Water Content of Tektites and Impact Glasses and Related Chemical Studies

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To study the difference in water content between genetically different types of tektites and impact glasses, we have analysed six Muong Nong type indochinites and five samples from the Zhamanshin impact crater, using the infrared absorption spectrometry method. Muong Nong type tektites are different from normal tektites in several respects, including higher volatile trace element abundances, which is further confirmed by our analyses. We find that Australasian Muong Nong tektites are also enriched in H_2O by a factor of about 1.5 relative to splash-form tektites from the Australasian strewn field. The Zhamanshin glasses show similar results: irghizites, known to be the most homogeneous and to have the lowest volatile element abundances among Zhamanshin impact glasses, also have the lowest water content, but are distinctly higher than even Muong Nong type tektites. Removal of water from sediments (the alleged precursor rocks of tektites and impact glasses) to form the dry tektites has been cited as a problem for the impact model, but published analyses for atomic bomb glass give a water content similar to tektites. Thus, dry glass can be formed in a single high temperature event. We also show that the water content in impact glasses and the intensity of shock melting experienced by the glass are inversely correlated, in accordance with the volatile trace element contents. Lunar rocks are completely devoid of water, thus the measured water content of tektites further supports a terrestrial impact origin.

INTRODUCTION

Impact glasses and tektites are rather water-poor natural glasses: approximate ranges of water contents in tektites are 0.002-0.02 wt %, and 0.02-0.06 wt % H_2O for impact glasses (*Friedman,* 1963; *Gilchrist et al.,* 1969; *v. Engelhardt et al.,* 1987). Most other terrestrial natural glasses, such as obsidian, contain a lot more water than impact glasses, around 0.1-1 wt % H_2O (*Gilchrist et al.,* 1969; *v. Engelhardt et al.,* 1987). Most terrestrial sediments, generally cited as the precursor rocks for tektite and impact glass formation (e.g., *Taylor,* 1973; *Koeberl,* 1986b), contain up to a few percent H_2O. Different sediments from the Ries crater area, for example, which may have been among the precursor rocks for moldavites, show a water content ranging from about 0.2-12 wt % water (*Luft,* 1983). Since it is theoretically difficult to understand how water is removed from the glass in the formation process (*O'Keefe,* 1964), the dryness of tektites has been cited as an argument against a terrestrial origin for tektites (e.g., *O'Keefe,* 1976). The analyses of lunar rocks, however, have revealed that water is practically nonexistent on the Moon, with abundance levels several orders of magnitude below those of tektites. No indigenous lunar water has so far been identified, and all water found in lunar samples at all has been attributed to terrestrial contamination or from reaction with hydrogen from the solar wind (*Epstein and Taylor,* 1974; *Taylor,* 1975, p. 228ff).

The early water analyses of tektites, performed with a variety of different techniques, yielded results that were not always consistent with each other or modern data. Chemical methods (*Clarke and Carron,* 1961) yielded a H_2O content of 0.02 wt % for a Georgia tektite, while *King* (1964) cites an even higher water content for another Georgia tektite, which he himself considered to be doubtful. This was in contrast to the results from the manometric method of *Friedman* (1958), who heated cleaned pieces of tektites and impact glasses (and other natural and artificial glasses) in Pt vessels under vacuum conditions to temperatures of up to 1450°C, and then measured the released H_2O. With a few exceptions, he has measured an average water content of 0.004%, with a spread of 0.0003-0.01%. This would mean that tektites have an average water content of much below 100 ppm, and before Apollo this may have appeared consistent with lunar rocks.

However, the application of a nondestructive method for water analysis, namely, infrared spectrometry, to tektites and impact glasses, yielded somewhat different results. *Gilchrist et al.* (1969), in a careful investigation of tektites and similar materials using the infrared technique, showed that the water content of tektites is in fact higher and clusters around 0.01 wt %. Obviously, the manometric method failed to release all the water bound to the silicates. This water content is still very low, but compared to lunar samples it is higher by many orders of magnitudes. Thus the results of *Gilchrist et al.* (1969) are consistent with a terrestrial origin of tektites. It would seem implausible to find a source for the water enrichment if they are of lunar origin.

