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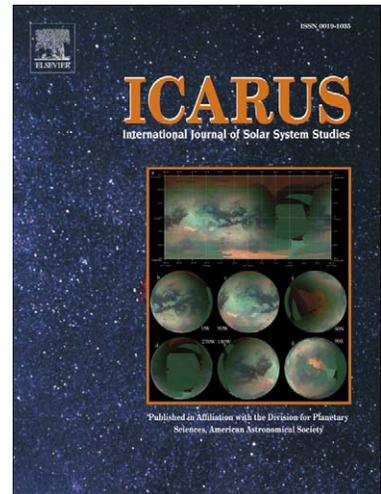
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**Response of sandstone to atmospheric heating during the STONE 5 experiment:
Implications for the palaeofluid record in meteorites**

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Running Head: Meteorite heating during atmospheric entry

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Abstract

A 1 cm thick sandstone disk exposed to atmospheric re-entry on the heat shield of a spacecraft (the STONE 5 experiment) shows alteration of fluid inclusions compared to a control sample. The sandstone contained inclusions in quartz grains, feldspar grains and calcite cement before flight. After flight, inclusions in the feldspar were all decrepitated, few inclusions in calcite survived intact and they yielded widely varying microthermometric data, and the quartz inclusions also yielded disturbed microthermometric data. The quartz becomes less affected with depth below the surface, and extrapolation suggests would be unaffected at a depth of about 2 cm. These data show that fluid inclusion data from meteorites must be treated with caution, but that a genuine fluid record may survive in the interior portions. The possibility of thermal sterilization to 2cm depth also implies that small meteorites may be unsuitable vehicles for the transfer of microbial life from one planetary body to another. As the interiors of larger meteorites tend to have very low porosity and permeability, microbial colonization would be difficult, and the potential for panspermia is accordingly low.

Keywords: Meteorites; Thermal histories; Astrobiology; Mineralogy; Panspermia

1. Introduction

1.1. Fluid record in meteorites

Some of the most direct evidence for the past existence of water and other volatiles throughout the Solar System can be found on Earth in the form of volatile-bearing constituents in meteorites. Fluid-rock interaction on the surface and near surface of Solar System bodies such as Mars and primitive asteroids has resulted in small volumes of fluid becoming entrapped within minerals, as fluid inclusions (Bodnar, 1998; 1999; Zolensky et al., 1999a,b).

Fluid inclusions are micron-scale volumes of fluid entrapped within minerals when they precipitate, and thus they represent the ambient fluids present during precipitation. If the inclusions survive unaltered, they have the potential to tell us about physico-chemical conditions during mineral precipitation, including temperature and pressure, fluid chemistry, fluid ionic strength and fluid isotopic composition (Shepherd et al., 1985; Goldstein & Reynolds, 1994). This information is determined partly by study of the fluid behaviour during heating and cooling (microthermometry) and partly from extracting the fluid for direct chemical measurements (Hode et al., 2006). They therefore have high value in reconstructing the conditions under which a wide variety of processes occurred in the geological record, such as cementation of aquifers and reservoirs (Grant & Oxtoby, 1992), hydrocarbon migration (England et al., 2002), metalliferous ore formation (Wilkinson et al., 1999), structural deformation (Evans, 1995) and rock dissolution (Baron & Parnell, 2007). In addition to understanding these subsurface processes, inclusions

trapped during mineral growth at the surface can provide information about surface environmental conditions in the past, including seawater chemistry (Satterfield et al., 2005) and atmospheric chemistry (Dennis et al., 2001).

Given their potential for reconstructing environments of formation, the occurrences of rare fluid inclusions in meteorites present great opportunities for understanding conditions on the meteorite parent body, especially where a meteorite has a known provenance such as Mars. Two-phase (liquid, vapour) fluid inclusions have been found in two SNC meteorites (Bodnar, 1998; 1999), two H chondrites (Zolensky et al., 1999a,b; Rubin et al., 2002) and five carbonaceous chondrites (Saylor et al., 2001). The fluid inclusions occur in both primary and secondary settings, range in diameter from 4 to 15 μm and reside in various mineralogies that include forsteritic olivine, Ca-carbonate, halite, and pyroxene. Studies of the inclusions have been hampered significantly by early erroneous reports of fluid inclusions in meteorites that centred on sample preparation issues (Bodnar, 2001). Only Zolensky et al. (1999a) have managed to extract quantitative data, from unprocessed portions of fluid inclusion-bearing halite in Monahans H5 regolith breccia (1998). Monahans (1998) halite contained both primary and secondary fluid inclusions and the paucity of vapour bubbles in the inclusions suggested low temperature ($< 100\text{ }^{\circ}\text{C}$) fluid entrapment. The most important conclusions drawn from past studies of fluid inclusions in meteorites is that meteorites appear to act as secure vessels for the transportation of extraterrestrial fluids throughout the Solar System and can potentially provide us with workable samples from which quantitative data can be obtained.

