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Micrometeorites: Insights into the flux, sources and atmospheric entry of extraterrestrial dust at Earth

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ABSTRACT

Micrometeorites (MMs) provide constraints on the flux and sources of extraterrestrial dust falling on Earth as well as recording the processes occurring during atmospheric entry. Collections of micrometeorites have been recovered from a wide variety of environments including Antarctic moraine, rock traps, ice and snow and on roof tops in urban areas. Studies of the mineralogy and composition of MMs suggest that most particles (>98%) >50 μm in diameter have asteroidal sources, whilst ~50% of particles smaller than 50 μm are likely to be derived from comets. The relative abundance of S(IV)-type asteroid materials, similar to ordinary chondrites increases with size, although C-type asteroidal materials, similar to carbonaceous chondrites dominate over all. Although MMs provide excellent evidence on the nature and abundance of extraterrestrial dust at the Earth's orbit they are not without bias and uncertainty. Mineralogical and compositional change during atmospheric entry makes the exact nature of their precursors uncertain complicating evaluation of source beyond basic classes of material. This is particularly true at larger sizes when complete melting to form cosmic spherules occurs, however, unmelted MMs >50 μm in size are also often thermally altered. Mixing with atmospheric oxygen and mass fractionation by evaporation furthermore complicates the use of oxygen isotope compositions in identifying parent bodies. All MM collections are suggested to exhibit biases owing to: (1) collection method, (2) terrestrial weathering, (3) terrestrial contamination, and (4) erosion and deposition by terrestrial surface processes. Even in the least biased collections, those collected by dedicated melting of Antarctic snow, erosive loss of material is suggested here to make fluxes uncertain by factors of up to ~2. The abundance of asteroid-derived MMs observed in collections contradicts models of the orbital evolution of interplanetary dust to Earth, which suggests >70% should be provided by comets.

1. Introduction

Micrometeorites (MMs) are extraterrestrial dust particles smaller than ~2 mm in diameter that survive atmospheric entry to be recovered from the surface of a planetary body (Genge et al., 2008). Extraterrrestrial dust particles collected in the stratosphere by NASA, in contrast, are known as interplanetary dust particles (IDPs) and are mostly smaller than MMs at diameters of <50 μm (Bradley, 2005). Micrometeorites and IDPs together provide a sample of the zodiacal dust cloud and give insights into the sources, flux and atmospheric entry processes of extraterrestrial dust falling on Earth.

Micrometeorites compliment observations of small meteors since they allow the minerals and compositions of these objects to be determined with the precision of laboratory techniques thus providing constraints by which spectroscopic data from meteor observations can be interpreted. The mineralogy and textures (the spatial relationships and shapes of phases within rocks) within MMs also provides information on their atmospheric entry (Kurat et al., 1994; Genge et al., 1997). Micrometeorites experience heating and a ram pressure during their deceleration in the atmosphere (Love and Brownlee, 1991) that causes changes to the pre-atmospheric mineralogies and compositions and can reveal the processes operating during atmospheric entry (e.g. Genge and Grady, 1998; Genge, 2006).

The least heated MMs preserve most of their original mineralogies and compositions, albeit with some terrestrial alteration owing to exposure on the Earth's surface. The mineralogy and composition of MMs

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provide information on the nature of their parent objects within the solar system, which are thought mainly to be asteroids and comets (Genge et al., 2008, 2018; Duprat et al., 2010; Cordier et al., 2011a; Van Ginneken et al., 2017). A small proportion of MMs could also be derived from planetary bodies as impact ejecta. Micrometeorites, therefore, contribute to the understanding of the sources of meteors providing information on their constituent materials that compliments the orbital and spectral data derived by observation.

The abundance of MMs on the Earth's surface reflects the flux of extraterrestrial dust being accreted to the Earth and the size distribution of particles within the Zodiacal cloud. The relative abundance of different types of MMs heated during atmospheric entry also relates to the velocity distribution of dust particles (Love and Brownlee, 1991; Genge, 2016b, 2017b). Certain aspects of the textures of MMs can even be used to delimit the dynamic behaviour of dust particles in space prior to their atmospheric entry (Genge, 2016a).

Micrometeorites have also been collected from sedimentary rocks (fossil MMs) spanning most of Earth history and thus record the past flux of extraterrestrial dust accreted by our planet (Taylor and Brownlee, 1991; Dredge et al., 2010; Onoue et al., 2011; Voldman et al., 2013; Suttle et al., 2017; Tomkins et al., 2016). These particles enable study of variations in the flux of micrometeorites in response to major events in solar system history. The alteration of micrometeorites in the Earth's atmosphere during their entry also makes them a proxy for atmospheric composition (Tomkins et al., 2016).

This paper reviews the collection and nature of MMs to provide an assessment of their implications for meteors. The biases effecting different collections and their alteration on the Earth's surface are considered to evaluate their uncertainties since these influence the constraints they provide on flux and sources. Finally a fundamental contradiction between models of the dynamic evolution of dust in interplanetary space, which suggest sources dominated by comets (Nesvorný et al., 2011; Carrillo-Sánchez et al., 2015), and observations of MMs, which suggest a source dominated by asteroids (Genge et al., 2008; Taylor et al., 2012; Suavet et al., 2010; Cordier et al., 2011a; Cordier and Folco, 2014; Van Ginneken et al., 2017), is highlighted as a major outstanding issue.

2. The collection of micrometeorites

2.1. Types of deposit

Micrometeorites are present everywhere on the Earth's surface but are difficult to collect in those regions where terrestrial dust particles are abundant. Optimal locations for the recovery of MMs are, therefore, those where minimal fine-terrestrial sediment occurs, often because they are distant from sources of terrestrial sediment, such as the deep oceans, or where limited exposure of rocks are present, such as in Antarctica. In the deep oceans, for example, the accumulation of terrestrial sediment can be as little as 3×10^{-3} mm yr^{-1} and thus micrometeorites can represent a significant fraction of the material present (Blanchard et al., 1980; Brownlee, 1985).

Preservation is also an important factor in the abundance of MMs. In the deep oceans, for example, particles are exposed to sea water prior to burial by marine sediments, and then to pore fluids within the sediment pile prior to diagenesis (the lithification of sediments into rocks). Collections from deep oceans exhibit lower abundances of the most easily weathered MMs, such as silicate-rich particles, and higher abundances (>5%) of those particles dominated by minerals resistant to alteration by water, such as magnetite (Fe_3O_4) and wustite (FeO) (Brownlee, 1985; Shyam Prasad et al., 2013). Iron-nickel metal is also often partially altered to iron hydroxides (rust) in these locations (Shyam Prasad et al., 2018). Owing to the slow accumulation of deep sea sediments the materials collected on the ocean floor samples several tens of thousands of years into the recent past (Shyam Prasad et al., 2013). Some MMs have also been recovered from lake deposits that have low sedimentation rates (Akulov et al., 2014).

The relatively low sedimentation rates in hot deserts are also suitable for the accumulation of MMs when combined with hyper-arid conditions leading to long-term preservation. Collections of MMs have been recovered from the Atacama desert (Van Ginneken et al., 2017) and some MMs have been reported from the Sahara (Fioretti et al., 1998). In these locations the best accumulations of MMs are likely to relate to periods with the most arid conditions.

