Exploration of tektite formation processes through water and metal content measurements

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Abstract–Impact events are a significant surface-modifying process on solar system objects lacking frequent resurfacing by atmospheric or igneous processes. To better explore the effects of impacts on surface materials, we measured the water and trace element compositions of tektites from Da Lat, Vietnam. Fourier transform infrared spectroscopy was used for water measurements and laser ablation inductively coupled plasma mass spectrometry was used for trace element measurements. Consistent with previous investigations of tektites, we found that the samples are depleted in volatile metals (e.g., Zn, Pb) as well as in water compared with the average continental crust, although water contents are still extremely high for rocks melted at atmospheric pressure. While Zn and Pb concentrations are linearly correlated with each other, there is no correlation between H_2O and Zn or Pb contents. Combined with water contents of other tektites in the Australasian strewn field, our results demonstrate that the source impact occurred at a wet site in or off the coast of the Indochina peninsula.

INTRODUCTION

Tektites are impact-associated glasses (Koeberl 1986) which have major element compositions similar to continentally derived crustal rocks on Earth (Urey 1955) and are thus interpreted to be melts of crustal material ejected from the site of the impact of an extraterrestrial object (Shaw and Wasserburg 1982). Tektites, aside from those of the Muong Nong type (Koeberl 1992), are extremely depleted relative to Earth's crust in volatile elements and species, such as Zn and H_2O (Koeberl 1986; Beran and Koeberl 1997; Moynier et al. 2009, 2010). Because of their origin as the products of extreme heating and volatile depletion, tektites may provide insights into the nature of impact events. For example, the degree to which elements of different volatilities are depleted may provide constraints on the temperature and duration of heating (Moynier et al. 2009).

A number of studies have already investigated tektite elemental compositions (Friedman 1958; Beran and Koeberl 1997; Moynier et al. 2009), but most have focused on fingerprinting the source rock (Tilton 1958; Taylor 1966; Glass 1990; Blum et al. 1992; Chaussidon and Koeberl 1995; Ferriere et al. 2010) rather than deciphering the origin of volatile element depletion. Recently, the mechanisms of volatile element depletion have been addressed through the volatile elements Zn and Cu based on isotope fractionation (Moynier et al. 2009, 2010). Highly fractionated Zn and Cu isotopes were interpreted by the authors to reflect diffusion-limited evaporation from the tektite. Tektite formation mechanisms have also been investigated by considering their macroscopic shapes in the context of droplet formation and breakup during projectile motion (Elkins-Tanton et al. 2003). Determination of the composition of bubbles within tektites has also been attempted (O'Keefe et al. 1962). As far as we know, a systematic study relating volatile metal and water concentrations has not yet been performed.

Here, we present H_2O concentration data on five tektite samples alongside Zn and Pb concentration data on 46 laser ablation spots from 19 tektite samples and

compare the degree of volatile depletion based on these elements and species. The relationships with Pb and H_2O, the former less volatile than Zn and the latter more so (Robie et al. 1979), will be used to better constrain the conditions of evaporation.

As the source crater for the Australasian strewn field has not been found, data narrowing its possible locations are important. We present a comparison of water concentrations from our tektite samples with previously measured samples from other regions of the strewn field. Combined with [10]Be data (Ma et al. 2004), we are able to more robustly constrain possible locations of the source crater.

SAMPLE DESCRIPTION

The tektites used were collected in Da Lat, Vietnam, in the Australasian strewn field, the source crater of which remains undetermined, although the event is dated at 0.78 million years ago (Kunz et al. 1995). Larger samples exhibit rotation-induced shapes (Elkins-Tanton et al. 2003), but smaller specimens are often elongated or amorphous. No crazing, patters of cracks on cooled vitreous surfaces, as seen in layered tektites from the Australasian strewn field (Futrell 1986), was observed. All the examined tektites exhibit some level of flow banding—alternating light and dark brown bands—but the intensity of banding varies widely. Figure 1A shows flow lines oriented normal to the surface of the tektite, but in other instances flow lines give the surface the appearance of a no-flow boundary.

In addition to flow banding, all of the samples include bubbles, both in the swarms illustrated above and as isolated bubbles, as shown in Fig. 1B. Most of the bubbles are small (<50 μm diameter) and fairly spherical, although larger bubbles more deformed by shear are also present. A few unusually large bubbles exhibit saucer or platter shapes and in some cases have dimensions larger than the thickness of the sections (approximately 1 mm). Bubbles <10 μm diameter are usually found in swarms which are generally around 100 μm across, slightly larger than individual bubbles and are composed of approximately 10–100 bubbles of widely varying sizes. A few small swarms of less than 10 bubbles also exist, usually composed of one large bubble with very small bubbles scattered around it.

