An increased abundance of micrometeorites on Earth owing to vesicular parachutes

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Abstract Micrometeorites (MMs) are extraterrestrial dust particles that survive atmospheric entry and can be recovered from sedimentary rocks. Fossil MMs allow events beyond the Earth, such as the collisional breakup of asteroids, to be identified. Here the effects of vesicle formation during melting of dust are investigated through numerical modeling and observations of Antarctic MMs. Vesicle formation is shown to cause a parachute effect that causes rapid deceleration, decreasing peak temperature. Vesicular parachuting enhances the abundance of melted MMs formed from phyllosilicate-bearing C-type asteroid dust on the Earth surface by a factor of 2. Micrometeorites recovered from the geological record, therefore, are biased toward breakup events involving hydrated C-type asteroids, whilst those involving phyllosilicate-poor particles are diluted by the enhanced background flux of hydrous dust. The parachute effect is also likely to increase the delivery of 3He to ocean sediments by C-type asteroid dust.

1. Introduction

Micrometeorites have been recovered from sedimentary rocks including Jurassic and Ordovician limestones [Taylor and Brownlee, 1991; Dredge et al., 2010] and Triassic marine siliciclastics [Onoue et al., 2011] and include particles up to 2 mm in size [Genge et al., 2008]. The oldest micrometeorites (MMs) have been recovered from 2.7 Ga limestones [Tomkins et al., 2016]. The abundance of MMs within sediments records the flux of extraterrestrial dust falling on Earth and can reveal dust production events beyond the Earth, such as the collisional breakup of asteroids [Farley et al., 2006] and the influx of new comets. Events that increase the extraterrestrial dust flux can affect the Earth through climatic changes caused by the influx of high-altitude dust [Winckler et al., 2004; Plane, 2012] or through a commensurate increase in the flux of larger impactors [Alvmark et al., 2012]. Micrometeorites recovered from sediments are mostly cosmic spherules (Figures 1a–1e), particles that have experienced high degrees of melting during atmospheric entry to produce subspherical droplets [Taylor and Brownlee, 1991; Onoue et al., 2011; Tomkins et al., 2016]. Collections of more recent MMs from the deep oceans [Brownlee, 1985; Rudraswami et al., 2011] and Antarctica [Maurette et al., 1991; Taylor et al., 2000; Duprat et al., 2007; Rochette et al., 2008], however, indicate that unmelted MMs (Figure 1i) and partially melted scoriaceous MMs (Figures 1f and 1g) also survive atmospheric entry. Their absence within sedimentary rocks is likely to be the result of terrestrial weathering [Taylor and Brownlee, 1991; Onoue et al., 2011]. The abundances of cosmic spherules, therefore, are a proxy for the overall abundance of past MMs and together with estimates of sedimentation rate have been used to trace the flux of extraterrestrial dust to Earth [Taylor and Brownlee, 1991; Onoue et al., 2011].

Atmospheric entry heating results in differences between the population of dust in near-Earth space and that reaching the Earth’s surface. Melting of dust produces scoriaceous MMs and cosmic spherules and is dependent on peak temperature, which increases with initial particle size, entry angle, and velocity [Love and Brownlee, 1991]. Increasing peak temperature is inferred in the sequence ScMMs (Figures 1g and 1h) < porphyritic spherules (Figures 1a and 1b) < barred olivine spherules (Figure 1c) < cryptocrystalline spherules (Figure 1d) < glassy spherules (Figure 1e). Complete evaporation can occur for high-velocity dust. A feature of MMs that relates to entry heating is the presence of abundant vesicles within certain particles. In ScMMs (Figures 1f and 1g) vesicle abundances are often up to a maximum of 70 vol % [Genge et al., 1997; Taylor et al., 2011a, 2011b], whilst in micro-Po spherules (Figure 1a) vesicles typically comprise <50 vol %. Observations of MMs, therefore, imply significant expansion of particles due to formation of vesicles...
during atmospheric entry that may affect the degree of heating that they experience. Here the effect of vesicle formation on the survival of dust from volatile-rich (CI and CM2) and volatile-poor (ordinary chondrite) precursors is investigated through numerical simulations of entry heating including vesicle growth and loss by migration under deceleration. The simulations allow the abundance of C-type and S-type asteroid dust found in sediments to be related to the near-Earth dust population.

