtektites, and other materials from one strewn field.   We have already mentioned the case of the recent discovery of tektite fragments together with microtektites from Barbados and DSDP Site 612.   Trace element studies, some of which are given in Table 9, have been used to show that all tektites really belong to the North American strewn field, but that there are also differences between the different localities (KOEBERL and GLASS, 1988).   The two bediasite analyses given show the average variation within one group, and it is evident that georgiaites are slightly different in trace

Table 9.   Trace element data for the newly discovered tektite fragments and microtektites
           from Barbados (BTF1=tektite fragment, BMT=microtektite) and DSDP 612 (two
           fragments, 612A and 612B), compared with data for bediasites and georgiaites, and
           the tektite from Martha's Vineyard.   All data in ppm; from KOEBERL and GLASS
           (1988).

	Barbados		DSDP Site 612		Bediasite		Georgiaite	Martha's Vineyard
	BTF1	BMT	612A	612B	BED8401	LET-6	DGA-1	M.V.
Sc	9.9	4.6	9.5	10.5	9.16	15.7	6.9	10
Cr	110	50	110	115	26	68	22	31
Mn	258	495	610	590	252	—	—	397
Co	20	20	8.5	8.0	9.1	17.8	6.7	7.6
As	<2	2.5	0.6	0.9	1	—	—	—
Rb	84	<130	85	90	73	70	66	72
Zr	<400	<600	<350	240	152	290	160	190
Sb	<2	<2.5	2.0	1.7	0.05	—	—	—
Cs	11	6	5	5	1.33	2.3	1.0	1.7
Ba	<800	<1000	700	700	450	390	620	390
La	29	15	29.3	29.5	22.9	45.9	19.6	<50
Ce	75	38	55	66	60.7	97	43	—
Nd	32	20	34	40	26	—	—	—
Sm	9.0	4.45	8.3	8.6	5.2	9.6	4.03	—
Eu	1.56	0.59	0.73	0.75	1.20	2.02	0.97	—
Gd	10	—	7	—	—	—	—	—
Tb	1.5	0.8	1.1	1.3	0.62	1.31	0.59	—
Dy	7.2	4.0	6.6	6.7	3.8	—	—	—
Tm	—	—	0.9	—	—	—	—	—
Yb	5.0	3.5	5.0	4.2	1.69	3.93	1.73	—
Lu	0.4	0.5	0.35	0.40	0.35	0.62	0.29	—
Hf	7.1	3	6	5.8	5.1	7.8	4.7	—
Ta	3	<6	1	1	0.70	—	—	—
Au	—	—	—	0.06	—	—	—	—
Th	6.6	4	8.5	10	6.8	9.0	4.9	—
U	<3	<6	—	3.6	1.82	3.1	1.25	—

element composition.   Furthermore, there are also some slight variations between the DSDP 612 tektites and the Barbados samples and the other previously known tektite types.   This is in agreement with extensive chemical variations within the Australasian strewn field (CHAPMAN and SCHEIBER, 1969), although the variations within the North American field are smaller.

Muong Nong type tektites have already been mentioned earlier, but before closing the trace element chapter we have to take a look at them in respect to trace elements. Table 10 gives the averaged trace element composition of Muong Nong type indochinites together with data for the light and dark layers which we mentioned earlier. In agreement with major element data, trace elements show mostly the same behavior in these layers: most elements are enriched in the light layers, including prospective color centers like Co.   The average Muong Nong data reveal another interesting factor: the enrichment in volatile elements compared to average splash-form tektites.   To allow

Table 10. Trace element data for an average Muong Nong type indochinite (average from 19 sambles), and for typical light and dark layers from sample MN 8319. All data in ppm; from KOEBERL (1986b).

	Muong Nong tekitite average	MN8319 dark layer	MN8319 light layer		Muong Nong tekitite average	MN8319 dark layer	MN8319 light layer
Li	42.1	—	—	Y	27	—	—
Be	3.70	—	—	Zr	290	700	—
B	47.7	—	—	Sb	0.82	—	—
C	70	—	—	Cs	5.09	4.4	5.2
F	97	—	—	Ba	340	340	—
S	10	—	—	La	24.4	26.6	30.9
Cl	170	—	—	Ce	60	68	78
Sc	7.70	7.72	10.0	Nd	21.7	34	75
V	72	—	—	Sm	4.82	4.70	5.95
Cr	61	61	70	Eu	0.84	0.76	0.65
Mn	675	640	670	Tb	0.69	9.9	1.9
Co	12.6	10.9	14.5	Dy	4.40	3.1	7.4
Ni	50	—	—	Yb	2.31	2.4	3.4
Cu	13.5	—	—	Lu	0.44	0.42	0.51
Zn	67	—	—	Hf	8.13	7.8	10.5
As	5.0	1.4	7.2	Ta	1.18	1.9	—
Br	4.1	—	—	W	0.9	—	—
Rb	110	160	140	Th	11.0	12.5	17
Sr	100	—	—	U	2.48	4.4	4.7

Table 11. Volatile element data for average australites compared with average Muong Nong type indochinites, in ppm. After KOEBERL (1986a) and KOEBERL and BERAN (1988).

