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Accumulation mechanisms of micrometeorites in an ancient supraglacial moraine at Larkman Nunatak, Antarctica

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Abstract–We report the discovery of a large accumulation of micrometeorites (MMs) in a supraglacial moraine at Larkman Nunatak in the Grosvenor Mountains of the Transantarctic Range in Antarctica. The MMs are present in abundances of ~600 particles kg^{-1} of moraine sediment and include a near-complete collection of MM types similar to those observed in Antarctic blue ice and within bare-rock traps in the Antarctic. The size distribution of the observed particles is consistent with those collected from snow collections suggesting the moraine has captured a representative collection of cosmic spherules with significant loss of only the smallest particles (<100 μm) by wind. The presence of microtektites with compositions similar to those of the Australasian strewn field suggests the moraine has been accumulating for 780 ka with dust-sized debris. On the basis of this age estimate, it is suggested that accumulation occurs principally through ice sublimation. Direct infall of fines is suggested to be limited by snow layers that act as barriers to accumulation and can be removed by wind erosion. MM accumulation in many areas in Antarctica, therefore, may not be continuous over long periods and can be subject to climatic controls. On the basis of the interpretation of microtektites as Australasian, Larkman Nunatak deposit is the oldest known supraglacial moraine and its survival through several glacial maxima and interglacial periods is surprising. We suggest that stationary ice produced by the specific ice flow conditions at Larkman Nunatak explains its longevity and provides a new type of record of the East Antarctic ice sheet.

INTRODUCTION

Micrometeorites (MMs) are extraterrestrial dust particles smaller than 2 mm that have survived atmospheric entry to be recovered from the Earth's surface (Genge et al. 2008). These materials were dust-sized particles within interplanetary space and are thought to be derived as collisional debris from asteroids and as ejecta from comets (Kurat et al. 1994; Genge et al. 1997; Genge 2008; Noguchi et al. 2015). Thus, MMs provide important natural samples from solar system small bodies. The current extraterrestrial dust flux is thought to be approximately 40 Kt yr^{-1} (Love and Brownlee 1993).

Micrometeorites were first recognized within deep-sea sediments (Blanchard et al. 1980; Brownlee 1985); however, they have since been recovered from a wide range of settings including varved lake sediments (Akulov et al. 2014), fluvial deposits (Bi et al. 1993), cryoconite lakes in Greenland (Maurette et al. 1986), Antarctic ice (Maurette et al. 1991; Taylor et al. 1998), Antarctic snow (Taylor et al. 1998, 2000; Nakamura et al. 1999; Duprat et al. 2007), and bare-rock traps in Antarctica (Rochette et al. 2008; Suavet et al. 2009). Of these sources, MM collections obtained by melting and filtering Antarctic snow are considered to be the most pristine and least biased (Taylor and Lever 2001).

Some previous studies have reported the recovery of MMs from Antarctic moraines, notably the Walcott Névé site, Antarctica (Harvey and Maurette 1991; Suavet et al. 2009). These locations provide favorable sites due

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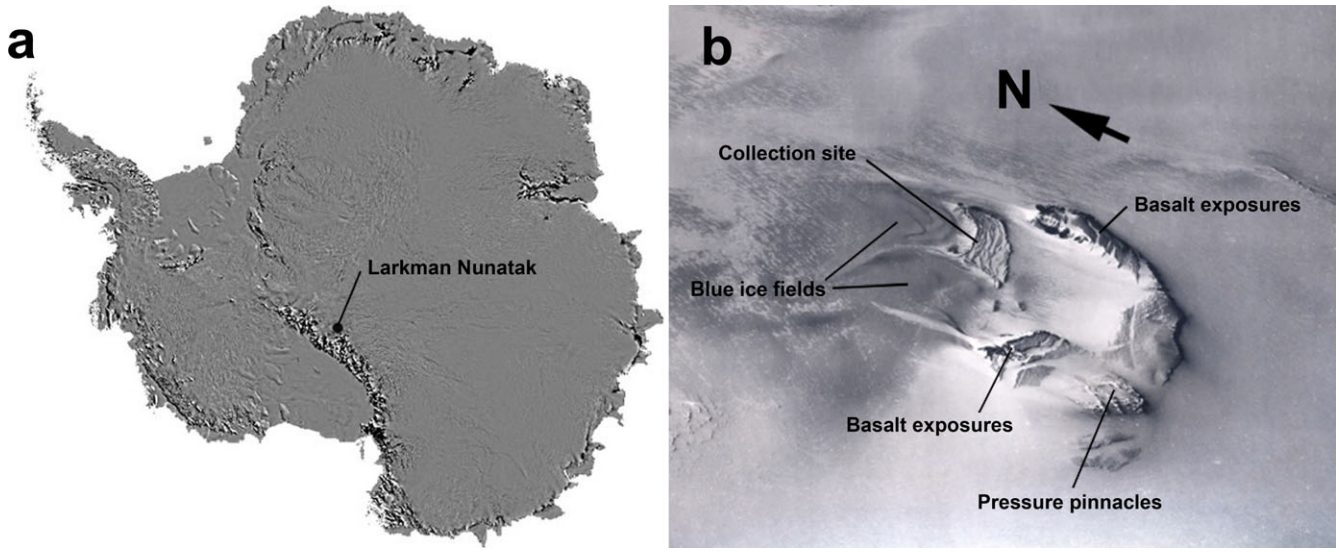


Fig. 1. a) Location of Larkman Nunatak on the Transantarctic Mountains and (b) a high-altitude aerial photograph of Larkman Nunatak showing the collection site in the moraine to the north of the nunatak.

to their widespread distribution and logistical ease of collection. In this paper, we report the first detailed study of the nature and abundance of MMs collected from a moraine at Larkman Nunatak in order to evaluate the mechanisms of accumulation and state of preservation within moraines as compared with other collection sites and methods. The results of the study suggest that supraglacial moraines can have an unexpected longevity.

GEOGRAPHIC AND GEOLOGICAL SETTING

Larkman Nunatak (86°46′S 179°20′E) is in the eastern Grosvenor Mountains and is the southernmost nunatak of the Shackleton Glacier drainage basin (Fig. 1). The site consists of a nunatak and a two smaller satellite outcrops. The main nunatak is 3 km in length and is elongated in an approximately SSE–NNW orientation broadly perpendicular to ice flow. Large outcrops of basalt are exposed on the southern, eastern, and at either end of the northern side of the mountain, leading to the formation of raised ice pressure ridges and wind scoops located to the east and west. On the northern side of the mountain, a shallow topographic depression extends northward into a large area of blue ice. This is an area of meteorite accumulation in which 1020 meteorites were collected by ANSMET (Meteoritical Bulletin 2017). Extensive bare ice areas lie northward. Southward, upflow of the glacier, blue ice exposure is limited and the surface is largely hardened firn (Fig. 1b).

Moraines are present in close proximity to Larkman Nunatak within the depression on the northern leeside of the peak. The moraine deposit forms an elongate (2 km) ridge raised some 25 m above the surrounding depression. Within the moraine subparallel ridges, tens of meters in width containing larger boulders up to 2 m in size are present and run broadly parallel to the elongation direction of the moraine (Fig. 2a). Between ridges snow accumulation occurs. Blue ice is also present within the moraine and is particularly apparent within wind scoops adjacent to larger boulders. The northern margin of the moraine is a gentle blue ice slope. On the slope, some linear areas of brown ice <30 cm wide and running for tens of meters were observed. The presence of blue ice within the moraine indicates it is supraglacial.