The accumulation of MMs in Antarctica benefits from both the low sedimentation rates of terrestrial grains and an excellent preservation potential owing to the hyper-arid nature of the continent (Maurette et al., 1991). Micrometeorite collections have been recovered from several different types of deposit in Antarctica. Moraines are areas where terrestrial rocks and fine-sediment accumulate in the vicinity of nunataks (mountains) or on the upper surface of glacial ice (Harvey and Maurette, 1991; Genge et al., 2018). Large numbers of MMs have been recovered from these locations and those derived from supraglacial moraines have terrestrial ages older than the age of the ice owing to accumulation by progressive sublimation (Genge et al., 2018). Crevasses in bare rock surfaces also are hosts for MMs in the Antarctic, particularly those at high altitude that have not experienced ice-cover for extended periods of time (Rochette et al., 2008; Suavet et al., 2009). Antarctic snow and ice also contain a high proportion of MMs compared with terrestrial grains in those areas distant from nunataks (e.g. on the Antarctic Plateau; Maurette et al., 1991; Taylor et al., 2000; Noguchi et al., 2015; Duprat et al., 2010). Glacial blue ice is formed by the compaction and burial of surface snow. Most blue ice is exposed in the vicinity of nunataks, in particular along the transantarctic mountains, and can be up to 300 ka in age (e.g. Grinsted et al., 2003). Accumulations of snow, in contrast tend to be relatively recent and offer the advantage that their stratification can be dated and time-correlated collections of micrometeorites obtained (Taylor et al., 2000; Duprat et al., 2007). The abundance of MMs within snow is, however, relatively low complicating the collection of large numbers of particles.

Some accumulation of MMs occurs within sedimentary traps on the Earth's surface. These are areas where dense particles, such as MMs containing significant FeNi metal or iron-oxides, become trapped whilst lower density terrestrial grains are removed in wind or water currents. Micrometeorites have been reported, for example, within fluvial gravels (Bi et al., 1993) and within sand dunes (Fioretti et al., 1998). Antarctic moraines are also undoubtedly wind traps for dense particles (Genge et al., 2018). Bare rock crevasses also have the potential to trap wind transported grains (Tomkins et al., 2019).

Recently MMs have also be found within sediment in gutters on urban roof tops (Genge et al., 2017a). Although this is one of the most unlikely localities to expect the accumulation of MMs, owing to the large abundance of terrestrial grains, these collections accumulate as sedimentary traps owing to the high density of grains. Large amounts of gutter sediment need to be reprocessed to recover MMs. Roof top collections were pioneered by Jon Larsen (2016), and more recently Scötte Petersön who make an important contribution as citizen scientists. They sample MMs that have often fallen in the last few years (Genge et al., 2017a).

Finally, MMs have also been recovered from ancient sedimentary rocks up to 2.7 Ga (Tomkins et al., 2016). Most of these collections have been recovered from limestones including Archean (Tomkins et al., 2016), Ordovician (Dredge et al., 2010), Jurassic (Taylor et al., 1991) and Cretaceous (Suttle and Genge, 2017). Some collections have also been made from deep ocean siliciclastics (mudstones) of Triassic age (Onoue et al., 2011), and fluvial deposits of Ordovician age (Voldman et al., 2013). Individual mineral grains from MMs, such as chromite, have also been recovered from sedimentary rocks (e.g. Schmitz et al., 2019). The recovery of micrometeorites from ancient sedimentary rocks is a natural consequence of the accumulation of these particles in surficial environments on Earth, which can become preserved during burial and lithification of sediments into rock.

2.2. Collection techniques

A wide variety of different techniques have been used to recover MMs owing to the diverse localities in which they are found. Micrometeorites from snow and ice are recovered by melting and filtering (Maurette et al., 1991), in some cases particles have been recovered from snow melted as drinking water at Antarctic bases such as in the South Pole Water Well (Taylor et al., 2000) and at Dome Fuji (Nakamura et al., 1999). In Antarctic moraine and bare rock traps MMs can be present in sufficient quantities that they may be picked by hand under a binocular microscope using appearance, colour and shape to select likely micrometeorites (Genge et al., 2008, 2018; Rochette et al., 2008). Magnetic separation is, however, sometimes used in these locations to increase the abundances of MMs. In other deposits, such as roof tops, deep ocean sediments and ancient sedimentary rocks, magnetic separation is frequently used to more easily recover particles prior to hand-picking, although some attempt to recover MMs from deep sea sediments without magnetic separation have been successful (Shyam Prasad et al., 2013). In the case of MMs derived from localities that contain fine-sediment, washing in acetone and sonic agitation is also sometimes used to remove adhered particulate matter (e.g. Van Ginneken et al., 2016).

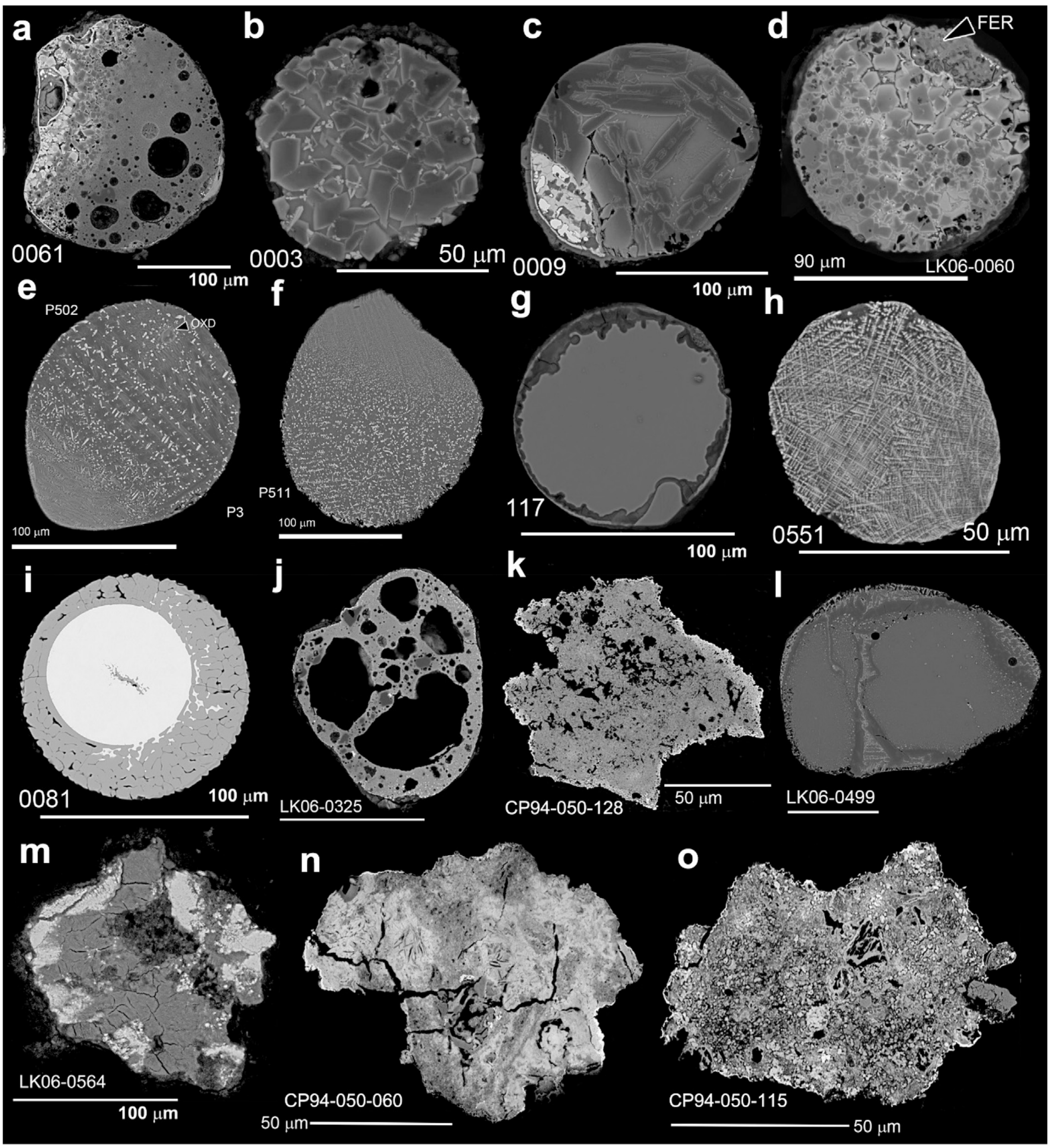

Fig. 1. Backscattered electron images of common micrometeorite types from Larkman Nunatak moraine, Cap Prudhomme ice (k,n,o) and urban roof tops (e, f). Cosmic spherules shown are (a–d) porphyritic S-types, (e) barred S-type, (f) cryptocrystalline S-type, (g) glassy (V-type) S-type, (h) G-type, and (i) I-type. A scoriaceous MM is shown in (j). Particles (k–o) are unmelted MMs and include: (k) a FgMM with an igneous rim, (l) a partially melted CgMM, (m) a CI-like FgMM with magnetite framboids, (n) a C2-like FgMM, and (o) a highly porous FgMM. Altered metal is labelled FER.