The study of the water content of tektites and impact glasses has some very interesting implications for the impact theory. In accordance with conclusions drawn from other chemical studies, the water content of impact materials should vary between different groups. Muong Nong tektites are known to contain higher abundances of volatile elements such as As, Sb, the halogens, Zn, Cu, B, and others (*Chapman and Scheiber,* 1969; *Müller and Gentner,* 1973; *Koeberl et al.,* 1984a,b). Also, they contain a much larger amount of bubbles per volume than normal splash-form tektites. Their Fe (III)/Fe(II) ratios are higher than in normal tektites (*Koeberl et al.,* 1984c).

They are inhomogeneous, and in contrast to splash form tektites, mineral inclusions have been found (*Glass and Barlow,* 1979). All this has been interpreted as indicative of a lower peak pressure and temperature during the formation of the Muong Nong type tektites (*Koeberl,* 1986a). A higher water content in Muong Nong type tektites would be in line with those arguments.

Another interesting question associated with the Muong Nong type indochinites concerns the colored layers. Typically, light layers contain higher abundances of almost all elements except Si, while dark layers are depleted in a complimentary way (*Koeberl,* 1985). This is surprising, because even elements usually thought to be associated with color changes, such as iron, are enriched in the light and not in the dark layers. A difference in water content between the colored layers would be an alternative explanation for the color variation, maybe due to oxidation state changes.

Zhamanshinites, which are impact glasses from the Zhamanshin impact crater (Khazakhstan, Aral Region, USSR), are similar to Muong Nong type indochinites. They are also rather inhomogeneous and have a similar appearance, structure (abundant bubbles), and chemistry. Furthermore, in the case of the Zhamanshin Crater we do have a sequence of different impact materials, including several different impact glass varieties. Irghizites are among the most homogeneous materials and have probably experienced the highest formation temperatures and pressures. Si-rich zhamanshinite and blue zhamanshinites (*Koeberl et al.,* 1986) have experienced less shock melting, and have thus remained less homogeneous, and contain more volatiles. The blue zhamanshinites have a chemistry that puts them (in some respects) between the irghizites and Si-rich zhamanshinites (*Koeberl et al.,* 1986). The least impact-metamorphosed glasses are the Si-poor zhamanshinites, which are the least homogeneous glasses found at the crater. If the current understanding of the formation of impact glasses is correct, then one should also expect a related behaviour of the water content.

To test the aforementioned ideas and look for possible correlations with other chemical features, we have analysed six Muong Nong type indochinites from Ubon Ratchathani, Thailand (samples numbers MN 8302, MN 8304, MN 8308, MN 8310, MN 8317, and MN 8319; for additional information on these samples, see *Koeberl et al.,* 1984a-d), one irghizite (USNM 6200; *Koeberl and Fredriksson,* 1986), one Si-poor zhamanshinite (Zh 57/4b), and three blue zhamanshinites (Zh 31/6b, BZ 8601, BZ 8602; *Koeberl et al.,* 1986) for water and a number of elements that may be of interest in comparison. Some of the samples have already been analysed in more detail for other elements, especially the Muong Nong type indochinites (*Koeberl et al.,* 1984a-d).

ANALYTICAL METHODS

The water content of the samples was determined using infrared spectrometry, similar to the method used by *Gilchrist et al.* (1969). The infrared absorption spectrum of Si-rich glass contains peaks related to the O-H stretching vibration and H-O-H bending vibration modes, at 2.73 μm and 6.2 μm. Usually in glasses similar to tektites only the 2.73 μm peak is found, indicating the predominance of the O-H stretching vibration due to voids in the network structure of silica. The addition of alkali metal causes some modification in the network, leading to hydrogen-bonding of the hydroxyl ions (caused by changes in electronegativity) and to the displacement of the 2.73 μm peak towards higher wavelengths. The measurement of that peak yields information pertaining to the water content.

