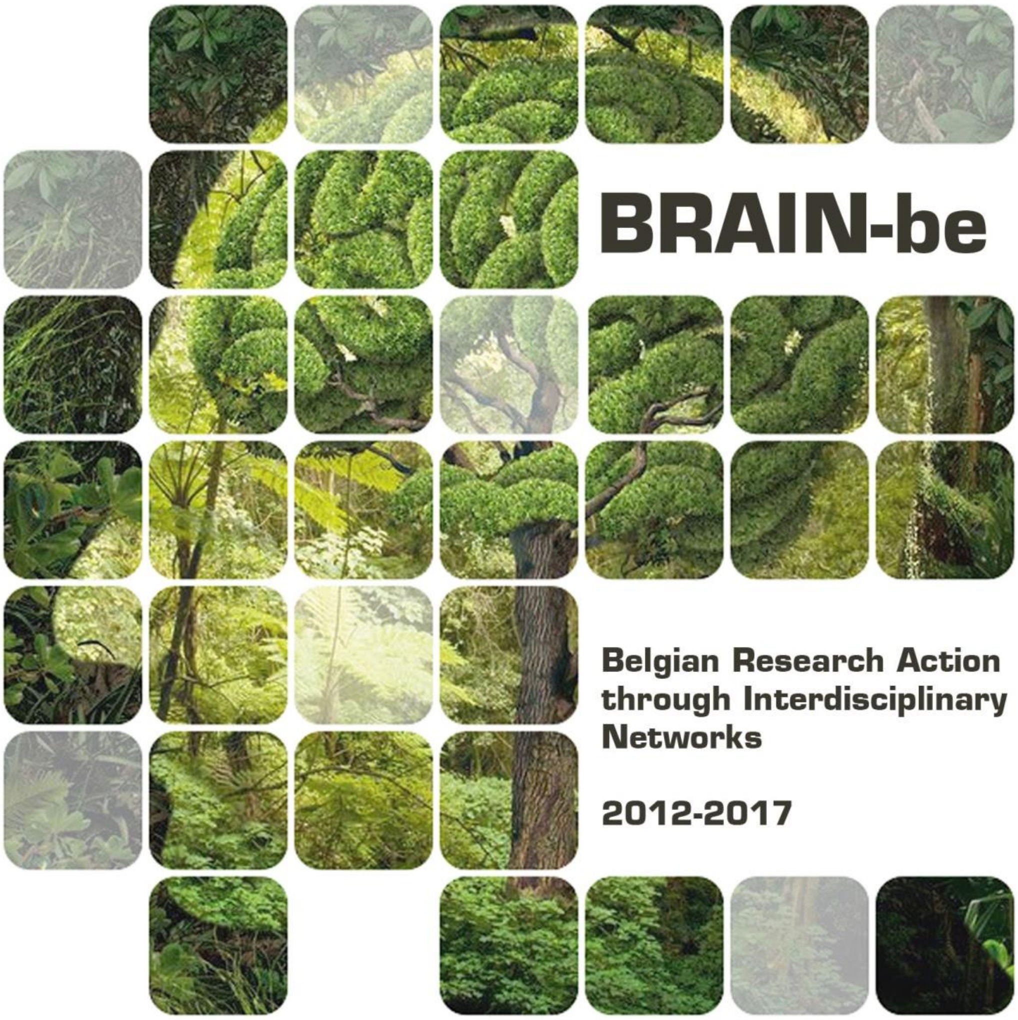

AMUNDSEN

Antarctic Meteorites cUratioN, Digitalization and conSErvatioN

Sophie Decrée (RBINS), Matthias Van Ginneken (VUB, ULB, RBINS), Philippe Claeys (VUB), Vinciane Debaille (ULB), Steven Goderis (VUB), Marleen De Ceukelaire (RBINS)

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AMUNDSEN

Antarctic Meteorites cUratioN, Digitalization and conSErvatioN

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FINAL REPORT

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ABSTRACT

Context

Over the last years, joint Belgian-Japanese missions in Antarctica (VUB-ULB, SAMBA project) have recovered more than 1200 pristine and unique meteorite samples. The arrival of these new samples strongly stimulates the curation of meteorite collections in Belgium, supported by the BELAM project (RBINS-VUB-ULB, 2012-2019, funded by BELSPO). Following the new regulation procedure for sample conservation that are implemented at the RBINS in the frame of the ISO9001 norm, the AMUNDSEN project provides a roadmap for conserving and studying extra-terrestrial samples in the best conditions possible. More specifically, the ISO9001 regulation requires two types of conservation, the preventive and the preservative that both need to be addressed for obtaining the certificate. Consequently, this project directly confronts the most troubling problem of the meteorite conservation, experienced by museum worldwide: the rapid alteration of the meteorite surface, which is already observed in some of the RBINS specimens, despite their recent recovery from Antarctica.

Objectives

The AMUNDSEN project is dedicated to the conservation, classification, valorisation and digitalization of meteorites at the RBINS with the goal to improve the maintenance of this fragile collection, develop best practice meteorite curation protocols, provide the most appropriate sampling procedure and stimulate and facilitate the scientific usage of the collection by the international research community. Three multidisciplinary approaches, highlighted below, are followed in the frame of the project.

The first approach investigates the best possible condition of conservation to limit the alteration process. To study the effect of the variations of temperature and humidity, we used samples of a selected H-type ordinary chondrites artificially altered in a climatic chamber. The approach selected is to experimentally reproduce in accelerate the alteration processes by taking ambient conditions (humidity and temperature) to extreme levels. Experiments were conducted over a certain amount of time to obtain significant results in terms of best temperature and humidity conditions.

The second objective is dedicated to the digitization of the most precious sample to provide on-line broaden access to rare and unique meteorite by digitizing thin sections of the most outstanding samples (achondrites and specific types of ordinary chondrites), providing directly online a navigable image obtained with the optical microscope. Such digitized thin sections will contribute to the study of RBINS meteorites, avoiding excessive handling, and will help requesters in their sample selection.

A third objective is to improve and advance the existing meteorite classification and curation at the RBINS.

Conclusions

From their recovery on the field to their storage in museum or research institute collections, meteorites are carefully maintained under controlled environments to greatly reduce the effects of terrestrial weathering. This is particularly the case for Antarctic meteorites, which are usually recovered on the field at subzero temperatures.

The present study shows how important maintaining stable environmental conditions is for the preservation of ordinary chondrites, especially the H types containing the most FeNi metal. The results show that humidity should be kept as constant as possible, and relatively low to ensure an optimal preservation of the meteorites. A humidity of 40% as this occurring in the repository of the RBINS is

rather suitable. The experiments show that the temperature changes (of about 30°C) appear to be less of a problem for meteorite conservation.

Considering the limited amount of alteration material produced during the experiments, the Mössbauer spectroscopy is not the best method to investigate such processes. The XANES and the Raman spectroscopy are more efficient for this purpose.

Finally, as an outcome related to the valorisation of the RBINS collection, a new webpage showing the digitized thin sections of selected outstanding meteorites has been designed and constitutes undoubtedly a showcase helpful for international researchers interested in loans and interesting for a broader audience.

Keywords

Alteration experiments, meteorite conservation, spectroscopic study, Antarctica, meteorite thin section digitization

1. INTRODUCTION

The BRAINS project AMUNDSEN is dedicated to the conservation and curation of the meteorite collection existing at the RBINS with the goal to improve the sustainable maintenance of this fragile collection. This is made accordingly with the implementation of the ISO9001 norm at the RBINS, which addresses the question of sample best preservation conditions and actions undertaken to provide both preventive and preservative curation procedures for meteorite specimens.

The first part of this project relates to the most troubling problems of meteorite conservation: their rapid alteration. While the alteration of chondrite under natural terrestrial conditions is relatively well documented, little is known about the alteration processes that may occur in so-called protected environments such as museum repositories. It has been observed, at the RBINS and in many other museums, that rust appears and increases with time on freshly sawed surface, even when cut without the use of any liquids. The curation conditions set up more than 40 years ago for the lunar samples from the Apollo program are known as utmost preventive and preservative procedures implemented. A few percentages of these samples are still pristine, kept in pure nitrogen atmosphere, and always handled in specific cabinets also containing nitrogen. However, a nitrogen purification device is a consequent investment, and requires constant care. In addition, the cost of implementing such installation, including the setup of specific cabinets, is disproportionate in the case of the RBINS meteorite collection. With this project, we aim at constraining the rate of this weathering process through a set of alteration/oxidation experiments and optimizing the conservation conditions.

This project also aims to provide on-line broaden access to rare and unique meteorite by digitizing thin sections of the most outstanding samples of the RBINS collection.

The followed approaches aim at pursuing and improving meteorite conservation and curation at the RBINS. This is of particular interest considering the number of meteorites collected during the successive field campaigns, which were also done in the frame of the AMUNDSEN project.

The AMUNDSEN project clearly encourages a responsible, long-term protective curation program for meteorites at the RBINS. This project supports the preservation and, through its research output, the valorization of Belgium museum collections and national heritage. It offers a unique opportunity for a multidisciplinary approach (petrology, mineralogy, and geochemistry) and international collaboration using state of the art techniques.

