

***Constraining the Thermal History of Tektites by Matching Temperature Dependent Silica
Diffusion Models to the SiO₂ Diffusion Profiles of Lechatelierite Inclusions***

by

Nora Shapiro

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Abstract

Tektites, a rare melt-ejecta product from impact cratering events, have a formation process that is poorly understood. Different models of formation have been proposed that assume thermal histories of tektites, but there has been little physical evidence to validate these models. Macris et al. (2018) utilized lechatelierite inclusions, which are high temperature, shock-melted quartz inclusions found within tektites, and their diffusion profiles to constrain the expected thermal history of tektites. They utilized an effective binary diffusion model of SiO₂ to match their concentration data of indochinite tektite sample LTS1 to a diffusion profile, then estimated the thermal history. Since that paper, Yu et al. (2019), has proposed a new temperature dependent model of SiO₂ diffusion. This thesis combines forward modeling of tektite cooling in air with that of temperature-dependent and concentration-dependent SiO₂ diffusion, and applies the modeling to the SiO₂ profiles found in the Macris et al. (2018) paper. The updated silica-diffusion model matches the Macris et al. (2018) diffusion profiles with less time heating at the initial temperature: ~42s rather than ~70s. Additionally, the maximum initial temperature before cooling of the LTS1 tektite can be constrained to approximately 2650K. The results provide constraints on the thermal history of tektites as well as hydrocode modeling of the impact process. In addition, the method developed here may be applied to investigate other tektites from other strew fields.

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1. Introduction

Impact cratering events are ubiquitous geologic events for every rocky planetary body studied and can provide insight into a planet's subsurface. However, the exact mechanisms and process for impact cratering is still unclear to geologists, as a major impact cratering event are unlike other Earth processes, and, indeed, would be dangerous to witness were one to have occurred during recorded human history.

The currently understood impact process is divided into three stages that occur on the order of seconds to minutes (Melosh, 1980, 1989; Osinski and Pierazzo, 2012). The first stage is the contact and compression stage, where the impactor penetrates the target's surface and the resulting shock waves, then rarefaction, vaporizes the projectile itself. During the second stage, excavation, the shock waves expand through the target material and thus excavate and displace material in the transient cavity. In the final stage, the crater is modified depending on the planet's gravity, lithology, and impactor size, possibly creating uplift of the crater floor, collapsing of steep walls, and faulting.

Another poorly understood process of cratering is the formation of tektites, millimeter to centimeter-sized impact melt ejecta with extremely low water content that are found up to thousands of kilometers away from the impact site in strewn fields. Tektite strewn fields have only occurred in 4 of the 155 identified terrestrial craters (Glass, 1990; Osinski and Pierazzo, 2012), and it is unclear as to what specific conditions of impact cratering allow for tektite formation to occur.

The origin of tektites has been heavily debated and were originally hypothesized to be from the Moon but are now thought to likely be ballistically ejected impact glass, formed early in the cratering process, from higher velocity impacts (Koeberl, 1986) with impact angles between 30 and 50 degrees (Howard, 2011).

Tektite composition indicates shale-like, quartz rich target materials (Koeberl, 1986). The ballistic trajectories of tektites indicate hypervelocity excavation. Hypervelocity excavation is hypothesized to occur during unique melt conditions, where the original tektite material is heated to extreme temperatures - higher than 2000°C - due to the initial shock wave from the impact, then is ejected in a high-pressure vapor and melt cloud due to depressurization after the shock wave passes through the material (Howard, 2011). This material is likely formed early in the excavation stage, as it does not mix with cooler target material to form impact breccias or other impact melts (Howard, 2011).

From the 4 known tektite fields studied, typical parameters such as target rock composition and impactor size, do not seem to control whether tektites are formed during an impact. However, its possible that, in addition to the conditions required to produce a hypervelocity excavation, there may have been a water-rich surface layer of sediment (Howard, 2011).

Previous models on impact events assumed a tektite temperature history without quantitative constraints to validate their models (Stoffler, 2002). However, the thermal history of a tektite is complex, and will vary based on the impactor, the impact angle, the composition of

the target, the ejecta plume, and other factors (Artemieva, 2002; Artemieva et al., 2004; Johnson and Melosh, 2014). The work in Macris et al. (2018) thus utilizes the presences of lechatelierite inclusions in tektites, a silica polymorph formed at temperatures greater than 1700°C, and their diffusion profiles into the largely rhyolitic tektite composition to further constrain the likely thermal history of tektites.

Since Macris et al. (2018) was published, there has been new work on how silica diffusion profiles are both compositionally and temperature dependent. This thesis looks to refine the thermal histories of the tektites studied in Macris et al. (2018) using Yu et al. (2019) silica diffusion relationship with temperature.