Tektite and impact glass samples were prepared as thick sections (thickness about 1 mm). The instrument used was a computer controlled Perkin-Elmer PE 580 B, with 8× beam condenser. Accumulated scans were taken to improve the signal/noise ratio. The calculations of the water content followed a standard Lambert-Beer law method, similar to that of *Gilchrist et al.* (1969). We have checked the extinction coefficient given by *Gilchrist et al.* (1969) and found, in agreement with their data, that 75±21 $\mathrm{mol^{-1}cm^{-1}}$ is the best value. This is very close to the numbers reported for other silica glasses (*Gilchrist et al.,* 1969). Small variations, depending on the exact structure of the glass, are possible but will not exceed the uncertainty given above. The calculations were performed using an average tektite and impact glass density of 2.40 g $\mathrm{cm^{-3}}$, which is the average of the densities of these glasses (see also *Gilchrist et al.,* 1969; and *v.Engelhardt et al.,* 1987), with deviations of less than a few percent. The density does not enter the calculations in a direct way, and thus small variations in the density affect the end result very little.

Other elements reported here have been determined using a variety of techniques. Lithium, Be, Cu, and Zn have been determined using atomic absorption techniques (see *Koeberl et al.,* 1984b,d for details); B has been determined using a tetrafluoroborate selective electrode (*Kluger and Koeberl,* 1985); F was analysed by F-selective electrode technique (*Koeberl et al.,* 1984a); and As and Br by neutron activation analysis. The data on the Muong Nong type indochinites are part of a larger dataset, including 19 samples at present.

RESULTS

The absorption spectra in the region near 2.8 μm are given in Fig. 1a and Fig. 1b for one of the Muong Nong tektite samples (MN 8302) and one of the blue zhamanshinites (BZ 8601). The transmission characteristics of the two impact glasses are different, as is the location of the peak maximum and the shape of the curve. Table 1 gives the peak location (in wavenumbers, $\mathrm{cm^{-1}}$), and the linewidth at half maximum (also in $\mathrm{cm^{-1}}$) for all the samples. From the data given there it is clear that none of the samples has its peak maximum at the ideal value of 2.73 μm (corresponding to 3660 $\mathrm{cm^{-1}}$) but all are shifted towards higher wavelengths (or smaller wavenumbers). The extent of the shift is different for the different tektite and impact glass groups, giving a peak maximum range of 2.77-2.82 μm. This means that the O-H stretching vibration is affected by other crystal field effects, leading to displacement of the peak maximum. One suggestion, which was also cited by *Gilchrist et al.* (1969), for the explanation of the displacement of the peak maximum in