However, meteorites have to face severe processes which could damage or destroy the inclusions. The act of formation of a meteorite involves impact

sufficiently violent to cause ejection off the planetary surface. The physical shock involved in this could damage the rock such that the inclusions are broken open or destroyed. Experimental simulations show that shock waves expected from meteorite impacts modify or destroy inclusions (Elwood Madden et al., 2004). Similarly, shocked samples of sandstone from Meteor Crater, Arizona, show re-equilibration or destruction of inclusions in quartz grains (Elwood Madden et al., 2006). When meteorites arrive at a planet they must experience the heat of atmospheric entry, which is high enough to melt the outside to form a fusion crust (Genge & Grady, 1999a), although the interiors appear to remain cool (Weiss et al., 2000). Studies of the shock state (Weiss et al., 2000; 2002) and isotope systematics (Weiss et al., 2002; Shuster & Weiss 2005) indicate only mild heating. The high thermal gradient from interior to exterior reflects brevity of heating (seconds). There is then a further risk of physical damage when the meteorite lands, although this is probably not significant for most small pieces. If inclusions are damaged during this history, there is the possibility of a new fluid replacing the original fluid, conceivably a terrestrial fluid entering the inclusions after fall. This is one of several aspects of the weathering processes to which meteorites are exposed after delivery to Earth, including hydration, hydrolysis and oxidation (Lee & Bland, 2004; Al-Kathiri et al., 2005).

1.2. The STONE 5 experiment

Our confidence in the survival of inclusions in meteorites, and consequently the interpretations made from them, will be increased by experiments that replicate the conditions experienced by them. The STONE experiments administered through the European Space Agency are designed to determine the effects of atmospheric

entry upon a range of rock types and microbial life embedded in them (Brack et al., 2002; Cockell et al., 2007). The STONE 5 experiment, conducted in 2005, included a disc of sandstone exposed during re-entry on a recoverable Foton-M spacecraft that had flown in low earth orbit at a height of 275 km above the Earth. The sample had been fixed to the surface of the ablative heat shield of the capsule, around the stagnation (hottest) point (Brack et al., 2002). A previous STONE experiment, conducted in 1999, recorded development of a fusion crust and melting of basalt fragments in an artificial regolith and melting of silica fibres in the heat shield, reflecting the heating of gas in the bow shock envelope of meteorites to several thousands of degrees (Brack et al., 2002). The sandstone recovered after return of the spacecraft to Earth was examined for its fluid inclusion record, and compared to a control sample of the same sandstone that had not been through the experiment.

The sandstone consists of quartz and potassium feldspar grains in a calcite cement (Brandstätter et al., 2008). These three components represent different types of mineral; mineral grains with cleavages, mineral grains without cleavages, and mineral cements. The distribution of mineral grains with and without cleavage is significant because minerals with cleavage are more likely to be susceptible to post-entrapment deformation and loss or alteration of inclusion fluids (Ulrich & Bodnar, 1988; Zhang, 1998). The alteration of fluids could involve re-equilibration to a different inclusion volume, and hence density change and possibly phase change, or replacement by other fluid, or selective loss of volatile components. The sandstone has no visible porosity.

2. Methodology

The sandstone was sampled from the Upper Oligocene of Wallsee, Lower Austria, Austria. It was prepared as a disc of 7 cm diameter and 1 cm thickness, and attached to the spacecraft. The spacecraft orbited the Earth for 16 days before return. During re-entry, the KERAMIK TPS-Experiment recorded heating up to a peak of about 1450 °C for a few seconds, 1000+ °C for about 100 seconds, and 500+ °C for about 220 seconds (unpublished data). However the temperature sensor was not at the stagnation point, and modelling of FOTON spacecraft re-entry suggests a mean temperature of 1840 °C for 150 seconds (Hald et al., 1993). Upon recovery of the spacecraft and attached samples in Kazakhstan on May 31, 2005, 0.8 cm of the original 1 cm thickness survived. 100 µm thick doubly polished wafers were made from a section of the flight sandstone normal to the disc surface, and the control sandstone.