2. Methods

A dimensionless, transient cooling model of a rhyolitic sphere and temperature dependent silica diffusion model were combined so that one could input the assumed starting temperature of the tektite, the assumed duration that the tektite maintained the initial starting temperature, and the location of a lechatelierite inclusion to compute the length of the SiO₂ diffusion profile.

2.1 Tektite Cooling Model

Using the approximations that tektites are relatively spherical and have thermal properties similar to rhyolite (the composition reported for sample LTS1 in Macris et al., 2018), the tektite was modeled as a rhyolite sphere that cooled by flying in air, experiencing both conduction through its liquid and solid body and convection on its exterior. This transient temperature profile of the tektite is modeled through the following partial differential equation (PDE) assuming constant thermal diffusivity.

$$\frac{drT(r,t)}{dt} = \alpha \frac{d^2 rT(r,t)}{dr^2} \quad (1)$$

In Equation 1, r is the distance from the center of the sphere and constrained between 0 and r_0 , the outer radius of the sphere (m), t is the time (s), and T is the temperature (K) which is a function of r and t . α is the thermal diffusivity. The thermal diffusivity for rhyolite (typical tektite composition) varies with temperature from $\sim 2 * 10^{-6} \left(\frac{m^2}{s}\right)$ at room temperature to $\sim 0.6 * 10^{-6} \left(\frac{m^2}{s}\right)$ at 1200°C (Whittington et al., 2009). At temperature $> 800^\circ\text{C}$, α is nearly constant. For simplicity, a constant value of $0.65 * 10^{-6} \left(\frac{m^2}{s}\right)$, which is the average of the high temperature α values, is taken for this study. Neglecting the variation of α with temperature would introduce errors mostly at lower temperatures, which would not significantly affect modeling SiO₂ diffusion profiles because diffusion mostly occurs at high temperatures.

The initial condition of the PDE is $T(r, 0) = T_0$, which assumes the tektite sphere has been heated evenly to the same initial temperature. The two boundary conditions are described below:

$$\frac{dT(r_0,t)}{dr} = -h * \frac{T(r_0,t) - T_\infty}{k} \quad (2)$$

$$|T(0,t)| < T_0 \quad (3)$$

If one defines $V(r, t) = T * r$, the PDE and its boundary conditions become as follows:

$$\frac{dV(r,t)}{dt} = \alpha \frac{d^2V(r,t)}{dr^2} \quad (4)$$

$$\frac{dV(r_0,t)}{dr} = -h * r_0 * \frac{T(r_0,t)-T_\infty}{k} + T(r_0,t) = -h * \frac{(V(r_0,t)/r_0)-T_\infty}{k} + \frac{V(r_0,t)}{r_0} \quad (5)$$

$$V(0,t) = 0 \quad (6)$$

The convective heat transfer coefficient, h ($\frac{W}{m^2K}$), is dependent on the size of the particle flying through a fluid, the type of fluid, speed of the fluid, and temperature of the fluid the sphere is cooling in; for this model for a tektite moving through air, h is assumed to be $200 \frac{W}{m^2K}$ (Xu and Zhang, 2002). T_∞ is the ambient temperature, assumed to be approximately room temperature at 300K. The thermal conductivity, k , is calculated below.

$$k = \alpha * Cp * \rho \quad (7)$$

Cp is the heat capacity of rhyolite liquid at constant pressure, which can be approximated as $1300 \frac{J}{kgK}$ (Lange and Navrotsky, 1992). The density of rhyolite, ρ , is taken as a constant $2400 \frac{kg}{m^3}$ (Lange and Carmichael, 1990).

One can numerically solve for $V(r,t)$, in MATLAB by approximating the differential equation using a finite difference equation. First, the step sizes dx and dt are assigned for radial distance steps and time steps, respectively. The number of nodes considered along the radius of the sphere is the radius of the sphere divided by dx plus one, and the number of time steps is the maximum run time divided by dt . $V(r,t)$ and $T(r,t)$ are initialized as empty matrices with the same number of rows as nodes, and same number of columns as time steps.

The scheme of numerical calculations is as follows. Let i indicate the spatial nodes, and j indicate the time steps. First, the values of T and V at $t = 0$ ($j=0$) at every node (all i 's) are assigned the initial conditions. $V_{i,j+1}$ can then be approximated as such:

$$V_{i,j+1} = V_{i,j} + dt * \alpha * \frac{d^2V(r,t)}{dr^2} \quad (8)$$

Using the second order finite difference numerical approximation method, the second order derivative of $V(r,t)$ is modeled as the following:

$$\frac{d^2V(r,t)}{dr^2} = \lim_{\Delta r \rightarrow 0} \frac{1}{\Delta r^2} (V(r + \Delta r, t) - 2V(r, t) + V(r - \Delta r, t)) \approx \frac{1}{\Delta r^2} (V_{i+1,j} - 2V_{i,j} + V_{i-1,j}) \quad (9)$$