3. Types of micrometeorite

Micrometeorites are subdivided based on features related to both their atmospheric entry heating and their pre-atmospheric properties. In many MMs atmospheric entry effects dominate the over-all appearance of particles (Fig. 1). The classification of MMs presented below has evolved with studies of MMs with major elements of the terminology defined by Brownlee (1985), Taylor and Brownlee (1991), Genge et al. (2008), Taylor et al. (2012).

3.1. Melted micrometeorites

Micrometeorites can be subdivided into melted or unmelted particles. The degree of melting in MMs is, however, gradational and an arbitrary threshold of 50% melted is used to distinguish the two groups. Particles that have extensively melted and formed sub-spherical droplets owing to surface tension are known as cosmic spherules (CSs). These particles are further subdivided based on composition and texture. Silicate-dominated particles are known as S-types, whilst those dominated by iron oxides and metal are known as I-types. An intermediate group of particles that contain near equal proportions of iron-oxides and silicates are termed G-type particles. The S-type particles are dominated by olivine crystals, formed by crystallisation during cooling in the atmosphere, within glass with or without iron oxides such as magnetite. S-type cosmic spherules are subdivided on the basis of texture into porphyritic (Po), barred (Bo), crypocrystaline (C) and glassy (V-types) spherules. Porphyritic spherules can also be subdivided into micro-porphyritic (uPo; Fig. 1a) or coarse-porphyritic (cPo; Fig. 1b–d) spherules, in which the former have grain-sizes of <2 μm in diameter.

A wide range of textural sub-types of S-type spherules exist based on the shapes of their olivine crystals and the presence of relict phases that survived melting in the atmosphere (e.g. Genge et al., 2018). Forsterite and enstatite are the most common relict phases, however, iron-rich olivines and chromite can also occur in some spherules (e.g. Taylor et al., 2000; Genge et al., 2008). Relict phases are most common within porphyritic spherules. A proportion of spherules also contain FeNi metal and sulphide beads (Fig. 1a,c).

Micrometeorites that have experienced <50% melting are known as Scoriaceous MMs (ScMMs) and are highly vesicular containing up to 70 vol% vesicles within a melted mesostasis comprising micron-scale olivine within glass (Fig. 1j). These particles usually have well developed external rims of magnetite and frequently contain relict olivine and or enstatite. Magnetite rims are rare on CSs but appear on some Po spherules that have metal/sulphide beads (Fig. 1a).

3.2. Unmelted micrometeorites

Unmelted micrometeorites are either fine-grained or coarse-grained. Their textures are largely pre-atmospheric, although many have experienced some mineralogical and chemical change during entry heating. Fine-grained MMs (FgMM) are dominated by sub-micron phases and contain irregular porosity (Fig.1k,m-o). The majority of fine-grained MMs have magnetite-rims that testify to some heating during atmospheric entry (Toppani et al., 2001; Toppani and Libourel, 2003; Genge et al., 2008). The textures of these particles indicate that they have not experienced significant melting, although many have rims with igneous textures (crystals within glass and vesicles) that indicate surface melting (Genge, 2006, Fig. 1k). The interior of such particles also frequently have gas cavities and dehydration cracks that form by thermal decomposition of volatile-bearing phases (Genge, 2006; Suttle et al., 2019a,b). Different textural and compositional groups of FgMMs are also recognised and are described in section 4 since they help identify the source objects of MMs.

Coarse-grained MMs (CgMMs) are dominated by olivine and pyroxene with grain-sizes greater than several μm in size (Fig. 1l). Often CgMMs have igneous textures with crystals within glass that indicate crystallisation from a melt. The irregular shapes of CgMMs indicate the melting occurred prior liberation from the parent body and is thus a primary feature, however, partial melting in the atmosphere can occur resulting in smooth surfaces formed by a meniscus of melt. Angular shapes can also be observed on some cosmic spherules fractured on the Earth's surface. Most CgMMs consist of either Mg-silicates, glass and FeNi-metal or iron-rich silicates, glass, FeNi metal and/or iron oxides (often chromite). A proportion of CgMMs contain small selvages of fine-grained matrices on their outer surfaces and have been termed composite MMs by Genge et al. (2005).

Different types of unmelted MM appear at small sizes (<50 μm). Some of these particles consist mainly of organic carbon, with sparse embedded olivine, pyroxene and FeNi sulphides and are known as ultracarbonaceous MMs (UcMMs; Duprat et al., 2007; Duprat et al., 2010; Dartois et al., 2018). These particles also contain objects consisting of glass with embedded metal and sulphide, known as GEMS, that are a few nm in size (Dartois et al., 2018). Fine-grained MMs at small sizes also include highly porous carbon-rich grains with GEMS, enstatite whiskers and anhydrous silicates such as olivine and pyroxene (Noguchi et al., 2015). These particles bear a close resemblance to anhydrous IDPs collected in the stratosphere (Bradley, 2005). Similar GEMS-bearing hydrous IDPS are known that include phyllosilicates (Nakamura-Messenger et al., 2011).

4. The flux of micrometeorites

Estimates of the flux of extraterrestrial dust to the Earth's surface have been made using the South Pole Water Well collection of micrometeorites and suggest a flux of 1600 t/a (Taylor et al., 1998, Fig. 2). This value corresponds well with estimates from micro-impact craters on the LDEF (Long Duration Exposure Facility) satellite of 30,000 t/a (Love and Brownlee, 1993), assuming loss of 90% of particles by evaporation during atmospheric entry (Taylor et al., 1998).

Attempts have also been made to estimate the flux of micrometeorites to the surface in the Earth's past. Values estimated for Triassic, Jurassic and Cretaceous I-type cosmic spherules have provided values within uncertainty of the current day flux (Onoue et al., 2011; Taylor and Brownlee, 1991; Suttle and Genge, 2017). In contrast estimates of the micrometeorite flux made from extraterrestial chromite grains from

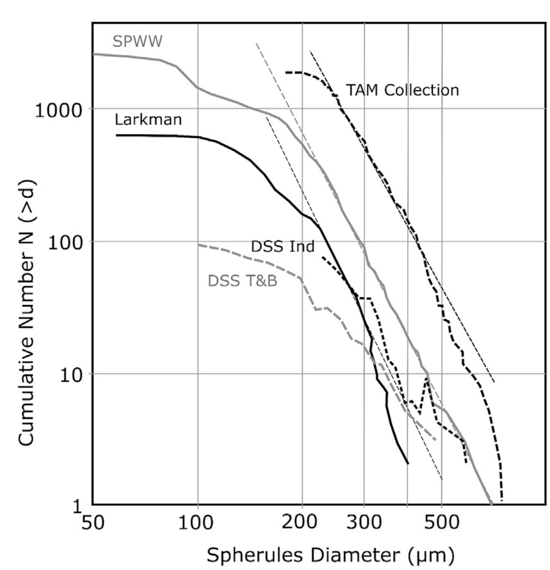

Fig. 2. A figure showing size distributions from the South Pole Water Well (SPWW; Taylor et al., 1998), the Transantarctic Mountains collection (TAM; Suavet et al., 2009), Larkman Nunatak moraine (Genge et al., 2018), Deep Sea Spherules from the Indian Ocean Collection (DSS Ind; Shyam Prasad et al., 2013) and from Taylor and Brownlee (1991) (DSS T&B). The absolute cumulative number relates to the total number of particles collected. Inflection points are likely to relate to removal of particles by weathering or currents.

