Igneous rims on micrometeorites

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Abstract

Melting of micrometeorites (MMs) due to atmospheric entry heating causes significant changes in the textures, mineralogies and compositions of particles that obscure their primary properties and greatly complicate interpretation of these extraterrestrial materials. Despite the abundance of melted MMs, the nature of melting processes in these materials is poorly constrained. In this study, mineralogical, textural, and compositional data on 77 MMs with igneous rims are presented, which suggest that fusion of micrometeorites during atmospheric entry occurs initially by surface melting. Textural and mineralogical evidence are presented that demonstrate unequivocally that igneous rims crystallized from a melt surrounding a largely unmelted core and establish melting as a gradational process. The compositions of igneous rims on fine-grained MMs (fgMMs) are broadly similar to those of the unmelted core except for depletions in volatile and moderately volatile elements produced by partial evaporation and suggest the formation of the rims by melting of the fine-grained matrix core. Enrichments in Fe/Si, Ni/Si, and Mn/Si in igneous rims compared with unmelted cores within fgMMs are suggested to occur due to the migration of Fe–S eutectic liquids from the core of the particle into the surface melt layer. The sulphide liquids are probably generated in the core of the particle under reducing conditions resulting by the pyrolysis of carbonaceous materials. The presence of igneous rims on fgMMs is enabled by the thermal decomposition of phyllosilicates and, therefore, indicates that fgMMs were hydrated particles prior to atmospheric entry. In contrast the compositions of igneous rims on coarse-grained MMs (cgMMs) are difficult to reconcile with those of the unmelted core and instead closely resemble those of fgMMs. The igneous rims of cgMMs are, therefore, suggested to form by melting of fine-grained matrix that was present on the exterior of these particles prior to atmospheric entry. Coarse-grained MMs with igneous rims thus were originally composite micrometeoroids, which consist of both fine-grained and coarse-grained materials, and are thought to be samples of chondrule-like objects. The abundance of composite MMs to cgMMs allows a first estimate of the mean chondrule radius within the parent bodies of MMs of ~625 μm to be made.

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1. Introduction

Micrometeorites (MMs) are large interplanetary dust particles (>25 μm) that survive atmospheric entry to be recovered from either deep sea sediments (Brownlee, 1985) or polar ice (Maurette et al., 1991). They dominate extraterrestrial materials falling on Earth with an estimated flux of around 40,000 tonnes per annum (Love and Brownlee, 1993). Previous studies have shown that MMs are closely related to the most primitive CI1, CM2, and CR2 carbonaceous chondrites and are, thus, probably derived from asteroidal or possibly even cometary bodies (Engrand and Maurette, 1998; Genge et al., 1997; Kurat et al., 1994). The small size of micrometeoroids leads to relatively gentle deceleration in the upper atmosphere allowing some fragile and high velocity particles to survive atmospheric entry (Love and Brownlee, 1991). Micrometeorites, therefore, provide samples of primitive solar system materials that may not be found as larger meteorites.

Heating experienced by MMs during their deceleration from hypervelocities in the atmosphere results in thermal alteration that complicates the interpretation of their mineralogies, textures, and compositions. The degree of
alteration experienced by MMs varies widely and ranges from mild heating, in which even low-temperature phases such as phyllosilicates can be preserved (Genge et al., 2001; Gounelle et al., 2002; Nakamura et al., 2001; Noguchi et al., 2002), to complete fusion and significant partial evaporation (Taylor et al., 2000). Micrometeorites are sub-divided largely on the basis of their thermal alteration into unmelted MMs, partially melted MMs (scoriaceous MMs), and extensively melted MMs (cosmic spherules) (Genge et al., 1997; Kurat et al., 1994). Unmelted MMs provide the most information on the nature of their parent bodies and occur as fine-grained MMs (fgMMs), with affinities to the matrices of CI1, CM2, and CR2 chondrites (Genge et al., 1997; Kurat et al., 1994), coarse-grained MMs (cgMMs), which are generally chondritic igneous objects dominated by pyroxene, olivine and glass (Genge et al., 1997; Robin et al., 1990), and composite MMs, which consist of a mixture of fine- and coarse-grained materials (Genge et al., 2005).

Observations of fgMMs (Genge et al., 2000) and experimental pulse heating studies of particles of CI1 and CM2 chondrites (Greshake et al., 1998; Toppani et al., 2001) indicate that even though fgMMs undergo thermal decomposition of volatile-rich matrix phases as a result of entry heating, their textures and compositions are largely preserved allowing these to be used to evaluate their origins. Melting of unmelted fgMMs to form scoriaceous MMs, however, completely obscures primary matrix textures. The nature and onset of melting within MMs is, therefore, important to understand if their primary mineralogical and textural features are to be identified.

On the basis of observations of igneous rims on MMs it has been argued that the onset of significant partial melting of fgMM occurs by surface melting (Genge et al., 1997). Similar igneous rims have also been reported on deep sea fgMMs (Brownlee and Bates, 1983) and on hydrous interplanetary dust particles (Szydlik and Flynn, 1992), suggesting that surface melting of small particles is a fundamental process during atmospheric entry. Modelling of the thermal evolution of interplanetary dust during atmospheric entry has revealed that surface melting is facilitated by endothermic decomposition reactions of volatile-bearing phases which support the required large thermal gradients (Szydlik and Flynn, 1992). Igneous rims have also been reproduced experimentally within CI1 and CM2 particles during pulse heating and suggest formation by melting of fine-grained matrix materials (Toppani et al., 2001).

Although the igneous rims have been identified in previous studies of MMs, few details of their mineralogy, composition, and occurrence have been reported to establish rigorous criteria by which they can be identified or by which their origins and mode of formation can be established beyond doubt. In the current study, the nature of igneous rims on 77 particles, including both fine-grained and cgMMs from a total collection of 518 particles is described in order to: (1) rigorously define the nature of igneous rims, (2) to constrain the development of surface melting as part of the overall sequence of thermal alteration during atmospheric flight, (3) to characterize compositional changes due to melting of micrometeoroids in the atmosphere, and (4) to establish criteria by which the pre-atmospheric nature of particles can be identified. The data, together with models of heating of hydrous micrometeorites performed by Szydlik and Flynn (1992), strongly suggest that igneous rims on all micrometeorite types, including coarse-grained particles, are generated by surface melting of hydrous fine-grained matrix. Coarse-grained particles with igneous rims must, therefore, have had svelages of fine-grained matrix prior to atmospheric entry and represent composite MMs. Composite particles, which are argued to represent samples of small, chondrule-like objects, are thus relatively abundant among micrometeorites. Furthermore, the presence of igneous rims on fgMMs also indicates that these were hydrated materials prior to atmospheric entry.