The above equation allows the calculation of V values at all interior nodes. $V(0,t)$ is set to 0 per the boundary condition in equation 6, and the boundary condition in equation 5 is approximated below so that $V_{N_x+1,j+1}$, i.e., V at $r = r_0$ at time step $j+1$, can be calculated.

$$V_{N_x+1,j+1} = \frac{V_{N_x,j+1} + (h * r_0 * T_\infty * \frac{dr}{k})}{1 + (h * \frac{dr}{k}) - \frac{dr}{r_0}} \quad (10)$$

Once $V(r,t)$ is calculated at all nodes, the temperature can then be calculated by dividing $V_{i,j}$ by r_i . However, the temperature at $r = 0$ ($i=1$) must be approximated using extrapolation. A quadratic extrapolation was used as follows:

$$T_{1,j+1} \approx T_{2,j+1} - \frac{T_{3,j+1} - T_{2,j+1}}{3} \quad (11)$$

This model was run at an arbitrary T_0 , T_∞ , and r_0 , to produce a temperature model that assess the temperature at 51 nodes for 300 seconds. This model was then made non-dimensional

by using the relationships described in the equations below and exported, so that one could apply the temperature profile to any initial temperature and tektite size.

$$\theta(r, t) = \frac{T - T_{\infty}}{T_0 - T_{\infty}} \quad (12)$$

$$\tau = t \frac{\alpha}{r_0^2} \quad (13)$$

Figure 1 below illustrates the non-dimensional temperature profile at each node, for a cooling profile that utilizes only 11 nodes for visual clarity. This variability of the thermal model allowed for testing multiple thermal histories for each tektite.

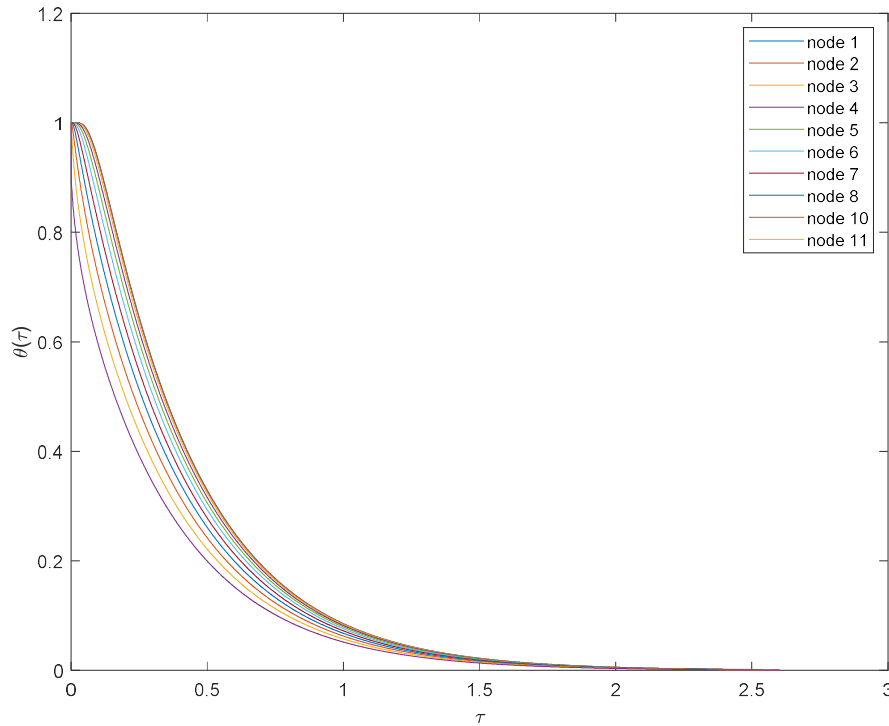


Figure 1: Non-Dimensional Cooling Profile at Each Radial Node

2.2 Silica Diffusion Model

Once the non-dimensional temperature profile was calculated, it could then be applied to the temperature dependent diffusion of SiO_2 between lechatelierite and matrix rhyolite in any part of the spherical tektite. Because the length of the diffusion profile is typically only tens of micrometers, the temperature is defined to be that at the diffusion interface between lechatelierite and matrix glass and the temperature variation along the diffusion profile is ignored. That is, temperature is a function of time only for a given lechatelierite diffusion into the matrix. The SiO_2 diffusivity is related to temperature and SiO_2 concentration in the melt as defined in Yu et al. (2019), shown below

$$D_{\text{SiO}_2} = e^{-7.086 - .09469 \cdot C - \frac{26109 + 28.77 \cdot C}{T}} \quad (14)$$

D_{SiO_2} is the diffusivity of SiO₂ into rhyolite (m²/s), C is the concentration (wt%) of SiO₂.