2. STATE OF THE ART AND OBJECTIVES

2.1. State of the Art

Meteorites have been a subject of scientific scrutiny for centuries, even before the publication of Chladni's book in 1794 arguing that these unusual rocks came from space (Marvin, 2006; McCall et al., 2006). The fall of the Wold Cottage and L'Aigle meteorites in 1795 and 1803, respectively, was paramount to convincing the scientific community that meteorites were indeed extraterrestrial in origin (Gounelle, 2006). Significant efforts around the world have focused on the acquisition of samples to establish meteorite collections ever since. The oldest and one of the biggest repositories of meteorites is held at the Museum of Natural History in Vienna, Austria, which was founded in the mid-eightieth century (Brandstätter, 2006). Following this trend, museum and research institute all over the world started establishing their own meteorite collections (Caillet Komorowski, 2006; Ebel, 2006; Russell and Grady, 2006). However, even though this field attracted a lot of attention, technical limitations prevented detailed analyses of samples up until the huge technological leap forward of the mid-twentieth century, which saw the invention of the scanning electron microscopy and electron probe microanalyses, allowing an unprecedented level of precision for chemical and petrological analyses. The use of these modern techniques allowed meteoriticists to elaborate the classification scheme that is still used today (Brearley and Jones, 1998; Krot et al., 2007; Mittlefehldt et al., 2019; Weisberg et al., 2006). Another limitation preventing the field of meteoritics to fully reach its potential was the limited number of samples available for the scientific community, which was around 2000 in the early seventies. The discovery during the 1969 Japanese Antarctic Research Expedition of nine meteorites in Antarctica started what was to be one of the most crucial chapter in the history of modern meteoritics, that is the systematic search for meteorites in Antarctica (Kojima, 2006). Within two decades, the number of samples available to the scientific community was increased by an order of magnitude. The discovery of numerous samples in hot deserts, mainly Northwest Africa, in the late eighties further increased the size of collections worldwide (Bevan, 2006). Since 2009, Belgium has been an important player in this field, with the discovery of more than 1200 meteorites in the Sør Rondane Mountains, Queen Maud Land, Antarctica (De Ceukelaire et al., 2013; Kaiden et al., 2011; Zekollari et al., 2019). Belgian expedition for the search of meteorites were carried out within the framework of a collaboration between the ULB, VUB and the Japanese National Institute of Polar Research (NIPR). Samples are divided between the NIPR and the Belgian institutions, which then stores them at the Royal Belgian Institute of Natural Sciences.

Meteorites are rare and precious samples by essence, thus, preserving them from the terrestrial environment is essential. All meteorites interact with the terrestrial environment to various extent. Meteorites for which the fall were observed and that were collected shortly afterward show the lowest degree of interaction with the terrestrial environment. The interaction of meteorite with the terrestrial environment results in terrestrial weathering, whose effects depend on factors such as the humidity and terrestrial age (i.e., time spent on the surface of the Earth). Indeed, the overwhelming majority of meteorites were collected on the Earth's surface a long time after their fall (i.e. the so-called "finds"), sometimes hundreds of thousands of years in the case of Antarctica (Jull, 2001; Nishiizumi et al., 1989). The most visible weathering products on meteorites are evaporites and rust (mainly Fe oxyhydroxides), which result from the precipitation of salts due to water evaporation and corrosion of metal within the rock, respectively (Benoit and Sears, 1999; Bland et al., 2006; Gooding, 1986, 1982; Jull et al., 1988; Lee and Bland, 2004; Losiak and Velbel, 2011; Velbel, 2014, 1988; Velbel and Gooding, 1990). Therefore, the effects of terrestrial weathering are visible in most Antarctic meteorites, albeit to a much lower extent than in meteorites recovered under more humid and/or hot climate (Bland et al., 2006; Maeda et al., 2021). Even though terrestrial weathering is unavoidable, it is nonetheless necessary to preserve them in an environment that will slow or, ideally, stop the progression of terrestrial weathering. To mitigate these effects of weathering, museums and research institutes worldwide have curation facilities entirely dedicated to meteorites (e.g., Righter et al., 2014). Such facilities vary significantly from one institute to the other, mainly depending on the nature of the meteoritic samples (e.g., unique volatile-rich falls such as the Tagish Lake meteorite require specifically designed curation facilities). However, the curation of large meteorite collections requires significant financial and human resources. Therefore, it is essential to understand how environmental factors (i.e. mainly temperature and humidity) in a curation facility affect meteorites to make as efficient as possible.

2.2. Objectives

The AMUNDSEN project aims to improve the sustainable conservation of the Antarctic meteorite collection at the RBINS and addresses the following questions:

Preventive conservation: What are the best humidity/temperature conditions for preserving meteorites in museum collection? How can we limit as much as possible the human handling of meteorites?

Preservative conservation: What are the possible actions for avoiding further alteration on already altered samples?

Curation of meteorites: How can we improve the curation procedure at the RBINS, as a duty to the international scientific community?

This is achieved through three objectives:

(1) The first objective is to provide the best practice for taking care of meteorites curated at the RBINS and investigate the best possible condition of conservation, including humidity and temperature that slows down as much as possible the alteration process, for a relatively low cost. This includes the study of how meteorites react to changes in the main environmental parameters. To better constrain the rate of this weathering process and optimize the conservation conditions, a set of alteration/oxidation experiments were planned. Alteration processes will be experimentally reproduced by taking ambient conditions (humidity and temperature) to extreme levels, using a climatic chamber, over a certain amount of time.

(2) The second objective is to provide access for research purposes to the meteorite while at the same time protecting them as much as possible from alteration. The rationale is that handling chondrites actually means taking the samples out from their protected environment, touching them (even with gloves) and often cutting them. All those operations enhance the alteration processes. We aim at reaching the second objective through the digitization of the most precious samples (including achondrites and carbonaceous chondrites). By digitizing the most precious meteorites, and putting this data online, scientists worldwide will be able to navigate through the RBINS collection and select samples for further research without necessarily touching them, hence limiting the handling of those samples. Providing

those digitized thin sections on the website of the RBINS will also allow scholar (high School and University), and the public, to learn about those precious and fascinating samples.

(3) The third work package is dedicated to improving the curation skills and techniques at the RBINS, including the application of classification procedures (see Pittarello et al., 2015). The project, while being focused on a new type of expertise, constitutes a relay for the BELAM project (2012-2019, funded by BELSPO), and ensures its long-term sustainability of the skills and knowledge gained. Indeed, the AMUNDSEN project valorizes BELAM results, and improves the curation facilities for the RBINS meteorite collection while in parallel, strengthening the development of a network of scientific expertise. As the fate of a collection is also to grow and live, a new Antarctic campaign is planned together with the NIPR for collecting samples in the blue ice field surrounding the Princess Elizabeth Station.

3. METHODOLOGY

3.1. Alteration experiments

Sample: The weathering experiments were carried out on the H5 ordinary chondrite Asuka 10177 (hereafter A10177), which was selected from the RBINS meteorite collection. The H chondrites are mainly constituted of silicate minerals such as olivine and low-Ca pyroxene, with up to approximately 20% FeNi metal and 5% troilite (Brearley and Jones, 1998). This chondrite was recovered during the 2010-2011 Belgian Antarctic Research Expedition (BELARE)/ Japanese Antarctic Research Expedition (JARE) joint expedition within the Nansen Icefield (approximately 72.7° S, 24.2° E), south of the Sør Rondane Mountains chain, Dronning Maud Land, Antarctica (Fig. 1). Upon recovery, the mass of A10177 was 233.82 g. The weathering grade of this chondrite is B/C. This weathering scale was created to describe the degree of terrestrial weathering suffered by hand specimen, and not polished sections. A weathering grade of B/C means that all metal grains observed with the naked eye on the surface of the meteorite were altered to limonite (Fig. 2). It is noteworthy that this alteration occurred during the storage of the meteorite in the Antarctic environment. Although the terrestrial age of this meteorite is not known, a recent study shows that the terrestrial age of meteorites recovered from the Nansen icefield ranges from a few ka up to several tens of ka (Zekollari et al., 2019). It is likely that A10177 fell several thousand years before being recovered.

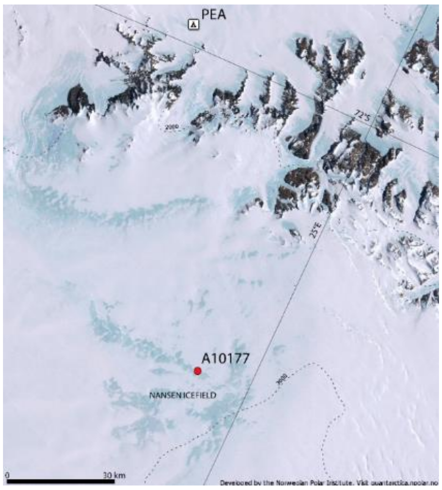


Figure 1. Landsat satellite map of the sampling location of A10177 on the Nansen Icefield. PEA: Princess Elizabeth Antarctica station.

Figure 2. Photograph of the external surface of the sample of A10177 held at the RBINS. The black area corresponds to the fusion crust that has not flaked off. Brownish red patches correspond to "metallic rust", that is a common product of terrestrial alteration of FeNi metal in Antarctic meteorites (Bland et al., 2006; Gooding, 1986).

After recovery, A10177 was cut and divided between the RBINS and the National Institute of Polar Research (NIPR) in Tachikawa, Japan. Approximately 105 g is currently being held in the RBINS collection. The sectioning of A10177 allowed its interior to be observed, showing that the interior exhibits large patches of FeNi metal more than 1 centimetre in size (Fig. 3).

This meteorite was chosen for the weathering experiments based on the following criteria:

- This sample is amongst the largest in the RBINS collection, allowing for the preparation of centimetre-scale subsamples.
- H chondrites represent approximately 46% of ordinary chondrites, which in turn account for 80% of all chondrites (Brearley and Jones, 1998). We specifically avoided rare and precious samples (i.e. achondrites or carbonaceous chondrites), as the main aim of the experiments is to alter the meteorite.
- The weathering scale based on polished sections is W1, meaning "Minor oxide rims around metal and troilite; minor oxide veins" (Fig. 4; Wlotzka, 1993)). A sample as pristine as reasonably possible is necessary for these experiments.

Figure 3. Photograph of the sectioned side of A10177, exhibiting its interior. The brownish areas near the edge of the sample correspond to weathered FeNi metal grains to limonite. In the most severe cases, the metal dissolved entirely, leaving cavities partially filled with weathering products. However, light grey areas correspond to pristine FeNi metal grains and/or troilite, showing that the interior of the meteorite is mostly unweathered.