	Australites	Muong Nong Indochinites
Li	40	42
B	19	48
F	36	97
S	3	10
Cl	7	170
Cu	6.5	13.5
Zn	2.0	67
Br	0.18	4.1

a better comparison, Table 11 gives the respective data for average australites and average Muong Nong tektites. We clearly see that some of the elements (only volatile elements have been chosen) are enriched by at least an order of a magnitude, while for others the enrichment factor in only 2 or 3. Together with some other arguments, this points to lower peak temperature and pressure during the formation of Muong Nong type tektites. Other arguments would include incomplete reduction of iron (in contrast to splash form tektites, Muong Nong type tektites have retained a fraction of their iron in the $+3$ state), mineral inclusions, inhomogeneity, and other petrographic

features. Muong Nong type tektites may thus be interpreted as being close to the impact site.   In this respect it is interesting to note that the DSDP 612 tektite fragments show indications of some Muong Nong characteristics, which would put them closer to the impact site than, for example, the bediasites.

3.6. Water content of tektites

Tektites, like impact glasses, are rather water-poor natural glasses, especially if compared to other terrestrial natural glasses like obsidian. Water contents of tektites range from about 0.002 to 0.02 wt% H_2O, similar to impact glasses, which range up to about 0.06 wt% H_2O. Obsidians, on the other hand, have water contents of some few tenths of a percent. Analyses, which led to the recognization of this difference in water content have been performed only on a few samples (Gilchrist et al., 1969; Engelhardt et al., 1987; Koeberl and Beran, 1988), thus the database is not very strong. The conclusion from the low water content of tektites would be that we have to look for a mechanism for driving out water very effectively from the sedimentary precursor rocks, which have water contents of up to several percent (Luft, 1983). The scarcity of water in tektites has been cited as an argument against a terrestrial origin because in glass making theory there are no easy ways for driving out the water fast and effectively (O'Keefe, 1976). The lunar origin theory, as advocated by O'Keefe (1976) allegedly would not have these problems, but after analyzing lunar samples it became clear that lunar rocks have virtually no water at all, thus is would be an even larger problem for the lunar theory to explain the provenance of water. Recent investigations by Koeberl and Beran (1988) have shown that there is a correlation between the water content in tektites and impact glasses and the peak pressure and temperature experienced by the different glasses. This is in favor of an impact origin. Table 12 gives examples for water contents of all different types of natural glasses. It is clearly visible that the average water content of tektites is lower than for impact glasses.

Table 12.   Water content of tektites, impact glasses, and obsidians, in wt% H_2O.   Data from Gilchrist et al. (1969), Engelhardt et al. (1987), and Koeberl and Beran (1988).

Material	Water content	Material	Water content
North American strewn field		Czechoslovakian strewn field	
Bediasite B-50	0.014	Moldavite (Radomilice)	0.011
Bediasite B-6	0.011	Moldavite (Nechov)	0.010
Bediasite B-85	0.020	Impact glasses	
Australasian strewn field		Irghizite USNM 6200	0.026
Javanite JS-6	0.007	Blue zhamanshinite BZ 8601	0.050
Indochinite IDC-1-17	0.004	Aouelloul glass A-0-7b	0.025
Indochinite 40-15	0.010	Darwin glass DGCp-1(5)	0.046
Australite 97-2	0.009	Obsidians	
Philippinite 96-2	0.019	Obsidian (Peru) 41-15	0.213
Muong Nong indochinite 8302	0.015	Obsidian	0.126
Muong Nong indochinite 8310	0.017		

4. Petrographic Characteristics

Tektites show flow structures and evidence of layering at least in some cases. Flow structures are evident in many samples as schlieren of slightly varying chemical composition. This structure becomes evident when looking at a thin section. In spherical forms (splash forms) the flow structure is usually folded or contorted, in ablated forms it is parallel to the front surface, but truncated by the rear surface. The flow structure in tektites is important because it is evidence of fast melting and quenching of material which formed glasses of slightly varying composition. Layers of different chemical composition and color (see above) are abundant in Muong Nong type tektites (Fig. 9).