This equation can be written as the form below if $D_1(T) = e^{-7.086 - \frac{26109}{T}}$, and $a(T) = 0.09469 + \frac{28.77}{T}$.

$$D_{SiO_2} = D_1(T)e^{a(T)*C} \quad (15)$$

The diffusion of SiO₂ between lechatelierite and matrix glass when measured perpendicularly to the long edge of the lechatelierite can be approximated by a one-dimensional diffusion couple. Because SiO₂ diffusivity depends on SiO₂ concentration, the concentration of SiO₂ can be determined through the PDE below.

$$\frac{dC(x,t)}{dt} = \frac{d(D_1(T(t))*e^{a(T(t))C}*\frac{dC(x,t)}{dx})}{dx} \quad (16)$$

In the above equation, x is defined as the length over which diffusion is being considered, t is time, and T is the temperature. The time dependent temperature profile is approximated by inputting the distance of the lechatelierite from the center of the approximated tektite sphere and selecting the temperature profile at the nearest node. To account for possible time at the initial high temperature (that is, after impact melting and before cooling in ambient air), one can append a constant t_0 for any length of time at the beginning of the thermal history, which is useful to investigate potential thermal histories that hypothesize the tektite was heated for some duration and then allowed to cool as modeled in section 2.1.

One can solve for $C(x, t)$ using the finite difference method. To initialize the calculations v (Equation 17 below), a , C , and D_1 are each defined as empty matrices with the number of rows equal to the number of steps being consider over the length of the diffusion profile and columns equal to the number of time steps. At the first time step, C is initialized to be equal to the minimum concentration, or the concentration in the far field tektite, at all x less than 0, and maximum concentration, or the lechatelierite concentration, at all x greater than 0. Due to the dependence of D_{SiO_2} on C , at $x=0$, the interface, C is initialized as 45% minimum concentration plus 55% maximum concentration rather than the average of minimum and maximum concentrations. The initial conditions of matrix v and a are calculated at the first time step utilizing the thermal history and initial concentration conditions.

$$v = \frac{(e^{a(T)C} - 1)}{a(T)} \quad (17)$$

Prior to using the finite difference method to calculate $C_{i,j+1}$, at each time step, j , and each space step, i , the constants of a and D_1 must be defined, then $v_{i,j}$ must be defined as shown below.

$$a_{i,j} = 0.09469 + \frac{28.77}{T_j} \quad (18)$$

$$D_{1(i,j)} = e^{-7.086 - \frac{26109}{T_j}} \quad (19)$$

$$V_{i,j} = \frac{(e^{a_{i,j}*C_{i,j-1}})}{a_{i,j}} \quad (20)$$

The finite difference method can then be employed for all space steps of x —except for the start and end nodes of the diffusion profiles, which must be approximated as

$C_{1,j+1} = C_{2,j+1}$, $C_{end,j+1} = C_{end-1,j+1}$ to avoid singularities. Hence, the number of nodes must be enough so that these conditions are satisfied. For interior points, C at time step $j+1$ can be calculated as follows:

$$C_{i,j+1} = C_{i,j} + D_{1i,j} * \frac{dt}{dx^2} (V_{i+1,j} - 2V_{i,j} - V_{i-1,j}) \quad (21)$$

Once the concentration of SiO_2 is determined at each space step and time step, one can plot the final concentration as a function of x . The diffusion profile length can be calculated by determining the space step of the intersection of a percent variation of the minimum and maximum concentrations. The upper-limit variation and lower-limit variation for any percentage, p , are calculated below:

$$C_{Upper} = C_{max} * (1 - p) + C_{min} * p \quad (22)$$

$$C_{Lower} = C_{min} * (1 - p) + C_{max} * p \quad (23)$$

Following Macris et al. (2018), the value of p is taken to be 0.16. A variety of method can be used to find the x values at which the diffusion profile intersects the upper and lower variation limits; the method used in this model is the MATLAB function `polyxpoly`, which takes the vector input of x , the SiO_2 concentrations, and a constant value vector for the variation limits, and outputs the x value at the approximate intersection. The difference between the x values gives the diffusion profile length.

3. Results

The model was run using initial temperatures ranging from 2000K to 2700K, and at various distances from the surface of a spherical tektite with a radius of 10mm. It was found that lower initial temperatures resulted in shorter diffusion profiles, and lechatelierite inclusions closer to the edge of the tektite also had shorter diffusion profiles (Figure 2a, 2b, 2c), as expected. The diffusion profile lengths were calculated with 16% variation.