2. Vesicle Formation Mechanisms

The mechanisms of vesicle formation are important in their dynamic behavior and survival of atmospheric heating. Volatile-rich CM2 and CI-like precursors [Genge et al., 1997; Noguchi et al., 2015] are phyllosilicate rich (Figures 1f and 1i) and have water contents of 8–12 wt % [Jarosewich, 1990]. Dehydration of phyllosilicates such as serpentine, however, occurs at subsolidus temperatures of ~1000 K [Llana-Funez et al., 2007]
potentially allowing significant loss of volatiles—prior to melting at the solidus at ~1400 K. The retention of gas within ScMMs and porphyritic spherules, therefore, requires trapping to occur.

The mass of gas retained within melted MMs can be estimated from vesicle sizes and abundances using the Young-Laplace equation that relates vesicle size to gas pressure through surface tension. Using a silicate melt surface tension of 0.35 N m⁻¹ [Walker and Mullins, 1981] and a maximum volume of 70 vol % vesicles measuring 10 μm in size, and calculating mass assuming an ideal H₂O vapor, an H₂O abundance of ~0.02 wt % is derived. Despite the large uncertainty in this estimate, it is clear that a significant proportion of the original volatile content could have been lost prior to melting.

Vesicles could form from H₂O released by phyllosilicates in two ways: (1) through dissolution of volatile components into the forming melt, followed by exsolution of vesicles from the supersaturated liquid, or (2) through direct hydrodynamic trapping of gas within the melt. Exsolution of gas dissolved in the melt is an inherently slow process since it is dependent on diffusion of volatiles. Estimates of the growth rates of vesicles by diffusion in basaltic liquids are ~3 × 10⁻³ μm s⁻¹ [Masotta et al., 2014] and are thus too small to explain the vesicle formation in MMs which are above the solidus for only 1–5 s. Observations of MMs, however, suggest that direct trapping is likely to occur [Taylor et al., 2011b]. Igneous rims that occur on phyllosilicate-bearing MMs indicate the formation of a surface melt layer that is likely to seal particles and impede gas loss (Figure 1i) [Genge, 2006; Taylor et al., 2011b]. The large thermal gradient required to generate the igneous rim is enabled by the endothermic decomposition of phyllosilicates that acts as a heat sink [Genge, 2006]. The formation of vesicles within melted cosmic dust particles during atmospheric entry will thus be rapid and dependent on the time over which melting occurs.

An approximate duration of melting can be estimated from the thermal flux across the igneous rim-unmelted core interface. Observations of the boundary between the melted rim and unmelted core of fine-grained micrometeorites suggest that a very high thermal gradient of 600 K over a few microns is maintained during melting (Figure 1i). Given an enthalpy of phyllosilicate (serpentine) decomposition of ~500 kJ kg⁻¹ [Llana-Funez et al., 2007] and a latent heat of melting of 400 J kg⁻¹, the time required to melt a particle can be estimated to 0.2 to 0.01 s depending on the proportion of phyllosilicate present.

Although volatile trapping by a surface melt layer on phyllosilicate-rich particles is likely to lead to rapid vesicle formation and expansion, the vesicle abundance is also important since it determines maximum size during expansion. Scoriaceous MMs exhibit maximum vesicle contents close to 70 vol % (Figure 1g) [Genge et al., 2008; Taylor et al., 2011b], with few having vesicle abundances <50 vol %. Given that significant volatile loss occurs at subsolidus temperatures, the vesicle abundances generated by trapping on melting are unlikely to be sensitive to the variations in the volatile content of the precursor and more likely to relate to the trapping process. The most vesicular scoriaceous particles are effectively foams having thin menisci of liquid separating vesicles. The maximum vesicle content, therefore, is likely to be dictated by the stability of a foam in which meniscus collapse occurs at >77 vol % vesicles in magmas with low water content [Zhang, 1999]. Initial trapping of gas is, therefore, likely to be efficient with initial vesicle abundances controlled by collapse of foams. Subsequent loss of vesicles by migration under the influence of deceleration, as discussed by Genge [2016], then decreases vesicle content with further heating.