The tektites are visibly free of crystals under a microscope at 40× magnification, but several samples do contain swarms of small bubbles which may have formed from nucleation around a microlite, as shown in Fig. 1C. Frequently, flow lines are found in large parallel groups, but individual lines curving and in some cases completely reversing direction are also present. Figure 1D shows a particularly active location, with some deformed and
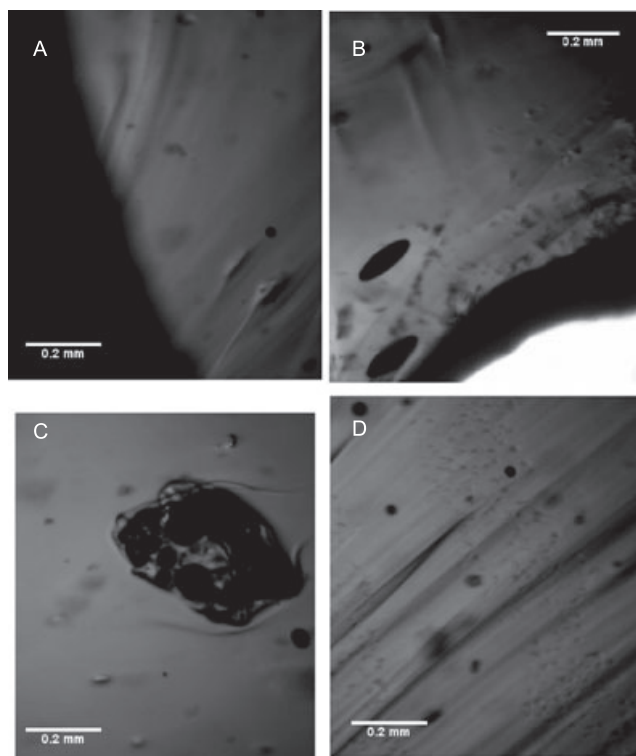

Fig. 1. Photomicrographs of areas of interest from tektite 04b. A) Flow banding exiting through sample wall. B) Large saucer-shaped bubbles. C) Swarm of bubbles with a wake. D) Complicated flow patterns in heavily banded region.

some spherical bubbles and flow lines curving and disappearing. The tektites are approximately 70% silica by weight, ranging from 73.8% to 68.24%.

MATERIALS AND METHODS

All work was performed at the Rice University Department of Earth Science, Houston, Texas. We used Fourier Transform Infrared spectroscopy to determine water contents in glasses (Newman et al. 1986). A polychromatic infrared beam is modulated with an interferometer and passed through the sample (Libowitzky and Beran 2004). Light of specific infrared wavelengths is capable of causing vibrations in molecules, including H_2O and OH groups, resulting in absorption of light of those wavelengths in proportion to the path-integrated molecular amount of water (Beran et al. 2004).

Thin slices, approximately 1 mm thick, were cut from five tektites using a Beuhler Isomet low-speed saw. These slices were polished on both sides using 1 μm grit and infrared spectra were taken from points of interest with a Thermo Electron Nicolet Continuum FT-IR microscope. To obtain the spectra, a background (air) spectrum was first obtained and subtracted from the
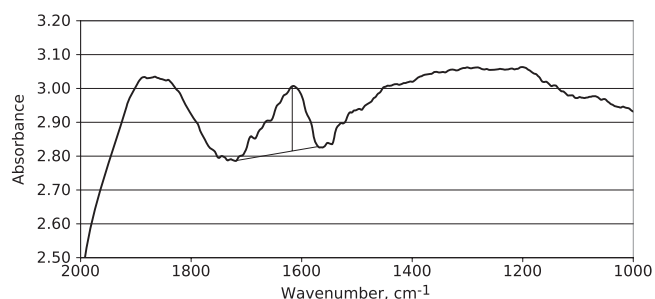
Fig. 2. Determination of peak height for tektite 02. Line is a 10-measurement moving average.

Fig. 3. Ten-measurement moving average of spectra of all five tektites. Slight peak dislocations from 1630 cm^{-1} are assumed to be due to matrix effects.

spectra of tektite sections. The infrared beam size was 100×100 μm. Water contents were determined from interpretation of the 1630 cm^{-1} absorption band, using absorbance values determined by Newman et al. (1986) plugged into Beer's Law,

$$c = \frac{18.02a}{\rho d \varepsilon} \qquad (1)$$

where c is the concentration of the species (in this case H$_2$O) in weight percent, a is the absorbance measured using the FTIR spectrometer, ρ is the density of the sample in g L^{-1}, assumed to be 2300 g L^{-1}, which is typical of rhyolitic glass (Newman et al. 1986), d is the polished section's thickness in centimeters, and ε is the molar absorptivity in L/(mol $\times$ cm). Absorbance was determined by calculating the height of the largest peak in the 1630 cm^{-1} region above a baseline defined by linear interpolation between the shoulders of the peak. The peaks used in infrared spectrometry move slightly because of matrix composition; for example, the 3570 cm^{-1} peak identified by Newman et al. (1986) is shifted in silica glass (Tomozawa et al. 2001). To reduce noise, 10-measurement moving averages were used instead of the original spectra. An example measurement is shown in Fig. 2. All five spectra are shown in Fig. 3. Sample thickness was measured with a micrometer. Detection limits ranged from 0.0057% to 0.0084% (3σ).