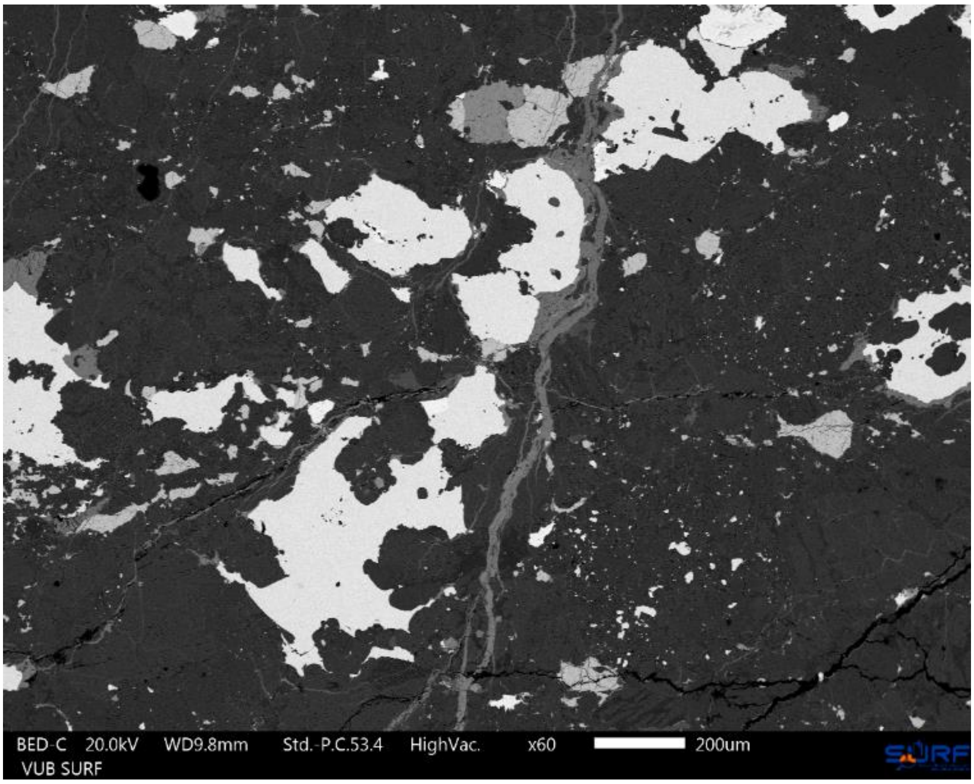


Figure 4. Scanning Electron Backscattered image of a representative area of A10177, showing the extent of terrestrial weathering in the Antarctic environment. White areas represent elements with a high Z-contrast, that is FeNi metal; dark grey areas represent elements with a low Z-contract, that are silicate phases; light grey represent iron oxide rims around FeNi metal grains or oxide veins.

Five fragments of A10177 approximately 1 x 0.5 cm in size were prepared at the RBINS that were subsequently embedded in Epoxy resin and polished. The fragments were labelled MET-1 to 5.

<u>Experimental methods</u>: The weathering experiments were carried out using a Weiss Technik WKL 34/40 climatic chamber at the Laboratoire G-time at ULB (Fig. 5), that was acquired in the frame of the project. This instrument allows experiments over a wide range of temperatures and humidity, that -72 to +100 °C and 20% to 90%, respectively. The control of the relative humidity consisted in the injection (i.e. increasing humidity) or purging (i.e. decreasing humidity) of demineralized water. On this instrument, precise temperature and humidity cycles can be programmed to last indefinitely or over a fixed period. Over the course of the project, three 100-days alteration cycles were undertaken. Each cycle consisted in variations of temperature and/or humidity on a 12-hours basis (Fig. 6). Asuka 10177 fragments were exposed in the climatic chamber to the various weathering cycles.

Figure 5. A Weiss Technik WKL 34/40 climatic chamber.

It is noteworthy that over the course of the project, the instrument encountered two major breakdowns that required the intervention of a technicians of Weiss Technik. The first issue concerned the water outlet situated at the back of the instrument that is used to purge the excess of demineralized water when humidity decreases, resulting in erroneous readings by the humidity probe. The second issue concerned the motherboard of the computer controlling the instrument (i.e. behind the panel on the upper part of the instrument on Fig. 5). The second issue was first misdiagnosed, resulting in erroneous humidity readings and requiring repetition of a cycle.

The first alteration cycle consisted in varying the temperature only in the climatic chamber. The temperature varied from 15 °C to 25 °C every 12 hours, with a fixed humidity of 30%. After this first cycle, artificially altered sample MET-2 was observed using a Scanning Electron Microscope (SEM) at the Vrije Universiteit Brussel. Subsequently, the surface of MET-2 was drilled using a 300 µm-wide tip drill at the VUB.

The second cycle consisted in changing both the humidity and temperature every 12 hours, from 35 to 45% and 15 to 25 °C, respectively. Samples MET-2 and MET-3 were then observed using a FEI Quanta 300 Scanning Electron Microscope (SEM) at the RBINS. The chemical composition of weathering products was determined used an EDAX Energy Dispersive Spectroscopy (EDS) detector. All observation were carried out at 15 kV to avoid deteriorating the weathering products. Additional EDS analyses and element mapping were carried using a Hitachi S4700 Field Emission Gun SEM equipped with a Bruker X-Flash Quad EDX detector at the School of Physical Science, University of Kent, United Kingdom. This detector presents the advantage of allowing precise EDS analyses and chemical mapping of rough samples.

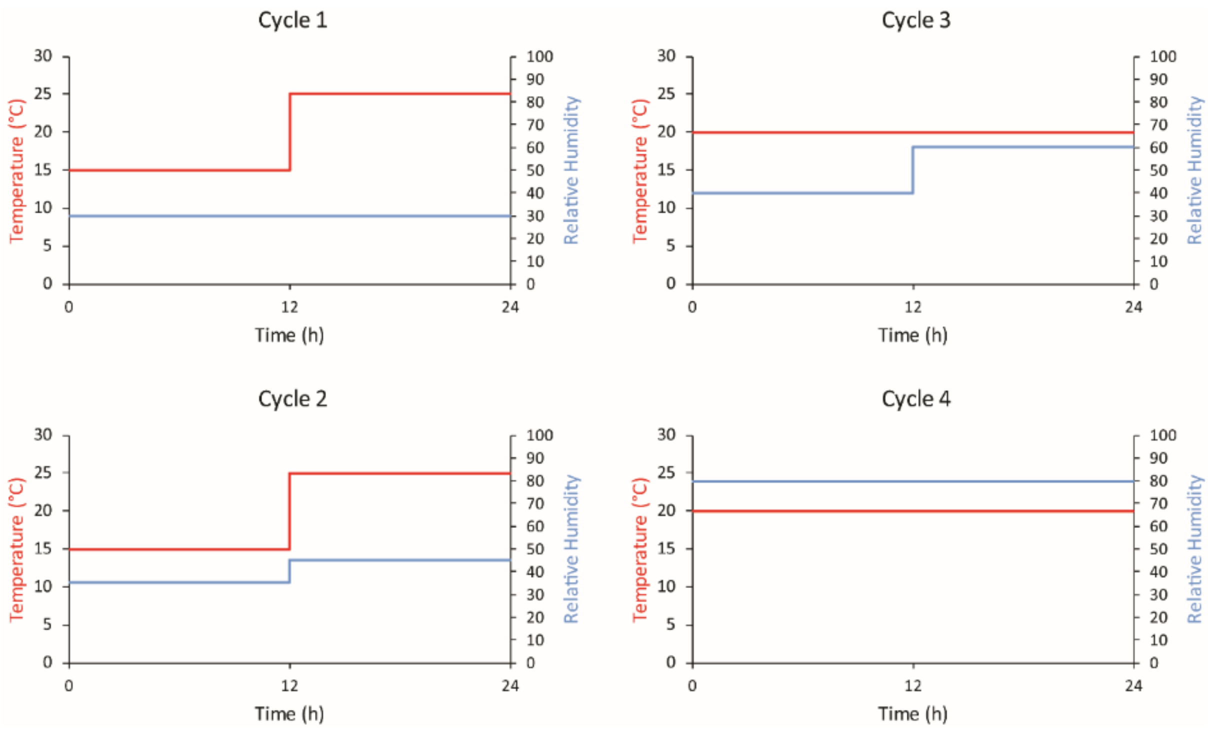


Figure 6. Diagrams showing the temperature (°C) and humidity (%) parameters used for the four weathering cycles.

Approximately 1 mg of the MET-2 powder was sent to the Institut für Geowissenschaften Fachbereich of the Goethe Universität, Frankfurt am Main, Germany, to determine the relative abundances of Fe^0, Fe^{3+} and Fe^{2+} in the altered area using Mössbauer spectroscopy, which illustrate the amount of Fe-oxyhydroxide in the sample. Mössbauer analyses were carried out at room temperature using a standard mössbauer spectrometer. Approximately 1 mg of drilled out powder from the witness sample MET-1 (i.e. unweathered) was also sent for mössbauer analyses for comparison. The third cycle on sample MET-4 consisted in changing humidity only from 40 to 60% every 12 hours. Finally, a fourth cycle on MET-5 consisted in maintaining a high humidity of 80% continuously. For both cycles, the temperatures was fixed at 20 °C. Micro-Raman spectroscopy was used to characterize the weathering phases in MET-3, MET-4 and MET-5. The instrument used is a SENTERRA Dispersive Raman Microscope (BRUKER), equipped with a thermoelectrically cooled CCD (ANDOR DU420-OE) with a spectral resolution of ~9 cm-1in the 200-1200cm^{-1} range (50x1000µm slit) and a continuous automatic calibration (0.1cm-1accuracy) with a solid-state laser corresponding to red light (784 nm) at 2mW for excitation at the RBINS. Raman spectra were processed using the software Spectragryph by Friedrich Menges. References spectra from the RRUFF online database were used to identify mineral species (Lafuente et al., 2016). The result of the first work package have been published in the peer-reviewed journal *Meteoritics and Space Sciences* as van Ginneken et al. (2022).

3.2. Digitizing of thin sections

The second work package selected achondrites and other rare and relevant meteorites from the collection for the digitizing process. A chip (ca. 1.5 g of material) was sawed from each meteorite and send to a laboratory specialized in precious and fragile thin section making. The section was then sent to the Open University (UK) for the preparation of the digitizing and then returned to the RBINS. The high-quality scan was done under polarized light of the section. The digital images were loaded on a website linked to that of the RBINS meteorite collection. It will be available to any user, thanks to dedicated software that reproduces the sample handling with a petrographic optical microscope. The Open University already demonstrated a strong experience in digitizing for NASA, lunar samples from the Apollo program.