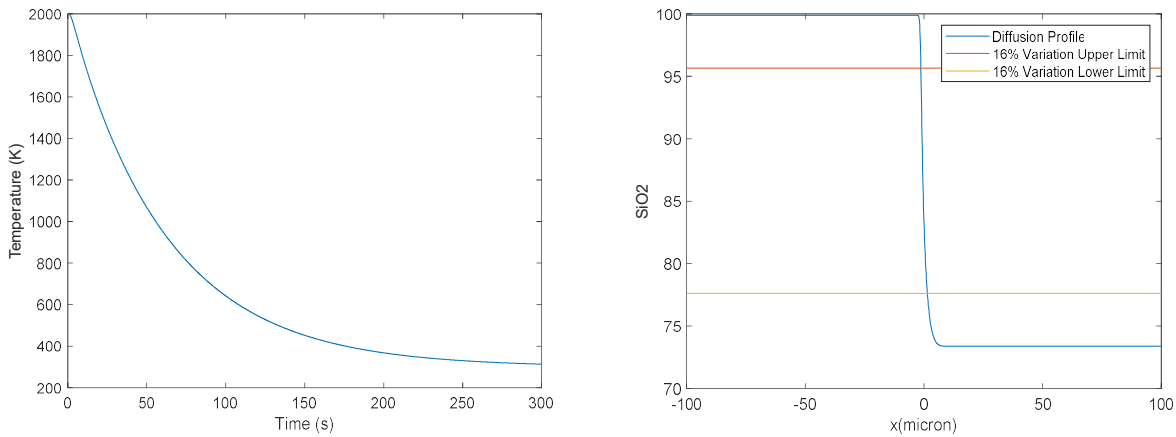


Figure 2a: The left image shows the temperature profile of a lechatelierite inclusion 3 mm from the surface of a spherical tektite with radius of 10mm, heated to 2000K instantaneously. The right image shows the modeled profile, whose length is 2.74 μm .

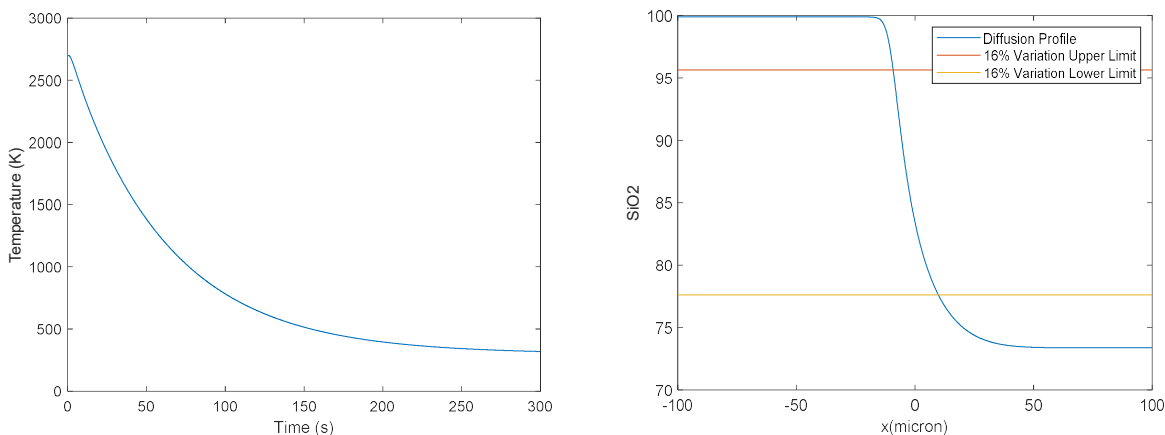


Figure 2b: The left image shows the temperature profile of a lechatelierite inclusion 3 mm from the surface of a spherical tektite with radius of 10mm, heated to 2700K instantaneously. The right image shows the modeled profile, whose length is 19.06 μm .