Although vesicle formation by trapping is likely to be the most appropriate mechanism for phyllosilicate-rich precursors, degassing of sulfides during oxidation may also produce vesicles [Taylor et al., 2011b]. Sulfide degassing, in particular, is likely to explain the presence of vesicles in some spherules heated to supraliquids temperatures. Given that sulfides, although common in chondrites, are unlikely to be abundant within precursors due to their larger grain size than phyllosilicates, vesicle formation by their degassing will be ignored but may play a role in generating vesicles within some otherwise volatile-poor particles and explain vesicles found in <10% of high-temperature spherules [Taylor et al., 2011b]. Sulphur and carbonaceous matter within hydrated primitive particles may also contribute to gas production; however, they have significantly lower abundance than water [Jarosewich, 1990].

Loss of vesicles also occurs during atmospheric deceleration resulting in a decrease in particle size during heating. Micrometeorites show a decrease in vesicle abundance with inferred peak temperature with ScMMs containing the largest abundances (Figures 1g and 1h), porphyritic olivine cosmic spherules exhibiting the lower vesicle contents (mostly <50 vol %; Figure 1a), and barred, cryptocrystalline, and glassy
spherules, formed by heating to supraliquidus temperature, exhibiting significantly low average vesicle contents, most containing no vesicles [Taylor et al., 2011a, 2011b]. Vesicle loss occurs due to migration of vesicles by flow under the influence of the large decelerations experienced by particles.

3. Numerical Model

A numerical simulation based on the model of Love and Brownlee [1991] is used here to simulate atmospheric deceleration of silicate micrometeoroids and includes a treatment of the evaporation of particles in addition to their equations of motion and heat transfer. To model the formation of vesicles, the melting process was simulated using thermodynamic calculations to predict the compositions and abundances of phases. Calculations were performed using the MELTS code [Ghiorso and Sack, 1995; Asimow and Ghiorso, 1998] at a pressure of 1 atm and fO2 fixed at the iron-wustite buffer. The thermodynamic model predicts a solidus temperature of 1414 K and a liquidus temperature of 1700 K. The densities of silicate partial melt, olivine, clinopyroxene, and magnetite over the temperature range of melting were predicted following Niu and Batiza [1991]. Melt viscosity was calculated from liquid compositions using the formulation of Giordano et al. [2008] for silicate magmas with the effects of crystal content, which significantly increases effective viscosity, evaluated using the Einstein-Roscoe relation [Einstein, 1906; Roscoe, 1952]. The bulk composition used for particles corresponds to an ordinary chondrite spherule (Table S1 in the supporting information). Considering the minor differences between chondrites, this composition is likely to be appropriate for all chondritic particles. The temperature-dependent phase abundance, density, and viscosity calculated using the composition are shown in Figure S1. Volatiles are ignored in this calculation assuming rapid volatilization and negligible dissolution in the melt. All other physical properties used in the model are derived from Love and Brownlee [1991].

Vesicle formation, and commensurate expansion of particles, was modeled as a linear increase in volume and decrease in density over 0.2 s after temperature exceeds the solidus on the basis of their formation by direct trapping during the generation of a surface melt layer. This is suggested reasonable since it occurs over a relatively small period of time compared with total suprasolidus flight of 1.0–5.0 s. Vesicle content is assumed to reach 70 vol %.