3.3. Improvement of curation

To improve curation at the RBINS, Vinciane Debaille, named honorary curator of the RBINS Antarctic meteorite collection, together with Matthias Van Ginneken, the post-doc researcher hired in the frame of the AMUNDSEN project, are committed to participate in curation meetings often organized in the frame of scientific conferences. They also contribute to develop and optimize alternative meteorite classification methods and techniques, such as for example the recently implemented utilization of Raman spectroscopy for chondrite classification instead to the EPMA (Pittarello et al. 2015). They also import the best practices from other curation centers and share the results obtained in the frame of the AMUNDSEN project with other institutes. In addition to these actions, continuous efforts must be made to get funds in order to maintain an improving curation.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1. Alteration experiments

4.1.1. Results

After the first cycle of experiment, which consisted in changing the temperature only, MET-2 did not exhibit structural or petrographic changes commonly observed in weathered chondrites, such as mineral dissolution, efflorescence and formation of secondary phases (Bland et al., 2006). However, after MET-2 went through the weathering cycle 2, weathering products were observed in the drilled cavities exclusively, with limited spreading on the polished surface of the sample (Fig. 7). These weathering products line the walls of the cavity, suggesting that they were not produced during the weathering experiment but rather are products of terrestrial alteration during storage in the Antarctic environment.

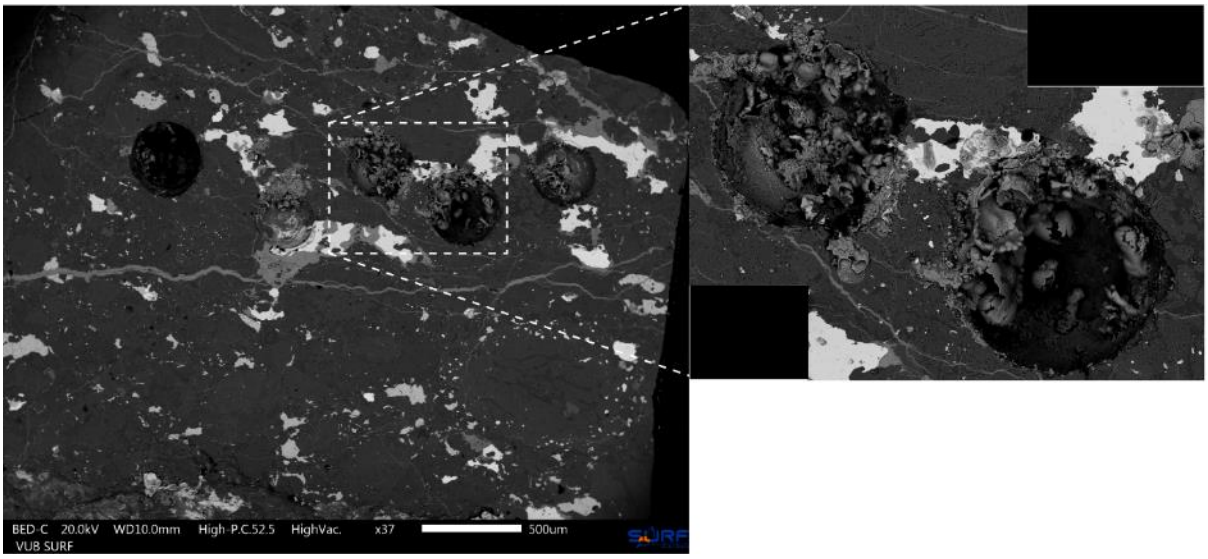


Figure 7. Scanning electron backscattered image of a drill cavity in MET-2 after the second cycle of weathering. Abundant tubular overgrowths are in the cavity, which consist essentially of iron oxide with Cl detectable with EDS.

After the subsequent weathering cycles, weathering products are partially covering samples MET-3, MET-4 and MET-5 and are characterized by a red-brownish colour characteristic of "metallic rust" (Figs. 8a, 9a and 10a), which typically results from the oxidation of metallic (Fe^0) or ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron. Weathering products appear as outgrowths on the polished surface of the samples. The roughness of these products with respect to the polished surface of the samples allows for them to be readily distinguished from other phases using reflected light (Figs. 8b, 9b and 10b).

The extent of weathering by total surface area varies from 1% in MET-4 to 13% in MET-5. It is noteworthy that this extent does not represent the surface of sample that was altered but rather how much the weathering overgrowths spread. In both MET-3 and MET-4, the weathering products mainly occur on the border of the sample with Epoxy resin, whereas for MET-5 they also occur in the inner part of the sample.

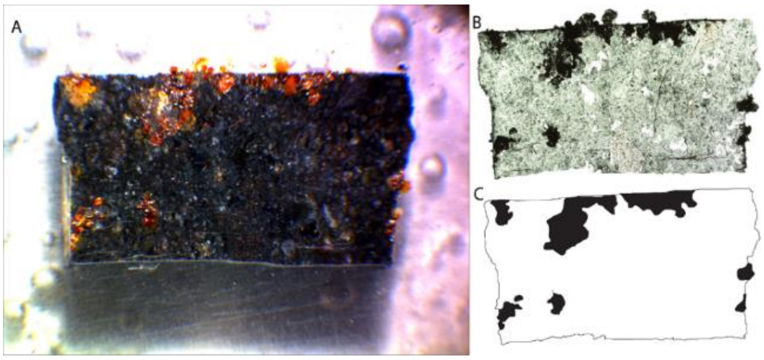


Figure 8. Extent of weathering after the cycle 2 on MET-3. A) Optical image of the weathering products, which are evidenced by a red-brownish colour, typical of rust. B) Reflected light image of the sample, allowing a clear identification of the rough weathering product (C)

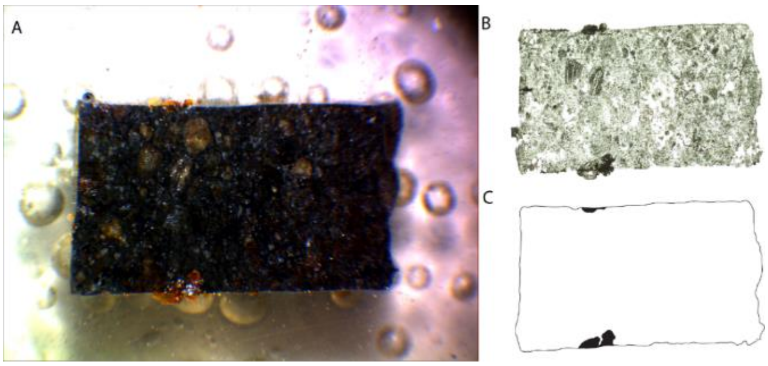


Figure 9. Extent of weathering after the cycle 3 on MET-4. For A, B and C, refer to figure 8 caption.

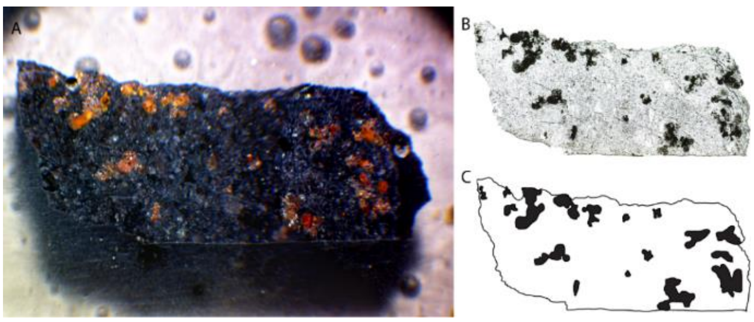


Figure 10. Extent of weathering after the cycle 4 on MET-5. For A, B and C, refer to figure 8 caption.

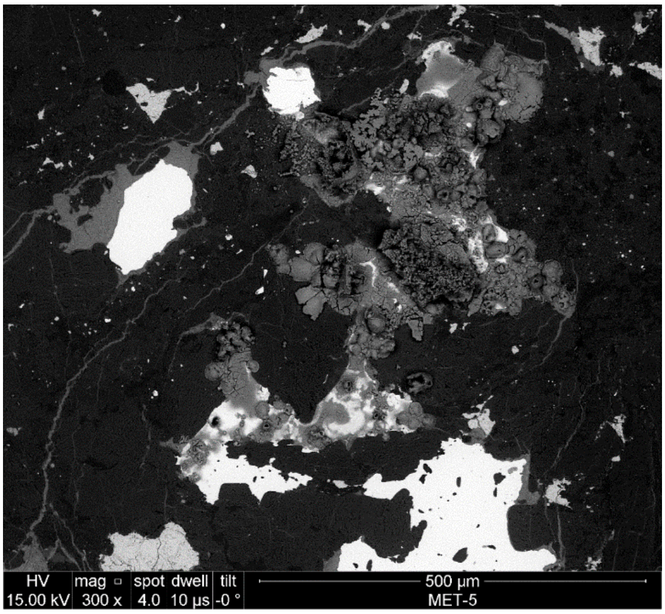


Figure 11. Scanning electron image of a weathered area of MET-5 showing that at an early-stage weathering products are associated with FeNi metal.

It is notable that in some instances, weathering products are exclusively associated with surfaces of FeNi metal (Fig. 11). The morphology of weathering products does not vary from one weathered area to the other, even when associated with FeNi only, suggesting that this latter phase is the only mineral phase affected by weathering.

Results of the petrographic study of the samples after the weathering experiments are summarised in Table 1.

In all weathered samples, the only observed weathering products are Fe-oxide/oxyhydroxides, which include a range of minerals that cannot be identified using SEM-EDS due to their fine-grained nature (i.e. micrometre to submicrometric size) and their wide range of chemical compositions (e.g., Lee and Bland, 2004). In most cases, weathering product occurs as tubular and/or subspherical shells of poorly crystalline material, with sizes ranging from a few tens up to several hundreds of micrometres (Fig. 12). The poorly crystalline nature of these weathering products prevents a clear identification using SEM only.