Laser ablation measurements were carried out on a ThermoFinnigan Element 2 single collector magnetic sector ICP-MS coupled to a 213 nm New Wave laser. Samples were ablated with an energy flux of 16–18 J cm^{-2} at a 10 Hz repetition rate and a spot 55 μm in diameter. ^{66}Zn was determined in medium mass resolution mode (m/Δm approximately 3000) and ^{208}Pb in low mass resolution (m/Δm approximately 300). Long-term magnetic drift in medium mass resolution was corrected for during every run by centering on the ^{40}Ar^{40}Ar dimer. Hysteresis effects in medium mass resolution were accounted for by applying specific offsets to each mass analyzed. These effects were not important
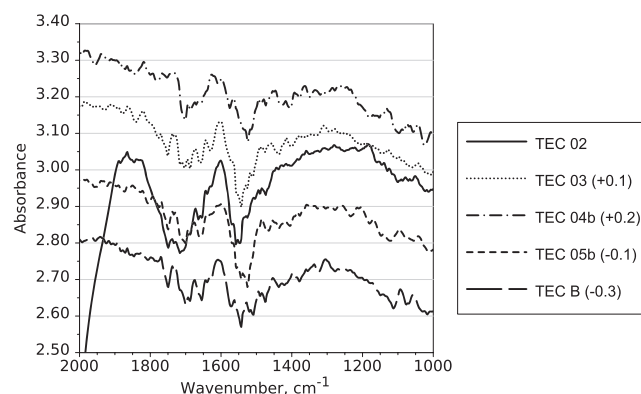
for low mass resolution mode. Signal intensities were converted to concentration by first correcting for internal drift using an internal normalization standard (^{30}Si) and then by external normalization to international standards (USGS BHVO-1g and BIR-1g). Detection limits were 0.5 ppm for both Zn and Pb.

RESULTS

Measured water contents are listed in Table 1. The average water content of our tektites was 0.0209 ± 0.0035% by weight. A comparison of our water contents with those given by Beran and Koeberl (1997), shown in Fig. 4, demonstrates that our results are consistent with previous measurements of tektite water contents from the Australasian strewn field. However, we note that water contents, including ours, from the Australasian strewn field are slightly higher than those found in other strewn fields (Beran and Koeberl 1997). No correlations between flow band frequency, bubble frequency, and water content were observed.

As shown in Fig. 5, Zn and Pb are highly correlated ($R^2 = 0.89$). The Pb (1–9.6 ppm) and Zn (2–18.9 ppm) contents of the tektites are highly depleted compared with upper continental crust (Pb approximately 17 ppm and Zn approximately 67 ppm; Rudnick and Gao 2003), which we take as an approximate target/protolith composition of the tektites. Curiously, we also find that the Pb/Zn ratio of the tektites (0.49) is higher than that of upper continental crust (0.25) and primitive mantle (0.00273; McDonough and Sun 1995). The increased Pb/Zn ratio is assumed to be due to differential volatilization, as Zn is more volatile than Pb (Robie et al. 1979). There is no correlation between water contents and Zn or Pb concentrations ($R^2 \leq 0.1$), as shown in Fig. 6.

Finally, motivated by studies attempting to locate the source crater of the Australasian strewn field from

Table 1. Table of results. Samples are homogeneous.

Sample	TEC01a		TEC01b		TEC02			2TEC03	TEC03	
Spot	1	2	1	2	1	2	3	1	1	2
SiO$_2$, wt%	73.86	70.22	70.39	71.51	73.42	71.49	69.09	69.30	73.82	70.02
Zn, ppm	5.9	7.8	8.6	8.2	6.6	6.6	8.6	5.4	9.2	10
Pb, ppm	3.6	4.5	4.4	3.8	3.5	2.7	4.8	3.0	4.6	5.0
H$_2$O, wt%	No data		No data		0.0431			No data	0.0185	