2. Samples and techniques

The MMs reported in the current work were all collected by melting and filtering of Antarctic ice. The particles were recovered by melting and filtering of blue ice near Cap Prudhomme by Maurette et al. (1991) and particle SP96-100-001 was recovered from the South Pole water well by Taylor and Harvey in 1996 (Taylor et al., 1996). The particles described in the current paper were discovered amongst a total 518 unmelted MMs derived predominantly from Cap Prudhomme. The selection procedures used to separate and prepare samples as polished grain mounts are described in detail in Genge et al. (1997).

Backscattered electron images of the particles described in the current work were obtained using a JEOL 5900LV scanning electron microscope at the Natural History Museum. Analyses of minerals and mesostasis were determined by energy dispersive spectroscopy (EDS) using the JEOL 5900LV. Analyses were obtained using a beam current of 1 nA at 20 kV and standard matrix corrections applied with a gain calibration on a vanadium standard. Repeat analyses of mineral standards suggest detection limits of ~0.5 wt% for most elements heavier than F.

Wave dispersive spectroscopy (WDS) was used to determine the compositions of minerals larger than ~4 μm in diameter and to obtain spot analyses of fine-grained materials present within the particles. The analyses were obtained using a Cameca SX50 at the Natural History Museum. Analyses were obtained against mineral standards and Cameca matrix corrections were applied. Repeat analyses of mineral standards suggest detection limits of 0.01–0.05 wt% within single phases.

The compositions of the igneous rims and the unmelted cores on MMs were determined as the mean of individual WDS spot analyses. The effective spot size of the electron microprobe is roughly 4 μm and provides an approximation to the composition of the excited volume of the
sample. The mean of multiple spot analyses will, therefore, approach the bulk composition of the sample, albeit within the analytical uncertainties inherent in the analysis of porous multi-phase materials. Complications arise due to porosity and vesicles since void spaces decrease the intensity of emitted X-rays below that of a continuous solid of the same composition and mineralogy and result in low analytical totals. Since void spaces are not considered within matrix corrections analytical uncertainties are larger than those of single mineral phases. Analyses of igneous rims with totals lower than 80 wt%, due to vesicles, and of fine-grained matrix lower than 60%, due to porosity, were not included in the evaluation of means. Repeat analyses of porous matrix, however, indicate that although primary variation in elemental ratios occurs, means evaluated as an average of elemental ratios to Si approach a constant value for any particular sample and fall within the overall range observed for fgMMs.

3. Results

Igneous rims were identified on 77 out of 518 micrometeorites included in the current study; they occur as a surface correlated feature, with textural and mineralogical evidence for a high degree of partial melting, surrounding a core that has experienced only minor partial melting during entry heating. The textural, mineralogical, and compositional characteristics of unmelted cores and igneous rims are described in this section of the paper to provide rigorous criteria by which these may be distinguished for both fgMMs and cgMMs. These data are interpreted in the discussion section to demonstrate that the described igneous rims formed due to surface partial melting during atmospheric entry and to identify processes that control the mineralogical, textural, and compositional evolution of particles during the melting process.

3.1. Mineralogy and textures of igneous rims

Igneous rims observed on all micrometeorites in the current study are composed of euhedral to subhedral olivine microphenocrysts within a glassy mesostasis, usually with <10% by volume dispersed magnetite (Fig. 1a). Magnetite may, however, be entirely absent, in particular, in the presence of a well-developed external magnetite rim. Olivine microphenocrysts vary considerably in size from <1 μm to a maximum of ~5 μm with larger crystals exhibiting normal zoning with more fayalitic margins. Although most olivine microphenocrysts are too small for analysis using SEM and EPMA techniques, larger olivine crystals have compositions of ~Fa50, although uncertainties, due to matrix overlap with the surrounding glass, are of an order of ~Fa30. No systematic variation in olivine microphenocryst size is observed with the width of the igneous rim, however, the largest microphenocrysts are generally found on those particles in which the igneous rim comprises a significant volumetric proportion of the particle.

All igneous rims observed in the current study are crystal-rich with only small regions of homogeneous, glassy mesostasis within interstitial areas that cannot be analysed directly using analytical SEM techniques. The overall chondritic compositions of rims (described below), however, suggests this homogeneous glass phase left as a residual liquid after the crystallization of olivine. In many particles irregular shaped voids bound by the microphenocrysts occur in interstitial areas and no glassy phase can be observed (Figs. 1b and c). Glass is, however, likely to be removed by chemical etching by melt water within Antarctic ice and during collection, particularly in the surface layers of particles.

In addition to olivine microphenocrysts, some igneous rims also include small (<7 μm), usually anhedral, pyroxenes and more rarely Mg-rich olivines (Fig. 1a). Although matrix overlap prevents accurate analysis, the Mg-rich nature of these relict grains is evident from qualitative EDS spectra and their low backscattered electron potentials. Both the relict pyroxenes and the relict olivines are often surrounded by rims of phases similar in backscattered electron potential to the fayalitic olivine microphenocrysts. Small relict Mg-bearing silicates are most commonly observed within igneous rims on fgMMs that contain small (<10 μm) isolated Mg-rich pyroxenes and/or olivines within their unmelted cores.

All igneous rims observed in the current study, including those on cgMMs, contain vesicles that vary in shape from rounded, but irregular, to spherical voids. Vesicle abundances are also variable ranging from ~10 to ~50% by volume of the rim and are generally higher when surrounding fine-grained rather than coarse-grained unmelted cores.

Magnetite occurs as an external rim on the outer surface of igneous rims and usually surrounds the entire particle. Magnetite rims are ubiquitous on scoriaceous micrometeorites (SMMs) and are also observed in most unmelted MMs as partial envelopes (Genge et al., 1997). Both the textures and mineralogies of igneous rims bear a close resemblance to those of the mesostases of SMMs which are likewise dominated by fayalitic olivine microphenocrysts within glass (Fig. 1d). Scoriaceous MMs have previously been suggested to originate due to a relatively high degree of partial melting of fine-grained matrix during atmospheric entry heating (Genge et al., 1997; Greshake et al., 1998; Toppani et al., 2001).

3.2. Mineralogy and textures of unmelted cores

Igneous rims surround unmelted cores that vary considerably in their textures and mineralogy between different micrometeorite groups. In cgMMs, cores usually have an igneous texture, however, their mineralogy and texture are distinct from those of the igneous rim. In fgMMs with igneous rims, the matrices of unmelted cores, however, exhibit textural features that strongly suggest they have not experienced significant fusion.
3.2.1. Coarse-grained MMs

Coarse-grained MMs with igneous rims have cores that are usually dominated by anhydrous silicates, principally pyroxene, with less common olivine, interstitial glass and sometimes FeNi metal and/or FeNi sulphide (Fig. 2). The cores generally have igneous textures, with porphyritic or radiating pyroxene textures, although some are granular or single crystals. Unmelted cores can be distinguished from igneous rims by: (1) the presence of pyroxene phenocrysts, (2) their much larger crystal sizes, (3) truncation of phenocrysts within the core by the igneous rim, and (4) their more Mg-rich pyroxene and olivine compositions.