Loss of vesicles by migration during deceleration was included in the model by numerical integration of vesicle velocities obtained by Stokes law driven by the deceleration derived from the entry heating model. To evaluate the proportion of vesicles lost with time and the associated volume decrease and density increase, the migration distance of vesicles of a fixed size is compared to particle diameter. In reality, vesicles within molten MMs have a range of sizes and will evolve by coalescence during migration. Observations of cosmic spherules suggest that maximum vesicle size is broadly proportional to particle size [Taylor et al., 2011b] simply because migration distance controls vesicle growth by coalescence. To reflect this process, vesicle size was chosen to be 10% of particle size.

4. Results

The simulation results suggest that vesicle formation on melting of micrometeoroids significantly decreases the peak temperature attained during entry heating (Figure 2). The reason for the decrease in temperature is evident from the particle radius and velocity over the course of the simulation. Vesicle formation causes a rapid increase in particle radius, followed by minor decrease by some loss of vesicles by migration and evaporation. The increase in particle size, together with the decrease in density, leads to rapid deceleration acting in a similar manner to a parachute. This vesicular parachute effect changes the entry heating survival of volatile-bearing dust.

The influence of entry angle, initial particle size, and entry velocity on peak temperature and survival of particles for vesicle-free and vesicle-bearing particles is shown in Figure 2. Peak temperature increases with entry angle, initial size, and entry velocity for all particles; however, the peak temperature attained by vesicle-bearing particles is lower than those of vesicle-free particles at temperatures higher than the solidus (1414 K). The magnitude of peak temperature decrease is largest (>100 K) for particles that partially melt, whilst those with peak temperatures above the liquidus show smaller (<50 K) decreases. The minor decrease in peak temperature above the liquidus occurs since although increased deceleration was experienced at
subliquidus temperatures owing to vesicular parachuting, subsequent vesicle loss at supraliquidus temperatures, where viscosity is low, decreases particle size by the time peak temperature is attained. The change in peak temperature due to vesicle formation also increases the range of initial particle sizes over which partial melting occurs. Without vesicle, formation particles entering the atmosphere at 12 km s⁻¹ at an entry angle of 45° undergo partial melting at initial diameter between ~40 and 100 μm, whilst with vesicles partial melting occurs within particles with initial diameter of ~40 to 180 μm. At higher velocities of 14 km s⁻¹ the size interval over which partial melting occurs is more restricted; however, vesicle formation increases the interval by approximately the same factor of 2. The final radii of model particles are shown in Figure 3 and demonstrate that vesicle-bearing partially melted ScMM and porphyritic cosmic spherules have significantly larger final radii than nonvesicular particles. Contraction of particles by vesicle loss also occurs rapidly at temperatures above the liquidus, although some vesicle loss also occurs at temperatures just below the liquidus owing to the low crystal content and decreased viscosity. Enhanced deceleration of vesicular particles also results in shorter heating pulses (Figure 4) at any specific initial particle size with vesicular particles having times above the solidus ~0.6 times that of nonvesicular. Vesicular parachuting, therefore, significantly increases the entry heating survival of volatile-bearing C-type asteroid dust compared with volatile-poor S-type particles resulting in enhanced abundances of ScMMs, micro-Po spherules, and barred spherules.

5. Effects on the Abundance of Fossil Micrometeorites

Previous studies have suggested that partial melting of volatile-bearing micrometeoroids similar to the fine-grained matrices of CM2 or CI-like chondrites results in the formation of highly vesicular scoriaceous micrometeorites at lower temperatures [Genge et al., 1997, 2008; Taylor et al., 2011a] and microporphyritic olivine spherules, at higher temperatures approaching the liquidus [Van Ginneken et al., 2015]. In contrast,
volatile-poor micrometeoroids, resembling fragments of chondrules [Genge, 2008], are thought to form coarse or skeletal porphyritic olivine spherules [Van Ginneken et al., 2015]. The relative abundance of micro-Po to coarse-Po spherules amongst a collection of 1200 cosmic spherules from Larkman Nunatak in Antarctica is 21% in the size range 50–400 μm. The abundance of ScMMs is reported as 22% of all MMs in the size range 50–100 μm from those collected from blue ice at Cap Prudhomme [Genge et al., 1997]. Numerical simulations of the effects of vesicle formation suggest that the survival of partially melted,
volatile-rich particles is elevated by a factor of 2 compared with volatile poor as a result of vesicle formation. The abundance of volatile-rich CM2 and CI-like dust is, therefore, suggested to be lower than would be predicted from that of ScMMs and micro-PO spherules.