Bedrock exposed at Larkman Nunatak is restricted to thick lava flows of the Kirkpatrick basalt with well-developed columnar jointing evident on larger exposures. Extensive hydrothermal alteration of the basalt has occurred in places with abundant amygdales filled with zeolites and calcite. Within the moraine, basalt also represents the most abundant lithology among larger boulders (~80 vol%, Fig. 2b); however, a diverse assemblage of lithologies are present, including pale ocher calcareous siltstones, micritic limestones, dolerite, and sparse anthracitic coal. Siltstones tend to form tabular clasts due to extraction along bedding and include abundant well-preserved fossil ferns (Fig. 2c). Silicified carbonized fossil wood is also present in these rocks. A significant concentration of meteorites is present within the moraine, in particular close to the northern margin and on the blue ice slope to the north with specimens up to ~30 cm found by ANSMET, although most finds were small, 1–3 cm in size. Larger concentrations were also noted within wind scoops close

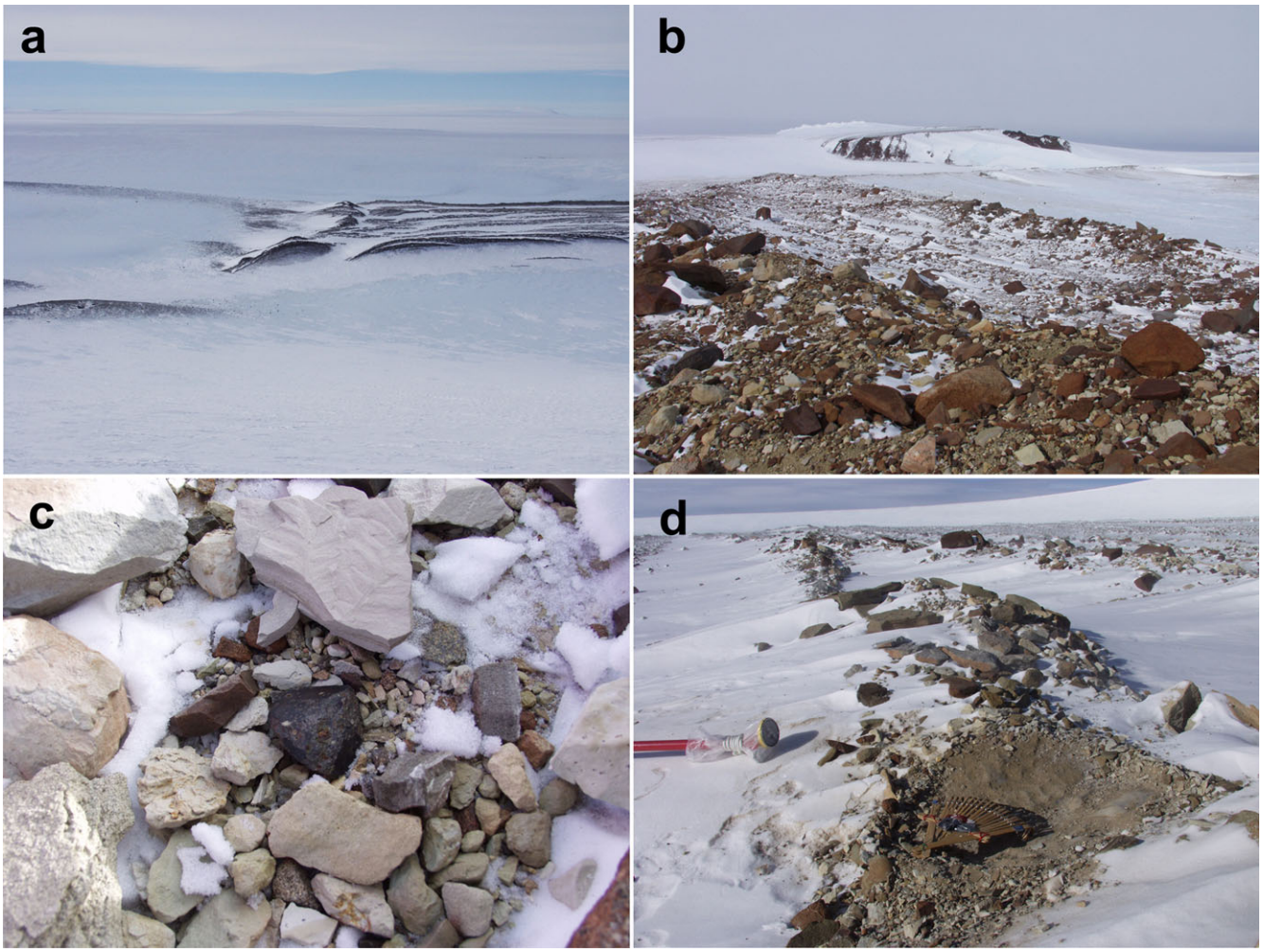


Fig. 2. Locality photographs from Larkman Nunatak. a) The western margin of the moraine seen from the top of Larkman Nunatak shows distinct pressure ridges with intervening lanes of snow. b) The top of the eastern end of the moraine shows large boulders of dolerite and basalt and smaller clasts of siltstone. c) Moraine clasts a few meters from the collection site show abundant siltstone clasts; one showing fern fossils (top of image) and smaller basalt clasts. In the center of the field of view is an ordinary chondrite. Field of view is 70 cm. d) The collection site with the thin snow layer removed to expose fine-grained debris below the surface. (Color figure can be viewed at wileyonlinelibrary.com.)

to larger boulders. The majority of meteorites are ordinary chondrites; however, basaltic achondrites and a lunar meteorite were also present. A layer of fine-grained material ranging from clay to granule grade up to 5 cm thick was present throughout the snow-covered areas of the moraine at the margin between the snow and the underlying blue ice. Reverse grading was noted in the fine-grained layer (Fig. 2d). Samples were collected from the fine-grained layer in order to assess MM abundance.

METHODS

Collection

Fine-grained materials were collected from the moraine from the layer at the boundary between blue ice and the overlying snow. Samples were collected from within 30 m of the northern margin of the moraine at the location shown in Fig. 1b. Snow was removed using a scoop and a fine-grained sample, which included the full depth of the sediment deposit, was placed into a sealed plastic bag. Care was taken to ensure no meteorites or snow was accidently included with the sample. In total, 3 kg of sample was collected.

Sample Preparation

Preliminary examination and picking of potential MMs was undertaken on dry separates of moraine fines under a binocular microscope in order to evaluate the abundance of cosmic spherules. The criteria for selecting MMs were based on those specified by Genge et al.

(2008). Dark grains with clear single crystal habits typically mostly proved to be ilmenite, derived from the local basalt or dolerites. MMs were picked by hand and mounted onto double-sided adhesive tape.

Magnetic separation techniques were employed for some samples to concentrate MMs. The magnetic fraction separated from the samples comprised 1.7% by mass of the deposit and contains terrestrial magnetite, ilmenite, basalt particles, and many magnetite-bearing, light-colored sedimentary particles as well as MMs. Ultrasound cleaning, using a water solvent, was performed on approximately 70% of the cosmic spherules studied. This removed micron-sized dust particles and mineral encrustations.

The extraterrestrial origin of particles was determined by scanning electron microscope (SEM) investigation, including quantitative chemical analysis using the criteria described in Genge et al. (2008). After initial examination by secondary electron imaging of particle exteriors, particles were embedded in resin and prepared as polished grain mounts.

Analytical Techniques

Analytical investigation was performed on the EVO LS15 Zeiss SEM at the Natural History Museum, London. Backscattered electron images of polished grain mounts were used to determine mineralogy and petrology in order to classify particles. Mineral and area major and minor element compositions were determined by energy dispersive spectroscopy on carbon-coated polished sections. Analyses were collected at an accelerating voltage of 20 kV and beam current of 3 nA. Quantitative analyses were obtained by comparison to a gain calibration and mineral standards with standard Zeiss matrix corrections applied. Oxygen abundance was calculated using stoichiometry assuming all iron was present as Fe^{2+} except for sulfides and metal where no oxygen was included. Detection limits are ~0.1 wt%; analytical precision varies by element but is typically <0.5 wt%. Mineral analyses were evaluated by stoichiometry and analytical totals.

RESULTS

During the preliminary examination of the Larkman moraine materials, 634 MMs were picked and analyzed, including 616 cosmic spherules. The composition, mineralogy, and size distribution of the Larkman Nunatak collection are described below to demonstrate their identity as MMs and provide constraints on the abundance of MM types. Bulk compositions are given in Table 1.

Size Distribution and Micrometeorite Concentration

A total mass of ~1.1 kg of sediment yielded 634 MMs. The diameters of particles range from 60 to 450 μm. The cumulative size distribution is shown in Fig. 3. A power law distribution with an exponent of −5.34 was fitted over a small portion of size range from diameters of 210 to 330 μm with abundance decreasing below the power law at high and low diameters.