The predominance of phenocrysts of pyroxene within cgMMs, either as enstatite in reduced Type I cgMMs (Genge et al., 2005), or Fe-rich, Ca-poor pyroxene in oxidized Type II cgMMs and occasionally diopside, contrasts strongly with igneous rims, which are dominated by fayalitic olivine. Grain sizes are also often distinctly different with pyroxene and olivine grains within the core usually having sizes >10 μm. Truncation of large phenocrysts is sometimes observed at the boundary between the core and the igneous rim (Fig. 2).

Finally, the composition of olivine within unmelted cores is significantly more Mg-rich than olivine within igneous rims, ranging from forsterite (Fa1) in Type I cgMMs to ~Fa35 in Type II cgMMs. Only very rarely do cgMM olivine compositions approach Fa50 (Genge, unpubl.) and as yet igneous rims have not been observed on such particles.

3.2.2. Fine-grained MMs

Fine-grained MMs with igneous rims have cores dominated by phases with small grain-sizes, typically <1 μm, such that matrix mineralogy cannot be determined quantitatively by analytical SEM techniques. High-resolution backscattered electron images, however, do allow the textures of the matrix to be examined for comparison with igneous rims and unmelted fgMMs. The unmelted cores can be distinguished from their igneous rims by: (1) their smaller grain-size, (2) the presence of porosity and/or dehydration cracks, (3) the absence of identifiable igneous textures (i.e., microphenocrysts within glass as observed in rims), and (4) their generally lower backscattered electron potential (Fig. 3).
The textures of the cores of fgMMs with igneous rims vary from those in which the morphology of individual mineral grains cannot be observed, resulting in areas with a homogeneous appearance, albeit interspersed with porous areas with equant sub-micron grains (Fig. 3a), to those in which the matrix contains micron-scale acicular to sheet-like phases reminiscent of phyllosilicate (Fig. 3b). Transmission electron microscope observations were not conducted on the cores since previous studies have demonstrated that phyllosilicates with identifiable lattice fringes are rarely preserved due to thermal decomposition at temperatures of 400–800 °C (Genge et al., 2001; Noguchi et al., 2002), however, amorphous elongate dehydroxylate grains have been found in many particles that appear to pseudomorph the original clay minerals (Genge et al., 2001; Gounelle et al., 2002). The remaining fgMMs studied by...
TEM and X-ray diffraction are dominated by fine-grained assemblages of anhedral to subhedral olivine and pyroxene embedded within amorphous materials that represent recrystallized dehydroxlates (Genge et al., 2001; Gounelle et al., 2002; Nakamura et al., 2001; Noguchi et al., 2002). Despite thermal decomposition, the matrix of most MMs with “phyllosilicate-like” phases preserve textures that strongly resemble the matrices of CI1, CM2, and CR2 chondrites.

In a small number of cores, the matrix is dominated by euhedral to subhedral ferromagnesian silicate grains, thought to be relatively magnesian pyroxene and olivine on the basis of matrix chemistry, >1–2 µm in size, with subordinate acicular to sheet-like phases within interstitial areas (Figs. 3c and d). The textures of all these fine-grained cores are thus significantly different from the igneous textures of the rims.

Larger isolated anhydrous silicates (>4 µm) are observed embedded in the fine-grained cores of many particles and consist principally of enstatite with less abundant forsterite, consistent with fgMMs in general (Genge et al., 1997; Maurette et al., 1991); rare Fe-rich pyroxenes and olivines also occur in some particles. These isolated silicate grains usually are irregular in shape suggesting they are broken fragments of larger crystals. Similar isolated grains are found in the matrices of CI1,
CM2, and CR2 chondrites. Isolated grains within fine-grained cores lack the overgrowths observed in igneous rims (Fig. 3d).

The matrix of all fine-grained particle cores exhibits irregular shaped pore spaces, which vary from micropores (<1 μm in size) within compact homogeneous or “phylosilicate-like” matrices (Fig. 3b) to larger scale (>1 μm) pores in anhydrous silicate-rich matrices (Fig. 3c). Porosity in these latter particles can reach a maximum of ~50% by volume. Irregular networks of fractures are also found within the cores of some fine-grained particles (Fig. 3e). Rounded irregular to spherical voids found within fine-grained cores appear to be distinct from porosity and resemble vesicles. Such voids are most abundant within particles with thick igneous rims where they are often have homogeneous ferromagnesian silicate rims several microns thick.

The textures and observed mineralogies of most fine-grained cores of MMs in the current study are comparable to those of fgMMs lacking igneous rims, although a much higher proportion of the latter particles have textures that are reminiscent of phyllosilicates. Large (>4 μm) FeNi-sulphide grains, which are sometimes observed within fgMMs, are absent amongst particles with igneous rims.

Fine-grained particles with compositionally heterogeneous matrices can include areas with similar textures to igneous rims. Some fgMMs exhibit significant variations in backscattered electron potential on scales ~10 μm within their matrix relating to differences in Fe-content (Genge et al., 2001). These particles were suggested to be related to petrologic type 2 chondrites (i.e., C2 particles), which show similar variations due to spatial differences in the abundance of Fe-rich clay minerals and tochilinite (Fig. 4). Within some of these C2 particles, the Fe-poor matrix exhibits micron-scale acicular to sheet-like phases, whilst the Fe-rich matrix is highly vesicular and contains sub-micron anhydrous silicates. The textures and backscattered electron potential of vesicular Fe-rich matrix in C2 particles is difficult to distinguish from those of igneous rims containing micron-sized olivine microphenocrysts. In two further particles in the current study core heterogeneity occurs with Fe-rich silicate vein networks extending from the igneous rim into the core of the particle (Fig. 3f).

### 3.3. The occurrence and abundances of igneous rims

Igneous rims are common in MMs occurring on 77 of the 518 particles (15%) studied in the current work, however, they are more frequently found on fgMMs (unmelted and SMMs), 60 out of 216 (28%) than on cgMMs, 17 out of 89 (19%). All igneous rims observed in the current study have rounded smooth external surfaces (Fig. 5).

Differences between the igneous rims on fgMMs and cgMMs occur in their lateral extent and width. The thickness of igneous rims on the studied micrometeorites varies from ~5 μm, below which the igneous rim is difficult to distinguish from the magnetite rim, to approximately the radius of the particle. Unmelted fgMMs are classified as those in which the melted portion, represented by the igneous rim, comprises less than 50% by volume of the particle, those MMs with larger igneous rims are classified as SMMs. There is, therefore, a complete gradation from completely unmelted fgMMs, through fgMMs with igneous rims, to SMMs with cores of fine-grained matrix (Fig. 5).