Sample	TEC04a			TEC05a			TEC06		
Spot	1	2	3	1	2	3	1	2	3
SiO$_2$, wt%	73.02	72.96	72.22	71.18	69.85	71.25	70.56	68.24	69.24
Zn, ppm	10	13	15	9.9	13	14	8.9	8.9	10
Pb, ppm	5.0	4.8	8.3	5.6	6.0	4.7	4.6	4.2	4.8
H$_2$O, wt%	No data			No data			No data		

Sample	TEC07a		TEC07b		TEC08		TEC09	
Spot	1	2	1	2	1	2	1	2
SiO$_2$, wt%	72.28	72.38	70.77	71.81	70.98	70.50	69.76	73.01
Zn, ppm	7.5	11	16	12	6.9	9.2	9.0	8.0
Pb, ppm	4.4	4.2	8.1	5.3	3.7	3.9	5.0	4.0
H$_2$O, wt%	No data		No data		No data		No data	

Sample	TEC10a				TEC10b		TEC04b		TEC05b	
Spot	1	2	3	4	1	2	1	2	1	2
SiO$_2$, wt%	68.76	70.89	70.47	71.64	68.28	72.17	69.76	71.13	71.97	71.92
Zn, ppm	6.9	10	6.7	8.1	5.2	5.7	5.5	10	19	19
Pb, ppm	3.1	4.1	3.3	3.9	3.3	3.8	2.4	5.9	9.6	9.3
H$_2$O, wt%	No data				No data		0.0121		0.0175	

Sample	TECA			TECB		TECC	TECD		
Spot	1	2	3	1	2	1	1	2	3
SiO$_2$, wt%	73.65	70.11	70.33	70.66	70.72	69.46	71.98	72.02	70.27
Zn, ppm	2.3	3.9	2.8	3.6	6.6	11	3.9	2.4	4.2
Pb, ppm	1.5	1.8	1.7	1.2	2.8	5.0	2.0	1.4	1.4
H$_2$O, wt%	No data			0.133		No data	No data		

variations in the [10]Be activity of tektites from different localities within the strewn field (Ma et al. 2004), we compare average water contents of tektites sampled from various localities in the Australasian strewn field. While there are significant gaps in the water data, it appears that tektite water content decreases with distance from Indochina, as shown in Fig. 7. This is consistent with work showing decreasing Na and K content with distance from Indochina (Folco et al. 2010).

DISCUSSION

Because Zn, Pb, and water are all volatile, we had anticipated that water contents would correlate with Zn and Pb concentrations. Moynier et al. (2009, 2010) suggested that volatile metals were lost from the tektites by a combination of internal circulation, outward diffusion, and evaporation at the tektite surface. We thus expected to see differences in water content varying with flow structure if the mechanism of water and volatile metal loss were identical. As there is no correlation between metal and water contents, it is very unlikely that the process which removed the volatile species could also have removed water from the tektite. Although circulation within the molten mass of ejecta is thought to be an important process for removal of volatile metals according to Moynier et al. (2009), the lack of any systematic variation of water content with Zn or flow banding frequency, suggests the low water concentrations must be explained by other processes.

Because metal depletion does not appear to correlate with water depletion, it is possible that water in the molten tektites was buffered by water vapor in bubbles within the molten rock and/or in a hot, moist enveloping cloud formed during impact. However, given the lack of correlation between bubble frequency and water content, along with earlier studies which did not find water vapor or condensed water droplets in tektite bubbles (O'Keefe et al. 1962), it seems unlikely that water present in the bubbles could have buffered water dissolved in
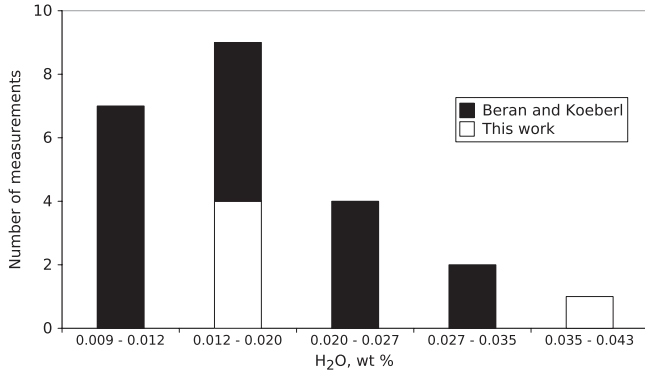
Fig. 4. Comparison of water contents from the five tektites examined in this work with measurements of Australasian strewn-field tektite water contents from Beran and Koeberl (1997).
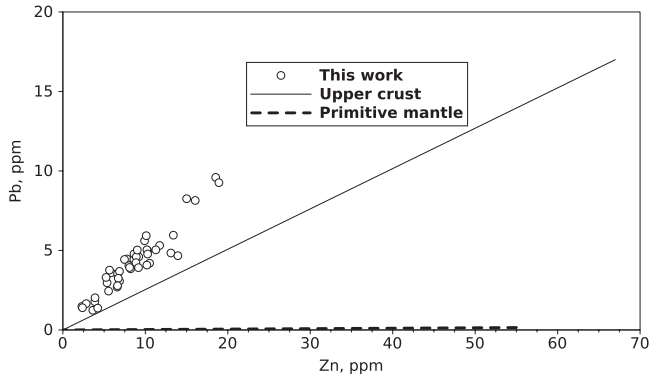