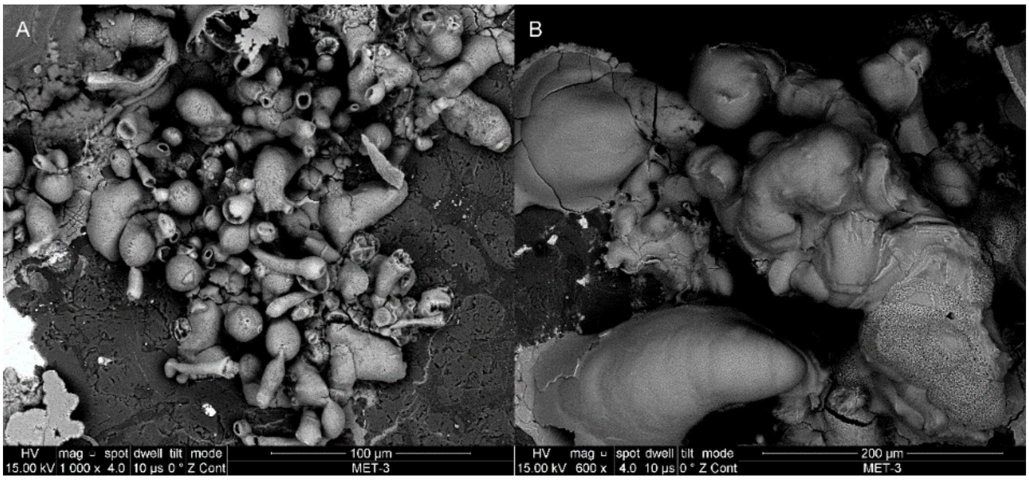


Figure 12. Scanning electron backscattered image of tubular weathering products on the surface of MET-3 and MET-4.

Some occurrences of incomplete shelled structures are observed, exhibiting crystalline material in their interior (Fig. 13). These iron oxide/oxyhydroxide structures are consistent with FeOOH material, such as akaganeite, lepidocrocite or goethite, material that are commonly associated with the aqueous alteration of metallic iron in a humid environment (e.g. Selwyn et al., 1999). The innermost part of these structure exhibit "cigar-shaped" crystals resembling akaganeite (Fig. 14a), whereas in some instances the broken side of the walls of the structures appear to have evolved to a more globular morphology (Fig. 14b). Other areas exhibit "cotton-ball" crystals typical of akaganeite above an area of "fine plates" crystals typical of lepidocrocite (Fig. 14c). "Cotton-ball" crystals typical of akaganeite are often observed as well (Fig. 14d).

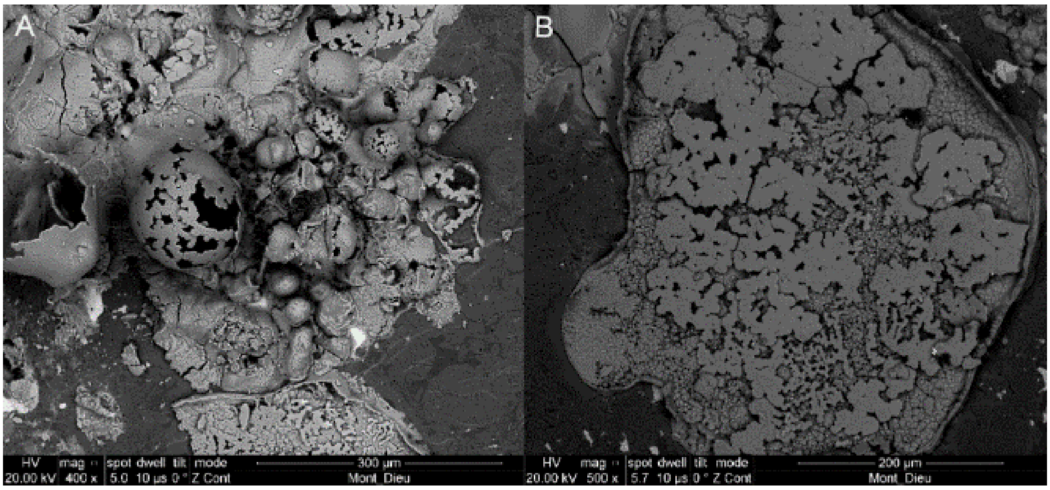


Figure 13. "Incomplete" shelled structures on MET-3.

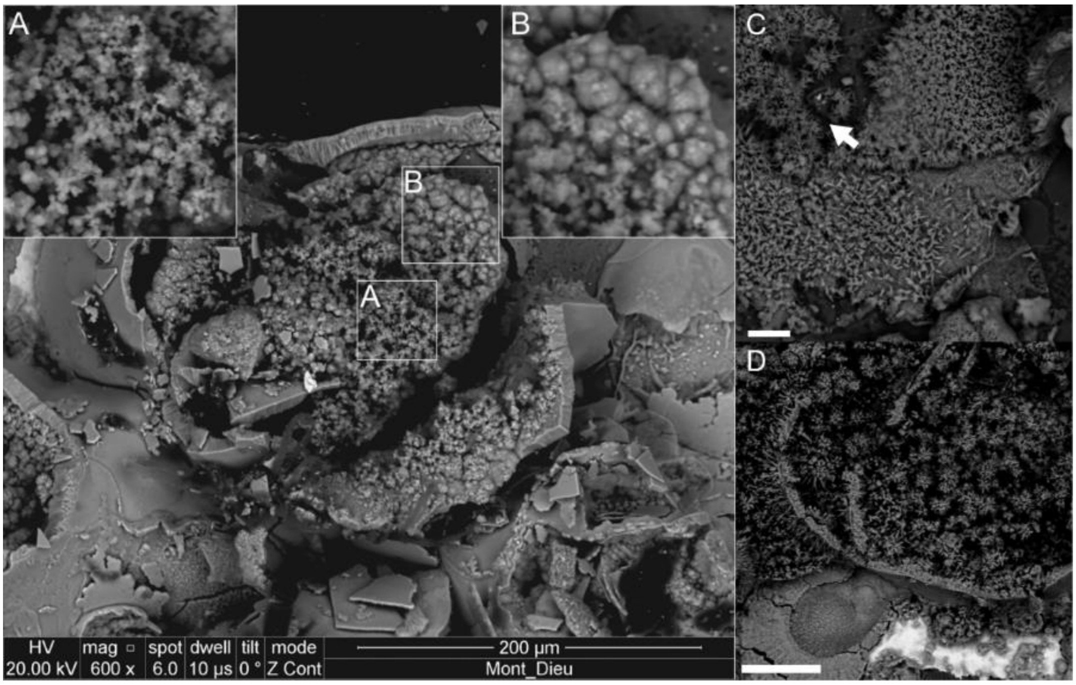


Figure 14. Scanning backscattered image of a "collapsed" shelled structure on MET-3. A) The material in the inner part of the structure show "cigar-shaped" crystals, typical of akaganeite; B) "globular" structures typical of goethite; C) Arrowed are "cotton-ball" crystals typical of akaganeite above an area of "fine plates" crystals typical of lepidocrocite; D) The interior of some shelled structures is exclusively constituted of "cotton-ball" crystals typical of akaganeite.

Table. 1. Petrograhic characteristics of samples after weathering experiment.

Sample	weathering cycles	Petrography of FeNi metal and troilite	Evidence of silicate dissolution	% surface extension of alteration	Secondary phases	Comment
MET-1	Witness sample	No alteration	No	N/A	None	
MET-2	1	Limited alteration of FeNi grains	No	< 1	Tubular Cl- bearing Fe-oxyhydroxide	In drilled cavities only
MET-3	2	Limited alteration of FeNi grains	No	12	Tubular + fibrillar Cl- bearing Fe-oxyhydroxide	Border of the sample
MET-4	3	Partial alteration of FeNi grains	No	1	Tubular + fibrillar Cl- bearing Fe-oxyhydroxide	Border of the sample
MET-5	4	Partial alteration FeNi grains + troilite	No	13	Tubular + fibrillar Cl- bearing Fe-oxyhydroxide	

Chemical composition of weathering phases: Energy Dispersive X-ray Spectroscopy (EDS) analyses of weathering phases in MET-3 and MET-5 are shown in Table 2. Corresponding areas of analyses and EDS spectra are shown in Fig. 15.