Differences in the lateral extent of igneous rims are observed between fgMMs and cgMMs. Most igneous rims found on fgMMs completely surround the particle in a layer of relatively constant thickness, at least in fgMMs with rims comprising <50% by volume of the particle (Figs. 5a–d). Only particles that have been clearly fractured after solidification of the rim, for example, due to stress during storage within Antarctic ice or aeolian transport prior to incorporation in the ice, and those with deep embayments extending into the particle, either irregular cracks or large pore spaces, have igneous rims that are not continuous (Fig. 5d). In contrast to those of fgMMs, the igneous rims on cgMMs are often laterally discontinuous (Fig. 5f) and can be restricted to only one side of the particle.

### 3.4. Compositions

The compositions of the igneous rims and the unmelted cores on MMs were determined by wave dispersive spectroscopy using an electron microprobe as the average of individual spot analyses. The compositions of both igneous rims and unmelted cores of MMs are broadly chondritic,
for all but the most volatile elements. The bulk compositions of igneous rims and unmelted cores for selected MMs are shown in Table 1.

### 3.4.1. Fine-grained MMs

The compositions of the unmelted cores of fgMMs are shown in Fig. 6 relative to CI chondrite for the 15 elements analysed and fall entirely within the range of the matrices of fgMMs that lack igneous rims. Unmelted cores and fine-grained MMs in general exhibit depletions in Ca/Si, Na/Si, P/Si, and S/Si, and minor enrichments in K/Si relative to whole rock CI chondrite. In most cores, all other analysed elements fall within a factor of three of whole rock CI abundances. The compositions of fine-grained matrix are very similar to those of carbonaceous chondrite matrices as discussed in Genge et al. (1997); however, most have lower Ni/Si, Na/Si, and S/Si, and many are depleted in Mn/Si. Some fine-grained cores also have slightly lower Ca/Si ratios than carbonaceous chondrite matrix.

Igneous rims on fgMMs likewise have broadly chondritic compositions that fall mostly within the range of the matrices of fgMMs (Fig. 7) and exhibit similar enrichments.
in K/Si and depletions in Na/Si, Ni/Si, and S/Si compared with bulk CI chondrite. The most notable difference between the composition of igneous rims and the matrices of fgMMs is that the Mn/Si, Fe/Si, and Ni/Si ratios of igneous rims are higher than the majority of matrices, and their average Na/Si and K/Si ratios are lower than the average within matrices.

The compositions of co-existing igneous rims and unmelted fine-grained cores of several fgMMs are shown in Fig. 8. In the majority of particles, the composition of the igneous rim is broadly similar to that of the melted core having similar relative enrichments/depletions relative to bulk CI chondrite of one element compared with another. Differences between the Al/Si, Ca/Si, and Ti/Si ratios of igneous rims and unmelted cores are variable and show no systematic depletion or enrichment in these elements and thus the differences may well be attributable to analytical uncertainties. Igneous rims are enriched, however, in Fe/Si and Mn/Si relative to their co-existing unmelted fine-grained core in all particles and Ni/Si is also enriched in the majority of rims. Although some Fe and Ni enhancement within analyses is likely to be attributable to matrix overlap with magnetite rims, the observation that SMMs with thick igneous rims surrounding small cores of unmelted matrix, in which matrix overlap could be avoided, also demonstrate enrichments of Fe/Si, Mn/Si, and Ni/Si implies these are not principally analytical artifacts. No systematic variation in the magnitude of enrichments was observed with the width of the igneous rim.

The majority of igneous rims have depletions in Na/Si, K/Si, and S/Si relative to their co-existing unmelted cores. Differences in P/Si and Cl/Si between igneous rims and unmelted cores, however, are variable showing both enrichments and depletions. These two elements are present in small but detectable amounts within the resin used to prepare grain mounts, and their abundances, particularly for Cl, increase with observable porosity and vesiculation presumably due to the presence of resin.

### 3.4.2. Coarse-grained MMs

Analysis of the compositions of igneous rims and the unmelted cores of cgMMs is difficult due to the generally...
large grain-size of the cores of these particles and the poor-developement of their igneous rims. Large grain-sizes, relative to particle size, make accurate bulk analysis of the cores of cgMMs by electron microprobe techniques problematic since the composition of the surface of a polished section is unlikely to be representative of that of the particle as a whole. Although an estimate of the composition of the unmelted cores of cgMMs can be calculated from analyses of individual phases and their apparent abundance, it is unlikely to be sufficiently accurate to provide a meaningful comparison with that of the much finer-grained igneous rim. Only in the case of cgMMs with relatively fine-grained (although igneous) cores and those dominated by a single phase are comparisons possible. The small width of igneous rims on most cgMMs also presents significant analytical difficulties due to matrix overlap with the external magnetite rim and/or the unmelted core. In this work, only two particles (CP94-050-103 and CP94-100-166; hereafter 103 and 166, respectively) had sufficiently large melted rims and either relatively fine-grained or monomineralic cores to allow a meaningful comparison to be made. The compositions of a further six igneous rims on cgMMs, however, were also determined, albeit without that of the co-existing core. Their compositions are shown in Table 2.

The compositions of the igneous rims on all the particles are broadly chondritic and fall largely within the range of the igneous rims of fgMMs, except for small depletions in Fe/Si and Ni/Si in some particles (Fig. 9). The average Mn/Si, Fe/Si, and Ni/Si for igneous rims on cgMMs is also lower than those of fine-grained particles.

Although having compositions similar to the igneous rims of fgMMs, the rims of particles 103 and 166, exhibit significantly higher Mn/Si, Fe/Si, and Ni/Si ratios than to their unmelted cores (Fig. 10). Enrichments in Fe/Si in these two particles are an order of magnitude larger than those observed for the rims of fgMMs. In contrast to the igneous rims of fine-grained particles, particles 103 and 166 also exhibit enrichments in Na/Si, K/Si, and S/Si relative to their unmelted cores.

4. Discussion

4.1. Evidence for surface melting during entry heating

Distinguishing between primary textural and mineralogical features within micrometeorites and those generated during atmospheric entry requires evidence for surface correlated heating and is often problematic for individual particles. Textural and mineralogical evidence described above, however, strongly suggests that igneous rims on MM are generated by surface partial melting of largely solid particles that almost certainly occurred during atmospheric entry heating.