Micrometeorite Types and Petrology

Unmelted Micrometeorites

Unmelted MMs (UMMs) are particles that have escaped melting during atmospheric entry (e.g., Genge et al. 2008). Eleven unmelted MMs were recovered and comprise five coarse-grained (CgMMs) and two fine-grained (FgMMs). The coarse-grained particles are shown in Figs. 4 and 5 and are dominated by relict olivines and pyroxenes with grain sizes within 10% of particle size within a glassy mesostasis containing vesicles and zoned olivine phenocrysts. They exhibit poorly developed, partial magnetite rims. One particle, LK06-0312, closely resembles a cryptocrystalline cosmic spherule (Fig. 5b); however, the presence of a near-complete magnetite rim and a thin-vesicular melted rim indicates this has experienced surface melting during atmospheric entry and was, therefore, a radiating pyroxene chondrule with attached fine-grained matrix (Genge et al. 2005).

Two FgMMs were found. Particle LK06-0565 consists of relatively coarse sheet-like crystals that, on the basis of composition and crystal morphology, are likely to be cronstedtite, the iron-bearing variety of serpentine within a fine-grained matrix with chondritic major element compositions (Table 1). Particle LK06-0564 consists of fine-grained, low-porosity matrix comprised of sheet-like grains up to 4 μm in size with areas containing framboidal magnetite consisting of equant, subspherical, magnetite grains up to 2 μm in diameter.

Scoriaceous Micrometeorites

Eleven scoriaceous micrometeorites (ScMMs) were found in the current collection and are shown in Fig. 6. The particles all have significant abundances of vesicles within a fine-grained groundmass consisting of micron-sized, equant, iron-rich olivines within a glassy mesostasis. All particles have partial magnetite rims. Several particles (LK06-0095, LK06-0362, and LK06-0325) contain Mg-rich relict silicate grains (forsterite and enstatite) that have survived atmospheric entry. All particles have chondritic compositions.

Table 1. Bulk compositions of particles determined by area EDS analyses. Values marked with a "–" are below detection limits. Cosmic spherule types are given using standard abbreviations as described in the text.

Particle	0002	0003	0521	0522	0504	0506	0503	0524	0525
Type	PO	PO	BO	BO	BO	C	C	C	C
Na	–	–	–	–	–	–	–	–	–
Mg	12.8	12.2	15.4	18.4	20.9	17.8	22.7	16	14.2
Al	1.1	1.8	1.3	1.0	–	1.9	0.5	1.9	1.2
Si	15.3	17.1	19	18.1	18.8	18.6	18.5	18	15.7
S	–	–	–	–	–	–	–	–	–
K	–	–	–	–	–	–	–	–	–
Ca	4.0	1.7	1.8	1.2	0.9	2.0	0.4	2.2	1.6
Cr	–	0.4	0.7	–	0.3	–	–	–	0.3
Fe	28.8	29.2	22.2	22.2	18.6	17.5	17.5	21.2	29.2
Ni	0.4	–	–	–	–	–	–	–	0.9
Mn	–	–	–	0.8	0.4	–	0.2	–	0.3
O	36.8	38.3	40.4	40.7	41.1	40.4	41.7	39.6	37.7
Totals	99.1	100.7	100.8	102.3	100.9	98.2	101.4	99	101.1

Particle	0528	0057	0514	0516	0011	0564	0565	0956	1131
Type	C	V	V	V	SMM	FgMM	FgMM	IS	IS
Na	–	0.2	–	–	–	0.3	–	0.6	0.9
Mg	16.9	12.8	21.5	22.4	15.4	3.1	5.8	16	15.4
Al	1.7	1.5	1.0	1.1	1.6	3.9	6.8	1.2	3.6
Si	17.8	16.1	20.8	24.2	17.2	19.8	15.6	25.9	25.0
S	–	0.2	–	–	0.4	–	–	–	–
K	–	0.1	–	–	–	2.3	0.7	–	–
Ca	1.5	1.4	1.5	1.5	0.5	0.5	0.9	0.8	0.9
Cr	–	0.3	–	–	0.3	–	–	–	–
Fe	21.8	26.4	12	4.7	25.1	23.8	21.6	10	8.4
Ni	–	3.3	–	–	–	–	–	–	–
Mn	–	–	0.3	0.4	–	–	0.9	0.3	–
O	39.8	37.8	42.8	45.4	39.3	44.5	47.4	44.5	45.0
Totals	99.5	100.2	99.8	99.8	99.9	98.3	99.7	99.3	99.2

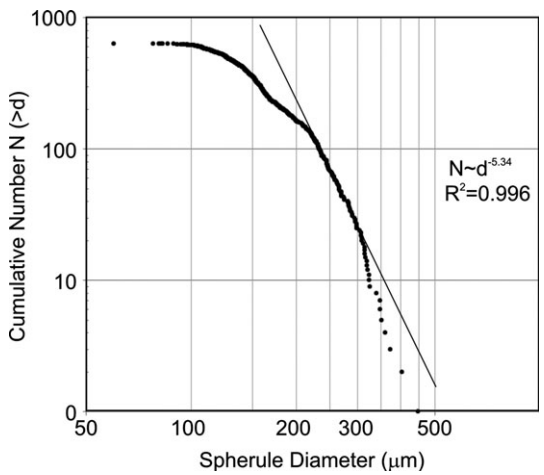


Fig. 3. The cumulative size distribution of recovered spherules. The distribution is fitted to a power law function between 330 μm and 210 μm with an exponent of −5.34 and shows significant divergence from the power law at high and low diameters.

Cosmic Spherules

Cosmic spherules (CSs) are MMs that have experienced high degrees of partial melting during atmospheric entry to form molten droplets. They are subdivided into (1) silicate-dominated (S-type), (2) iron-dominated (I-type), and (3) intermediate G-type spherules.

S-type cosmic spherules are the most abundant in the collection with 567 particles recovered. These particles are subdivided into porphyritic olivine (PO), barred olivine (BO), cryptocrystalline (C) spherules, and glassy (V) spherules (Taylor and Brownlee 1991; Taylor et al. 2000, 2007; Genge et al. 2008). All observed cosmic spherules have broadly chondritic compositions (Table 1), although with depletions in the most volatile elements (Na and S) as reported by previous studies (e.g., Genge et al. 1997). Metal-sulfide beads are relatively common with these spherules and contain >1 wt% Ni.