The petrography of fluid inclusion assemblages was first examined at low magnifications using a NIKON Eclipse E600 microscope equipped with both transmitted white and ultraviolet light sources. Inclusions were divided into primary, and secondary types based on the criteria of Roedder (1984). Fills were estimated at room temperature using the standard charts of Roedder (1984). Images were captured using Leica DC 200 computer software and a digital camera. Microthermometric analysis was carried out using a calibrated LINKAM TH-600 stage and measured with the aid of a video screen coupled to a Nikon OPTIPHOT 2-POL microscope. Homogenization temperature (T_h) measurements were determined using a heating rate of 10 °C/min⁻¹. Final ice melting (T_m) temperature measurements were determined using a heating rate of 1 °C/min⁻¹. Salinities were estimated from T_m measurements using the methods of Bodnar (1993).

3. Data

All three components (quartz, feldspar, calcite) are preserved in the portion of the sandstone exposed at the surface upon retrieval. However this portion exhibited a conspicuous change in appearance from the inner surface against the spacecraft, coloured grey like the control sample, to brown in the outermost surviving surface. The calcite had darkened due to severe thermal alteration and in places it had partially decomposed and adjacent quartz grains exhibit a reaction rim of calcium silicate (Brandstätter et al., 2008). The depth of visible alteration is 0.8 cm below the original outer surface.

The control sample contains inclusions in each of the quartz, feldspar and calcite. All are two-phase inclusions consisting of a liquid and a vapour bubble. In each mineral, the temperature/salinity data obtained plots over a limited range (Table 1, Fig. 1), giving us high confidence that the inclusions have survived unaltered since entrapment (Goldstein & Reynolds, 1994). In the quartz and feldspar grains, the inclusions are spherical in shape, between 2 and 9 μm in size, and secondary, trapped within cross-cutting trails (Fig. 2). Inclusions were measured in trails that cross-cut more than one grain, showing that they were trapped since formation of the sandstone and were not inherited from the previous history of the minerals. These inclusions have a near-constant liquid-vapour ratio, from 90-95% liquid fill. The inclusions in calcite are rounded cubic/rhomboidal in shape, between 6 and 13 μm in size, and trapped during mineral precipitation (Fig. 2). They have a liquid fill of 80-95%. The inclusions in quartz and feldspar yield the same ranges of homogenization temperature 68 to 84 $^{\circ}\text{C}$ (mean 76 $^{\circ}\text{C}$; $n = 46$; Fig. 1) and salinity 1.7 to 3.2 wt.% equiv. NaCl (mean 2.5%; $n = 46$; Fig. 1), suggesting that they represent the same

fluid, trapped during fracturing of the sandstone before cementation. The inclusions in calcite yield temperatures in the range 74 to 104 °C (mean 90 °C; n = 32; Fig. 1) and salinities of 3.6 to 5.1 wt.% equiv. NaCl (mean 4.4%; n = 32; Fig. 1).

The spatial density of inclusions is consistently 60 to 70 % lower in the post-flight sample. The inclusions in feldspar are all decrepitated, i.e. empty of fluid (Fig. 2). The surviving inclusions in quartz are intact, but slightly stretched so that they have elliptical shape and are between 4 and 19 µm in size (Fig. 2). They have variable liquid-vapour ratios, from 80 to 95% liquid fill. Most (85 to 90%) calcite inclusions are decrepitated, and the few that survive are stretched with variable rounded/elliptical shape, range in size from 8 to 24 µm and a liquid fill from 60 to 80% (Fig. 2). The quartz inclusions yield homogenization temperatures over a higher range than in the control sample, from 93 to 133 °C (mean 116 °C; n = 32; Fig. 1) and a wider salinity range from 1.2 to 7.3 wt.% equiv. NaCl (mean 4.1%; n = 32; Fig. 1). The surviving inclusions in calcite yield homogenization temperatures much higher than in the control, from 116 to 224 °C (mean 172 °C; n = 12; Fig. 1) and a very wide salinity range from 1.4 to 17.9 wt.% equiv. NaCl (mean 10.8%; n = 12; Fig. 1). This data was obtained over the whole field of the section.