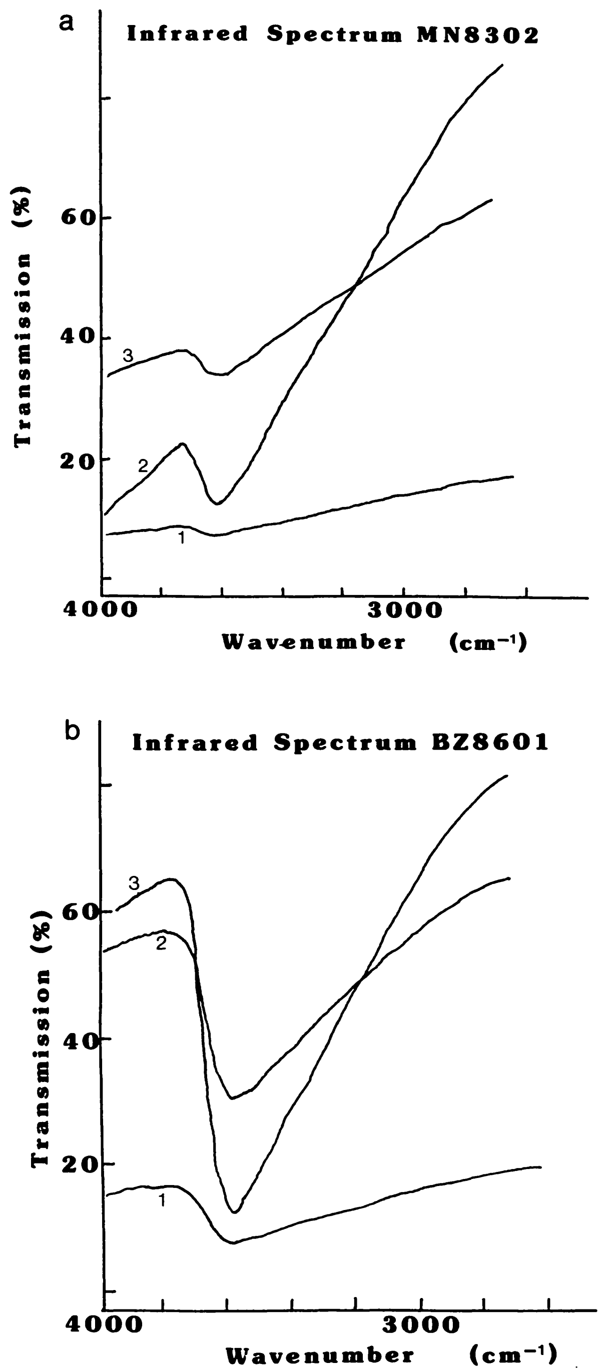

Fig. 1. Infrared absorption spectra of (a) a Muong Nong type indochinite and (b) a blue zhamanshinite. The sample numbers are given in the figure. The three curves from bottom to top are (as they start from the left ordinate): a single scan spectrum (1), an accumulated scan (5 scans) in a stretched version (2), and the original accumulated scan (5 scans) (3). The accumulated scans clarify the shape and height of the peak. The transmission scale is valid in a strict sense only for the original (single scan) spectra. The difference in shape and peak form and location between the two glass varieties, as evident from the figures, is explained in the text.

TABLE 1. Wavenumbers and linewidth for the O-H stretching vibration peak, which was used for H_2O determination.

Sample	Wavenumber (cm^{-1})	Linewidth (cm^{-1}) (half maximum)
MN8302	3610	210
MN8304	3600	220
MN8308	3590	280
MN8310	3610	220
MN8317	3600	230
MN8319	3590	220
USNM6200	3590	310
Zh 57/4b	3550	450
Zh 31/4b	3580	460
BZ8601	3575	410
BZ8602	3580	410

TABLE 2. Water content of six Muong Nong type indochinites and five Zhamanshin impact glasses.

Sample	Water Content (Wt %)
Muong Nong tektites	
MN8302	0.015
MN8304	0.013
MN8308	0.017
MN8310	0.017
MN8317	0.009
MN8319	0.011
Glasses from the Zhamanshin Crater	
USNM6200 (irghizite)	0.026
Zh 57/4b (Si-poor zhamanshinite)	0.034
Zh 31/6b (blue zhamanshinite)	0.063
BZ8601 (blue zhamanshinite)	0.050
BZ8602 (blue zhamanshinite)	0.050

tektites versus pure silicate glasses, involves the addition of alkalis.

The Muong Nong tektites show the usual displacement to about 3600 cm^{-1}, similar to the results given by *Gilchrist et al.* (1969), but the Zhamanshin glasses show greater shifts and also larger linewidths. This cannot be due to the alkali effect alone, and points to a different structural environment for the O-H bonding between the tektite and the impact glass. In addition, slightly different absorption characteristics may add to the effect. The exact cause for the difference between the two groups is not yet known. Unfortunately, *Gilchrist et al.* (1969) do not give wavenumbers and linewidths for the impact glasses and tektites they measured, so we cannot conclude that there is a systematic difference or variation between the O-H bonding in impact glasses and tektites. Within one group, however, the alkali effect seems to be present. Irghizites have lower total alkali abundances than Si-rich zhamanshinites (or blue zhamanshinites), while Si-poor zhamanshinites usually have the highest total alkali abundances (especially Na). Table 1 shows that in fact the irghizite shows the smallest displacement (to 3590 cm^{-1}), while the Si-poor zhamanshinite shows the largest displacement (to 3550 cm^{-1}).