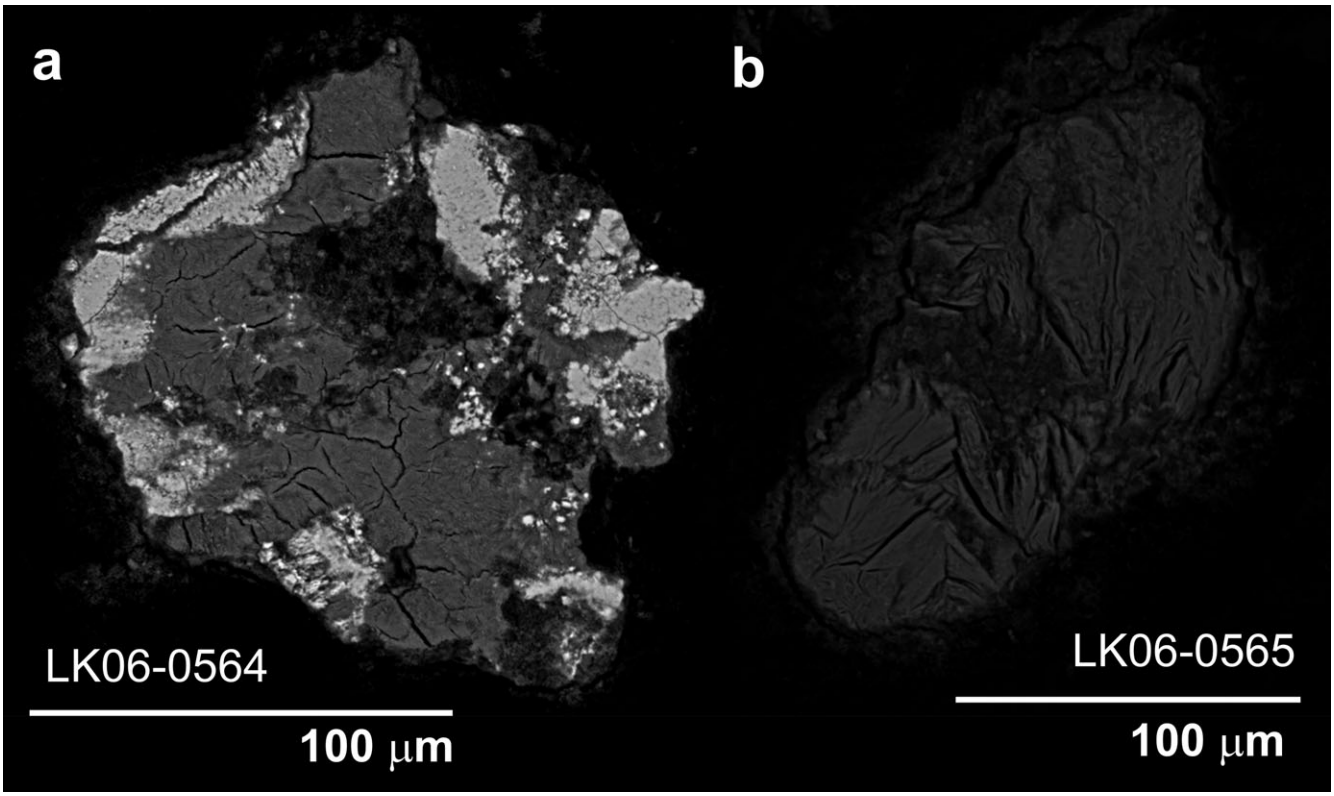


Fig. 4. Unmelted compact fine-grained micrometeorites showing (a) a CI-like particle with fine-grained matrix and framboidal magnetite, and (b) relatively coarse phyllosilicates. Both particles have dehydration cracks. Highly porous materials are cemented moraine fines. These samples were not washed during preparation.

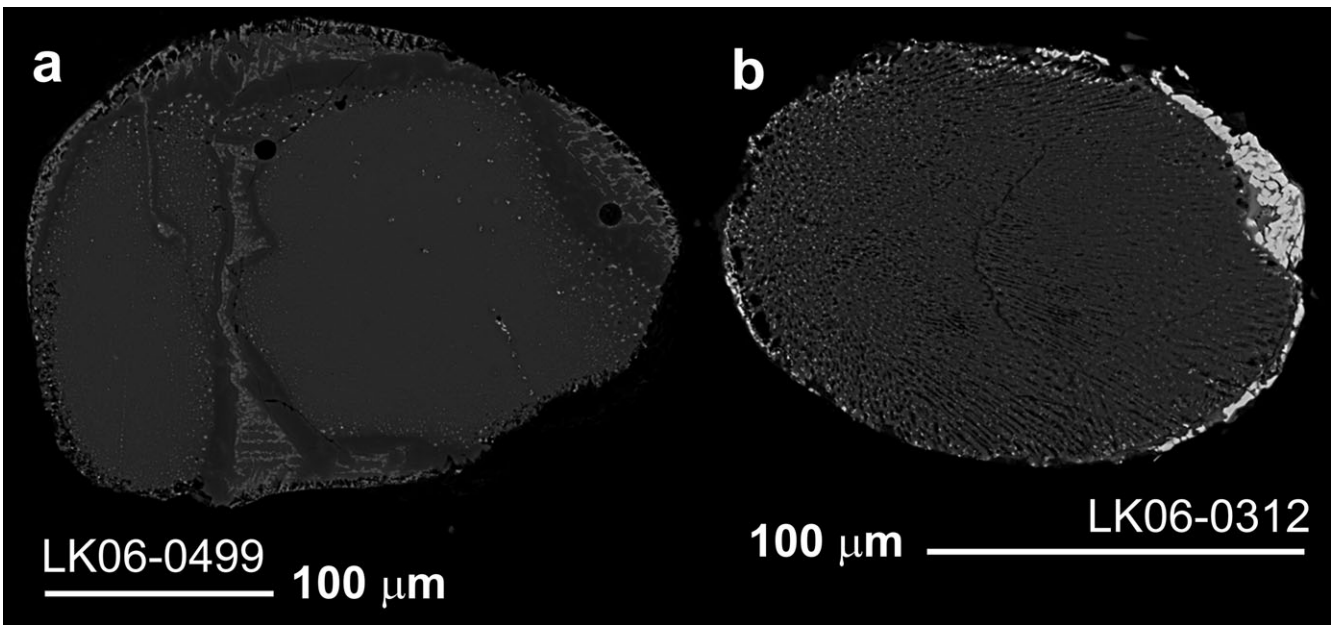


Fig. 5. Coarse-grained micrometeorites showing (a) a particle with two large iron-bearing olivines containing magnetite inclusions and surrounded by a magnesian-rich rim in melted glassy mesostasis, and (b) an ellipsoidal particle consisting of radiating pyroxene dendrites showing a magnetite rim and a metal-rich area on the outside.

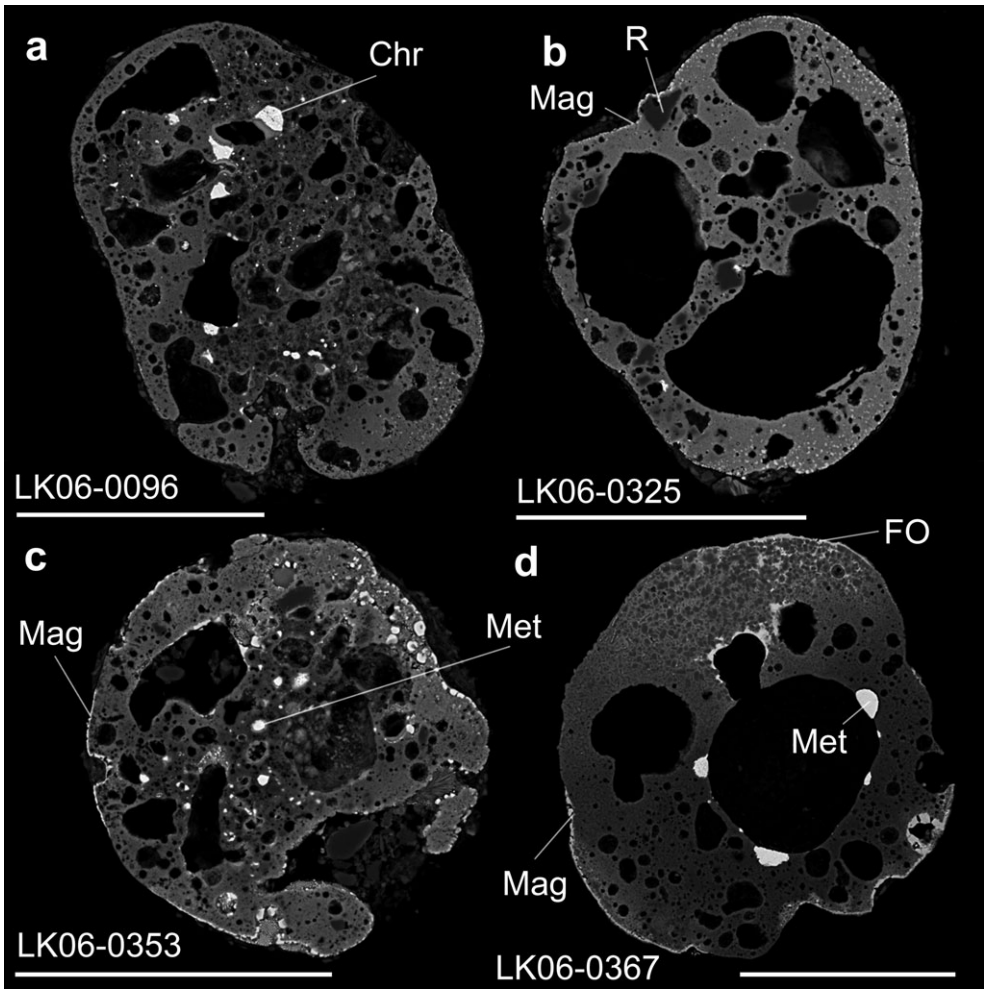


Fig. 6. Scoriaceous micrometeorites showing (a) a highly vesicular particle containing chromite relicts (Chr) and some areas of partially melted relict fine-grained matrix, (b) a particle with large vesicles containing relict Mg-rich silicates (R) and a partial magnetite rim (Mag), (c) a particle containing a dark core of partially melted relict matrix with metal grains (Met) and a magnetite rim, and (d) a particle containing FeNi metal droplets attached to a large vesicle. Scale bars are 100 μm.