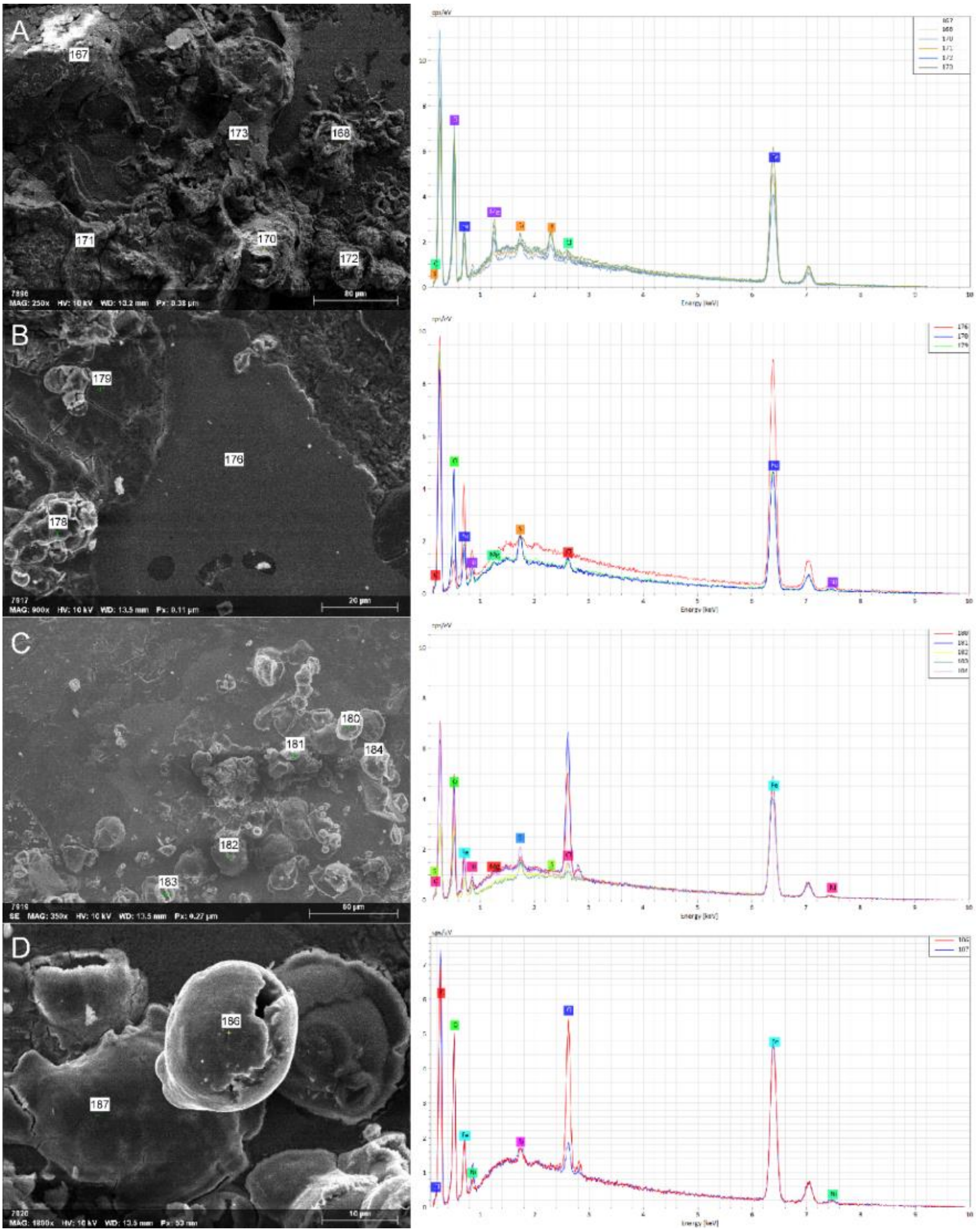


Figure 15. Secondary Electron images of areas of EDS analyses of weathering products in MET-3 (A) and MET- 5 (B, C and D) and corresponding EDS spectra.

Table 2. Representative Energy Dispersive Spectroscopy (EDS) analyses of weathering phases in MET-3 and MET-5. Results in Wt% normalized to 100%.

Spectrum	Phase	O	Mg	Si	S	Cl	Fe	Ni
Fig. 12a								
167	Weathering	44.4	0.31	-	0.16	-	49.2	5.79
168	Weathering	29.6	0.41	0.15	0.20	-	67.5	2.01
170	Weathering	45.7	0.23	-	0.20	-	49.9	3.96
171	Weathering	35.3	0.11	-	0.29	-	59.3	4.85
172	Weathering	32.8	2.04	0.48	0.16	-	62.8	1.61
173	Weathering	38.0	2.78	0.27	0.26	-	51.9	6.70
Fig. 12b								
176	FeNi metal	0.0	0.14	0.72	0.08	0.13	79.1	19.8
178	Weathering	33.5	1.34	0.54	-	0.13	55.3	9.24
179	Weathering	25.6	-	0.27	-	0.10	61.5	12.4
Fig. 12c								
180	Weathering	29.2	-	-	-	1.21	57.5	12.1
181	Weathering	29.2	-	-	-	1.81	57.1	11.7
182	Weathering	23.0	-	0.23	-	0.17	63.3	13.3
183	Weathering	22.9	-	0.31	-	0.10	67.3	9.3
184	Weathering	31.5	-	0.24	-	0.14	54.9	13.2
Fig. 12d								
186	Weathering	30.6	-	-	-	1.38	57.8	10.1
187	Weathering	32.8	-	0.17	-	0.19	51.9	15.0

In all occurrences, weathering products consist in Fe-rich material (>49.2 wt%), with significant Ni amount ranging from 1.63 to 13.3 wt%). Minor concentrations of Mg and Si are observed in most analyses of MET-3 and in about half analyses of MET-5, ranging from 0.14 to 2.78 wt% and 0.154 to 0.48 wt%, respectively. Most weathering phases observed in MET-5 contain minor amounts of Cl, ranging from 0.10 to 1.81 wt%. Sulfur is present in weathering products of MET-3 (0.16 to 0.29 wt%) but practically absent from weathering products of MET-5.

Element maps of MET-3, MET-4 and MET-5 show that weathering products are essentially made of Fe (Figs. 16, 17 and 18). Chlorine is ubiquitous in weathering products, although concentrations vary significantly, with the occurrence of “hot spots” associated with tubular or shelled structures. All weathering products inherited Ni from the FeNi metal to various extent, showing that they are mostly derived from this mineral phase.

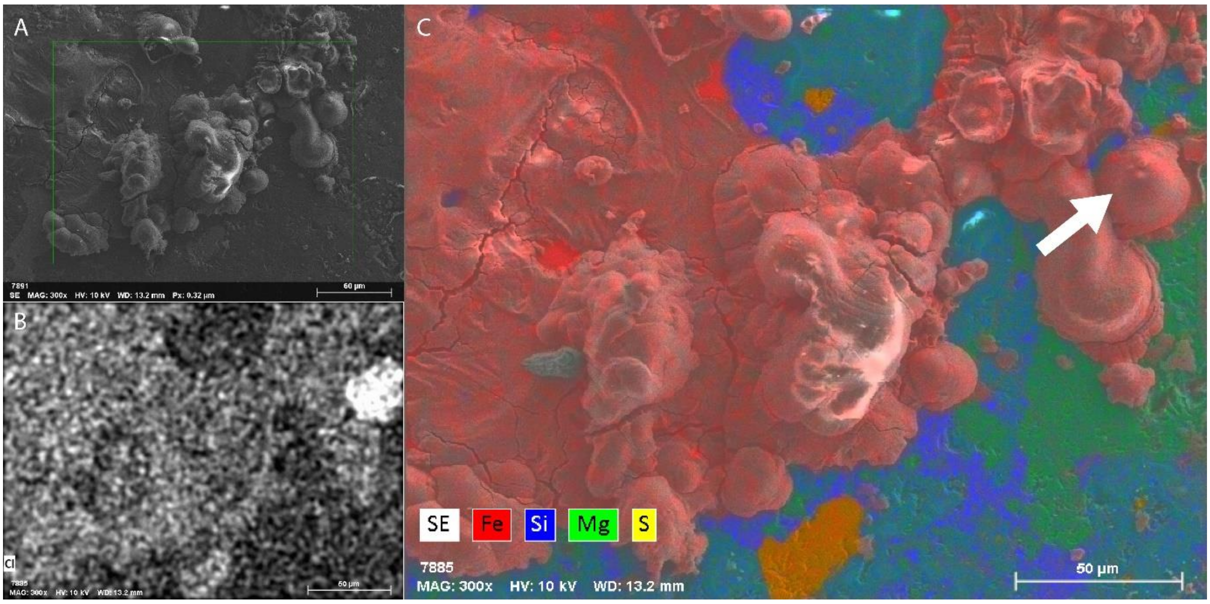


Figure 16. Major element map of weathering products of MET-3. A) Secondary Electron image of the area of analysis. B) Chlorine is detected in all products, but only rare "hot spots" are observed. C) Composite image showing that weathering products are essentially composed of iron. Blue, green and orange areas correspond to pyroxene, olivine and troilite, respectively.

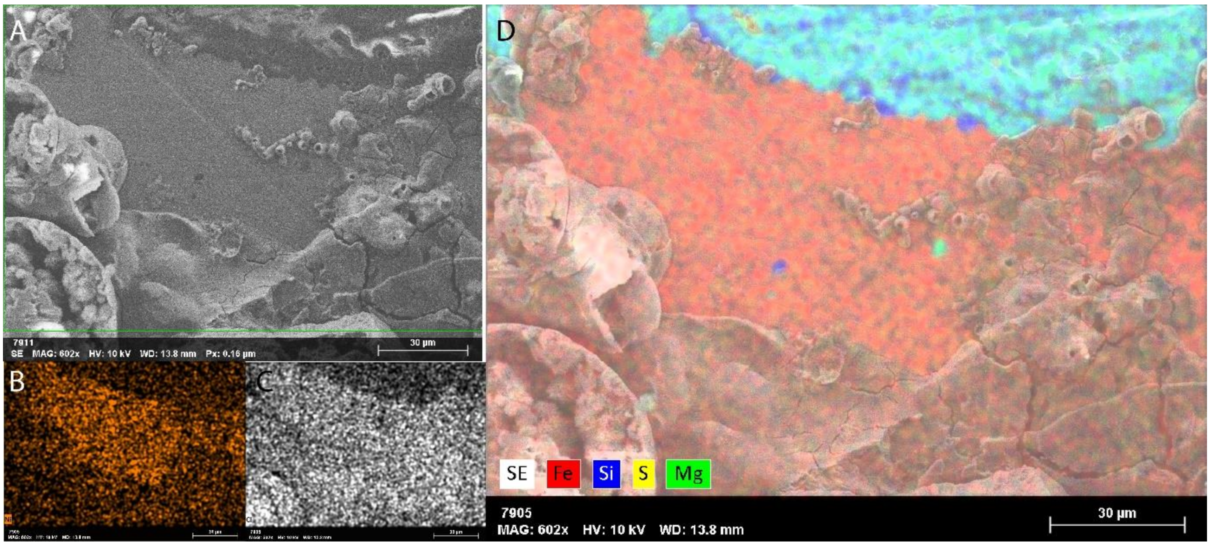


Figure 17. Major element map of weathering products of MET-4. A) Secondary Electron image of the area of analysis. B) Weathering products are rich in Ni. C) Chlorine is virtually absent from weathering products in this sample. D) Composite image showing that weathering products are essentially composed of iron. Blue and red areas correspond to olivine and FeNi metal, respectively.