Ordovician limestones provide estimates ~10x the current value (Schmitz et al., 2019). This agrees with the flux of meteorites during this time and has been suggested to relate to debris from the break-up of the L-chondrite parent asteroid.

Flux estimates for MMs have also been made from the ^{3}He isotopic composition of deep-sea sediments (Kyte, 2002). These studies reveal periods, such as the late Eocene, where transient increases in the flux of MMs have occurred, for example, as a result of the influx of new comets into the inner solar system (Farley et al., 1998).

5. The limitations of micrometeorites

Although an excellent sample of extraterrestrial dust falling on Earth MMs suffer from several factors that limit their applications to studies of the flux and sources of meteors. The uncertainties involved in MM studies are often poorly understood.

5.1. Flux estimates

Micrometeorite abundances have been used to validate models of the extraterrestrial flux to the Earth (e.g. Carrillo-Sánchez et al., 2015). Collections of MMs are, however, effected by biases that introduce uncertainties in their accumulation with time. The main biases affecting MM collections are: (1) uncertainties in the accumulation period, (2) biases owing to collection method, (3) removal of particles by weathering and (4) removal or concentration of MMs by surface processes.

Uncertainties in the duration of MM accumulation are most severe for ancient collections of fossil MMs. Usually an estimate of sedimentation rate is used to convert the mass and surface area of sediment processed for MMs to determine the accumulation time. Sedimentation rates are, however, relatively poorly known for most sediment types, for example, the rate of accumulation of pelagic carbonate ooze ranges from 0.03 to 0.5 mm/yr (Rothwell and Plimer, 2005). The flux derived can be, therefore, uncertain by at least a factor of ten.

Antarctic moraine and bare rock trap collections have long accumulation times of 700 ka determined by the presence of microtektites from the Australasian strewn field (Folco et al., 2008, 2010, 2011; Genge et al., 2018; Van Ginneken et al., 2018). The accumulation time is thus a minimum estimate for these deposits. Exposure ages of the glacial surface of 1 Myr have, however, been determined for the Transantarctic Mountains collection (Van der Wateren et al., 1999). Snow collections provide the best constrained accumulation periods since the layers of snow they contain can be dated relatively accurately. This is particularly true for the CONCORDIA collection that involves melting of snow specifically for the purposes of micrometeorite recovery (Duprat et al., 2007). The South Pole Water Well collection, in contrast assumes specifically that micrometeorites deposited in the central plateau in the well sample all the overlying snow (Taylor et al., 1998, 2000). Changes in the topography of the well earlier in its development and density currents, which could possibly have delivered some particles to this location, both introduce uncertainties that are difficult to constrain.

Perhaps the most accurate accumulation periods for MMs are for roof top collections of micrometeorites since the particles must have fallen within the age of the roof (Genge et al., 2017a). There have yet, however, to be any studies to make quantitative estimates of the modern flux of micrometeorites from roof top collections and are composed entirely of cosmic spherules. Differences in the abundance of cosmic spherule types, suggesting changes in entry velocity, however, have been used to suggest that the velocity distribution of dust varies with time (Genge et al., 2017a).

Collection method inherently introduces uncertainties into MM collections. Magnetic separation is associated with significant bias towards those particles containing magnetite or metal. Fortuitously this is most unmelted, scoriaceous and cosmic spherules, however, V-type spherules lack any magnetite and are thus under-represented, whilst the abundance of I-type cosmic spherules is significantly increased in such studies. Most deep ocean collections have been obtained by magnetic raking of the ocean sediment and thus the abundance of spherules is an underestimate (Brownlee, 1985). Attempts to hand-pick spherules from dredged sediments have been made to better identify the flux from these sources (Shyam Prasad et al., 2013). Studies of fossil MMs also mostly rely on magnetic concentration of I-types to allow their recovery, sometimes after acid digestion of host limestones. Suttle and Genge (2017) showed that acid digestion can lead to flocculation of clays with MMs and under-recovery of particles.

Micrometeorites recovered without significant processing include Antarctic collections where particles are typically recovered under a binocular microscope by eye (Maurette et al., 1991; Taylor et al., 2000; Rochette et al., 2008; Genge et al., 2008). Clustering of particles owing to static forces inevitably leads to some particles not being recovered, whilst human error in identifying MMs will result in some under-recovery. These uncertainties are likely to be relatively low, probably <20%. In other locations where abundant terrestrial sediment occurs, such as in Antarctic moraine, deserts and roof tops, the nature of terrestrial grains also strong affects the identification of particles. On roof tops, for example, I-type cosmic spherules are difficult to distinguish from metallic anthropogenic spherules (Larsen, 2016). In moraine from the Transantarctic mountains containing abundant basalt or coal there are many particles resembling unmelted MMs (Genge et al., 2018). In contrast the TAM collection is recovered from bare rock crevasses hosted on granite and much fewer dark terrestrial grains appear maximising recovery (Rochette et al., 2008).

Weathering and destruction of MMs in the terrestrial environment are particularly problematic in older collections of particles. Fossil MMs are the most affected by terrestrial alteration since they interact with pore fluids and undergo chemical changes during diagenesis as well as exposure prior to burial. Some replacement of I-type cosmic spherules was noted by Suttle and Genge (2017). The degree of alteration of fossil MMs varies considerably depending on the micro-environment present during burial and diagenesis. I-type cosmic spherules from Archean limestones, for example, preserve wustite and some metal, whilst in the Chalk most metal is dissolved and wustite is replaced by magnetite (Suttle and Genge, 2017). Diagenetic changes can vary even in a single deposit with rare metal-bearing particles found in the Chalk, and particles that may have been replaced entirely by iron-silicides. Nevertheless, pristine CSs were found in these studies and are likely to have been protected by the rapid growth of early cements (Suttle and Genge, 2017). Particularly intense alteration of MMs was noted in particles recovered from Triassic salt with nearly complete replacement by secondary phases (Davidson et al., 2007). The particles were, however, still recognisable as MMs by their characteristic morphologies and textures.

Deep ocean MMs are also susceptible to alteration owing to their prolonged exposure to seawater. Silicate micrometeorites are more sensitive to weathering than I-types leading to enhanced abundances of I-types in these collections (Blanchard et al., 1980; Brownlee, 1985; Shyam Prasad et al., 2013). Extensive alteration rims and partial dissolution of metal has been observed in deep sea collections testifying to weathering (Shyam Prasad et al., 2018).

Alteration of MMs also occurs in Antarctic collections. Moraine and rock trap collections exhibit dissolution of anhydrous silicates, partial alteration of glass to palagonite, pseudomorphic replacement of anhydrous silicates and the rusting and removal of FeNi metal (Van Ginneken et al., 2016). The long accumulation times of these collections are in part responsible for the degree of alteration observed, however, since particles are added over the entire history of these collections a wide range of weathering exists. Recent desert collections are also likely to exhibit significant weathering, although little characterisation has yet been conducted on these particles to evaluate their state of preservation.

Minimal weathering of MMs can be expected from snow collections in Antarctica, although some local transient melting of snow can be expected in the vicinity of MMs since particles are dark and absorb heat readily (Maurette et al., 1991). Additional weathering will affect MMs obtained from artificially produced melt water sources, such as the South Pole Water Well, since particles were contained in water for periods of 10s of years (Taylor et al., 1998). Nevertheless, the South Pole Water Well exhibits the lowest I-type to S-type ratio of any collection yet analysed for population statistics which suggest no complete destruction of spherules by water. Unfortunately, a fire in the well house at the South Pole produced a large amount of fine-grained particles that make it difficult to recover fine-grained micrometeorites (Taylor et al., 1998). Even collections recovered by specific melting of snow and ice, in which exposure time and temperature are minimised, will experience some dissolution of the most water-soluble phases such as halite or sulphates (Kurat et al., 1994). Cosmic spherules recovered from roof tops exhibit minimal etching of glass and metal largely owing to their short residence times despite the presence of abundant water (Genge et al., 2017a).