In order to test spatial variation with respect to the source of heat (the exposed surface), quartz-hosted inclusions were measured subsequently in six transects across the section, from the inner margin to the outermost surviving face of sandstone with data recorded, where possible, at 0.05 cm intervals. The data (Table 2) shows a linear relationship between homogenization temperature and depth below the exposed surface, decreasing with depth from a maximum 132 °C to a minimum 95 °C over the 0.8 cm depth range measured (Fig. 3). The evidence for decrepitation becomes

greater, and the spatial density of surviving inclusions becomes progressively less, towards the edge of the sample.

4. Discussion

4.1. *Effects on fluid record*

The fluid inclusion record in all three minerals has been affected by the flight. The change is most evident in the two minerals with cleavage. No inclusions survive in the decrepitated feldspars. Few survive in the calcite, and they yield data substantially different to the control sample. Their maximum size has almost doubled and they are conspicuously stretched. Stretching leads to increase in the vapour bubble size, and consequent increase in homogenization temperature (Goldstein & Reynolds, 1994), as observed. Stretching also results in a decrease in fluid density, which might be manifest as a lower salinity. The salinity values in the calcite are elevated but widely scattered. This may reflect partial fluid leakage, which is not surprising given that most of the inclusions in the calcite are decrepitated. Calcite is particularly susceptible to decrepitation of inclusions (Prezbindowski & Larese, 1987; Meunier, 1989).

The inclusions in quartz are the least affected, but nonetheless show increases in homogenization temperature and salinity. They exhibit stretching, which explains the change in homogenization temperature. In the case of quartz the elevation in salinity is less easy to explain than in calcite, as there is no evidence for fluid leakage. Modest temperature increases of < 100 °C after entrapment of inclusions in quartz during progressive burial of sedimentary rocks do not normally cause re-equilibration

of fluids (Robinson et al., 1992). Possibly the fluid has been modified by fluid-mineral interaction during exposure to high temperature during re-entry. Re-equilibration of inclusions with younger generations of fluid is a possible explanation for increase in salinity, and typically yields cross-plots of data with large ranges in temperature and salinity (Goldstein, 1986). Fluids in the crust tend to have higher ionic strength at higher temperatures (Moller et al., 1997), although this trend is normally observed in the pore spaces of rocks where there is more potential for interaction. However, there would have been little time for fluid-mediated reactions to occur. An increase in salinity is also possible due to diffusion of water from the inclusions. This has been observed in experiments where quartz has been exposed to very high temperatures over a period of days (Sterner et al., 1988). The re-entry exposure time is much shorter, but the observed growth of calcium silicates from quartz also requires rapid diffusion, so this mechanism may be feasible. Elwood Madden et al. (2004, 2006) similarly observed increased homogenization temperatures in quartz in sandstone samples from Meteor Crater and from impact simulations. The shift probably reflects stretching of the inclusions due to internal overpressuring during heating.

Although the composition of fluids in the quartz-hosted inclusions has changed, there is no visible evidence for leakage from them. However, it would be unwise to use these inclusions as a source of information on the parent fluid, for example on the isotopic composition of the water. The process(es) that caused change in chemical composition are likely to have disturbed all aspects of the original fluid.

4.2. Significance of decrepitation

Decrepitation is most common in medium/high-grade metamorphic rocks, where the inclusions have experienced temperatures much higher than during fluid entrapment (Shepherd et al, 1985). In sedimentary rocks, it is generally thought that quartz does not deform under normal conditions of heating to $<200\text{ }^{\circ}\text{C}$ (Robinson et al., 1992; Goldstein & Reynolds, 1994).

Decrepitation is ultimately caused by a pressure differential between the inclusion fluid and the exterior. A pressure differential could be caused by processes other than heating of the fluid, including low confining pressure in space, or due to growth of ice crystals in the fluid at low temperature. However, the gradient of homogenization temperature measured in quartz indicates that a short-term process is responsible, in which conduction of heat (in either direction) was limited. The low confining pressure in space is quite inadequate to cause the differential required for decrepitation (see below). The dynamic pressure during re-entry is similar to atmospheric pressure (Hald et al., 1993). The formation of ice is unlikely as the orbit does not bring the temperature below $0\text{ }^{\circ}\text{C}$, as also predicted for meteorites in Earth orbit (Mileikowsky et al., 2000). The increasing evidence for decrepitation, and greater sparsity of inclusions towards the edge, suggest that decrepitation was thermally controlled. We conclude, therefore, that rapid heating to very high temperatures (above $1000\text{ }^{\circ}\text{C}$) during re-entry was the cause.