4.1.1. Igneous rims

The most compelling evidence for the crystallization of rims from a melt are their igneous textures. The occurrence of zoned fayalitic olivine microphenocrysts within interstitial glass could not be produced by solid-state recrystallisation of the matrix and instead indicates a relatively high degree of partial melting followed by crystallization during rapid cooling, consistent with the thermal behaviour of micrometeoroids during atmospheric deceleration (Love and Brownlee, 1991). Irregular Mg-rich olivines and pyroxenes found within the rims of some fine-grained particles, however, are unlikely to have crystallized from melts of broadly chondritic composition. Since these are most often found in igneous rims of fine-grained particles containing isolated Mg-rich olivines and pyroxenes in their matrix cores, and have overgrowths of fayalitic olivine, such grains are probably relics that have survived melting.
The smooth, rounded surfaces of igneous rims indicate that surface tension plays an important part in their morphology. Despite the presence of relics in some rims, the degree of partial melting must have been sufficiently high that the surface melt behaves rheologically as a fluid. With increasing relative width of the igneous rim particle shapes tend towards smooth, lobate particles similar to SMMs that lack unmelted cores. The highly vesicular nature of rims likewise supports their formation as a melt layer on the surface of particles.

4.1.2. Fine-grained matrix cores

That the cores of the fgMMs did not experience significant partial melting is also supported by the textural and mineralogical data. The presence of acicular to sheet-like sub-micron phases within the cores of some fgMMs, thought to represent phyllosilicates or, more likely, their thermal decomposition products, clear indicates that the bulk of the silicate component of these cores has not partially melted. The occurrence of irregular pore space and irregular cracks is likewise significant. Irregular pore space, which in some particles comprises up to 50% by volume, is likely to be a primary feature of the particles. Irregular crack networks are similar to those observed within the thermally altered substrates beneath the fusion crusts of CI and CM chondrites and are thus probably dehydration cracks formed by volume decreases associated with the dehydration of phyllosilicate. The preservation of irregular voids and cracks within the matrix cores of fine-grained particles, therefore, are definitive evidence that the cores behave rheologically as solids during entry heating and preclude significant partial melting of the silicates. In contrast

![Graphs showing compositions of representative igneous rims compared with their co-existing unmelted cores for selected particles.](image)
to igneous rims, the lack of overgrowths or reaction rims on isolated Mg-rich olivines and pyroxenes in fine-grained matrix also constitutes evidence that little silicate partial melt is generated within the cores.

Sub-spherical voids observed within fine-grained cores are problematic since they resemble vesicles and yet are associated with irregular pore space and dehydration cracks that preclude a significant degree of partial melting. Sub-spherical voids within the matrices of fine-grained MMs might originate as gas expansion cavities resulting from the rapid decomposition of phyllosilicates or carbonaceous materials and clearly voids originate due to entry heating, however, since they are most abundant within small fine-grained cores of SMMs, which presumably have experienced the most heating. Experimental vesiculation studies of CI chondrite particles have demonstrated that vesicles appear at temperatures as low as 1200 °C (Toppiani and Libourel, 2002) but have not examined the possibility of vesicle formation at lower temperatures.

4.1.3. Coarse-grained cores

Several textural, mineralogical and morphological features of cgMMs suggest that their igneous cores survived atmospheric entry without significant partial melting. The irregular shape of many cgMMs with igneous rims is particularly strong evidence that these behaved rheologically as solid particles during atmospheric flight. The mineralogy of the cores of cgMMs is also inconsistent with crystallization from a melt generated during entry heating since these particles contain abundant pyroxene. Cosmic spherules, sub-spherical droplets formed by high degrees of melting of micrometeoroids during atmospheric deceleration, are

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Table 2: Average electron microprobe analyses (in wt%) of igneous rims and unmelted cores of cgMMs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cl</th>
<th>K</th>
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Low analytical totals are the result of porosity and microvesiculation. Abbreviation: b.d., below detection.
dominated by olivine with pyroxene present only as relics or as dendrites within the mesostases of particles (Genge et al., 1997; Taylor and Brownlee, 1991). Pyroxene is thought to be absent within these chondritic melts since its crystallization is kinetically impeded by rapid cooling of small particles in the atmosphere.

The large grain-size of phenocrysts within the cores of cgMMs (often 10 μm or larger) contrasts strongly with the micron-sized fayalitic olivine microphenocrysts observed within their igneous rims and suggests that the cores probably crystallized in an early thermal event at lower cooling rates than the igneous rim. Truncation of euhedral phenocrysts by the igneous rim within the cores of some cgMMs also confirms that the core existed an essentially solid grain during the heating event that produced the rims.

Vesicles present within the glassy mesostasis of the cores of some cgMMs, however, might suggest partial melting of the core during entry heating. However, vesicles may have formed due to remobilization of the glass during entry heating (Genge et al., 2005). Remobilization of glass occurs at the glass transition which is approximately 2/3 of the equilibrium melting temperature of the crystalline solid.

4.2. The formation of igneous rims on fgMMs

4.2.1. Thermal gradients

Considerations of the Biot number which describes heat conduction within solid materials suggest that particles smaller than ~1 mm should be unable to support thermal gradients during atmospheric entry and will, therefore, be thermally homogeneous (Love and Brownlee, 1991). The presence of igneous rims on MMVs surrounding a largely unmelted core, both of which have approximately the same composition, however, testifies to the presence of a largely molten surface layer and a largely unmelted core. Although the cores and igneous rims of particles do have subtly different compositions, the difference in their solidus temperatures is likely to be minor. The occurrence of sheet-like to acicular sub-micron phases within the cores of some particles implies that amorphous dehydroxylates of phyllosilicates have not entirely recrystallised suggesting temperatures that may be as low as 400–800 °C depending on the dominant phyllosilicate. The solidus temperature for CM2 matrix is ~1350 °C (Toppani et al., 2001). Igneous rims on fgMMs, therefore, imply temperature differences of up to ~950 °C across particles 50–100 μm in diameter. The existence of thermal discontinuities within fgMMs, therefore, is an apparent anomaly.

Similar igneous rims are found on smaller (<30 μm) hydrated interplanetary dust particles and likewise imply surface-correlated thermal discontinuities. These have been suggested to be supported by endothermic decomposition reactions of hydrated silicates (Flynn, 1995). This mechanism, in which thermal decomposition reactions consume heat, during its conduction into the particle, resulting in a high temperature outer layer and lower temperature core is also consistent with the precursor mineralogy of fgMMs, most of which are thought to be similar to C2 and C1 chondrites and thus are volatile-rich. Phyllosilicates are rarely observed within fgMMs due to their thermal decomposition during entry heating, however, the matrix mineralogy, determined by transmission electron microscopy, of most fgMMs is consistent with the presence of hydrated silicates prior to heating (Genge et al., 2001; Gounelle et al., 2002; Nakamura et al., 2001; Noguchi et al., 2002). Pulse heating experiments on CI1 and CM2 particles have also confirmed that surface melt layers are generated on such hydrous particles at temperatures >1350 °C and furthermore indicate that the size of the igneous rim increases with duration of the heating pulse over several seconds (Toppani et al., 2001).