Fig. 5. Measured Zn and Pb concentrations, with primitive mantle (McDonough and Sun 1995) and upper continental crust (Rudnick and Gao 2003) ratios for comparison. Samples are catalogued in Table 1.

the molten material. We thus speculate that water in the immediate atmosphere in the ejecta cloud from which the tektites emerged must have slowed or buffered exsolution of dissolved water from the tektites. If this interpretation is correct, it is reasonable to speculate that the impact site of the Australasian strewn field may have been in a wet or aqueous environment. As stated in the Results section, this is consistent with the fact that tektites from the Australasian strewn field have systematically higher water contents than those from other strewn fields.

As rocks melted by impacts on rocky worlds without atmospheres would not be buffered by a volatile cloud, it is possible that despite significant volatile contents in rocks of primitive composition, such as on the Moon (Saal et al. 2008), those altered by impacts would have negligible volatile contents, significantly reducing the volatile content of the surface of a highly cratered body.

We now assess whether the measured water concentrations are plausible at conditions expected in the
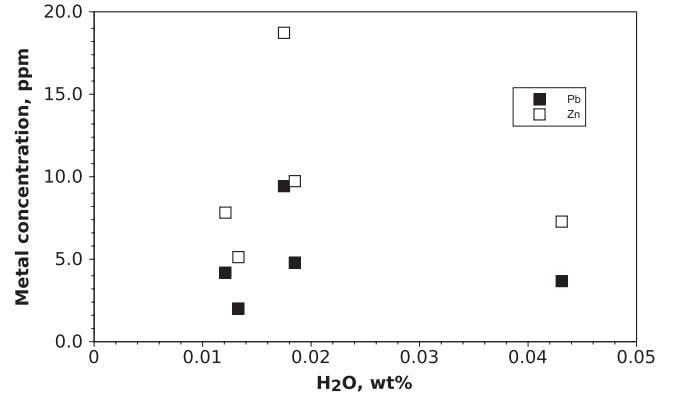

Fig. 6. Water contents compared with Zn and Pb concentrations.

vapor cloud associated with an extraterrestrial impact, essentially, 1 atm (101.325 MPa) pressure and very high temperatures ($>1400\,°C$). Using a model for water solubility in rhyolitic liquids at low pressures (Liu et al. 2005), the equation for water concentration in molten rhyolitic rock at equilibrium is:

$$C = \frac{354.94\sqrt{P_w} + 9.623P_w - 1.5223P_w^{3/2}}{T}$$
$$+ 0.0012439P_w^{3/2}$$
$$+ P_{CO_2}(-1.804x10^{-4}\sqrt{P_w} - 1.362x10^{-5}\sqrt{P_w}) \quad (2)$$

where C is the weight percent of water in the molten rock, P_w is the partial pressure of water (MPa) in the system, T is the temperature in Kelvin, and P_{CO_2} is the partial pressure of CO_2. Assuming negligible CO_2, i.e., $P_{CO_2} = 0$, Equation 2 becomes

$$C = \frac{354.94\sqrt{P_w} + 9.623P_w - 1.5223P_w^{3/2}}{T}$$
$$+ 0.0012439P_w^{3/2} \quad (3)$$

As tektites are exposed to the atmosphere during their formation, and $P_w = X_w P$, where X_w is the mole fraction of water in the atmosphere and P is the total gas pressure, $P_w = X_w * 0.101325$ MPa, assuming a sea level impact. Substituting for P_w yields

$$C = \frac{112.983\sqrt{X_w} + 0.97505X_w - 0.049099X_w^{3/2}}{T}$$
$$+ 4.012^*10^{-5}X_w^{3/2} \quad (4)$$

This equation shows that water solubility, C, decreases rapidly with increasing T and increases with increasing