Surface sedimentary processes resulting in the removal and concentration of particles according to density and will impose biases on MM collections wherever air or water currents occur. Concentration of dense particles, such as I-type cosmic spherules, occurs in sediment traps where a decrease in current velocity occurs allowing for the preferential settling of dense grains (e.g. Bi et al., 1993). In some localities in which micrometeorites are found, such as within fluvial deposits (Bi et al., 1993) or within sand dunes (Fioretti et al., 1998), the accumulation of particles is entirely the result of sedimentary concentration and thus abundances of MMs might be several orders of magnitude larger than the background flux (Tomkins et al., 2019). Roof top gutters can also be included in this category since they are essentially hydrodynamic traps and concentrate large dense particles at the expense of low density particles (Genge et al., 2017a).

Moraines and rock traps in Antarctica are also theoretically sites of preferential accumulation of wind-transported debris owing to their effect on wind velocity. In moraines preferential accumulation of dense materials is noted in wind-scoops on the windward side of boulders (Fig. 3b), debris that includes small cm-sized meteorites (Harvey and Maurette, 1991; Genge et al., 2018). Removal of low density grains from deposits is termed winnowing and also affects MM collections depending on the current environment. Winnowing has been suggested for deep ocean particles resulting from transient density currents and concentration of MMs in topographic lows in hummocky surfaces (Brownlee, 1985). In Antarctic moraine winnowing has been identified by the relatively low abundance of low density ScMMs and FgMMs compared with denser cosmic spherules (Genge et al., 2018). The size distribution of spherules testifies to winnowing of small grains owing to inflections of the curve below a power law distribution at small sizes (Fig. 2). Winnowing can also be expected to occur in crevasses in rock traps owing to the Bernouli effect during windstorms (Tomkins et al., 2019).

Antarctic snow collections are likely to be less affected by sedimentary processing than other MM collections, however, some bias owing to wind transport and erosion is likely. In the Larkman Nunatak moraine collection Genge et al. (2018) noted preferential accumulation of dunes of small stones and dust-sized debris on snow dunes (Sastrugi) particularly when sculpted by wind erosion (Fig. 3d and e). At this location in the Transantarctic mountains snow falls were observed to be largely

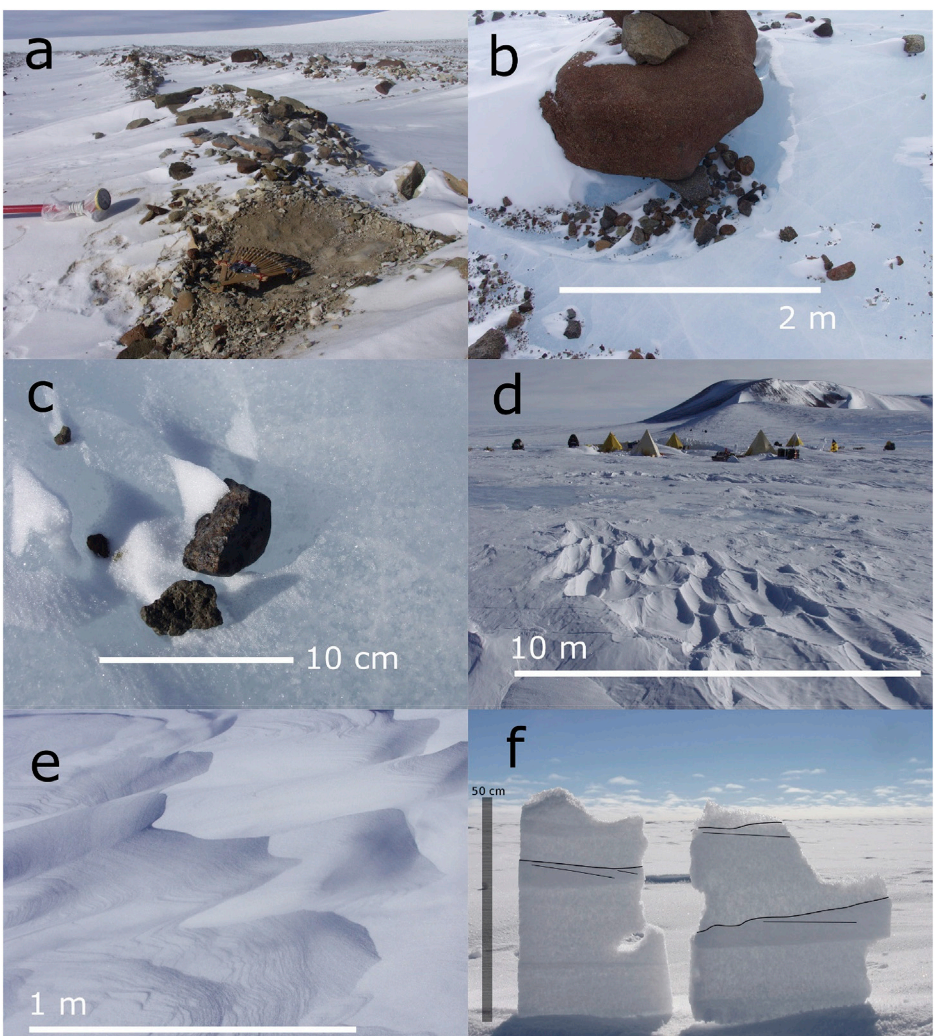

Fig. 3. Photographs illustrating processes that may bias Antarctic collections of MMs. (a) Moraine at Larkman Nuntak showing a snow layer overlying sediment that contains MMs. The snow decreases direct infall (Genge et al., 2018). (b) A wind scoop on a boulder in moraine at Larkman Nunatak. Boulders, snow dunes, and rock crevasses may act as wind traps for dense grains. (c) A meteorite breaking up in situ at Larkman Nunatak can release dust-sized meteorite weathering debris. (d) Sastrugi (snow dunes) at Larkman Nunatak. Sastrugi can act as wind traps and concentrate dense particles. (e) Interior laminations within Sastrugi at Larkman Nunatak indicate active erosion of snow. (f) Photograph of a thin vertical section extracted from 5m depth at Dome C in January 2010 from Picard et al. (2019). Bold lines show erosional surfaces identified by indentations and truncated laminations (fine lines). Laminations are likely to represent the deposition of blowing snow on the lee slopes of dunes. Darker layers are windpack. At these depths snow is partially recrystallised.

transient with windstorms removing a significant proportion of snow and their content of MMs. Conversely the Antarctic plateau experiences a net accumulation of snow with less significant erosion occurring since density driven winds are less prevalent (Picard et al., 2019). Net accumulation, however, is not the same as complete preservation and periods of blowing snow related to erosion are noted at locations such as the CONCORDIA station on Dome C with 60% of the surface reworked over the course of a year (Picard et al., 2019). Indeed, the location of the domes is necessarily in the source regions of the katabatic density winds and thus minimal deposition of blowing snow occurs with net erosion dominating over deposition of laterally transported snow.

Gallet et al. (2011) studied the stratigraphy of snow at Dome C in the immediate vicinity of the Concordia station and noted surface layers of rounded, wind transported snow (1–9 cm thick) over lying windpack snow (compressed by wind action). Up to four windcrusts 2–5 mm thick were observed in 4-m deep pits and testify to wind action and erosion. The stratigraphy of snow between pits is highly variable necessarily indicating variable wind erosion between pits several km apart since snow falls are relatively homogeneously developed (Fig. 3f). The effect of wind erosion on the Antarctic domes is minimised by lower average wind velocities (14 m s^{-1} compared with 28 m s^{-1} at Dumont D'Urville; Picard et al., 2019), however, it is increased by the low deposition rate of snow on the domes ($\sim$7 cm yr^{-1}) resulting in long term exposure to wind currents. The frequent presence of facetted rounded snow grains in deep layers (<1 m below the surface; Gallet et al., 2011) suggests that a significant proportion of the snow has been reworked by wind. This is confirmed by the presence of dune-bedding in heteorogeneities in snow observed in 5 m deep pits (Fig. 3f). Wind erosion will introduce a bias in the abundance of MMs accumulated over a period of time, which on the basis of a 60% reworked surface area observed at Dome C, could decrease average abundances by up to a factor of $\sim$2. The scale of areas of transient snow deposition or erosion are also likely to be important in relation to the volume of snow sampled for MMs. Localised areas may have experienced more erosion. The scale of snow dunes, which dominate topography and modify wind currents, control the length-scales of erosion and have wavelengths of decametres (Picard et al., 2019). Antarctic snow collections are likely to give the best estimates of flux, however, these are still likely to be associated with uncertainties.