Many fluid inclusions in quartz can be internally overpressured for years without deformation (Bodnar et al., 1989), but the very rapid application of heat to external temperatures of $>1000\text{ }^{\circ}\text{C}$ in the STONE experiment may have inhibited elastic deformation of the quartz and facilitated decrepitation. Experiments suggest a differential pressure of at least 200 MPa is required between the inside and outside of inclusions (Robinson et al., 1992). Inclusions with regular shape, as in the Austrian

sandstone, require relatively high internal pressure to cause internal deformation (Bodnar et al., 1989). Interpreting decrepitation in terms of temperature is not simple. In addition to mineralogy, the temperature of decrepitation depends upon the size and shape of fluid inclusions. Decrepitation occurs at higher temperatures in smaller inclusions (Bodnar et al. 1989). Decrepitation temperatures measured in quartz are commonly a minimum of 50 °C higher than homogenization temperatures, and may be substantially higher (Leroy, 1979; Bodnar et al., 1989; Robinson et al., 1992; Kendrick et al., 2006). Thus it is reasonable to assume that the sample had reached a temperature of 100 °C at the extrapolated depth of unchanged inclusion temperature (see below).

The Martian meteorites show moderate levels of shock, typically about 30 GPa (Head et al., 2002), which would be enough to cause decrepitation of fluid inclusions (Elwood Madden et al., 2004, 2006). Thus when we observe decrepitation in Martian meteorites (Bridges et al., 2000), it is reasonable to assume that this happened on Mars during the impact and ejection process there, although preparation difficulties mean that some contamination is possible. Our experiment shows that decrepitation can also occur during atmospheric entry, so the observation of decrepitation alone is not an indication of shock on a meteorite parent body.

As a guide to how quartz in sandstones responds to rapid exposure to high temperatures, we can examine fluid inclusions in the contact zones around igneous intrusions. Observations of samples adjacent to dykes and sills show that some decrepitation occurs, and that surviving inclusions become re-equilibrated to higher temperatures (e.g. Barker et al., 1998). The decrepitation and re-equilibration corresponds to what is observed in the STONE 5 experiment, but the heating time involved is very much longer.

4.3. Significance for meteorites

The STONE experiment has shown how inclusions can be altered at a depth of at least 1 cm below the exposed surface, greater than the depth of visible alteration. Clearly, many sampled meteorites are larger than this. We can estimate a depth at which some inclusions may be unaffected, at least in quartz, by extrapolating the trend of homogenization temperature against depth to the point at which the temperature corresponds to the range measured in the control sample (Fig. 3). This would occur at a depth of 1.3 to 1.8 cm below the original surface, assuming that the simple linear relationship between temperature and depth continues. For minerals other than quartz, more susceptible to decrepitation of inclusions, the minimum depth at which inclusions would be preserved may be considerably greater. This depth of influence is greater than the 3mm depth inferred from palaeomagnetic studies in ALH84001 (Weiss et al., 2000) and from calculations of thermal gradients (Sears, 1975; Fajardo-Cavazos et al., 2005).

The limited preservation of inclusions in calcite from the interior portion of the flight sandstone is comparable to many of the reported occurrences of inclusions in meteorites, which occur in minerals of relatively high solubility precipitated at low temperature. These minerals include Ca-carbonate, and halite (Zolensky et al., 1999a,b; Saylor et al., 2001; Rubin et al., 2002; Bridges & Grady 2000; Bridges et al., 2004). The typical occurrence of these minerals is as cements or interstitial precipitates between grains or crystals of high-temperature minerals. In the light of the damage to the calcite-hosted inclusions in the sandstone, the preservation of inclusions in halite in meteorites may seem surprising. However, the halite-bearing

meteorites (Monahans and Zag) were recovered as individual pieces with masses greater than 1 kg, which is big enough to allow protection in the interior. The Zag halite may also have two generations of fluid inclusions, increasing the likelihood that at least one is pre-terrestrial (Bridges et al., 2004). Note that the record of fluid inclusions in meteorites that contain readily dissolvable minerals and are not classed as ‘falls’ (observed landing and immediate collection) has attracted much scepticism (Rudnick et al., 1985), especially when meteorites have been recovered from ice sheets (Bodnar, 2001). If there is any uncertainty over the integrity of inclusions in halite, then proposals to search for evidence of Martian life trapped within halite crystals (e.g. Tasch, 1997; Fendrihan and Stan-Lotter, 2004) must also be open to question.