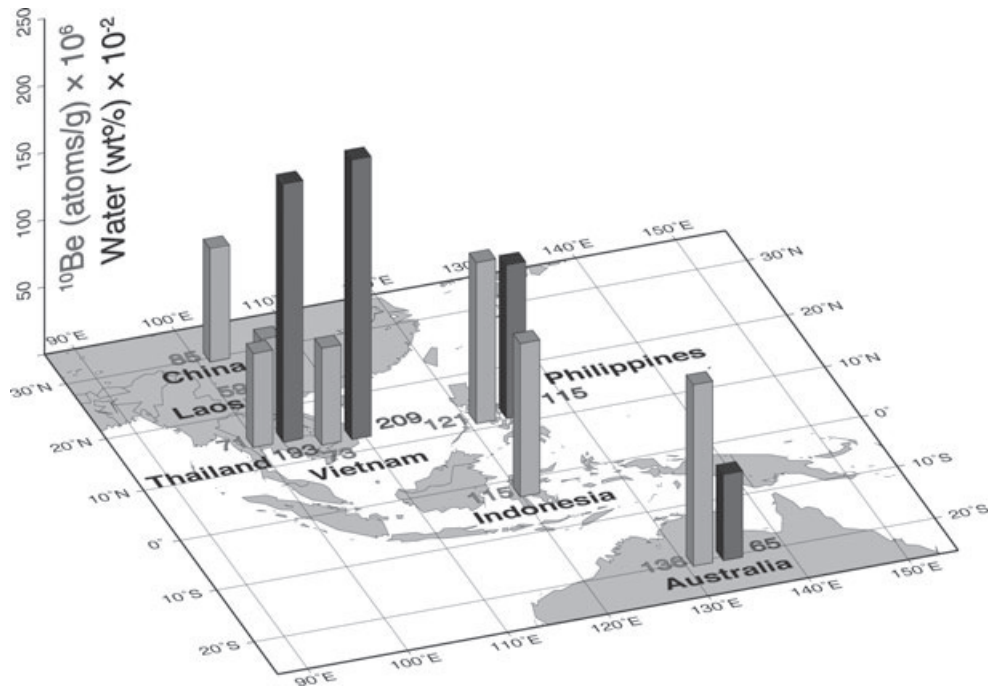Fig. 7. Comparison of [10]Be levels in Australian tektites (Ma et al. 2004) and water levels from this work and the literature (Beran and Koeberl 1997; Koeberl 1992).
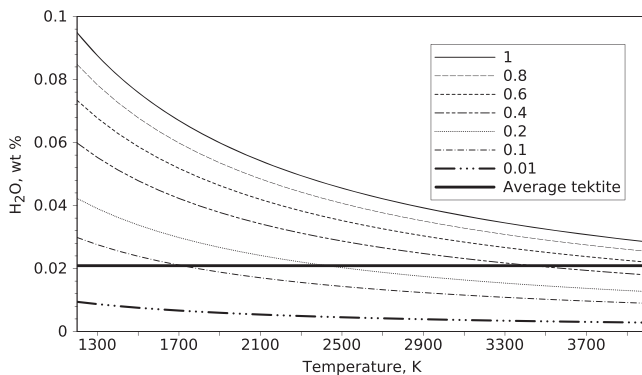

Fig. 8. Water solubility lines (curved) for various mole fractions of water vapor in the immediate atmosphere of the impact site compared with average measured water contents in the tektites.

X_w. For a given temperature and total pressure, maximum solubility of course occurs when $X_w = 1$. We have extrapolated our calculations to temperatures far beyond the quoted validity (< 1473 K) of the model of Liu et al. (2005), so our calculations are at best qualitative, but nonetheless predict the sense of how solubility changes with temperature, as shown in Fig. 8. At the temperatures required for vapor fractionation during the short duration of the formative event—in the range of 3000 K (Walter and Clayton 1967)—an X_w of approximately 0.3 is required to explain the water

contents in our tektites, assuming equilibrium between vapor and tektite. Although equilibrium is certainly not guaranteed, disequilibrium effects would only require higher values of X_w to implant water into the tektites. This suggests an enormous quantity of water vapor at the impact site.

At the very high temperatures experienced by tektites, most of the hydrogen dissolved in the melt would be in the form of OH (Stolper 1982), so our measurements may not show total water contents. However, given that the equilibrium constant for water speciation should be a function of melt composition (Stolper 1982), which can reasonably be assumed to be constant across our samples, our estimated H_2O contents should be considered minimum bounds on the total water content of the tektites.

Previous work on the origin of the Australasian strewn field (Glass and Barlow 1979; Blum et al. 1992; Chaussidon and Koeberl 1995; Ma et al. 2004) concluded that the impact likely occurred in a region of silty sediments and/or sedimentary rocks. Ma et al. (2004) suggested that the impact site was in northeastern Thailand or off the coast of eastern Vietnam based on geographic variation in the [10]Be activity of the tektites within the strewn field. They observed that [10]Be activity increased with increasing distance from the purported impact site and suggested that this could be explained if the stratigraphically highest layers of sediment at the

impact site, which would have contained the most [10]Be, were thrown the furthest from the impact, i.e., to Australia.