Porphyritic olivine spherules within the Larkman collection comprise 193 particles and examples are shown in Figs. 7a–m. Most S-type cosmic spherules consist of olivine phenocrysts with accessory magnetite within a glassy mesostasis; however, some lack magnetite. Irregular relict forsterite and enstatite grains, and some iron-bearing olivine (>Fa_{10}) are present in 54% of the spherules as previously observed from other collections (Beckerling and Bischoff 1995; Genge et al. 1997; Engrand and Maurette 1998; Taylor et al. 2000, 2007). Several subtypes of PO spherule are recognized on the basis of their texture. They are (1) micro-PO spherules (Figs. 7a and 7b), (2) coarse-PO spherules (Figs. 7c and 7d), (3) coarse-skeletal spherules (Figs. 7e and 7f), and (4) inclusion-rich olivine spherules (Fig. 7g).

Micro-PO spherules comprise 23% of PO spherules and consist of equant olivine phenocrysts that are <5 μm in size, and typically contain abundant vesicles (>10 vol%). Coarse-PO spherules constitute 29.4% of PO spherules and contain equant olivine phenocrysts >5 μm in size, often with normal zoning ($Fa_{13–49}$). Typically, coarse-PO spherules contain significant interstitial glass (>10 vol%) and low vesicle abundances (<10 vol%) and include particles with cumulate textures described by Genge et al. (2016). Coarse-skeletal PO spherules are the most abundant group in the Larkman Nunatak collection comprising 43.9% of PO spherules and are characterized by the skeletal nature of their olivine phenocrysts. Inclusion-rich olivine spherules are relatively rare (4% of PO spherules) and contain Fe-bearing olivines (Fa_{15}–Fa_{40}) with abundant magnetite inclusions. They tend to be vesicle poor.

Barred olivine S-type spherules comprise 123 particles in the Larkman Nunatak collection and are

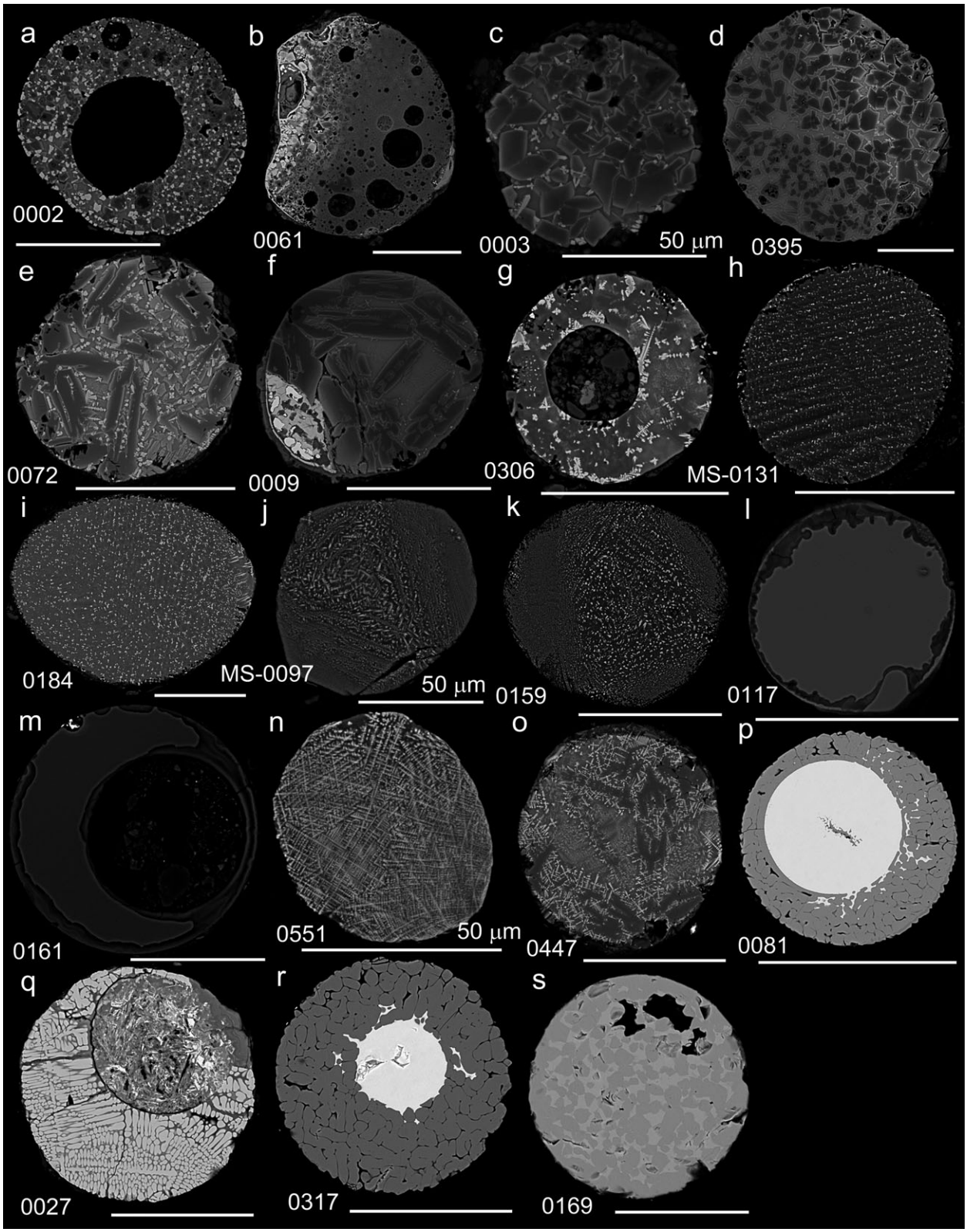


Fig. 7. Backscattered electron images of cosmic spherules. S-type spherules where (a–g) are porphyritic olivine spherules, (h, i) are barred olivine spherules, (j, k) are cryptocrystalline spherules, (l, m) are V-type spherules; (n, o) are G-type spherules; and (p–s) are I-type spherules. Scale bars are 100 μm unless otherwise specified. Sample numbers are shown to the lower left of each particle.

characterized by parallel growth olivines observed in the plane of section as a series of parallel bars (Figs. 7h and 7i). Cryptocrystalline S-type spherules comprise 141 particles within the collection and are dominated by dendritic olivine crystals, usually arranged in several different orientation domains, with magnetite dendrites present within interstitial glass (Figs. 7j and 7k). Glassy V-type spherules comprise 110 particles and are dominated by glass that is broadly chondritic in composition (Table 1); most are entirely spherical (Figs. 7l and 7m).

I-Type Cosmic Spherules

I-type cosmic spherules are dominated by iron oxides and can contain FeNi metal. Thirty-three I-type spherules are present in the current collection (Figs. 7p and 7s). Three varieties of I-type are recognized within the collection. They are (1) metal-bearing wüstite (MET) spherules (Fig. 7s), (2) magnetite and wüstite OX spherules (Figs. 7p–r), and (3) magnetite-dominated OX spherules. The petrology and mineralogy of a larger set of I-types from Larkman have been described in Genge et al. (2017b).

G-Type Cosmic Spherules

Fourteen G-type cosmic spherules are present in the Larkman Nunatak collection and consist mainly of extended magnetite dendrites within a glassy mesostasis; however, three also contain <20 vol% skeletal forsteritic olivine phenocrysts (Figs. 7n and 7o). Magnetite within these particles often forms domains with consistent orientation of dendrites.

Micrometeorite Preservation

Several different types of weathering effect are observed within the Larkman collection as described in detail by Van Ginneken et al. (2016) and include (1) dissolution of olivine and glass producing cavities (Figs. 7d, 7e, and 7h); (2) direct replacement of metal and glass by weathering products, typically ferrihydrite and palagonite, respectively; and (3) precipitation of weathering products, often jarosite, within cavities to produce pseudomorphs of existing phases. Minor weathering effects are observed in most particles recovered from Larkman Nunatak but in most are limited to the exteriors of particles. The depth and abundance of etched rims observed in the Larkman Nunatak collection are shown in Fig. 8.

IMPACT SPHERULES

Forty-four pale yellow, translucent glass spherules, 107 and 388 μm in diameter, are present in the Larkman Nunatak deposit and have nonchondritic compositions representing impact spherules (Van Ginneken et al. 2018). In section, these particles strongly resemble V-type spherules and are dominated by glass with rare iron oxide. The composition of these spherules (Table 1) overlaps with Australasian microtektites as observed by Folco et al. (2008, 2010) within the Transantarctic Mountains (TAM) Collection and forms an extension of the volatilization trends in Na and K against Ca, Al, and Ti observed in these microtektites (Van Ginneken et al. 2018).