The decrepitation of inclusions in the feldspar grains is comparable to decrepitation in mineral grains with cleavage in meteorites, such as clinopyroxene in the Nakhla meteorite. Most inclusions appear to be ruptured in this meteorite (Bridges et al., 2000), but a few survive (Fig. 4).

Quartz is not a widespread mineral on Mars, and sands/sandstones there consist of grains composed of volcanic minerals (Clark et al., 2005) and possibly sulphates (Langevin et al 2005). On Earth, most quartz sand is derived from the erosion of granites (Smalley, 1966), but only very limited occurrences of granitic rock have been detected on Mars (Christensen et al., 2005). This is in turn a consequence of the lack of plate tectonics on Mars (Parnell, 2005). The preservation of inclusions in quartz may not tell us much about preservation in Martian meteorites, and meteorites in general only rarely contain quartz (Rubin, 1997).

Temperatures experienced during re-entry are high enough to melt basalt and silica fibres in the heat shield of the spacecraft, so are comparable with those

experienced by meteorites (Brack et al., 2002). The velocity of the spacecraft is lower than that of meteorites, so temperatures generated by frictional heating on re-entry will be lower. However this must be at least partly counterbalanced by the rotation of meteorites which limits exposure of any specific surface to the highest temperatures.

A further limitation on the analogy with real meteorites is that meteorites are generally basic igneous rocks, with a lower solidus temperature (typically ~ 1100 °C for basalt) than the sandstone used in the STONE experiment. Consequently meteorites develop a molten fusion crust (Genge & Grady, 1999a,b), which experiences ablation, and thereby loss of heat and the inward migration of the outer surface.

4.4. Significance for panspermia

The STONE experiments were designed particularly to investigate the possibility of panspermia (Brack et al., 2002; Cockell et al., 2007). The concept of panspermia holds that simple life can be transferred between planets on meteoroids, most probably on meteorites. The probability of life on asteroids, comets and other small bodies is negligible (Clark et al., 1999), so we must focus on Mars as a source of panspermia to Earth. Accordingly many models have assessed Mars as a source of life on Earth (Mileikowsky et al., 2000; Kirschvink and Weiss, 2002; Melosh, 2003). Calculations of the flux of meteorites from Mars to Earth suggest >10 per year, hence very large numbers over the history of the solar system, and by inference a greater number early in Solar System history when the impact rate was greater (Melosh, 2003; Gladman, 1997). Even though the proportion of these travelling by rapid trajectory is small, Gladman (1997) suggests that a few meteorites may pass from

Mars to Earth in less than a few years for each launch events at a \sim Myr interval. This is believed to be a survivable time frame for microbial life, and implies that opportunity for panspermia between Mars and Earth is adequate.

Does the depth of alteration measured in the STONE experiment have consequences for the likelihood of panspermia? Even if the temperature required for decrepitation is taken as the minimum 50+ °C above homogenization observed in other studies, the decrepitation observed in the Austrian sandstone implies exposure to temperatures over 100 °C to a depth of about 2 cm. A temperature of 100 °C has been adopted as a limit for the survivability of microbes (Mileikowsky et al., 2000), which is not far below the temperature experienced by the most specialist thermophile identified to date on Earth (Kashefi & Lovley, 2003). For a less adapted microbial population, the upper limit for survival might be somewhat lower. As a benchmark of the temperature required to destroy non-heat-resistant forms of micro-organisms, pasteurization typically involves exposure to 72 °C for 20 or 25 seconds (Grant et al., 1999). However, although short-term exposure to this level of heating would significantly reduce the bioload it may not completely eliminate it (Nicholson et al., 2005).

The duration of exposure to heating is a critical factor. Meteorites are exposed to heating during re-entry for an estimated few seconds (McCrosky et al., 1971; Kimura et al., 2003). However, the very low angle of entry of the FOTON spacecraft supporting the STONE 5 experiment (the velocity was reduced just marginally to trigger the change from orbiting to re-entry) means that heating above 1000 °C lasted for 100 seconds and above 500 °C for over 200 seconds. The depth of penetration of the thermal wave is approximately proportional to the square root of heating time. Using the simplified expression $\sqrt{(\kappa t_e)}$ used by Fajardo-Cavazos et al. (2005), where κ