4.2.2. Chemical fractionation

The compositions of igneous rims on fgMMs are consistent with their formation by the melting of the fine-grained cores of these particles since they have broadly similar elemental patterns for the 15 elements analysed. Several characteristics of the elemental abundance patterns of both unmelted cores and igneous rims, however, also appear to originate by heating. Depletions in Na/Si and S/Si relative to CI chondrite and the range of CM2 chondrite matrices (Zolensky et al., 1993) suggest evaporative loss during entry heating from both igneous rims and fine-grained unmelted cores. Such depletions could, however, also simply represent primary differences in composition between the parent bodies of fgMMs and chondrites. The observation that many particles exhibit elevated K/Si relative to CI chondrite and CM2 chondrite matrix, contrary to expected evaporative losses of this element, indicate that primary differences from chondrite do occur. In all particles, however, the Na/Si, K/Si, and S/Si ratios of igneous rims are depleted relative to their unmelted cores strongly suggesting additional evaporative loss of volatile and moderately volatile elements from rims consistent with their expected higher temperatures. Comparisons between the compositions of igneous rims and their co-existing unmelted cores, therefore, provide a means of evaluating chemical fractionation due to heating that is not possible through consideration of bulk or core compositions alone in which changes are obscured by primary variations between micrometeorites.

The maximum Na/Si, K/Si, and S/Si values within igneous rims relative to CI chondrite for igneous rims roughly decreases with increasing apparent relative volumetric proportion of the rim consistent with increasing evaporative loss of these with progressive heating (Fig. 11). The lack of well-defined correlations for these elements could reflect primary variations in the abundances of these elements. Calcium depletions relative to CI chondrite are also observed in many particles and have previously been suggested to be the result of either thermal decomposition of Ca-bearing carbonates/sulphates during entry heating or their dissolution in the terrestrial environment (Engrand and Maurette, 1998; Genge et al., 1997; Kurat et al.,...
The observation that those particles in which the unmelted cores exhibit Ca/Si depletions also exhibit Ca/Si depletions within the igneous rim, however, implies that loss of Ca occurred prior to melting. These data are, therefore, consistent with either the loss of Ca by dissociation of Ca-bearing volatile-rich phases prior to melting or are a primary feature of these hydrated materials. Calcium depletions are a ubiquitous feature of hydrated carbonaceous chondrite matrix (Zolensky et al., 1993) and the majority of fgMM matrices do have Ca/Si abundances within the range of these materials. The highest Ca/Si ratios with igneous rims, however, are observed in those with the smallest apparent volumes suggesting some Ca loss during heating. It should be noted that neither Na- or Ca-depletions have been reproduced in pulse heating experiments (Toppani et al., 2001).

Enrichments in Mn/Si, Fe/Si, and Ni/Si ratios in igneous rims relative to their co-existing unmelted core are observed for all particles and are difficult to reconcile with the generation of igneous rims by melting of the unmelted core. One obvious explanation for the enrichment of the igneous rim in Fe/Si and Ni/Si might be matrix overlap of analyses with the magnetite rim, since such magnetites have been shown to comprise a significant trevorite component (Robbin et al., 1992; Toppani and Libourel, 2003). This cannot, however, explain enrichment in Mn/Si and is also not consistent with the observation of enrichments in those particles with thick igneous rims in which matrix overlap can be discounted, and the qualitative observation that igneous rims have higher backscattered electron potentials than cores.

Enriching the surface melt layer in Fe, Ni and Mn represents a similar problem to the Fe and Ni enrichment that appears to be associated with the formation of magnetite rims on MMs in general. Previous studies have shown that accretion of Fe from the atmosphere, specifically from the atmospheric E-layer, is unable to account for even the modest enrichments in Fe represented by magnetite rims due to the low column density of atmospheric iron (Flynn, 1994). Experiments demonstrate, however, that magnetite rims can be generated during pulse heating on particles CM2 and CI1 matrix at temperatures >1200 °C and suggested that Fe-rich partial melts, generated at the periphery of particles by melting of Fe- and volatile-rich phases, leads to the crystallization of spinel in the Fe-saturated surface partial melt. The experiments also revealed

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![Figure 11](image-url)
that at temperatures of 1200 °C, with short duration heating, iron-rich regions occur on the periphery of particles and along the margins of dehydration cracks implying that iron-enrichment occurs as a precursor to magnetite rim formation and the visible development of a partial melt (Toppani et al., 2001). This observation is consistent with the observation of regions iron-rich matrix of the periphery of fgMMs without igneous rims.

Enrichment of the surface layer of fgMMs in Fe through small degrees of partial melting also provides an explanation for enhanced Fe/Si of igneous rims, however, the migration of partial melt towards the surface, as opposed to the in situ decomposition and partial melting of Fe-rich phases (Toppani et al., 2001), is clearly necessary to produce elemental enrichments. Small degree partial melts generated in the largely unmelted core of the particle could enrich the surrounding igneous rim in Fe if these were able to migrate towards the surface of the particle. To generate the observed enrichments in Mn/Si and Ni/Si, however, these elements would also have to be abundant within the partial melt. The composition of the enriching partial melt will be largely controlled by the composition of the source volatile-rich phase since melting during pulse-heating occurs under non-equilibrium conditions and little equilibration of the partial melt is likely to occur. Elevated Ni abundances would be expected within partial melts generated from the decomposition products of tochilinite (CM2-like particles) or ferrihydrite (CI-like particles) which generally contain Ni abundances greater than bulk CI chondrite (Brearley and Jones, 1998), however, neither phase is particularly Mn-rich.

The observation that Fe-enrichment of the periphery of fgMMs is observed as a precursor to visible evidence for partial melting (Toppani et al., 2001) may suggest that Fe-rich silicate melts are not solely responsible for the observed enrichments since it implies temperatures below the solidus of the silicate components. Iron–sulphur liquids, however, have eutectic temperatures <1000 °C and are thought to be the first partial melts generated by chondritic materials (Taylor et al., 1993). Both tochilinite and ferrihydrite contain appreciable sulphur and eutectic Fe–S liquids could be generated by partial melting of their thermal decomposition products under reducing conditions. Reduction during heating of fine-grained matrix is likely to occur due to pyrolysis of carbonaceous materials and has been reported for the thermally altered substrates beneath the melted fusion crust of CI1 and CM2 chondrites leading to the generation of Fe–S eutectic liquids (Genge and Grady, 1999a). Reduction due to pyrolysis might also explain the origin of Mn/Si enrichments since Mn becomes chalcophile under reducing conditions and may be preferentially partitioned into sulphide liquids as observed in the fusion crusts of enstatite chondrites (Genge and Grady, 1999b).