5.2. Sources of MMs

Studies of mineralogy and composition have been used to constrain the parent bodies of both unmelted and melted MMs. For unmelted particles the majority of large FgMMs (>50 μm) are thought to be largely derived from primitive asteroids, in particular those similar to hydrated CM2, CR2 and CI chondritic meteorites (Genge et al., 1997, 2008; Taylor et al., 2012; Suttle et al., 2019a). Rare examples of CV3 (Van Ginneken et al., 2012) and CO-like particles (Suttle et al., 2019) also exist. The textures and compositions of fine-grained MMs in particular are similar to these meteorite groups with CM2-like particles the most abundant. Analyses of noble gas isotopic composition in large MMs (>300 μm) from the Transantarctic Mountains suggest exposure ages consistent with the asteroid belt parent bodies, with only one particle identified that originated beyond Jupiter (Baecker et al., 2018). Some differences to meteorite parent bodies, however, are noted with higher average carbon abundances and larger D/H ratios (Engrand and Maurette, 1998), higher pyroxene/olivine ratios (Gounelle et al., 2005), different assemblages of organic molecules (Battandier et al., 2018) and higher abundances of presolar grains (Dai et al., 2002). It must be concluded that FgMMs are on average more primitive than their meteorite counterparts. These differences may in part relate to the destruction of weaker meteorites during their atmospheric entry.

A significant uncertainty in the sources of FgMMs is introduced by their thermal alteration during atmospheric entry. Although many of these particles survive at small sizes with relatively little heating, phyllosilicates with observable base spacings are rarely detected suggesting these have mainly thermally decomposed to amorphous dehydroxylates (Genge et al., 1997; Nakamura et al., 2001). Amongst those particles that do preserve phyllosilicate both saponite and serpentine are observed in contrast to CM2 chondrites, which are dominated by the latter mineral (Nakamura et al., 2001), and thus suggest a closer affinity to CI chondrites.

The thermal decomposition of phyllosilicates presents a problem in identifying parent body association through comparison to meteorites or through comparison of their spectral signature to that of asteroids. The presence of igneous melted rims on the majority of heated FgMMs, however, indicates the pre-atmospheric occurrence of phyllosilicate since the large thermal gradients required to generate these rims are provided by the endothermic nature of phyllosilicate thermal decomposition (Genge, 2006). Fragmented olivines within ScMMs likewise indicate these experienced large thermal gradients during heating and thus contained phyllosilicates prior to partial melting (Genge et al., 2017c). Studies of the abundance of MMs reveal that fine-grained hydrated particles dominate the flux of MMs at sizes of 30–300 μm in diameter (Taylor et al., 2012; Genge et al., 2017c).

Coarse-grained MMs are also thought to largely be samples of primitive asteroids since most have igneous textures and minor element compositions similar to chondrules from CM2, CR2 and ordinary chondrites (Genge et al., 2005; Suttle et al., 2019c). Some CgMMs have olivine and pyroxene compositions that are consistent with equilibrated (metamorphosed) ordinary chondrites, with the L chondrites the most represented group (Genge et al., 2005; Genge, 2008a). Ordinary chondrites are materials from S(IV) asteroids as demonstrated by the results of Hayabusa 1 mission (Nakamura et al., 2011) and asteroid spectroscopy (Binzel et al., 2001). High Mn forsterite within 13% of MMs 50–100 μm containing chondrule fragments have been reported and suggested to be cometary owing to the similarity to high Mn-chondrules within comet 81P samples (Imae, 2013). Much lower abundances of high Mn-olivine of 2.5%, however, are observed in larger chondrule-derived CgMMs (50–400 μm; Genge et al., 2008). Rare CgMMs have mineral and oxygen isotope compositions suggesting they are derived from basaltic (V-type) asteroids (Gounelle et al., 2009; Badjukov et al., 2010) and CK chondrites (Cordier et al., 2018).

The source objects of UcMMs and small (<60 μm) carbon-rich MMs, which resemble anhydrous IDPs, are most likely to be derived from comets (Bradley, 2005; Noguchi et al., 2015). This assumption is based largely on their carbon-rich nature that corresponds to observations of cometary nuclei (Bardyn et al., 2017). The structure of anhydrous IDPs which is highly porous and consists of carbonaceous matter with embedded GEMS and anhydrous silicates, including enstatite whiskers (Bradley, 2005), also corresponds closely with theoretical predictions of the nature of interstellar grains in which silicate amorphous particles are mantled by organic matter (Greenberg and Li, 1996; Ishii et al., 2018). The largest uncertainty in the identity of the parent bodies of these grains, however, is the lack of in-situ analysis of other potential sources such as P- and D-type asteroids.

Cosmic spherules are challenging to link with specific parent bodies on the basis of their mineralogies and chemical compositions alone owing to melting and partial evaporation during entry heating. The majority of S-type cosmic spherules are, however, broadly chondritic in composition albeit with depletions in volatile and moderately volatiles elements such as Na, K and S (e.g. Kurat et al., 1994; Genge et al., 1997). Depletions in Fe and Ni also occur in some spherules owing to the separation of FeNi metal and sulphide beads during atmospheric deceleration. Some constraints can be placed on the nature of their parent bodies, for example, some spherules contain relict olivines and pyroxenes with minor element compositions similar to ordinary chondrites (Shyam Prasad et al., 2015; Genge et al., 2017a), including equilibrated ordinary chondrites (Genge et al., 2018). The presence of chromite and its composition also resembles these meteorites (Rudraswami et al., 2019). Some iron-rich olivines have abundant inclusions suggested to be FeNi metal and appear to be sourced from ordinary chondrites (Shyam Prasad et al., 2015). The Ni-content of neoformed olivine, crystallised on cooling in the atmosphere, has also been used to suggest that >30% of spherules larger than ~300 μm in diameter are derived from ordinary chondrite-like asteroids, whilst the remainder are derived from carbonaceous chondrite-like (C-type) asteroids (Cordier et al., 2011a, Suavet et al., 2011). A small proportion of glassy spherules (2% of all MMs) have major element compositions similar to basaltic meteorites and thus are likely to be derived from V-type asteroids (Taylor et al., 2007; Cordier et al., 2011b, 2012). Some of these particles had oxygen isotope compositions that suggest asteroid 4-Vesta is not the only source of HED-like materials (Cordier et al., 2012).

The best evidence for the sources of CSs comes from their oxygen isotope compositions but is associated with an inherent uncertainty arising from the change in isotope composition during atmospheric entry. Oxygen isotope composition changes owing to mass fractionation, resulting from partial evaporation, leading to enrichments in heavy oxygen ($\delta^{18}O$), and through mixing with atmospheric oxygen (Suavet et al., 2010; Engrand et al., 2005; Cordier and Folco, 2014). High precision oxygen isotope studies reveal that the majority of coarse-porphyritic spherules have compositions consistent with ordinary chondrites, whilst those of barred olivine S-type spherules have compositions consistent with carbonaceous chondrites (Van Ginneken et al., 2017). Suavet et al. (2010) identified one group of spherules with positive $\Delta^{17}O$ that could not be produced from any know meteorite group, however, these represent a small proportion of large (>300 μm) spherules.