is the thermal diffusivity and t_e is the entry time, and thermal diffusivity values for sandstone of about $10^{-6} \text{ m}^2\text{s}^{-1}$ (Vosteen & Schellschmidt, 2003; Kubičár et al., 2006), the 500+ °C heating would have penetrated to about 1.5 cm. This approaches the observed depth of alteration. A more sophisticated modelling assesses how temperature changes with depth as heat is applied. Following Kimura et al. (2003), thermal conduction has been treated as a one-dimensional heat flow problem. Adopting an initial temperature of 0 °C, a thermal diffusivity of $10^{-6} \text{ m}^2 \text{ s}^{-1}$, and application of 1000 °C for 100 s (as reported), temperature-depth profiles with time are calculated as shown in Figure 5 (for details of mathematical treatment see Carslaw & Jaeger, 1989; Kimura et al., 2003). The result is that at 2 cm depth a temperature of almost 200 °C is achieved after 100 seconds. This is consistent with the alteration depth deduced above from the fluid inclusion data. Given that over the 100 second heating time, the temperature actually exceeded 1000 °C, a temperature above 200 °C may have been achieved at 2 cm depth. The implication is that meteorites entering the atmosphere at low angles, with consequent long heating times, could experience a depth of alteration greater than normally assumed. However, this model does not take account of the loss of mass in a meteorite due to ablation, which can be substantial (Bland & Artemieva, 2003). Thus erosion of the surface could occur at a rate significant compared to the inward conduction of heat, and the true temperature-depth profile would be steeper than shown in Figure 5.

If temperatures of 100 °C *were* experienced to a depth of 2 cm in a meteorite due to long heating time, and this proportion is considered sterilized, that constrains the size of the meteorite that could preserve life undamaged to greater than 4 cm. At this level of alteration, a spherical meteorite in which 50% of the mass escapes the alteration would need to be approximately 20cm diameter. In a stony meteorite of

density 3000 kgm^{-3} this equates to a mass of 13 kg. A more realistic shape, based on the mean maximum/minimum diameter ratio for a stony meteorite of 1.6 (Krinov, 1981), and assumed intermediate diameter of 1.3, would equate to a mass of 26 kg for 50% alteration. A more marginal 20% mass free of alteration would require a mass of 3.3 kg using the mean shape. The 50% alteration-free mass is bigger than any known martian meteorite (Head et al., 2002), while the 20% alteration-free mass is larger than almost all of them. This implies that a substantial proportion of martian meteoritic material arriving at Earth, and small enough to survive impact, could be sterilized. Eugster et al. (2002) calculated that martian meteorites were a minimum 22-25cm diameter and 150-220 kg mass before atmospheric entry. The distinction between pre-atmospheric size and the known martian meteorites may be due to extensive fragmentation (Bland & Artemieva, 2003) and high ablation rates, typically 90% for stony meteorites (Baldwin & Sheaffer, 1971; Bland & Artemieva, 2003). Heating and alteration continues after fragmentation (Artemieva & Shuvalov, 2001), so thermal alteration affects greater volumes of rock than predicted from pre-atmospheric masses.

Despite the calculations above, the minimum size required to avoid sterilization remains just 4 cm, as any volume above this is sufficient to host a substantial number of microbes (Mileikowsky et al., 2000). Of the pre-ablation sizes of martian meteorites listed by Head et al. (2002), one third would be excluded by this constraint. However, a further consideration is that the rock types likely to best survive the processes of ejection from Mars and arrival at Earth are those of very low porosity and very low fracture density, and accordingly the recognized martian meteorites are basic igneous rocks (Head et al. 2002). Those rocks that survive are by

their very nature difficult to colonize, which mitigates against a high bioload within the centres of large meteorites.

5. Conclusions

This study has made the first measurements in fluid inclusions exposed to conditions designed to simulate meteorite transit through the Earth's atmosphere. Although exposure to high temperature for a short time altered the fluid inclusions below the outermost surface (equivalent to the fusion crust in meteorites), the brevity of the event has limited the conduction of heat. Thus inclusions within the centre of meteorites are likely to survive unaltered, as shown by decreasing homogenization temperature with increased depth below the surface in our experimental sample. Over a 0.8cm depth sampled, the mean homogenization temperature in quartz decreases from 132 °C to 95 °C towards the sample interior. Samples show progressively greater degrees of inclusion decrepitation towards the exterior. The thermal alteration measured in the STONE 5 sandstone sample suggests a temperature of 100 °C experienced up to 2 cm depth below the surface, consistent with the heating time that is longer than that experienced by most meteorites. This thermal alteration also implies that panspermia is unlikely in small meteorites. If this depth were applied as a constraint on the bioload possible in known martian meteorites, much of the meteorite volume would be excluded. Given that the meteorites that survive have negligible intergranular or fracture porosity (and low permeability), any bioload beneath the outer sterilized zone, and the probability of panspermia, is likely to be very limited.