The role of eutectic Fe–S liquids in the Fe enrichment of igneous rims can, therefore, reconcile the unmelted textures of silicates within the cores of most fgMMs with igneous rims and the requirement for melt generation. Sulphide liquids may also explain how melt migration occurs since, unlike Fe-rich silicate melts, eutectic sulphide liquids have low viscosities (Vaisburd and Fisher, 1990). Migration of liquids to the surface of the particle could be driven by degassing in the core and flow of gas towards the surface. Within the surface melt layer of the igneous rim the added sulphur will then be removed by evaporation. Later in the melting process, in particles in which the cores reach temperatures of 1200–1350 °C, appreciable partial melting of Fe-rich silicates may occur producing the veined cores of some SMMs and vesicular iron-rich areas observed in some C2 particles (Fig. 3f).

The model proposed above for the observed enrichment of igneous rims in Fe/Si, Mn/Si, and Ni/Si implies exchange with the core of the particle and thus an increase in the enrichment of these elements with progressive melting might be expected. No correlation between (Fe/Si)core/(Fe/Si_rim) with the apparent volume of the igneous rim is observed to support such an exchange process. The lack of a correlation, however, may simply indicate that the original differences in Fe content between particles exceed the variations due to the exchange process.

4.3. Formation of igneous rims on cgMMs

The origin of igneous rims on cgMMs is problematic since these particles lack low temperature phases such as phyllosilicates that could support thermal gradients through endothermic decomposition. Considerations of the thermal behaviour of micrometeoroids suggest that such particles should not be able to maintain thermal discontinuities or temperature gradients larger than a few degrees (Love and Brownlee, 1991). Igneous rims on cgMMs are, therefore, highly unlikely to have formed by direct melting of the core of the particle.

The compositions of igneous rims on cgMMs also suggest there are not generated by direct melting of the coarse-grained core since they demonstrate significantly higher Fe/Si, Mn/Si, and Ni/Si ratios. Although Fe/Si, Mn/Si, and Ni/Si enrichments are also observed for igneous rims on fgMMs, these are usually by less than a factor of 2 and it is difficult to reconcile a 10-fold higher Fe/Si abundance in the igneous rims. The higher Na/Si, K/Si, and S/Si ratios of the igneous rims are also significant since a surface melt layer generated from the coarse-grained core would be expected to be depleted in such elements due to partial evaporation. One possible explanation for enrichments in Na and K might be melting of the mesostasis of the cores of the particles and extrusion of this melt onto the surface. The feldspathic nature of mesostasis in cgMMs (Genge et al., 2005), however, would also lead to enrichments in Ca and Al which are not observed. Furthermore, although one of the analysed particles (#166) does contain small amounts of mesostasis between radiating pyroxene crystals, the other (#103) consists of granular enstatite and thus contains no apparent mesostasis.
The compositions of the igneous rims on cgMMs and fgMMs also suggest both have similar precursor materials, specifically fine-grained matrix. Furthermore, the occurrence of composite MMs, consisting of both coarse-grained igneous objects and fine-grained matrix (Genge et al., 2005), confirms that fine-grained matrix can occur on the exterior margins of cgMMs. The lower solidus temperature of fine-grained matrix compared with all but the mesostasis of cgMMs will ensure that the fine-grained matrix preferentially melts during atmospheric entry.

An origin of igneous rims on cgMMs by melting of selvages of fine-grained matrix is supported by the occurrence of igneous rims on these particles. Whilst igneous rims on fgMMs extend over the entire surface of the particles, those of cgMMs can be restricted to just one part of the external surface, consistent with melting of a small and discontinuous selvage of fine-grained matrix as observed on some composite particles (Genge et al., 2005). Additionally, although the composition of igneous rims on cgMMs is similar to that of igneous rims on fgMMs their slightly lower Fe/Si and Ni/Si ratios are nevertheless consistent with melting of fine-grained matrix. The Fe/Si and Ni/Si ratios of igneous rims on fgMMs are, suggested above, to be enriched by melt generation within the largely unmelted core of these particles, however, in cgMMs this enrichment process could not operate. Without an enrichment process the igneous rims of cgMMs would, therefore, be expected to have Fe/Si and Ni/Si ratios less than those of igneous rims of fgMMs, but within the range of those of unmelted fine-grained matrix, exactly as observed.

5. Implications

5.1. Atmospheric entry heating

The development of igneous rims on fgMMs has significant implications for their behaviour during atmospheric entry due to the effects of an isothermal melt layer and thermal decomposition reactions on the surface temperature of micrometeoroids. Calculations show that endothermic decomposition reactions of phyllosilicates result in a large temperature discontinuity inwards of the igneous rim/core boundary allowing an unmelted core to be preserved (Flynn, 1995). Since a large thermal gradient is not possible across the molten rim of the particle, the melt in the igneous rim must, therefore, remain at the melting temperature of the matrix whilst the unmelted core exists. The surface temperature of micrometeoroids, therefore, must remain approximately constant over an interval of atmospheric heating during which fusion of the core of the particle is occurring. The observation that 28% of unmelted fgMMs exhibit igneous rims implies that this interval of constant surface temperature probably corresponds to a significant period of the heating duration for many particles. The roughly constant surface temperatures will influence the overall degree of heating of particles because they will minimize heat losses due to thermal radiation and also reduce evaporative mass loss.

5.2. Volatile contents and survival of phyllosilicate

Shock recovery experiments on CM2 chondrites have been used to suggest that a significant proportion of fgMMs may originate through explosive fragmentation of CM2 materials due to dehydration of phyllosilicate during collisions (Tomeoka et al., 2003). If correct then the high abundance of hydrated asteroidal fgMMs may be a result of the dust production mechanisms rather than the abundance of their parent bodies in the main asteroid belt.

Observations made in the current study, however, indicate that compact fine-grained particles commonly exhibit igneous rims. The formation of igneous rims, as described above, is an expected consequence of the endothermic decomposition of phyllosilicate during entry heating and, therefore, indicate that hydrated phyllosilicate still exist in most fgMMs just prior to atmospheric entry.

Igneous rims, however, are also observed on highly porous fgMMs dominated by anhydrous silicates with textural evidence for only minor phyllosilicate. The occurrence of igneous rims on such particles implies that small amounts of hydrated phyllosilicate, perhaps in combination with the decomposition of carbonaceous materials, are sufficient to allow maintain thermal gradients and form igneous rims. Complete dehydration of hydrated asteroidal materials during dust production is nevertheless precluded by the generation of igneous rims during atmospheric entry.