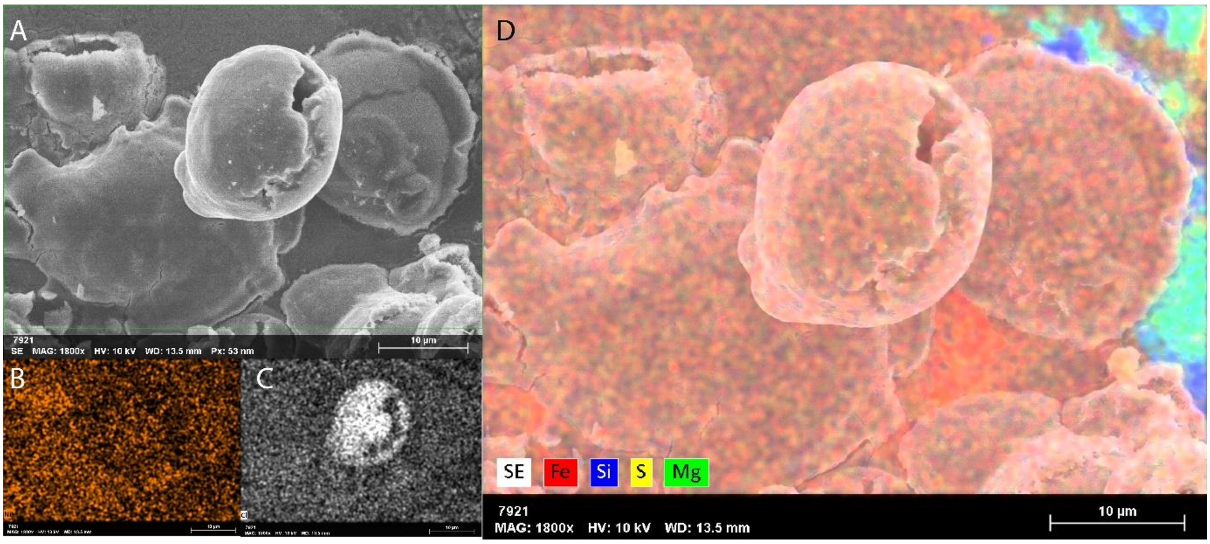


Figure 18. Major element map of weathering products of MET-5. A) Secondary Electron image of the area of analysis. B) Nickel map. B) Tubular structures are usually richer in Cl than surrounding phases. D) Composite image showing that weathering products are essentially composed of iron. Blue, green and red areas correspond to pyroxene, olivine and FeNi metal, respectively.

Mössbauer spectroscopy**:** Drilled powder of samples MET-1 and MET-2 containing weathering material was analyzed using Mössbauer spectroscopy. This technique has been extensively used to study the degree of alteration of meteorites as it allows determining the degree of ferric oxidation of primary iron-bearing phases resulting for terrestrial weathering (Bland et al., 2006, 1998). The aim of these analyses was to determine whether the partitioning of Fe^0, Fe^{2+} and Fe^{3+} in MET-2 with respect to MET-1. The Mössbauer spectra of MET-1 and MET-2 after the second cycle of weathering cycle are shown in Figs 19 and 20, respectively. The Mössbauer hyperfine parameters of the doublets, such as isomer shift (I.S.) and quadrupole splitting (Q.S.) are presented in Table 3.

In both MET-1 and MET-2 powders, five different phases are observed, two of which are magnetic and are comprised of sextets (red and green on Figs. 19 and 20). The red sextet corresponds to the hyperfine parameters of the FeNi metal phase kamacite. The green sextet appears to correspond to a sulphide, likely troilite (FeS). The remaining phases appear as doublets spectra. The blue doublet is consistent with olivine, whereas the lavender one is likely related to pyroxene. The brown doublet (2) has hyperfine parameters correspond to Fe oxyhydroxide. As mentioned previously, A10177 has suffered terrestrial weathering to a certain extent before being collected on the Antarctic ice, as evidence by the weathering rinds around FeNi metal grains and veins of Fe oxyhydroxide. It appears that weathering products produced during the experiments are indistinguishable from the ferrihydrite resulting from terrestrial weathering. The relative abundances of the phases observed is identical in both Mössbauer spectra, suggesting that the minute amount of weathering products resulting from the weathering experiment of MET-2 are not readily identified using this technique.

Table 3. Mössbauer parameters of the phases constituting MET-1 and MET-2 powders.

	MET-1			MET-2		
	IS (mm/s)	QS (mm/s)	Bhf (T)	IS (mm/s)	QS (mm/s)	Bhf (T)
sextet 1	0.01	0.00	33.9	0.01	0.01	33.8
sextet 2	0.64	-0.42	30.0	0.59	-0.24	29.7
doublet 1	1.16	2.97	N/A	1.15	2.95	N/A
doublet 2	0.45	0.73	N/A	0.44	0.71	N/A
doublet 3	1.07	2.28	N/A	1.04	2.30	N/A

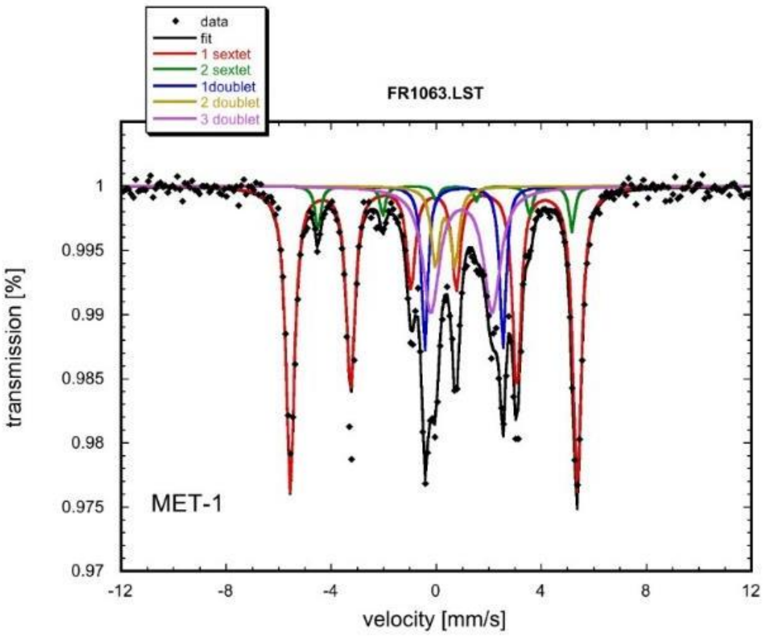


Figure 19. Mossbauer spectra (black line) of MET-1 powder. Several sextet and doublets are identified. Red sextet is identified as kamacite; Green sextet is identified as an Iron Sulphur (probably troilite); Blue and lavender doublets are identified as olivine and pyroxene, respectively; finally, brown doublet is difficult to identify and may be ferrihydrite.

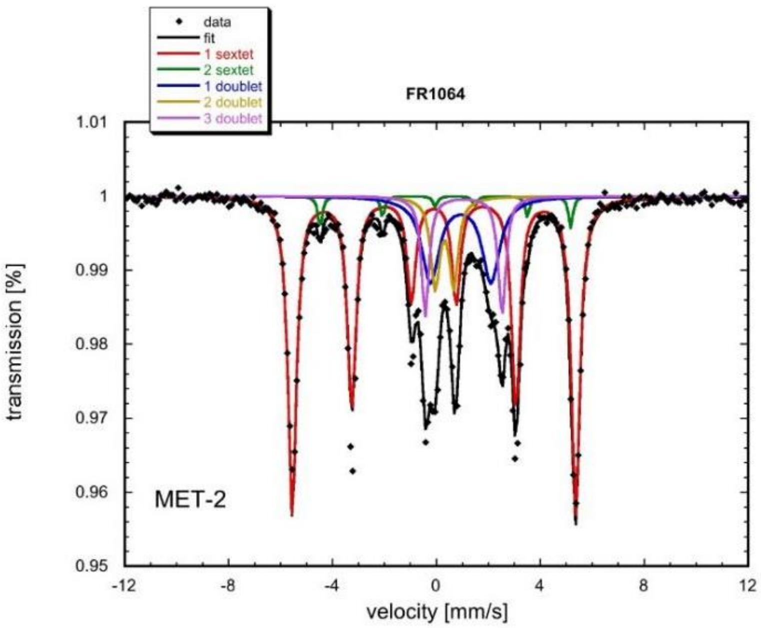


Figure 20. Mossbauer spectra (black line) of MET-2 powder. Peaks are identical as those observed in MET-1.

Raman spectroscopy: Weathering products of MET-3, MET-4 and MET-5 were analyzed by Raman spectroscopy at RBINS. The Raman spectra are shown in figures 21, 22 and 23. The collected spectra were compared to minerals in the RRUFF online database. Figures 21a, 21b, 23a and 23c show that a significant part of weathering products exhibits Raman peaks at ca. 250, 295, 380 and 525 cm^{-1}, which match the peaks of lepidocrocite (γ-Fe^{3+}OOH). Figures 21c, 22 and 23c show that another weathering product observed in all samples exhibits peaks at approximately 245, 300, 387 and 549 cm^{-1}, which correspond to goethite (α-Fe^{3+}OOH).