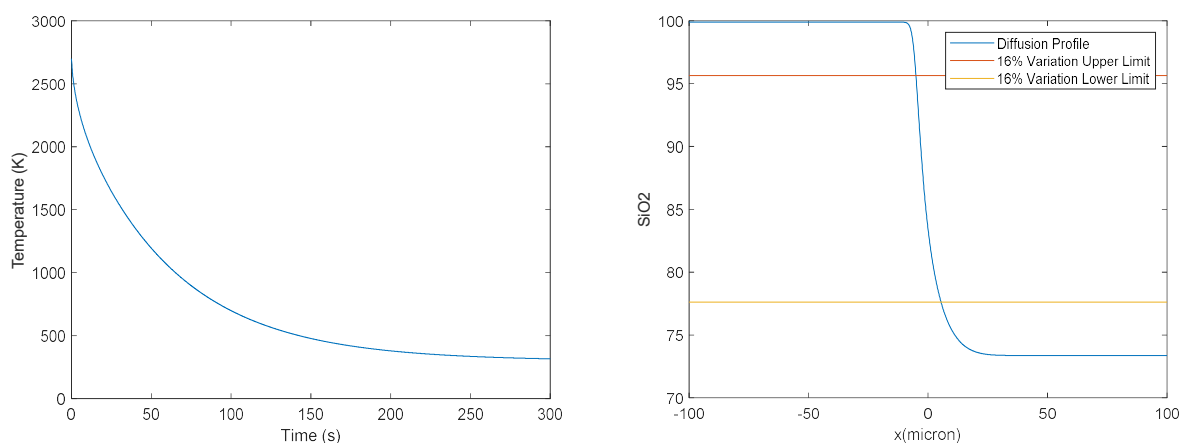


Figure 2c: The left image shows the temperature profile of a lechatelierite inclusion 0.5 mm from the surface of a spherical tektite with radius of 10mm, heated to 2700K instantaneously. The right image shows the modeled profile, whose length is 10.51 μm .

4. Applications and discussion

4.1 Modeling the Natural Inclusions Reported in Macris et al. (2018)

Macris et al. (2018) collected concentration profiles of several oxide compounds from 6 lechatelierite inclusions in a single natural tektite sample LTS1, utilizing an electron-probe micro-analyzer with backscattered electron images. The tektite used is approximately 6x1.3x2cm, and tear-dropped shaped. The average SiO_2 diffusion length, calculated with 16% variation, was 19.1 μm .

The data from the LTS1 sample includes the distance of the lechatelierite inclusion from the edge of the sample, the assumed initial temperature in Kelvin, and the diffusion profile length. To compare the LTS1 sample data to the temperature dependent diffusion model described above, the lechatelierite inclusions were assumed to be in the approximately spherical tear-drop head, approximated in our model as having a 10mm radius.

Each of the lechatelierite inclusion's diffusion profiles studied in the Macris et al. (2018) paper were modeled at temperatures ranging from 2000 to 2700K because the minimum temperature required for lechatelierite formation is approximately 2000K (Howard, 2011) and temperatures above 2700K were not considered in Macris et al. (2018). The results in Table 1 below illustrate the length of time at the starting temperature required (t_0), prior to cooling in ambient air for 300 seconds, required to achieve $19.1 \pm 0.2 \mu\text{m}$ diffusion length using this model. The t_0 required were found through trial-and-error application of the cooling and diffusion models.

Table 1: Required constant heating time (in seconds) to achieve approximate $19 \mu\text{m}$ diffusion lengths at various initial temperatures and Lechatelierite locations

T_0 (K)	2000	2100	2200	2300	2400	2500	2600	2700
	<i>Inclusions 3.746 and 3.736 mm from the edge</i>							
t_0 (s)	298	147	75	39	20	9	2	*
	<i>Inclusions 3.535 mm from the edge</i>							
t_0 (s)	298	147	76	39	20	9	3	*
	<i>Inclusions 3.36 and 3.219 mm from the edge</i>							
t_0 (s)	299	148	76	40	21	10	3	*
	<i>Inclusion 0.222 mm from the edge</i>							
t_0 (s)	304	154	82	46	21	16	10	6

* N/A, at 0s the diffusion profile was longer than $19.3 \mu\text{m}$

Of the 6 samples reported in Macris et al. (2018), the samples 3.746 and 3.736 mm from the edge, as well as the samples 3.36 and 3.219 mm from the edge, had approximately identical diffusion profiles at each temperature in this model due to the space step fidelity in the temperature cooling profile being limited.

Focusing on one of the Macris et al. (2018) reported of lechatelierite inclusions, a 3.36mm from the surface inclusion with a reported profile length of $19 \mu\text{m}$ with 16% variation, one can apply the above model to attain the thermal history. Different initial temperatures were tried. If the initial temperature is 2672K and then immediately cooled by flying through air, the resulting profile length matches the measured length (Figure 3).

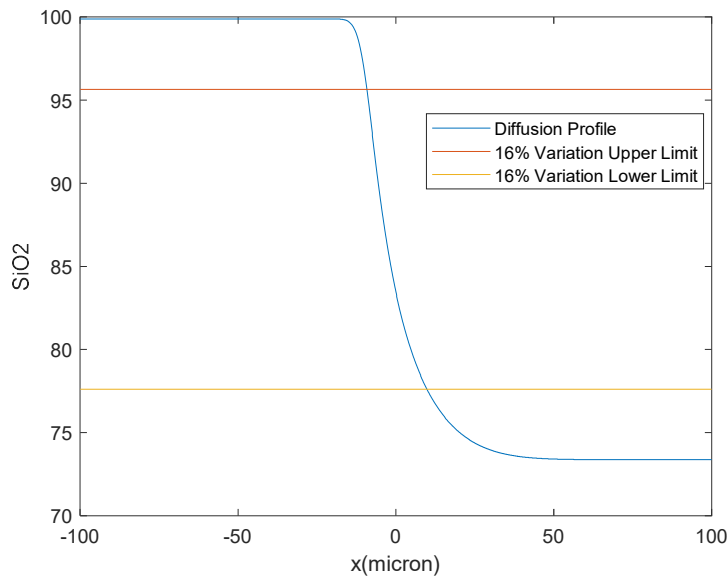


Figure 3: Silica diffusion profile of a lechatelierite inclusion 3.36mm from the surface of a spherical tektite with radius of 10mm, heated to 2672K instantaneously. The length of this modeled profile is 19.0 μm .