In most tektites, vesicles are quite common, with the possible exception of some North American tektites, where they are rare. Larger vesicles and more vesicles per volume unit can be found in Muong Nong type tektites. The gas pressure in vesicles within tektites is very low, but again in Muong Nong type tektites it can be up to half of the atmospheric pressure. Analyses of the gas in tektite bubbles have revealed that N_2, Ar, Kr, and Xe as well as their isotopes occur in roughly the proportions of the terrestrial atmosphere (e.g. JESSBERGER and GENTNER, 1972).

4.1. Mineral and other inclusions

Lechatelierite (pure silica glass) particles of varying shape and size are found in all tektites. In splash form tektites they tend to be elongated, probably due to melt flow, while in Muong Nong types they are equant in shape. Other high silica inclusions are also observed. It is commonly inferred that the lechatelierite has been derived from the melting of quartz crystals present in the precursor rocks, indicating temperatures of 2000° in the melt. Recently, GLASS et al. (1986) reported the discovery of quartz grains, quartz grains partly melted to lechatelierite, and lechatelierite particles all in the same tektite fragment from DSDP Site 612. This important result adds further to the evidence of a sedimentary precursor material for tektites. In addition, shocked minerals (feldspar, garnet, etc.), most probably forming an ejecta layer, have been found together with the tektite fragments at Site 612.

Coesite has also been reported from Muong Nong type tektites some time ago, and has recently been confirmed by GLASS et al. (1986). Coesite is, due to its high temperature and pressure origin, another impact indicator. Relict minerals, which are thought to predate the glass and to represent minerals present in the precursor material, include quartz, zircon, rutile, chromite, and monazite, and have been found in Muong Nong type tektites (see, e.g., GLASS and BARLOW, 1979). This is not surprising, since we have already presented several arguments that Muong Nong type tektites experienced lower temperatures and pressures, and thus the preservation of precursor minerals is more likely.

4.2. Metal spherules

In some tektites, especially in philippinites, metal spherules have been found and previously been interpreted as being of cosmic origin (CHAO et al., 1964). Similar spherules have been reported from impact glass from the Aouelloul Crater, and were also thought to form some kind of projectile remains. The spherules are mainly of

NiFe composition and occur in association with troilite and schreibersite. The Ni content is variable, some spherules have only 2–4 wt% Ni, others up to 13 wt%. Recent studies of trace elements in individual spherules by GANAPATHY and LARIMER (1983) have shown, that the Ni to Ir, W, Au, As, and Co ratios have a close correlation with the respective terrestrial ratios. Only Ir and Au would be consistent with known cosmic ratios. This led GANAPATHY and LARIMER (1983) to conclude that the spherules formed by *in-situ* reduction of metal contained in the precursor rocks during the impact.

5. Isotopes and Ages

Numerous isotope studies for tektites have been reported, including the measurement of oxygen, silicon, rubidium-strontium, samarium-neodymium, and lead isotopes. Oxygen isotopes are in agreement with a terrestrial origin, as cited by TAYLOR and EPSTEIN (1969), although the δO^{18} data reported are not in complete agreement with sediments, but rather with some igneous rocks. A novel suggestion to explain that discrepancy has recently been made by ENGELHARDT *et al.* (1987), who suggested that the admixture of small amounts of oxygen from meteoric pore water (which is present in all sediments, and has a highly negative δO^{18}) would easily lower the sedimentary δO^{18} values to the tektite values.

Sm-Nd studies (SHAW and WASSERBURG, 1982) have been instrumental in showing the provenance of the precursor materials for tektites. Again, sediments, which had been derived from the late Precambrian crust, have been the best candidates. For the Ivory Coast tektites the results are consistent with results obtained from the Bosumtwi crater in Ghana, and for the moldavites there is a correlation with material from the Ries crater in West Germany. Lead isotope data (TILTON, 1958) are also consistent with a terrestrial origin of the precursor material. WAMPLER *et al.* (1969) have used lead isotopes to show another connection between the Bosumtwi crater and the Ivory Coast tektites as well as between Ries material and the moldavites. Space limitations prevent a more detailed discussion of isotopic studies, but the results cited so far are in clear favor of the impact model.

Age determinations on tektite material are summarized in Table 13. Amongst the main methods used for age determinations of tektites are the K-Ar, the Ar-Ar, and

Table 13.   Ages of tektites and impact glasses.   After O'KEEFE (1976).