Table 2 gives the results of the water determinations in all 11 samples. Since the extinction coefficient does not vary between different samples by more than a few percent, the analytical precision and the accuracy of the measurement are both within ±5% deviation. The average water content for Muong Nong indochinites, calculated from our six specimens, is 0.014 ± 0.003 wt % H_2O.

The Zhamanshin samples show a higher water content than the Muong Nong type tektites and are more variable. There is a considerable difference between the three different impact glass varieties measured, with the irghizite showing the lowest water content.

DISCUSSION

Gilchrist et al. (1969) have analysed two Muong Nong type tektites, one with 0.017 wt % H_2O, and another one with 0.008 wt %. From that they concluded that Muong Nong tektites have approximately the same water content as other tektites. The average water content of their indochinites (three samples) is 0.008 ± 0.003 wt % H_2O, and of all the Australasian tektites they measured (12 samples, excluding one anomalous philippinite) is 0.011 ± 0.005 wt % H_2O. Tektites from the North American strewn field, as measured by *Gilchrist et al.* (1969), seem to have a slightly higher water content than the average Australasian tektites, and thus change the overall average quoted by *Gilchrist et al.* (1969).

If we compare the water content in Muong Nong type indochinites, as given in the previous section, with the average water content of Australasian tektites (*Gilchrist et al.,* 1969), we see that Muong Nong type tektites show an enrichment compared with splash-form tektites. The comparison with the average Australasian tektite datum gives an enrichment factor of about 1.3, while a comparison with the splash-form indochinites (*Gilchrist et al.,* 1969), which are geographically closely related, would give an enrichment factor of 1.75. We feel that since we have a larger database than *Gilchrist et al.* (1969), who analysed only two Muong Nong tektites (one of which is consistent with the upper limit of our range, and the other one with the lower limit of our range), we can make the conclusion that there is in fact an enrichment of water in Muong Nong type tektites compared with splash-form tektites.

This result is in excellent agreement with our expectations based on the enrichment in other volatile elements. The enrichment of water is smaller than for other volatile elements. Table 3 gives the analyses for eight more or less volatile elements in the six Muong Nong tektites also analysed for water. In addition, the same information is given for an average australite. The enrichment factor varies: it is very high for Zn or Br, and less than 2 for Li or B. The halogens do not behave consistently, although one would expect a different behaviour for F and Br. Fluorine is enriched by a factor of about 2-2.5, and since F^- in silicate structures shows some similarities to OH^-, it is interesting to note that water is enriched by a similar order of magnitude. Water is, of course, one of the most volatile compounds, and thus impact processes are expected to affect it easily. The water removal during a high temperature effect such as an impact may be so thorough that the difference between the water contents in Muong Nong tektites and splash-form tektites is not larger.

We have also tried to address the question of the different colored layers in the Muong Nong tektites, and areas of about 1 mm in diameter have been analysed in some sections, where the layers have been evident. The results are ambiguous. In most cases we have not been able to detect a difference in the water content of light and dark layers. This may well be due to the intergrowths of the layers at this scale. More ideal samples and the use of a smaller beam diameter (which we are planning for future investigations) may give better results. In a few cases, however, we have found indications that the water content in the dark layers seems to be slightly lower than in the light layers (e.g., 0.013 versus 0.014 wt %), but at present we are not able to draw any conclusions from this possible difference.