Our high water contents suggest that the impact site must have been wet to generate a water-rich ejecta cloud. We speculate that water contents in the tektites during formation were homogenized by melting at very high temperatures in a very wet local atmosphere generated at the impact site. As they were still very hot while flying through the atmosphere, those that were thrown the furthest spent more time flying through ambient air of normal (dry) composition, resulting in subsequent diffusive loss of water because the ambient atmosphere no longer buffered the water activity. Those that were not ejected very far spent a greater proportion of their time within the ejecta vapor cloud near the impact site. Far-traveled ejecta may have thus had a longer time to lose water, whereas the tektites which fell close to the impact site had less time to lose water, retaining the high water contents from their formation in a cloud of water vapor above the impact site.

While diffusion of Zn and, presumably, Pb is slower ($< 10^{-10}$ m s^{-2}) (Moynier et al. 2010) than the diffusion of heat in silicate liquid ($> 10^{-6}$) (Bagdassarov and Dingwell 1994), this does not render implausible the scenario of diffusion-controlled (Moynier et al. 2009, 2010) escape of volatiles while the tektite is molten. In the upper atmosphere, a tektite will be thermally insulated by the lack of material around it to absorb heat from the tektite; meanwhile, evaporation of volatile species (e.g., water) from the surface of the tektite will still occur owing to their low vapor pressure in the upper atmosphere. While radiation would remove some heat, clearly the tektites remained sufficiently hot to be found as glass rather than crystallized objects across the entire strewn field. We thus envision three stages in the short (Moynier et al. 2009) flight of a tektite (1) ejection and lower atmosphere contact, where metals evaporate freely but water evaporation from the tektite is limited by the high water vapor pressure due to volatilization by the heat of the impact, (2) flight through upper atmosphere, where low pressures retard cooling and encourage evaporation of water, (3) re-entry and quenching upon impact. Evidence that tektites from the Australasian field remained molten in flight is provided by the finding of decrease in Na and K with increasing distance all the way to the Transantarctic Mountains (Folco et al. 2010).

CONCLUSIONS

There is no correlation between water depletion and volatile metal (Zn, Pb) depletion in the sampled tektites.

Therefore, different processes are required to explain the water and volatile metal content in tektites. High water content is due to implantation of water from water vapor-rich ejecta clouds while low Zn and Pb contents are due to volatile loss. In other words, the water content of the tektites may have been buffered by the water in the ejecta cloud, whereas Zn and Pb are depleted because the vapor cloud was free of Zn and Pb. We conclude that the Australasian strewn field was created by an impact at a site sufficiently wet to raise the concentration of water vapor in the air. Tektite water content within the Australasian strewn field decreases with distance from the general area of the presumed impact site. This is expected because, as the tektite travels further from its impact site, it leaves its water-rich ejecta cloud and enters ambient and dry atmosphere.

Editorial Handling—Dr. Christian Koeberl

REFERENCES

Bagdassarov N. and Dingwell D. 1994. Thermal properties of vesicular rhyolite. *Journal of Volcanology and Geothermal Research* 60:179–191.

Beran A. and Koeberl C. 1997. Water in tektites and impact glasses by Fourier-transformed infrared spectrometry. *Meteoritics & Planetary Science* 32:211–216.

Beran A., Voll D., and Schneider H. 2004. IR spectroscopy as a tool for the characterisation of ceramic precursor phases. In *EMU notes in mineralogy*, edited by Beran A. and Libowitzky E. Budapest, Hungary: Eötvös University Press. pp. 189–226.

Blum J. D., Papanastassiou D. A., Koeberl C., and Wasserburg G. J. 1992. Neodymium and strontium isotopic study of Australasian tektites: New constraints on the provenance and age of target materials. *Geochimica et Cosmochimica Acta* 561:483–492.

Chaussidon M. and Koeberl C. 1995. Boron content and isotopic composition of tektites and impact glasses: Constraints on source regions. *Geochimica et Cosmochimica Acta* 593:613–624.

Elkins-Tanton L., Aussillos P., Bico J., Quere D., and Bush J. 2003. A laboratory model of splash-form tektites. *Meteoritics & Planetary Science* 389:1331–1340.

Ferriere L., Koeberl C., Thoni M., and Liang C. 2010. Single crystal U–Pb zircon age and Sr–Nd isotopic composition of impactites from the Bosumtwi impact structure, Ghana—Comparison with country rocks and Ivory Coast tektites. *Chemical Geology* 275:254–261.

Folco L., Glass B. P., D'Orazio M., and Rochette P. 2010. A common volatilization trend in Transantarctic Mountain and Australasian microtektites: Implications for their formation model and parent crater location. *Earth and Planetary Science Letters* 293:135–139.