Therefore, one possible thermal history of the tektite studied by Macris is as follows. The tektite was produced by sudden heating to 2672K and immediately ejected into ambient-temperature air and cooled by flying through air. Because cooling in ambient-temperature air is the most efficient cooling available, the tektite temperature could not have exceeded 2672K.

However, the initial temperature might be lower than 2672K because there are other factors increasing the diffusion profile length: (1) Heating to temperature T_0 might have taking some time (such as a few seconds). Any time above the melting temperature of quartz would have generated some diffusion and increased the profile length. (2) After initial heating, the tektite might not have been immediately ejected. Rather, it might have spent seconds to minutes in the pool of melt before ejection into air. (3) Ejection of tektite is likely accompanied by ejection of many other tektites and a hot silicate vapor enveloping the tektite (Howard, 2011), resulting in slower cooling because the ambient temperature is higher than normal air temperature. All of these would have contributed some profile length in addition to diffusion during cooling by flying through air at 300K.

To account for these contributions, an initial time (t_0) at the initial high temperature was allowed as a free parameter. Adding a short duration t_0 at the initial temperature prior to the cooling period resulted in longer profiles. The model, when initialized using data from natural tektites found in Macris et al. (2018), indicates that, to achieve lechatelierite profiles consistent with the reported 3.36 mm from the edge SiO_2 profile, the tektite could have been heated to approximately 2672K instantaneously (Figure 4a) or kept at 2000K for approximately 299 seconds (Figure 4b). Figure 4 below shows both of these endmember temperature profiles for the 3.36mm from the edge lechatelierite sample needed to achieve the diffusion profile length found

in Macris et al. (2018). The t_0 required to achieve the $19\mu\text{m}$ diffusion profile length at other starting temperatures, for each inclusion reported in Macris et al. (2018), is reported Table 1, and illustrated for the inclusion 3.36mm from the edge in Figure 5, below.

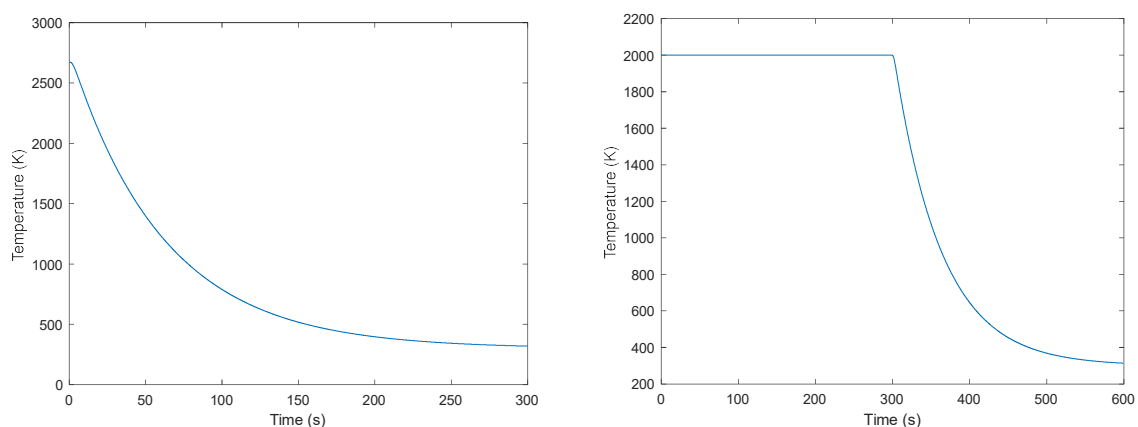


Figure 4: Both of the above temperature profiles result in $19.1\pm 0.2\mu\text{m}$ diffusion profile lengths for a lechatelierite inclusion 3.36mm from the edge of a 10mm spherical tektite.