5.3. Chondrules among micrometeorites

On the basis of their textures, mineral assemblages and state of oxidation (Genge and Grady, 2001) have suggested that the majority of cgMMs represent fragments of chondrules from chondritic parent asteroids broadly similar to those of the chondritic meteorites. The occurrence of composite MMs with both coarse-grained igneous objects, indistinguishable from cgMMs, and fine-grained matrix, is strong evidence that these particles are fragments of chondrules that sample the chondrule/matrix interface from the same parent bodies as many fgMMs (Genge et al., 2005).

A major conclusion of the current study is that igneous rims on cgMMs are formed by melting of selvages of fine-grained matrix attached to the surface of the particle during atmospheric entry. Coarse-grained MMs with igneous rims, therefore, represent composite MMs in which fine-grained matrix has melted during atmospheric entry and consequently are also probably fragments of chondrules that sample the chondrule/matrix interface.

The proportion of unmelted composite MMs and melted composite MMs (i.e., cgMMs with igneous rims) to cgMMs without igneous rims provides the first opportunity to estimate the mean size of chondrules in the parent bodies of MMs. The probability of randomly sampling the
chondrule/matrix interface to produce a composite cgMM will change with chondrule size as a function of the volume of the chondrule and the volume of the fragment produced. Fig. 12 shows a scenario with a spherical chondrule of radius \( R \) sampled by random spherical fragments (i.e., micrometeorite precursors) of radius \( r \). Only fragments with central coordinates lying within a spherical shell delimited by the radii \( R + r \) and \( R - r \) will sample the chondrule/matrix interface (shown as fragments A and B). These fragments represent composite MMs. All other fragments of the chondrule, those whose central coordinates lie with \( R - r \) of the chondrule will not sample the chondrule/matrix interface. These fragments represent cgMMs without igneous rims or fine-grained matrix.

An expression for the fraction of chondrule-derived cgMMs that sample the interface with the surrounding matrix (i.e., composite particles) can be derived by consideration of the relative volumes of the spherical shell and the whole chondrule and is given by

\[
F_{\text{comp}} = 1 - \frac{(R - r)^3}{(R + r)^3}.
\]

Fig. 13 shows the fraction of composite MMs to cgMMs for several different mean sizes of chondrules and MMs (i.e., the fragmented samples). In the current study cgMMs comprise 89 out of a total of 518 MMs, of which 12 composite MMs with unmelted fine-grained matrix and 17 have igneous rims and thus represent melted composite particles. In total, therefore, melted and unmelted composite MMs comprise 29 out of 89 cgMMs representing \( \sim 30\% \) of all coarse-grained particles. If, for the purposes of this discussion, all cgMMs are assumed to be samples of chondrules, the fraction of samples of chondrule/matrix interface to total chondrule samples is, therefore, 0.3. Given the average particle radius, determined from an equivalent volume sphere, in the current study of \( \sim 40\mu m \) this would imply a mean chondrule radius within the parent bodies of MMs of \( \sim 675\mu m \).

Chondrules in meteorites, however, exhibit a range of sizes, broadly following a normal distribution and the studied MMs are also variable in size. The effects of variations in chondrule size on the calculation of mean chondrule size, however, are relatively minor since the mean size is similar to the mode of the population due to its normal distribution. The range in MM size, from 25 to 100 \( \mu m \) in radius, however, has a much more significant influence due to the lack of a distinct mode but allows a maximum mean chondrule radius of 1650 \( \mu m \) and a minimum mean chondrule radius of \( \sim 425\mu m \) to be specified.

The mean chondrule sizes, calculated above, make comparisons with the bulk properties of the chondrites possible. If cgMMs are predominately derived as fragments of chondrules then for any particular size of micrometeorite the fraction of chondrule/matrix interface to chondrule samples should lie somewhere on the appropriate size curve between the expected range of chondrule sizes (the vertical dashed lines shown in Fig. 13). The mean chondrule radii estimated in the current study is \( \sim 675\mu m \), which lies outside this range and may suggest that a significant proportion of cgMMs (\( \sim 60 \) to \( \sim 23\% \)) are derived from a non-chondrule source (i.e., from significantly larger igneous objects). However, given the large statistical uncertainty inherent in the estimated mean radii of \( \sim 675\mu m \) the data are also likely to be consistent with a scenario in which cgMMs are derived from a set of chondrules dominated by those \( \sim 500\mu m \) in radii similar to L/LL/CV3 and CR2 chondrites.
Chondrule mean sizes, predicted from inferred chondrule to chondrule/matrix interface samples, on their own provide little real predictive insight into the nature of MM parent bodies. In combination with constraints on the mineralogical, textural and chemical associations of cgMMs, however, they potentially may allow the contribution of discrete parent body sources of MMs to be identified. Such comparisons, however, which involve an in-depth study of the nature of a large number of cgMMs are beyond the scope of the current paper.

6. Conclusions

Mineralogical, textural, and compositional data are presented on 77 MMAs with igneous rims which suggest that fusion of micrometeorites occurs initially by surface melting followed by increases in the width of the melt layer with progressive heating. Textural and mineralogical evidence indicate that demonstrate unequivocally that igneous rims crystallized from a melt surrounding a largely unmelted core and establish melting as a gradational process.

The compositions of igneous rims on fgMMs are shown to be broadly similar to those of the co-existing unmelted cores except for depletion in moderately volatile and volatile elements. Such depletions indicate that partial evaporation does occur at relatively low temperatures in contrast with the results of previous experimental studies. Furthermore, depletions in Ca/Si relative to CI chondrite found in both igneous rims and unmelted cores suggest low Ca/Si ratios were established prior to melting due to either thermal decomposition of carbonates or as original features of these materials. Enrichments in Fe/Si, Ni/Si, and Mn/Si of igneous rims relative to unmelted cores in fgMMs are also identified and are suggested to be the result of the migration of Fe-S eutectic liquids from the largely unmelted core into the igneous rim under reducing conditions produced by the pyrolysis of carbonaceous materials. The compositions of the igneous rims of fgMMs suggest they originate by direct melting of fine-grained matrix.

The compositions of igneous rims on cgMMs are shown to differ significantly from those of their co-existing unmelted cores and instead are similar to those of fgMMs. Enrichments in Na/Si, K/Si, and S/Si of igneous rims compared with the unmelted core suggest these igneous rims formed by melting of fine-grained matrix attached to the exterior of the particle rather than the coarse-grained core. This conclusion is also consistent with the absence of volatile-bearing phases within the core of the particle that could support the large thermal gradients required to generate a surface melt layer by endothermic decomposition reactions. Coarse-grained MMAs, therefore, are identified as composite MMAs in which the fine-grained portion has melted during atmospheric entry. Composite MMAs are thought to represent samples of chondrule-like objects and are shown to represent ~30% of all cgMMs.

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