Terrestrial Particles

The moraine dust is largely composed of angular lithic fragments (~15%), which form the majority of the coarser size fractions (>300 μm), and subangular, rounded, aeolian quartz grains (~60%). Weathered basalt fragments are also common (~20%) and are present as irregular fractured olivine grains, rounded plagioclase, and subrounded magnetite and ilmenite grains. Calcite, biotite and muscovite mica fragments, glauconite, coal, and clay minerals are also present. Precipitation of a cement has resulted in the formation of grain aggregates up to 0.5 mm in size. The cement is principally composed of jarosite, and rapidly dissolves in water.

DISCUSSION

Comparisons with Other Collections

Published abundances of particle types from different collections are shown in Table 2 and indicate a significant variation in MM-type abundances between collections. The CONCORDIA collection was recovered by melting of Antarctic snow (Duprat et al. 2007), and can be expected to be the least affected by terrestrial biases as shown by the presence of fragile highly primitive particles (fine-grained fluffy and ultracarbonaceous particles) and the high abundance of sulfides which are sensitive to weathering (Nakamura et al. 1999; Duprat et al. 2007). The smaller size range (13–300 μm for CONCORDIA; Dobrica et al. 2010) due to the low accumulation period of such deposits makes direct comparisons to collections recovered from deposits with long accumulation times, such as the blue ice-derived collections, Transantarctic Mountain (TAM) traps, and Larkman Nunatak, problematic. The CONCORDIA collection, however, indicates that unmelted particles are abundant with 36% present as fine- and coarse-grained (crystalline) particles (Dobrica et al. 2010) and, thus, provides a benchmark by which biases in other collections can be evaluated. The much lower abundances of UMMs and ScMMs in either the Cap Prud'homme (Kurat et al. 1994; Genge et al.

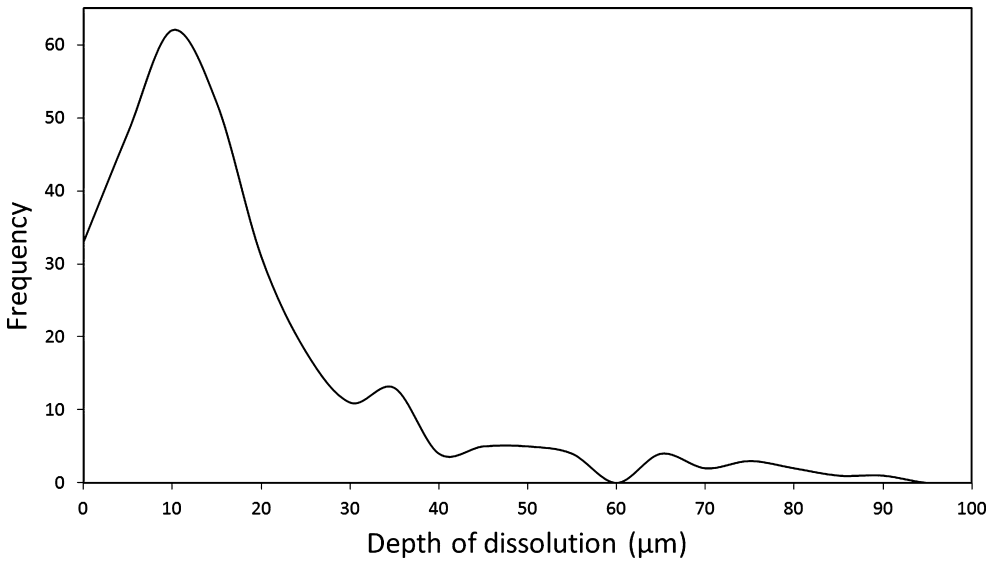


Fig. 8. The depth of dissolution rims around micrometeorites evaluated for 310 cosmic spherules.

Table 2. Published abundances of micrometeorite types from different collections. Abundances of S-, I-, and G-type spherules are given as a percentage of total spherules, and abundances of PO, BO, C, and V spherules are given as a percentage of S-type spherules.

Types	Larkman	Cap Prud'homme[a]	SPWW[b]	CONCORDIA[c]	TAM[d]	Walcott Névé[d]	Indian Ocean[e]
CSs	97.2	35.6	na	44	96	100	100
S	92.1	95.4	97	na	96	98	90.7
PO	34.0	43.9	23	na	na	na	25.1
BO	21.7	20.3	41	na	na	na	50.1
C	24.9	24.0	12	na	na	na	7.5
V	19.4	16.0	17	na	na	na	7.9
I	5.4	6.6	2	na	3	1	5.5
G	2.3	2.0	1	na	1	1	3.5
ScMM	1.7	13.6	na	22	na	na	na
UMM	1.1	50.4	na	34	4	na	na
FgMM	25	61.3	na		na	na	na
CgMM	75	38.7	na		na	na	na

[a]Abundance of Cap Prud'homme particles from Genge, unpublished data of 550 particles in size range >50 μm dominated by particles in the size range 50–100 μm producing an overabundance of UMM.
[b]Taylor et al. (2000) where PO spherules include relict-bearing and vesicular spherules.
[c]Dobrica et al. (2010).
[d]Suavet et al. (2009).
[e]Shyam Prasad et al. (2013).
na = not available; PO = porphyritic olivine; BO = barred olivine; C = cryptocrystalline; V = glassy; ScMM = scoriaceous micrometeorites; UMM = unmelted micrometeorites; FgMM = fine-grained micrometeorites; CgMM = coarse-grained micrometeorites.

1997), Larkman Nunatak, or TAM (Rochette et al. 2008) collections must indicate terrestrial reprocessing or collection bias. The South Pole Water Well (SPWW) collection was also derived by melting of snow (Taylor et al. 2000); however, unmelted particles are present in a low, unspecified abundance.

Comparisons against the abundance of cosmic spherule types are more readily applied between collections, albeit with issues related to disparate size fractions. The CONCORDIA collection reports 44% CSs for size ranges <300 μm (Dobrica et al. 2010), while a maximum abundance in the TAM collection is ~96% for the size fraction >200 μm (Suavet et al. 2009). The abundance of spherules within the Larkman collection is thus broadly equivalent to the TAM collection at 92% when taking into account the smaller size range. While these results suggest loss of unmelted particles from the Larkman and TAM collections, the

larger particle sizes partially account for this difference since melted CSs dominate at larger sizes owing to atmospheric entry effects (Love and Brownlee 1991).

The abundance of cosmic spherule types is relatively well documented between collections. The Larkman Nunatak and Cap Pud'homme abundances in Table 1 are very similar, including the relative abundance of PO, BO, C, and V spherules, but different from the SPWW values. The Indian Ocean cosmic spherules show similar abundances to the SPWW collection. The difference between the abundances of spherule subtypes might be due to subtle differences in the classification scheme used for S-type spherules. In this study, BO spherules are defined according to Genge et al. (2008) as having parallel olivine bars, while those with nonparallel dendrites are classified as cryptocrystalline. Considering the textures of S-type spherules form a broad continuum, slight differences in classification might readily explain the higher BO spherule and lower C and PO spherule abundances in the SPWW and Indian Ocean collections and reconcile the differences with the Larkman and Cap Prud'homme collection. The good agreement in the abundance of V-type glassy spherules, which require no subjectivity in classification, between the current study, Cap Prud'homme, and the SPWW supports this conclusion, although the lower abundance of V-type spherules within the Indian Ocean collection is probably due to the selective alteration of spherules during long residence times in marine environments (Fredriksson and Robbin Martin 1963; Peucker-Ehrenbrink and Ravizza 2000; Shyam Prasad et al. 2013). A study of MMs derived from urban rooftops, however, reports similar BO/C ratios to both the SPWW and Indian Ocean collections and suggests that the longer collection periods of Larkman, TAM, and Cap Prud'homme may indicate a systematic change in the velocity of dust arriving at Earth (Genge et al. 2017a).