The Zhamanshin glasses show a range of water contents of 0.026-0.063 wt %. The irghizite, in accordance with the expectations, has the lowest water content of all Zhamanshin samples measured (0.026 wt %), but it is above the tektite average. One irghizite has previously been analysed for water by *King and Arndt* (1977), who give 0.051 wt %. Unfortunately, they have measured only one sample and give no comparison data for other zhamanshinites or chemical data, so the results

TABLE 3. Concentration (in ppm) of various volatile elements in six Muong Nong type indochinites.

Element	MN8302	MN8304	MN8308	MN8310	MN8317	MN8319	Ave. Australite
Li	35.0	37.2	48.0	50.5	47.2	48.9	40
Be	3.2	2.7	4.4	3.4	4.3	5.5	2.2
B	30.8	31.7	30.0	77.5	48.3	37.0	19
Cu	151	20.1	22.1	7.5	9.3	10.8	6.5
Zn	78.3	56.2	63.9	65.6	62.2	79.0	2.0
As	4.6	3.0	3.2	3.6		5.6	
F	90.3	99.2	55.9	72.5	124	121	36
Br	4.5	3.5		7.9			0.18

Data for the average australite from *Koeberl* (1986b).

are probably not directly comparable. The four zhamanshinites we analysed have water contents of 0.034-0.063 wt %, which are higher than that of the one irghizite we analysed. This is consistent with the lower volatile element content of irghizites relative to zhamanshinites. The Si-poor zhamanshinite is intermediate in water content between the blue zhamanshinites and the irghizites. As of now, no Si-rich zhamanshinite has been measured, but related work is in progress. The expectation is that the water content of Si-rich zhamanshinites is in the same range as for blue zhamanshinites. There seems to be a connection between the volatile element content, water content, and a sequence of impact glasses, depending on the temperature and pressure they have experienced during their formation.

The mechanism for driving out water from the sediements during the impact melting process is still not known in detail. There are some obvious theoretical problems (*O'Keefe,* 1964). On the other hand, it is known that impact glasses, associated with impact craters, have low water contents (although not as low as tektites, but clearly they have experienced a similar process on a larger scale). *Gilchrist et al.* (1969) report H_2O contents for Darwin glass of 0.047 wt %, or Aouelloul glass of 0.025 wt %, which is close to that we observe for Zhamanshin glasses. Obsidians have a water content that is even higher, in the 0.X wt % range (*Friedman,* 1963; *Gilchrist et al.,* 1969; *v. Engelhardt et al.,* 1987). But even if there is as yet no explanation for this glass formation, it is definitely possible to produce a dry homogeneous reduced glass in a single high temperature event: glass produced during an atomic bomb explosion in Nevada contains 0.007 wt % H_2O (*Glass et al.,* 1986). *Gilchrist et al.* (1969) report water contents of around 0.04 wt % for synthetic glasses produced from materials including soil by solar furnace melting. *Luft* (1983) performed melting experiments under different conditions (e.g., not under atmospheric pressure, but under near vacuum conditions), using Tertiary sands as precursor material (which, as cited above, contain up to 12 wt % H_2O) and found no water at all in the resulting glasses. In conclusion, we feel that all these results clearly support the impact model, or pose no contradiction to it, and it seems more appropriate to seek to improve the glass-making theory.

SUMMARY

We have measured the water content of 11 tektite and impact glass samples and have been able to show that Muong Nong type tektites have a higher average water content than splash-form tektites from the same strewn field. This is consistent with the analyses of volatile trace elements in Muong Nong tektites that we report. Impact glasses from the Zhamanshin crater also show a clear connection between the water content and volatile element content, and homogeneity, and thus follow a genetic sequence. Impact glasses generally have a higher water content than tektites. This is a further indication that the processes leading to the production of tektites are similar to the processes leading to impact glasses, but have probably been at least an order of magnitude more violent, in agreement with what we know from the chemistry and petrology. The water content of tektites is in full agreement with the terrestrial impact model.

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