The parent bodies of I-type cosmic spherules are difficult to assess owing to fractionation by oxidation during atmospheric entry. Furthermore, all their oxygen is derived from the atmosphere (Engrand et al., 2005). The Ni/Co ratios of I-type cosmic spherules are similar to chondritic metal grains and some groups of iron meteorites (Herzog et al., 1999; Genge et al., 2017b). The presence of detectable Cr and textural evidence for the original occurrence of sulphide is consistent with a chondritic source (Genge et al., 2017b). Most I-types are likely, therefore, to have sources that are primitive asteroids containing abundant metal such as the S(IV)-types (ordinary chondrites) and C-types like the CR2 and CB chondrites (Herzog et al., 1999). The main uncertainty in the identification of the sources of I-types is the non-unique composition of much metal in chondritic meteorites and the partitioning of minor elements between oxides and metal during atmospheric oxidation (Genge, 2016b).

One further potential uncertainty in parent body identification must be considered – the mis-identification of dust-sized meteorite debris as MMs. The sites of MM accumulation are often also locations at which meteorites accumulate, particularly within the Transantarctic mountains where blue ice areas are common (Harvey and Maurette, 1991; Genge et al., 2018). Meteorites fragment on the surface in Antarctica by mechanical weathering and release dust-sized debris that can be blown downwind (Genge et al., 2018). Although this process is likely to contaminate MM collections with meteorite weathering debris (MWDs), the overall abundance of such material will be small compared to MMs except perhaps in the immediate vicinity of a weathering meteorite. Nevertheless, the potential presence of MWDs in MM collections is an issue in the interpretation of individual particles. The presence of magnetite rims on most unmelted MMs can be used to distinguish them from meteorite debris, however, caution must be applied to the least heated particles that lack magnetite rims. Fragments of meteorite fusion crust may also resemble melted MMs, however, studies of fusion crust have shown they have higher Na, K and S contents than CSs – a result of their evaporation in a melt layer rather than as isolated droplets (Genge and Grady, 1999). Finally, some particles present amongst MMs may have formed by ablation from larger meteoroids (Meteorite Ablation Debris; MAD). Such particles can be expected to be rare simply because of the much larger flux of extraterrestrial dust (30,000 t/a; Love and Brownlee, 1993) than meteorites (1600 t/a; Bland et al., 1996), however, they may be locally abundant in the event of large scale, low altitude airbursts (e.g. Harvey et al., 1998). Meteorite ablation debris has, however, been identified amongst MMs and differs in heterogeneity, composition and oxidation state to CSs (Van Ginneken et al., 2010; Genge and Van Ginneken, 2017).

5.3. Atmospheric entry heating

Micrometeorites provide constraints on the processes operating during atmospheric entry of extraterrestrial dust particles, which are directly relevant to the interpretation and modelling of meteors, and more rarely provide constraints on the entry parameters of dust. Igneous rims on FgMMs and ScMMs, for example, testify to surface melting and are contrary to the thermal conductivities of such small particles, which imply thermal homogeneity. The heat sink provided by the endothermic decomposition of phyllosilicates, however, can support thermal gradients of several hundred degrees and allow surface melting to occur (Genge, 2006). Surface melt layers are likely to enhance evaporative mass loss from particles that otherwise would not have been melted and assist in preserving low temperature materials within the cores of particles including organic matter (Genge, 2008b).

Observations of the thermal decomposition of phyllosilicates in FgMMs also suggest fragmentation is an important process during atmospheric entry. Decomposition of phyllosilicates is associated with a decrease in volume that leads to the formation of dehydration cracks (Genge et al., 2008; Suttle et al., 2019a). These fractures decrease particle strength and can lead to fragmentation owing to ram pressure. Evidence for fragmentation during peak deceleration has been identified by the presence of secondary (later-formed) melted rims on planar exterior surfaces formed by break-up during flight (Suttle et al., 2019). The fragmentation of FgMMs during flight introduces an uncertainty in the pre-atmospheric size-distribution of these particles since it will enhance small particles at the expense of large ones.

Vesicles within MMs reveal another significant process that influences heating. Vesicle abundance increases with heating of hydrous fine-grained MMs reaching up to 70 vol% in some ScMMs (e.g. Genge et al., 1997; Genge et al., 2008). Vesiculation increases particle volume, and thus projected area, and decreases density resulting in additional heating. The result of this process is a sudden increase in deceleration that drives vesicles out of particles causing a subsequent decrease in particle volume. Numerical models of this process suggest vesiculation reduces mass loss by causing a brief period of rapid deceleration (Genge, 2017a).

Identifying entry parameters, such as velocity and angle, has been attempted by several studies of MMs. Cosmic spherules with large olivine phenocrysts on the same side of the particle as FeNi beads suggest settling of crystals owing to deceleration (Fig. 1d). Numerical simulations suggest settling of small relict crystals, which survive entry heating, results in nucleation and growth of larger neoformed olivine during cooling but only in particles that have entry velocities >14 km s^{-1} (Genge et al., 2016). The threshold velocity increases with decreasing entry angle introducing an uncertainty for any particular particle.

Magnetite Ni-content has also been used to constrain entry parameters on the basis it increases with oxygen fugacity (fO_2) and thus decreasing altitude. Experimental data on Al and Ni content and FeO/Fe_2O_3 has been used to constrain fO_2 (Toppani and Libourel, 2003). The main issue with this method, however, is that magnetite crystals tend to be too small for accurate analysis in most MMs. Furthermore, fO_2 during atmospheric entry can be partially controlled internally by particles. This is particularly true for those particles that have high carbon contents since carbon reacts with free oxygen causing reduction (Genge and Grady, 1998).

Finally, one cosmic spherule has also been found with evidence for multiple heating events in the form of a melted rim with several layers. Several discrete pulses of heating as a result of atmospheric entry is possible during grazing incidence encounters, which can decelerate a particle sufficiently to allow re-capture by the Earth and reheating. An initial velocity of >30 km s^{-1} was suggested for this particle to enable spherule formation during the first aeropass (Genge et al., 1996).

6. The outstanding issue of the source dependent flux

Recent models of the orbital evolution of dust particles in interplanetary space suggests that Jupiter Family Comets (JFC) provide > 70% of that captured by Earth (Nesvorný et al., 2010, 2011; Carrillo-Sánchez et al., 2015). These models indicate that circularisation of orbits by PR-light drag and planetary perturbations result in similarly low entry velocities for asteroidal and cometary dust particles. The velocity distribution of the models reproduce observations of the sporadic meteor flux, in which low entry velocities predominate (Carrillo-Sánchez et al., 2015), however, they imply that the majority of MMs are cometary in origin. The main success of these models are they reproduce the infra-red signature of the zodiacal cloud at high latitudes.

Observations of MMs recovered from the Earth's surface, however, do not support a flux dominated by comets and instead suggest most particles >50 μm in diameter are derived from asteroids. Fine-grained unmelted micrometeorites are dominated by hydrated materials and mostly have similar textures and compositions to those of CM2, CR2 and CI chondrites (Genge et al., 1997, 2008; Taylor et al., 2012), albeit with some properties suggesting they are more primitive. At sizes >300 μm in diameter most particles are cosmic spherules and their mineralogies and oxygen isotope compositions suggest they are related to carbonaceous chondrites and ordinary chondrites (Cordier et al., 2011a; Cordier and Folco, 2014; Van Ginneken et al., 2018). Only a small number of particles have compositions that cannot be directly related to meteorite parent bodies group 4 of Van Ginneken et al. (2018). Likewise, anhydrous silicates in FgMMs have oxygen isotope compositions similar to carbonaceous chondrites (Gounelle et al., 2005). Small MMs, mostly <50 μm in diameter, in contrast, include significant numbers of carbon-rich particles that have been interpreted as cometary in origin and are similar to GEMS-bearing IDPs (Noguchi et al., 2015). Very few (≪2%) of particles >50 μm in diameter have the characteristics expected for cometary grains (Dartois et al., 2013, 2018).