The abundance of I-type spherules offers one means of correlating bias between MMs, as previously suggested by Taylor et al. (2000), since these magnetite- and wüstite-dominated particles are largely resistant to weathering. In the absence of published I-type abundances for the CONCORDIA collection, the SPWW value of 2% can be taken as a baseline value for an unaltered collection (Dobrica et al. 2010). The slightly higher abundance observed in the TAM collection of 3% (Suavet et al. 2009), therefore, could be taken to indicate up to 30% loss of S-type spherules due to weathering or wind transport if significant loss of metal-bearing I-types has not occurred. The high values in the Larkman and Indian Ocean collections are more problematic due to the use of magnetic separation techniques in sample collection and preparation which might be expected to concentrate I-types relative to S-type spherules. The lack of concentration of PO, BO, and C particles relative to V-types observed in the Larkman collection relative to the SPWW collection, however, would suggest that magnetic separation does not cause significant enhancement of I-type spherules considering V-types mostly lack magnetic phases. The similar abundance of I- and G-types between Larkman and Cap Prud'homme also support this conclusion since the latter were not prepared by magnetic separation.

If magnetic separation effects are considered unimportant, then the enhanced I-type abundances in Larkman and Cap Prud'homme relative to the SPWW could be explained by a significant loss (~50%) of S-type spherules by terrestrial processing. The small numbers of highly weathered spherules observed in the Larkman collection (Van Ginneken et al. 2016), the high abundance of impact spherules, which represent 780 kyr microtektites, together with the observed peak in etched rim width at 10 μm, however, argue against high losses by weathering; however, the presence of altered S-types confirms that a small proportion must be destroyed over extended periods.

Further biases must be considered for the Larkman Nunatak collection, in particular those related to accumulation mechanisms. Winnowing of small and low-density particles might concentrate high-density I-types and remove low-density particles such as ScMMs and UMMs, which as unmelted and partially melted particles are also more abundant at smaller sizes. The size distributions of spherules observed at Larkman (Fig. 3) do record a significant loss of particles at small sizes (<100 μm); however, at larger sizes (>220 μm), they follow a similar power law distribution with a similar exponent to the TAM collection (Suavet et al. 2009) and the SPWW collection (Taylor et al. 2000) implying negligible mass loss at larger sizes. The presence of low-density spherules with high vesicle abundances in the Larkman collection suggests that, if loss due to winnowing has occurred, it is relatively minor at least for particles >100 μm in size. The low abundance of ScMMs, however, is problematic since these are present in much higher abundances in both Cap Prud'homme and CONCORDIA collections. These very fragile particles may be sensitive to fragmentation during transport by saltation and then be removed by winnowing once sufficiently small in size. An alternative explanation might be fragmentation within ice owing to burial; although the Cap Prud'homme collection also samples blue ice, the ice at Larkman is likely to have experienced significant deviatoric stress due to its proximity to a nunatak.

The low abundance of UMMs, and in particular FgMMs, compared with the CONCORDIA collection

are likely, in part, to be due to the loss of the smallest size fraction by winnowing of smaller, low-density particles from moraine. Removal of FgMMs by weathering is also likely since the majority of these particles experience dehydration during atmospheric entry and are composed of amorphous materials (Genge et al. 2017c) that make them more sensitive to weathering than if they retained phyllosilicates (Van Ginneken et al. 2016). Similar low abundances of FgMMs were noted at Walcott Névé (Harvey and Maurette 1991).

The low abundance of CgMMs within the Larkman Nunatak collection compared with either CONCORDIA or Cap Prud'homme is particularly problematic. These crystalline particles, which mostly have igneous textures, are compact and have relatively high densities of >3000 kg m^{-3} and are thus unlikely to be preferentially depleted by winnowing. The similar mineralogies of CgMMs and S-type spherules also mean they are unlikely to be preferentially depleted by weathering, especially when glassy spherules are present in significant abundances. The low abundance of CgMMs observed in the Larkman Nunatak collection, therefore, may be the result of sample selection difficulties. Cosmic spherules, with their spherical morphologies, can be readily identified under a binocular microscope; however, irregular CgMMs and FgMMs are difficult to distinguish from dark-colored terrestrial particles that are abundant at Larkman Nunatak. It seems likely, therefore, that more UMMs remain in the Larkman collection to be recovered with improved separation protocols.

Mechanisms of Accumulation

The presence of blue ice within the moraine at Larkman Nunatak indicates that the moraine is supraglacial. The high diversity and abundance of sedimentary rocks, probably from the Beacon Supergroup (Barrett et al. 2013), which are not exposed at the surface at Larkman Nunatak, suggest that moraine accumulation occurs primarily by upwelling and sublimation of ice. The abundance of dolerite, probably from the Ferrar dolerite, also suggests upwelling. The location of the moraine in the lee of the nunatak, together with its topography, is also likely to minimize wind-blown accumulation of larger clasts (>5 mm). Some minor contribution, however, can be expected due to the nunatak's influence on wind speeds and subsequent fallout of entrained dust; however, the location of Larkman Nunatak restricts possible sources of terrestrial input due to the lack of outcrops upwind. Wind-transported dust grains delivered to Larkman Nunatak are, therefore, probably liberated from ice by sublimation upwind or have fallen directly into this large catchment area.

Loss of dust from the moraine through wind transport is likely with preferential loss of low-density and small particles. Evidence for such winnowing was observed in the occurrence of linear areas of brown ice downwind of the moraine; interpreted as sealed crevasses infilled by snow and wind-blown sediment. Dunes of small stones on sastrugi downwind of the moraine also imply wind transport and loss of fine-grained material. The cumulative size distribution (Fig. 3) supports loss of small particles from the moraine below diameters of about 100 μm. The formation of larger grains through cementation of moraine fines by jarosite, however, may help reduce aeolian removal of material.

Direct infall of MMs is unavoidable and its contribution depends on the accumulation rate of the fine-grained terrestrial sediment. In addition to direct accumulation of fines by sublimation, mechanical size reduction of larger clasts through cryogenic mechanical weathering, such as freeze–thaw within pore spaces, is likely to add to the abundance of fine terrestrial grains that dilute MMs. Evidence for transient water exists from weathering of MMs (Van Ginneken et al. 2016); the dissolution of phases and precipitation of components sourced from outside of particles indicates the transient interconnectivity of water volumes and localized melting presumably due to the heat island effect associated with the moraine. Variations in sediment abundance may also occur by local wind transport within the moraine, with redistribution between local wind traps provided by larger boulders and their associated wind scoops as previously suggested at Walcott Névé (Harvey and Maurette 1991). The presence of fine-grained dust below the snow layer, however, suggests that snow stabilizes the fine-grained deposits and reduces wind transport. Snow layers may also act to reduce accumulation of MMs by direct infall or wind transport since while present, they act as a barrier to accumulation from above and can be removed, together with their dust content, by strong katabatic wind storms. Accumulation of dust-sized debris by infall may, therefore, only occur during the periods when the snow layer is absent.

The reverse grading observed in the supraglacial sediment suggests that a mixing mechanism operates within the sediment layer. Reverse grading could occur by winnowing and removal of fines from the top surface of the layer similar to desert pavements; however, given predominant sediment supply by sublimation from underlying ice, this would imply loss of the oldest fines, which is not consistent with the abundance of microtektites. Cryogenic weathering might lead to preferential grain-size reduction at the base of the sediment layer where freezing of transient melt water might occur, although continual sediment supply from

below by sublimation is likely to preclude such a mechanism. Particle convection during fluidization is a common explanation for reverse grading within mass flow deposits (Dasgupta and Sen 2011) and can also be generated by seismic fluidization. Glaciers are associated with seismicity associated with release of elastic strain associated with their flow (e.g., Winberry et al. 2013) and icequakes could lead particle convection within sediment layers. Regardless of the mechanism by which reverse grading forms, it necessarily involves the downward migration of fines in the sediment layer and thus ancient particles, released earlier in sublimation of ice, will be preserved against surface loss.

Accumulation Period

The period over which the Larkman Nunatak moraine has been accumulating is difficult to determine quantitatively. The presence of microtektites, however, provides a minimum age if they can be assigned to a particular impact event. The compositions of the microtektites overlap with those of the Australasian strewn field found elsewhere in Antarctica (Folco et al. 2008, 2011) and more importantly have the same elemental correlations observed in Australites (Van Ginneken et al. 2018). Unfortunately, the small size and number of recovered particles currently preclude radiogenic age-dating; however, the similarities in composition and appearance between the Larkman spherules and those found elsewhere in Antarctica make it most likely that these are Australasian microtektites and thus suggest an age of at least 780 ka (Folco et al. 2008, 2011; Van Ginneken et al. 2018).