Friedman I. 1958. The water, deuterium, gas and uranium content of tektites. *Geochimica et Cosmochimica Acta* 14:316–322.

Futrell D. 1986. Buried crazed layers in Australasian Muong Nong-type tektites. *Journal of Non-Crystalline Solids* 86:213–218.

Glass B. P. 1990. Tektites and microtektites: Key facts and inferences. *Tectonophysics* 171:393–404.

Glass B. P. and Barlow R. A. 1979. Mineral inclusions in Muong Nong-type indochinites—Implications concerning parent material and process of formation. *Meteoritics* 14:55–67.

Koeberl C. 1986. Geochemistry of tektites and impact glasses. *Annual Review of Earth and Planetary Sciences* 14:323–350.

Koeberl C. 1992. Geochemistry and origin of Muong Nong-type tektites. *Geochimica et Cosmochimica Acta* 56:1033–1064.

Kunz J., Bollinger K., Jessberger E. K., and Storzer D. 1995. Ages of Australasian tektites (abstract). 26th Lunar and Planetary Science Conference. pp. 809–810 .

Libowitzky E. and Beran A. 2004. IR spectroscopic characterisation of hydrous species in minerals. In *EMU notes in mineralogy*, edited by Beran A. and Libowitzky E. Budapest, Hungary: Eötvös University Press. pp. 227–279.

Liu Y., Zhang Y., and Behrens H. 2005. Solubility of H_2O in rhyolitic melts at low pressures and a new empirical model for mixed H_2O-CO_2 solubility in rhyolitic melts. *Journal of Volcanology and Geothermal Research* 143:219–235.

Ma P., Aggrey K., Tonzola C., Schnabel C., de Nicola P., Herzog G. F., Wasson J. T., Glass B. P., Brown L., Tera F., Middleton R., and Klein J. 2004. Beryllium-10 in Australasian tektites: Constraints on the location of the source crater. *Geochimica et Cosmochimica Acta* 68:3883–3896.

McDonough W. F. and Sun S.-S. 1995. The composition of the Earth. *Chemical Geology* 120:223–253.

Moynier F., Beck P., Jourdan F., Yin Q.-Z., Reimold U., and Koeberl C. 2009. Isotopic fractionation of zinc in tektites. *Earth and Planetary Science Letters* 277:482–489.

Moynier F., Koeberl C., Beck P., Jourdan F., and Telouk P. 2010. Isotopic fractionation of Cu in tektites. *Geochimica et Cosmochimica Acta* 74:799–807.

Newman S., Stolper E., and Epstein S. 1986. Measurement of water in rhyolitic glasses: Calibration of an infrared spectroscopic technique. *American Mineralogist* 71:1527–1541.

O'Keefe J., Lowman P., and Dunning K. 1962. Gases in tektite bubbles. *Science* 137:228.

Robie R. A., Hemingway B. S., and Fisher J. R. 1979. *Thermodynamic properties of minerals and related substances at 298.15 K and 1 bar (105 Pascals) pressure and at higher temperatures*. Washington, D.C.: United States Government Printing Office. 456 p.

Rudnick R. L. and Gao S. 2003. Composition of the continental crust. In *The crust*, edited by Rudnick R. L., Holland H. D., and Turekian K. K. Treatise on Geochemistry, vol. 3. Amsterdam: Elsevier, Ltd. pp. 1–64.

Saal A., Hauri E., Cascio M. L., Orman J. V., Rutherford M., and Cooper R. 2008. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. *Nature* 454:192–195.

Shaw H. F. and Wasserburg G. J. 1982. Age and provenance of the target materials for tektites and possible impactites as inferred from Sm-Nd and Rb-Sr systematics. *Earth and Planetary Science Letters* 60:155–177.

Stolper E. 1982. The speciation of water in silicate melts. *Geochimica et Cosmochimica Acta* 46:2609–2620.

Taylor S. R. 1966. Australites, Henbury impact glass and subgreywacke: A comparison of the abundances of 51 elements. *Geochimica et Cosmochimica Acta* 30:1121–1136.

Tilton G. R. 1958. Isotopic composition of lead from tektites. *Geochimica et Cosmochimica Acta* 14:323–330.

Tomozawa M., Kim D.-L., and Lou V. 2001. Preparation of high purity, low water content fused silica glass. *Journal of Non-Crystalline Solids* 296(1–2):102–106.

Urey H. 1955. On the origin of tektites. *Proceedings of the National Academy of Sciences* 41:27–31.

Walter L. and Clayton R. 1967. Oxygen isotopes: Experimental vapor fractionation and variations in tektites. *Science* 156:1357–1358.