Material	Age (10^6 years)	Material	Age (10^6 years)
Australasian tektites		Moldavites	14.7
Australites	0.72	Ries glasses	14.7
Indochinites	0.73	Ivory Coast tektites	
Thailandites	0.72	Tektites	1.02
Microtektites	0.71	Microtektites	1.09
North American tektites		Bosumtwi glass	1.3
Bediasites	34.2	Darwin glass	0.72
Georgiaites	34.2		
Cuban tektite	35		
Microtektites	34.6		

the fission track method. During the high temperature event all previously incorporated Ar is lost, and all fission tracks are annealed, thus the age determinations give the time of the formation of the glass. In the impact model, tektites are required to fall on the earth very shortly afterwards. Tektites, however, are found in rather young sediments, and according to the age of the sedimentary layers in which australites are found, tektites should have fallen not earlier than 20000 years ago. This so-called age paradox (see, *e.g.*, CHALMERS *et al.*, 1976) is especially obvious for tektites from the Australasian strewn field. Some authors maintain that tektites could not have been transported and the stratigraphic age of the sediments thus gives the fall date–which is in obvious disagreement with the radiometric age determinations. It is the opinion of the author that with the discovery of microtektites (which are always found in deeps sea deposites of the correct–old–age) and tektites in the same stratigraphic layers at Barbados and DSDP Site 612 the age paradox has been resolved (see KOEBERL and GLASS, 1987)–tektites on land, occurring in younger deposits have been reworked.

Amongst the important conclusions that can be drawn from age determinations is the connection between impact craters and tektites. The Bosumtwi crater in Ghana has the same age as the Ivory Coast tektites, and the Ries crater in Germany has the same age as the moldavites. To yield such a result by pure coincidence is extremely improbable. Together with isotopic and chemical evidence this is indicative of a genetic connection between the craters and the respective tektite strewn fields.

One interesting point should be mentioned here: the age given for australites in Table 13 has been determined by the K-Ar and the fission track methods to be close to 0.72 Ma. However, recent redeterminations of the australite age (compared to indochinites) by STORZER and WAGNER (1980) yielded an age of 0.83 Ma for australites, which they interpreted in favor of two different events. No other chemical or isotopic evidence is indicative of two events for the Australasian strewn field (with exception of the HNa/K-"australites", as described above).

6. Conclusions about the Origin of Tektites

As already described in the History chapter, numerous theories for the origin of tektites flourished during the past decades, leaving only two theories which have been considered more seriously: the lunar volcanic theory (favored by O'KEEFE, 1976) and the terrestrial impact model (favored by most other workers). The lunar impact theory has lost any credibility after the first analyses of lunar rocks, and is thus no longer advocated. O'KEEFE (1976) cites several problems of a terrestrial theory (some of which have been mentioned in the previous sections), and focuses on glass making theory, the homogeneity and dryness of tektites, the discrepancy between most tektites and most impact glasses, and cratering mechanics. He proposes that tektites have been erupted from lunar volcanoes, being samples of the deep lunar interior. He states that lunar volcanoes may have the power to propell large quantities of glass to the earth, with velocities larger than the lunar escape velocity (2.5 km/s), and calculates that it is unlikely that an impact on the moon may accelerate macroscopic particles up to this velocity. In view of todays knowledge, after the discovery of lunar meteorites, which were obviously accelerated to velocities larger than the escape velocity, this statement

seems to be outdated. Space limitations preclude a more detailed description of the lunar volcanic model, so the interested reader is referred to O'KEEFE (1976, p. 195ff). Several workers have pointed out that the lunar hypothesis requires extensive revisions of our well accepted views of lunar composition, structure, evolution, and origin, to fit the observed characteristics of tektites. On the other hand, the terrestrial impact model, despite some questions, is an easy alternative which fits all data. Thus we should rather accept the "easy" solution, instead of trying to model the whole moon after a theory for tektites! We should not, however, forget the open questions for the impact model, which will be mentioned later. The lunar theory, however, seems to face so many difficulties (see, *e.g.*, TAYLOR, 1973, 1982; GLASS, 1982; KOEBERL, 1986b, 1987), that we will mention only a few crucial ones. The power supply of lunar volcanoes is by no means proven: O'KEEFE (1976) requires hydrogen to get the necessary velocities, but hydrogen does not exist on the moon. Furthermore, the theory requires the moon to be active until now. This is in complete contradiction to our knowledge of planetary and lunar evolution (see, *e.g.*, TAYLOR, 1982 and references therein). The chemical composition of the moon, as known today, is very different from the chemistry of tektites. Ballistic arguments for confining a tektite swarm on the way from the moon to the earth are at least as problemetic as alleged difficulties in impact mechanics. Isotopic evidence is by no means in agreement with a lunar source. In the following we will summarize the evidence in favor of a terrestrial origin, but before doing so we need to discuss another alternative model.