An ancient age for the Larkman Nunatak moraine is compatible with exposure age measurements on bedrock and moraine erratics from other localities in Eastern Antarctica. Nunatak bedrock exposure ages in the Grove Mountains can be up to 4 Ma (Lilly et al. 2015) and are correlated with altitude suggesting the peaks of some nunataks have remained emergent through several glacial maxima. In the Darwin Mountains, close to Lake Wellman, exposure ages of erratics in marginal moraines can also be up to 2.2 Ma (Ischa moraine), albeit with most considerably younger (1–19 ka; Storey et al. 2010). The nature of erratics in the Larkman Nunatak moraine is broadly consistent with long-period exposure since they are distinctly weathered and fractured similar to descriptions of the 2.2 Ma Ischa moraine in the Darwin Mountains (Storey et al. 2010).

If accumulation is assumed to be entirely due to direct infall of MMs, an estimate could be made on duration. Carrillo-Sánchez et al. (2015) estimated a surface flux of ~6 spherules m^{-2} yr^{-1} for the current day extraterrestrial flux. The estimated surface area of collection reported here is 0.0625 m^2 giving an accumulation time for the spherule abundance of 600 kg^{-1} of 1.6 ka. Even given uncertainties of an order of magnitude, this accumulation period is considerably shorter than the 780 ka suggested by the putative Australasian microtektites found in the deposit. If accumulation was entirely by infall, an abundance of 260,000 spherules kg^{-1} would be expected, suggesting an extreme loss of particles over the lifetime of the deposit. The loss of such a significant proportion of particles could probably occur by wind erosion; however, this is unlikely to allow preservation of large numbers of ancient microtektites, and is not consistent with the abundance of I-types that suggest no more than a 50% relative loss of S-types. It could also be argued that winnowing is likely to concentrate MMs rather than deplete them compared with lower density quartz and feldspar-rich terrestrial dust and that overall nature of the moraine as a wind trap makes significant net losses unlikely. Finally, the similar size distribution of Larkman Nunatak particles to those of the SPWW and TAM collections, at least for particles >100 μm, implies significant winnowing only occurs for smaller particles.

An estimate of the mass of MMs that could accumulate through sublimation of blue ice can be made using the mass of meteorites recovered from Larkman Nunatak. The Meteoritical Bulletin records that 254 kg of meteorites was collected from the area around the nunatak ~10 km^2 of blue ice. Since the extraterrestrial dust flux is around 100× that of meteorites (Love and Brownlee 1993; Bland et al. 1996), this gives approximately 2.5 g m^{-2} or ~12,000 spherules kg^{-1}. Given the large uncertainties inherent in this calculation, the divergence of an order of magnitude is unlikely to be significant and suggests that the abundance of spherules observed is broadly consistent with an influx dominated by sublimation of blue ice, perhaps with some loss of particles by winnowing and weathering. This also implies that direct infall is minor, occurring only when the snow layer is entirely removed by katabatic winds.

It is possible that microtektites present within the deposit might have been released relatively recently from blue ice and their occurrence in the deposit is, therefore, not a function of the age of the moraine, but a serendipitous consequence of the age of the underlying ice. The age of ice in the vicinity of Larkman is unknown; however, in other areas within the TAM, such as at Allan Hills, the maximum age of blue ice associated with abundant meteorites has been estimated at up to 200–150 ka through both meteorite exposure ages and modeling of ice flow (Grinsted et al. 2003). It would seem very unlikely, therefore, that blue ice at Larkman Nunatak is significantly older and

consequently the presence of microtektites must be due to either direct infall during the Australasian impact event or through sublimation of earlier generations of ice containing microtektites, probably within 200 ka of the event, and preservation within the deposit.

Although moraines older than 780 ka, such as Ischa, are known to occur in the TAM, these are marginal moraines that demark glacial high stands (Storey et al. 2010). The moraine at Larkman Nunatak is a supraglacial moraine which would not be expected to be significantly older than the underlying glacial ice. The location and shape of Larkman Nunatak, however, elongate and broadly perpendicular to ice flow, forces upwelling ice to encircle the nunatak toward a pressure shadow on the leeside of the mountain where, aside from upwelling, blue ice is likely to be stationary allowing long-term sublimation and moraine accumulation. The details of ice flow are likely to be complex with a degree of decoupling between the younger, fast-moving ice surrounding the nunatak and the older, less mobile ice trapped in the lee of the mountain. Inward flow into the trap is likely to be also partly controlled by sublimation, which is enhanced by the heat island effect of the moraine. Vertical shear between ice of different ages may indeed explain the separation of the system of moraines from the nunatak.

IMPLICATIONS

Moraine Accumulation and Collection of Micrometeorites

The current study indicates that Antarctic moraine provides a suitable location for MM accumulation and preservation. The accumulation period estimated here of 780 ka on the basis of the presence of Australasian microtektites, together with the ancient exposure ages of some marginal moraine (Storey et al. 2010), furthermore indicate that high-latitude moraines can accumulate MMs over very long periods potentially sampling the extraterrestrial dust flux over nearly 1–2 Myr. Supraglacial moraines are not likely to have the longevity to act as significant accumulation sites unless long-term upwelling of blue ice and near-stationary ice flow occurs in the lee of isolated nunataks.

Although moraines clearly do act as accumulation sites for MMs, the abundances of particles at Larkman Nunatak indicate that biases exist that influence the relative abundance of particle types. Low-density and small particles such as FgMMs are unavoidably lost from moraine due to winnowing in comparison to collections derived by melting of snow. Weathering is also more significant within moraine deposits, in part due to their much longer accumulation periods compared with snow, and also due to transient melting related to the heat island effect associated with the accumulation of significant amounts of dark-colored surface rocks. As a result of these biases, moraines make poor locations to find large numbers of primitive unmelted particles as noted previously at Walcott Névé (Harvey and Maurette 1991).

The accumulation mechanism of MMs in moraines will vary depending on the type of deposit. At Larkman Nunatak, accumulation is likely to occur due to sublimation from underlying ice; however, in other locations, such as Walcott Névé, direct infall and wind-transported dust may dominate. Accumulation in such areas occurs principally during periods of exposure when snow cover is removed and is thus probably not continuous. Influx events lasting shorter than a few years might not be preserved at all if snow cover trapped infalling dust and was then removed. MM and microtektite accumulation, therefore, is likely to be subject to climatic influences.

Dating of Moraine by MMs and Impact Spherules

Micrometeorites and impact spherules provide a potential means of dating moraine deposits that does not suffer from the same issues as cosmogenic dating of glacial erratics in moraines. Studies of the exposure ages of moraine materials are often complicated by the multistage histories of glacial erratics. Pre-exposure of surface bedrock prior to transport and incorporation within moraine, together with recycling of moraine clasts into later generations of drift make interpretation of exposure ages complicated (e.g., Storey et al. 2010).

The abundance of MMs will undoubtedly increase with moraine age; however, a simple relationship between abundance and age is unlikely given the number of accumulation and depletion mechanisms, many of which are likely to be site dependent. Wind accumulation and depletion by winnowing of MMs are, in particular, likely to be dependent on topographic setting. Accumulation by sublimation of blue ice will also play a role in supraglacial moraine. The prevalence of snow cover and proximity to the coast, which influences climatic factors, will also affect accumulation rates. Terrestrial residence ages of MMs, however, may provide a particularly useful means of evaluating accumulation time in the absence of significant meteorite concentration, albeit with the consideration that individual particles may have been derived from blue ice and transported and thus have ages older than the moraine in which they occur.

Impact spherules provide perhaps the most useful proxy for moraine age. Evidence presented here and in Van Ginneken et al. (2018) and Folco et al. (2008, 2010, 2011) suggest the 780 ka Australasian

microtektites can be found throughout Antarctica, while spherule aggregates formed in a Tunguska-like event 480 ka are likely to be widespread in the Eastern Antarctic ice sheet (Van Ginneken et al. 2010). The occurrence of numerous examples of either of these materials can be used to define minimum moraine age.

CONCLUSIONS

We report a unique collection of MMs collected in high-latitude supraglacial moraine that represent a new locality for the recovery of these materials. The presence of microtektites related to the Australasian tektite fields suggests that accumulation may have occurred over 780 to 580 ka providing a sample of the Earth's extraterrestrial dust flux over an extended period of time. Comparisons with other collections of MMs suggest that moraines are effective collectors of extraterrestrial particles that sample broadly representative collections, albeit with losses of small particles by wind erosion. Our observations also indicate that supraglacial moraines can survive for long periods extending over several glacial maxima given specific conditions are met and thus potentially record the history of the East Antarctic ice sheet.

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