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Figure captions

Fig. 1. Images of sandstone sample, and fluid inclusions. A, post-flight sandstone sample, showing white matrix (altered calcite) close to exposed margin. Fluid inclusions in control sample: B, two-phase inclusion in quartz; C, parallel arrays of inclusions in feldspar; D, two-phase inclusion in calcite. Fluid inclusions in post-flight sample: E, two-phase inclusion preserved in quartz, but stretched; F, stretched and decrepitated inclusions in feldspar; G, inclusions in calcite stretched (black arrows) or decrepitated (white arrows).

Fig. 2. Microthermometric data from fluid inclusions in control and post-flight sandstone samples. Cross-plot of homogenization temperature against salinity shows well-constrained fields for each host mineral in control sample. Fields for post-flight sample are displaced to higher values of homogenization temperature and salinity, and show greater spreads in data. All feldspar-hosted inclusions are decrepitated in post-flight sample, hence no measurements are possible.

Fig. 3. Homogenization temperatures measured in quartz, plotted with depth below exposed surface (data from transects in Table 2). Temperatures decrease with depth. A linear relationship is exhibited over the range measured, which would extrapolate to an 'unaltered' temperature (the range of values from the control sample) at a depth of 1.3 to 1.8 cm. Note original surface was an additional 0.2 cm above that now preserved.

Fig. 4. Fluid inclusions in clinopyroxene grain, Nakhla meteorite. Inclusions occur in cross-cutting trails (A) and are mostly decrepitated, but a few two-phase inclusions survive intact (B).

Fig. 5. Temperature distribution as a function of heating time (s) and depth (mm) from sample surface, assuming initial temperature of 0 °C, heating at 1000 °C for 100 s, and thermal diffusivity of $10^{-6} \text{ m}^2 \text{ s}^{-1}$. Calculation indicates a temperature of almost 200 °C achieved at depth of 20 mm.

Sample	n	Mineral host	Timing	Mean fill (%age liquid)	Maximum		Mean		Minimum		Mean salinity (Wt. % NaCl eq.)
					T _h (°C)	T _m (°C)	T _h (°C)	T _m (°C)	T _h (°C)	T _m (°C)	
Pre-flight	28	Quartz	Secondary	0.95	83.4	-1	75.8	-1.5	68.4	-1.9	2.6
Pre-flight	17	Feldspar	Secondary	0.9	82.5	-1	75.6	-1.5	68.8	-1.9	2.5
Pre-flight	32	Calcite	Primary	0.85	103.6	-2.1	89.9	-2.6	74.2	-3.1	4.4
Recovered	42	Quartz	Secondary	0.85	132	-0.7	115.6	-2.5	93.7	-4.6	4.1
Recovered	12	Calcite	Primary	0.65	224	-0.8	172	-7.6	116.6	-14.1	17.9

Distance from exposed surface (cm)	Transect 1 T_h (°C)	Transect 2 T_h (°C)	Transect 3 T_h (°C)	Transect 4 T_h (°C)	Transect 5 T_h (°C)	Transect 6 T_h (°C)
0	126.4	x	129.5	132.1	125.2	128.3
0.05	127.3	119.9	129.1	126.4	x	127.1
0.1	118.2	x	125.2	119.3	123.4	129.2
0.15	117.9	x	x	122.7	124.6	120.7
0.2	112.2	116.3	127.3	117.4	119.1	x
0.25	x	115.2	119.7	x	120.5	117.4
0.3	114.9	110.3	112.3	115.3	113.4	118.3
0.35	113.7	111.7	x	117.1	112.2	116.2
0.4	x	108.4	x	109.2	115.6	x
0.45	113.8	105.9	106.2	113.4	108.2	106.7
0.5	109.2	x	100.6	109.2	106.3	107.3
0.55	110.5	103.4	97.3	x	105.2	x
0.6	101.7	x	103.4	x	103.7	x
0.65	104.8	100.7	99.1	104.3	99.4	100.9
0.7	x	101.2	96.2	104.7	96	97.2
0.75	x	99.4	x	105.6	x	99.3
0.8	97.6	95.2	95.3	102.1	x	95.8

x = No fluid inclusion at reference point

n = 79