Several studies, however, have suggested that cometary materials may be similar to those of asteroids– with some previous studies suggesting that CI chondrites may be materials from comets (Gounelle and Zolensky, 2014). It remains possible that FgMMs could include abundant cometary material, but only if most comets closely resemble hydrated carbonaceous chondrites in mineralogy, chemical composition and oxygen isotope composition. Amongst particles returned from comet Wild-2 by the STARDUST mission are samples interpreted to represent fragments of chondrules and unusual CAIs (Zolensky et al., 2006). These objects are important components of meteorites and asteroidal materials. Their presence within a comet nucleus suggests radial mixing of grains in the solar nebula prior to accretion (e.g. Davidsson et al., 2016). In contrast cometary materials are expected to contain higher abundances of carbonaceous materials than observed in FgMMs, although collected STARDUST particles from Comet 81/P contained considerably less carbon than expected from cometary spectra (Sandford et al., 2006). Nevertheless, STARDUST carbonaceous material is subtly distinct from either IDPs or carbonaceous chondrites.

An important feature of FgMMs is their phyllosilicate-rich nature. Phyllosilicates were not detected by either the STARDUST (Zolensky et al., 2006) or ROSETTA (Davidsson et al., 2016) missions and thus conclusively are not present in any significant abundance within the JFC comets 81/P Wild 2 or 67P/Churyumov Gerasimenko. In contrast a phyllosilicate, nontronite, was detected in IR spectra of ejecta during the DEEP IMPACT mission to 9P/Tempel together with carbonates (Lisse et al., 2006). The same author also suggested the detection of nontronite in spectra from C/1995 O1 Hale-Bopp (Lisse et al., 2007). Nontronite, however, has not been observed in either meteorites or MMs casting doubt on its identification (Davidsson et al., 2016).

Some IDPs (hybrid IDPs) contain both the phyllosilicate saponite and partially altered GEMS and support the aqueous alteration of some comets, if these particles are not derived from highly primitive asteroids (Nakamura et al., 2005). Furthermore, experimental studies have shown that anhydrous IDPS are sensitive to incipient hydration (Nakamura-Messenger et al., 2011). The survival of GEMS in these particles and not in hydrated FgMMs, however, suggests significantly higher water to rock ratios in the parent bodies of MMs, similar to that of carbonaceous chondrites (e.g. King et al., 2017).

Reconciling numerical models of orbital evolution, which suggest comets dominate the terrestrial flux of extraterrestrial dust, with observations of MMs, which suggest that asteroids dominate, is problematic. A key observation from IDPs and MMs is that comet-derived dust is abundant at small sizes (<30 μm), whilst FgMMs with affinities to C-type asteroid materials dominate at sizes of 50–300 μm diameter, and increasing abundances of S(IV)-type asteroid material (ordinary chondrite) occur with increasing size (Fig. 4; Cordier et al., 2011a; Cordier and Folco, 2014; Van Ginneken et al., 2018). Prior to models that showed that orbital evolution decreases eccentricity of cometary dust (Nesvorný et al., 2010), the occurrence of cometary dust only at small sizes could have been understood as a result of its higher entry velocity. If cometary and asteroid dust both have similar low entry velocities, then the lower densities of anhydrous IDPs (<1.2 g cm^{-3}; Flynn, 2004) than carbonaceous chondrites (>2.1 g cm^{-3}; Flynn, 2004) should lead to a lower peak temperatures during entry heating enhancing the survival of comentary dust at large sizes.

The observed change in parent body type with size observed in IDPS and MMs, however, also correlates with compressive strength. Cometary material are thought to have low compressive strengths in the range 10–2 kPa (Groussin et al., 2019), whilst carbonaceous chondrites have strengths of 22–60 MPa and ordinary chondrites of 20–1100 MPa (Flynn et al., 2017). Fragmentation of particles during either atmospheric entry or prior to encounter with the Earth by collisional evolution might explain the observed variation. A necessary consequence of fragmentation during atmospheric entry is that the fragments of large cometary particles will be found amongst smaller particles (i.e. IDPs). Large cometary grains that fragment will have experienced rapid deceleration owing to their penetration to lower altitudes and should, therefore, experience significant heating. Large numbers of heated cometary IDPs have not been reported, in fact conversely the proportion of small cosmic spherules is relatively low (Noguchi et al., 2005).

7. Conclusion

Studies of MMs found on the surface of the Earth suggest that sources with mineralogies and compositions broadly similar to carbonaceous chondrite meteorites dominate. At particle diameters of <50 μm carbon-rich particles most likely to be derived from comets are, however, abundant and comprise nearly half the flux. At large size (>300 μm) MMs with similarities to ordinary chondrites also become abundant. Uncertainties exist in the interpretation of MMs owing to entry heating, weathering and surface processes. Entry heating obscures the primary mineralogical and chemical features of particles making it difficult to evaluate subtle differences in parent bodies. Amongst small MMs uncertainties in the exact nature of comets and primitive asteroids complicates the assessment of parent body, since carbonaceous chondrite-like MMs do exhibit some differences to meteorites and appear to be more primitive. The presence of abundant phyllosilicate in most FgMMs, however, distinguish these materials from the JFC comets Wild-2 and 67P/Churyumov Gerasimenko. Flux estimates from MMs are complicated by biases, such as weathering and erosion, and even the least biased snow-derived collections may have uncertainties of a factor of 2. Despite uncertainties, however, MM collections do not agree with the predictions of orbital models of interplanetary dust that cometary dust dominate the flux to Earth.

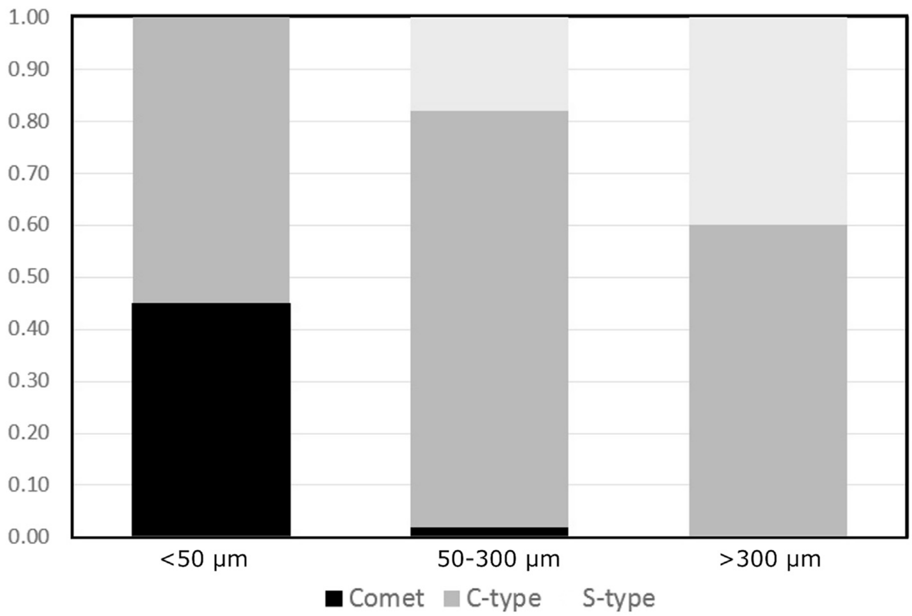

Fig. 4. The sources of MMs with diameter. The assessment assumes that anhydrous porous particles and ultracarbonaceous MMs are cometary and hydrous compact (FgMMs) are derived from carbonaceous chondrites (C-type asteroids). The data at sizes <50 μm are based on Noguchi et al. (2015). The presence of small numbers of cometary grains at 50–300 μm are based on Mn-bearing chondrule fragments at <100 μm (Imae, 2013) and some large ultracarbonaceous MMs (Dartois et al., 2013). There is considerable uncertainty (~10%) in the abundance of ordinary chondrite-like (S-type asteroid) MMs, however, the abundance at <300 μm is based on CgMMs observed by Genge et al. (2008), whilst the abundances at larger sizes are based on oxygen isotope compositions of cosmic spherules (Cordier and Folco, 2014; Van Ginneken et al., 2017).

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pss.2020.104900.

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