Micrometeorites collected from sediments are largely cosmic spherules, because they are less affected by terrestrial weathering and diagenesis than unmelted particles. Identification of particle types allows an evaluation of the sources of extraterrestrial dust to the Earth, albeit biased toward the low-velocity population [Carrillo-Sanchez et al., 2015]. Micro-PO spherules and barred spherules formed predominately by melting of phyllosilicate-bearing CM2 and CI-like precursors are thought to be derived from C-type asteroids on the basis of spectroscopy [Ziffer et al., 2011]. In contrast, coarse-PO spherules have affinities to ordinary chondrites and thus are related to S(IV)-type asteroids [Binzel et al., 1996]. Events such as the 5.8 Myr breakup of the S(IV)-type Karin group asteroids [Nesvorny et al., 2002] is likely to be associated with an increase in coarse porphyritic olivine spherules, whilst the 8.3 Myr breakup of the C-type Veritas parent asteroids [Nesvorny et al., 2006] is likely to be associated with an increase in the abundance of micro-PO and barred spherules. The vesicular parachute effect identified here increases the survival of spherules formed from phyllosilicate-rich C-type asteroid dust making collisional events involving these objects more readily identifiable in the geological record, whilst events resulting from disruption of S types are diluted by the background flux of C-type dust.

The parachute effect may also influence the $^3$He content of ocean sediments that has been used as a proxy for the micrometeorite flux [Farley et al., 1998, 2006]. Although unmelted MMs are likely to remain the highest abundance of $^3$He [Farley et al., 1997], such particles are most abundant at small sizes (<50 μm) whilst the peak in the mass flux of extraterrestrial dust occurs at ~200 μm [Love and Brownlee, 1993]. The survival of partially melted hydrous dust to 180 μm approaches this maximum enhancing the mass contributed by these particles. Large phyllosilicate-rich dust that survive atmospheric entry as ScMMs may retain a proportion of their indigenous $^3$He since many contain relit unmelted cores that may have experienced temperatures below 600°C [Genge et al., 1997; Genge, 2006], the expected threshold for He release [Farley et al., 1997]. The vesicular parachute effect increases the size range over which ScMMs form from phyllosilicate-rich dust during entry heating and thus will increase the delivery of $^3$He to ocean sediments from C-type asteroid dust. Sieving of deep sediment suggests that up to 20% of $^3$He is present in particles >50 μm in diameter [Mukhopadhyay and Farley, 2006]; however, given that many particles are likely to fragment during sieving, this is likely to be an underestimate. Other studies have concluded that MMs 50–100 μm are responsible for the majority of $^3$He [Stuart et al., 1999]. The enhanced survival of ScMMs at >60 μm owing to vesiculation may, therefore, play a factor in the delivery of $^3$He to the Earth’s surface and its record of extraterrestrial events.

In conclusion, the formation of vesicles within phyllosilicate-bearing extraterrestrial dust is predicted to have a significant effect on the abundance of their partially melted residues recovered from the Earth’s surface. The formation of vesicles within particles is suggested to occur mainly as a result of degassing of phyllosilicates during entry heating with trapping of gas occurring by the formation of a surface melt layer generated as a result of the endothermic decomposition of phyllosilicate. Numerical simulation of the atmospheric entry of phyllosilicate-rich dust suggests a decrease in heating owing to the vesicular parachute effect increasing their abundance by factor of ~2 compared to volatile-poor dust particles. The abundance of scoriaceous and vesicular cosmic spherules recovered from the Earth’s surface is, therefore, enhanced compared with the abundance of phyllosilicate-rich precursor dust in space and biases the geological record in favor of collisional events involving C-type asteroids.

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