NICOLAYSEN (1987) proposed an internal terrestrial model for the origin of tektites, based on his belief that what other workers describe to be impact craters are merely "crypotexplosion structures". His model assumes that there is in fact a correlation between geomagnetic reversals and tektite events (as mentioned above). Due to the interaction between the core and the lower mantle of the earth a geomagnetic reversal should take place, and that interaction would cause some mantle expansion. In the model of NICOLAYSEN (1987) the mantle is porous and loaded with volatiles, and thus a pressure buildup in the lithosphere results. A cataclysmic failure of the impermeable lithosphere then yields a hypervolcanic eruption, where volatiles (like CO_2 or H_2) would be vented. Critical to his model are the bottle green microtektites, which are assumed to have formed from a Ca and Al rich magma, depleted in alkalies, and coming from mantle regions. Normal tektites and microtektites are assumed to have formed from an alkali-enriched igneous magma and from the molten hood zone (crustal material which is blasted off).

Again, there are numerous problems associated with this model. The connection between tektite events and geomagnetic reversals is by no means proven. There are many reversals which are not associated with any tektite event. The mantle model is not necessarily in agreement with our current understanding of the mantle. No explanation can be given how terrestrial rocks should withstand the required pressure buildup without early leakage or failure. Bottle-green microtektites are much less common than the model would suggest, and furthermore no comparable tektites have been found. And, again, the chemistry of tektites is not in agreement with this model.

Throughout the last chapters we have mentioned arguments in favor of the impact model. Trace element ratios like La/Sc, Th/Sm, Th/Sc, and the REE patterns require

upper crustal material, which has to be post-Archean. Mineral inclusions, in the mixture present in tektites, require a sedimentary precursor material. Isotope data (especially Sm-Nd and Rb-Sr) also favor a sedimentary precursor component. The discovery of quartz grains which are partly molten to lechatelierite further add to the significance of the impact model. Water in tektites is not compatible with a lunar source, since there is no water on the moon. The chemical, isotopical, and age connections between two impact craters and two of the strewn fields give an immediate connection to impacts. Chemical investigations of the platinum group elements and other characteristic siderophiles have resulted in hints about the chemical composition of the projectiles (see review in KOEBERL, 1986b).

Muong Nong type tektites may be the key to the understanding of the exact processes of tektite origin. We have pointed out that several arguments (like the volatile content, the mineral inclusions, the layering, the large size, and others) favor the view that Muong Nong tektites have experienced a lower peak pressure and temperature than other tektites. Australites, showing ablation features, have traveled farthest. Thus Muong Nong type indochinites are close to the source crater. A recent investigation of the continental shelf close to Indonesia and Indochina by WALTER et al. (1986) yielded several prospective crater-like structures. The discovery of a probable Muong Nong signature in the DSDP 612 tektites (KOEBERL and GLASS, 1988) and the discovery of impact ejecta and shocked material in the same DSDP 612 layer also points to a crater close by, which may be situated on the continental shelf, as already suggested by SHAW and WASSERBURG (1982). Studies of impact craters, like the Zhamanshin crater in the USSR, and comparison of the data with tektites, especially Muong Nong type tektites, may yield further insight to the impact processes. Current problems of the impact model are mainly due to problems in the theoretical understanding of processes occurring during large scale impacts. Although we have several semi-quantitative or quantitative impact models, the numerical resolution is not good enough, and the equation of state data are not precise enough to describe the fate of objects as small as tektites. Thus also the alleged problems of the glass making theory cannot be discussed in this context, because we are not yet able to describe the processes happening during a large scale impact. One of the important points for future research is thus the improvement of impact calculations. More trace element data (e.g. for platinum groups elements) are needed for many tektite groups, and also for different types of source rocks. Pilot projects for impact craters like the Zhamanshin crater would be very useful in getting an exemplary impact model which may then more easily be extrapolated to tektites. Also, the glass making theory, which fails so far to explain the short-time origin of homogeneous, dry glasses, may have to be modified. Atomic bomb glasses, which have been produced during short time, high temperature events out of terrestrial sediments, are dry, homogeneous, and reduced (GLASS et al., 1986), thus it is possible to produce tektite like material in such events.

In conclusion, the present data together with a rather straightforward interpretation, leads us to state that tektites are impact glasses which have been produced during a hypervelocity impact of an asteroidal body on earth. Terrestrial precursor materials have been upper crustal post-Archean surface sediments.

Acknowledgments

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