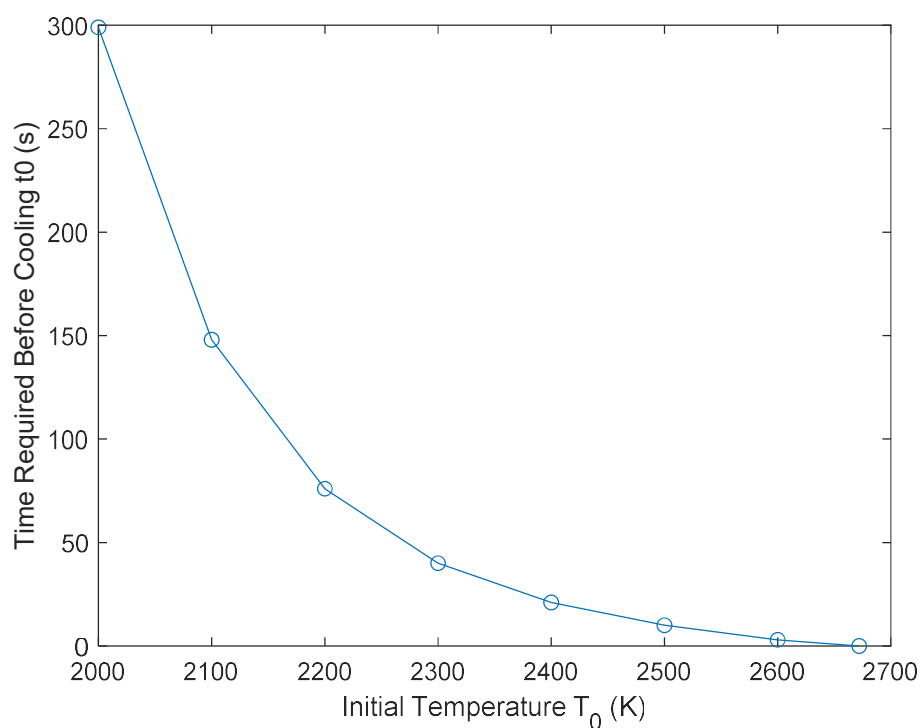


Figure 5: The required t_0 to produce diffusion profile lengths of $19.1\pm 0.2\mu\text{m}$ for a lechatelierite inclusion 3.36mm from the edge of a 10mm spherical tektite at each starting temperature considered.

The possible temperature-time solutions discussed in the Macris et al. (2018) paper include $\sim 2300\text{K}$ heating for 70 seconds with 1400s of and $\sim 2700\text{K}$ heating for 3s with 50s of cooling. The results from this model suggests that less heating time would be needed at these temperatures, with about 42 seconds required at temperatures of $\sim 2300\text{K}$. The model results also

show that instantaneous heating to 2700K exceeds the average diffusion length of $19.1 \pm 0.2 \mu\text{m}$ for most inclusions. Table 2, below, displays the temperature at which instantaneous heating results in the average diffusion length for each inclusion reported in Macris et al. (2018).

Table 2: Temperature (K) needed to achieve $19.1 \pm 0.2 \mu\text{m}$ instantaneously for each Lechatelierite inclusion.

Distance of Inclusion From Edge (mm)	3.746/3.736	0.222	3.535	3.219/3.36
Temperature needed to achieve $19.1 \pm 0.2 \mu\text{m}$ instantaneously (K)	2647	*	2659	2672

*The inclusion at 0.222mm from the edge does not reach $19 \mu\text{m}$ at temperatures below 2700K in this model

4.2 Implications for Tektite Thermal Histories

The results from this thermally dependent silica diffusion model indicate that, for the LTS1 indochinite tektite investigated by Macris et al. (2018), which originates from the Australasian strew field, temperatures at the tektite point of origin likely did not exceed $\sim 2650\text{K}$. It is likely that the tektites did not experience instantaneous heating then immediate cooling in ambient air due to expected crater impact event conditions; therefore, different thermal history possibilities were created with a variety of times at a variety of initial temperatures to match the diffusion profiles found in natural tektite samples. It is possible the tektite thermal history could have been heating at approximately 2000K for 299s and then cooling in ambient temperature.

Howard (2011) states that it is possible that certain regions closest to the impactor in impact events reach temperatures above 5000°C ; if this is the case, then it is likely this tektite originated further from the impactor. Were silica diffusion profiles of lechatelierite inclusions from other tektites within the Australasian strew field to be constrained, it may be possible to generalize results of this study to this specific impact event. To apply the temperature history results to other strew fields, a wider variety of tektites should be studied.

Stöffler et al. (2002) proposed the following model of tektite formation within the Ries impact: material from the cratering event is ejected 4 seconds after impact, along with hot gas that reaches a maximum of 1727K. In their model, 1.4 cm diameter tektites reached temperatures of $\sim 3500\text{K}$ and 2 cm diameter tektites reach temperatures up to 1000K, with flight times of 5-30 minutes. Their model suggests that the temperature history of the smaller tektite is initially heated to 3500K nearly instantaneously, then cools at a slower rate for several minutes until the tektite exits the hot gas cloud and can cool to average atmospheric temperatures. The temperature dependent diffusion model in this work could be adapted to this thermal history and validated with lechatelierite sample diffusion data.

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