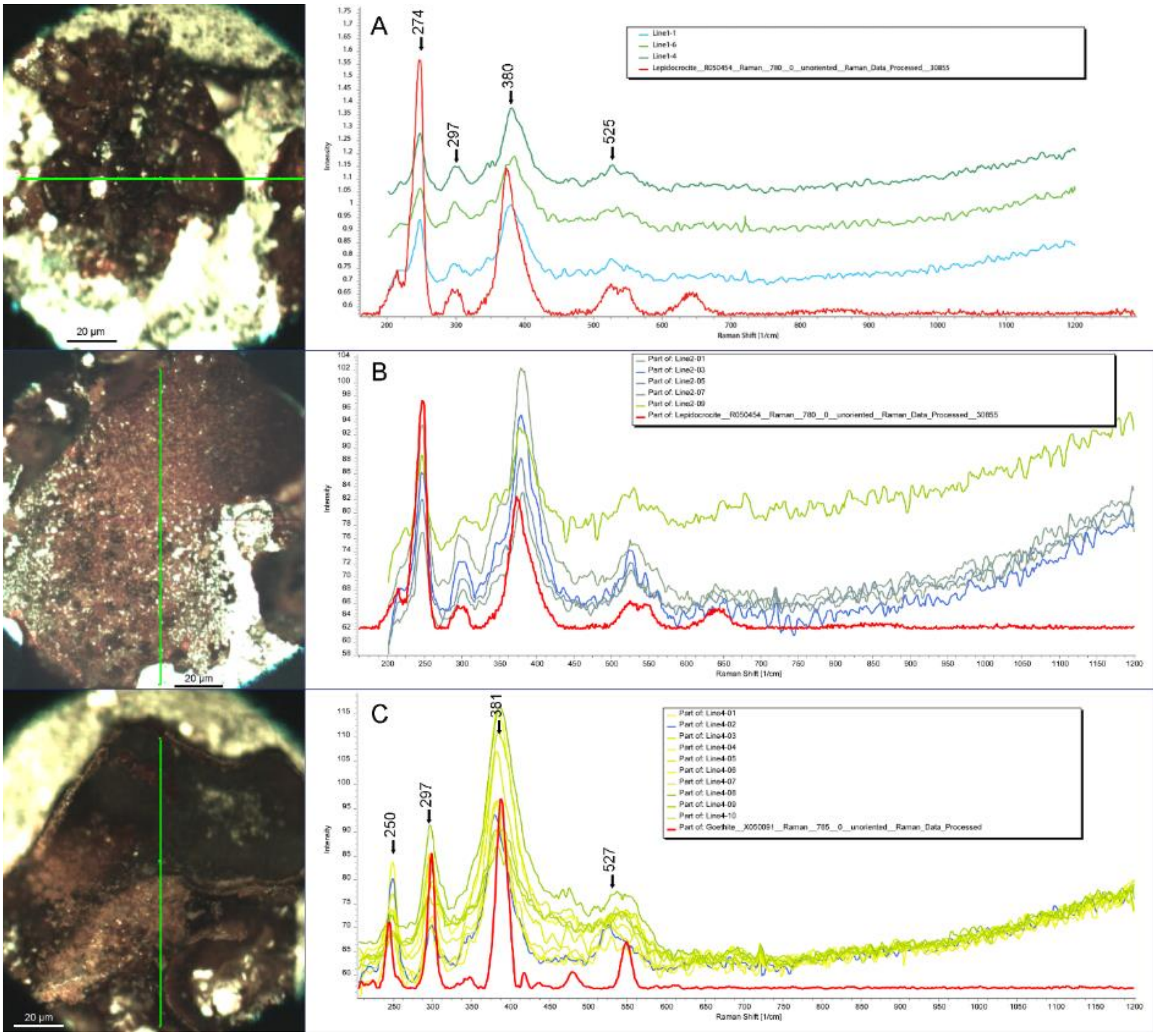


Figure 21. Raman spectra of weathering products in MET-3. All line analyses (green lines on optical images). A and B) most weathering products show a match with the spectrum of lepidocrocite (red line; RRUFF ID: R050554). C) some weathering products show a match with the spectrum of lepidocrocite (red line; RRUFF ID: R050554). C) some weathering products show a match with goethite (red line; RRUFF ID: X050091).

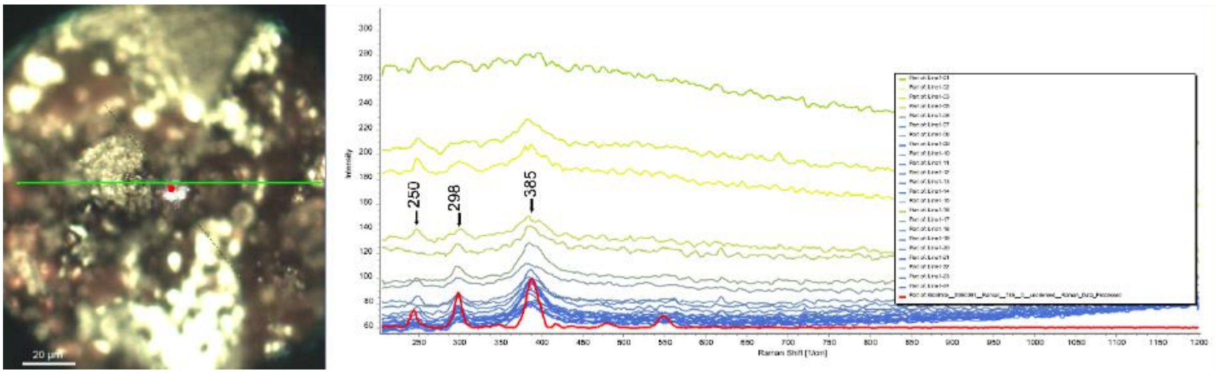


Figure 22. Raman spectra of weathering products in MET-4. Line (green on optical image) analyses showing good matches with goethite (red line; RRUFF ID: X050091).

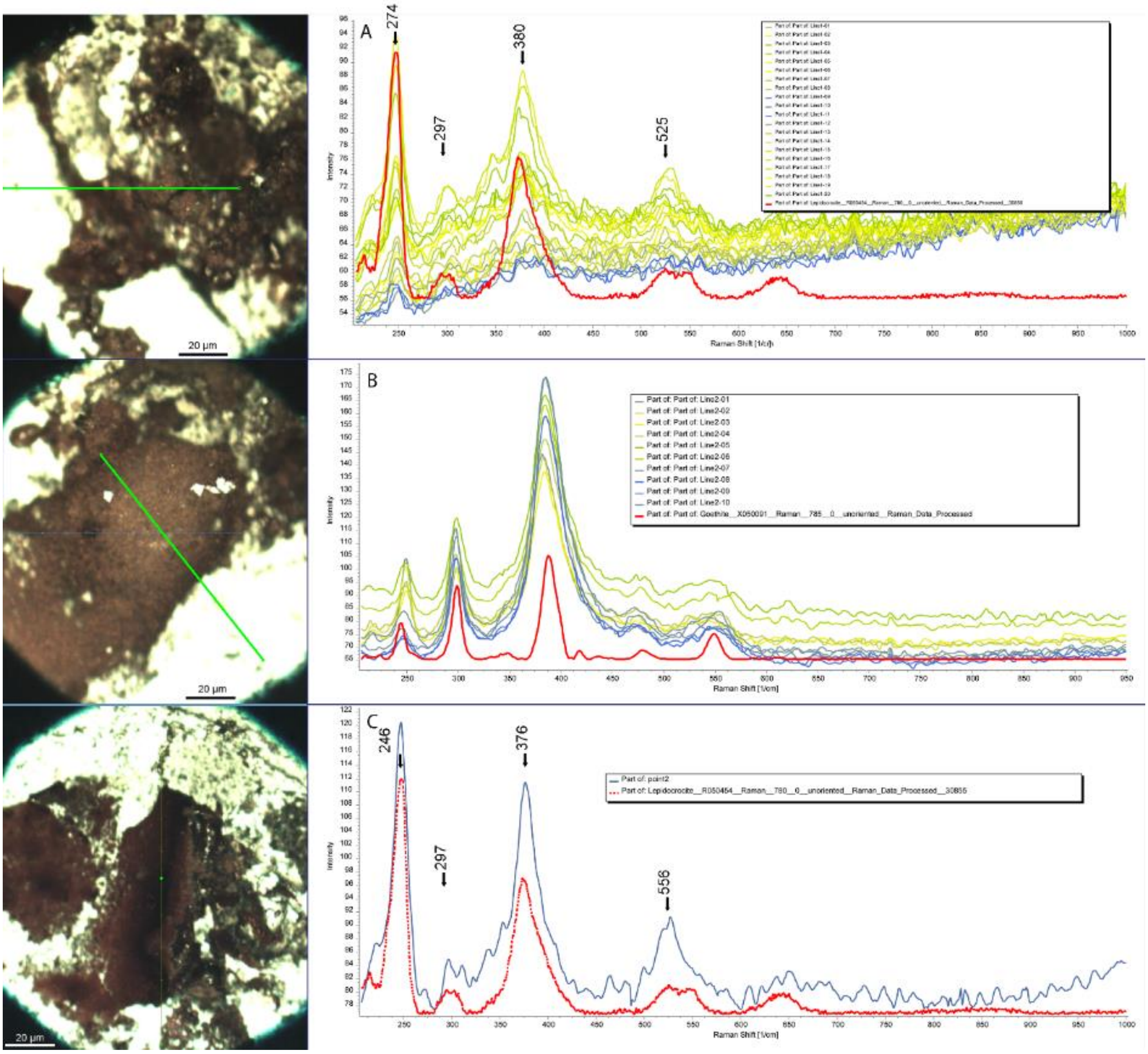


Figure 23. Raman spectra of weathering products in MET-5. A and B are line analyses (green lines on optical images) and C a point analysis (green point). A and B) most weathering products show a match with the spectrum of lepidocrocite (red line; RRUFF ID: R050554). C) some weathering products show a match with goethite (red line; RRUFF ID: X050091). Note: spectra of FeNi metal were not displayed.

4.1.2. Discussion

^{57}Fe Mössbauer Spectroscopic Analysis: The Mössbauer spectroscopy technique is widely used to determine the valence state of iron in geomaterials. In the field of meteoritics, this technique has been extensively used to study the extent of terrestrial weathering by identifying the products of alteration containing ferric iron (Bland et al., 2006, 1998, 1997). In particular, ordinary chondrites that have been collected shortly after their fall, such as Allegan (H5) and Barwell (L6), mainly contain metallic iron (Fe^0; FeNi metal, troilite) and divalent iron (Fe^{2+}; silicates), and virtually no trivalent iron (Fe^{3+}) resulting from oxidation of these primary mineral phases. Studies using this technique have shown that the degree of oxidation increases with increasing terrestrial age (i.e. time since the fall), while the relative abundance of primary phase decreases. This increase in oxidation with time occurs regardless of the environment in which the chondrites were collected, with Antarctic meteorites several tens of thousands of years old exhibiting up to 80% total oxidation. Indeed, even if the climatic conditions in Antarctica are ideal to preserve meteorites from terrestrial weathering, under certain extreme conditions, liquid water may appear as a monoatomic layer on mineral or even filling pores. This is mainly due to the fact that, due to their black colour, meteorites may sporadically heat up to temperatures above the freezing point of water. Interactions with water efficiently oxidize Fe^0 and Fe^{2+} to Fe^{3+}, resulting in the formation of Fe oxyhydroxides, which include magnetite, maghemite [γ-Fe_2O_3], ferrihydrite, lepidocrocite [γ-FeOOH], goethite [α-FeOOH], and akaganeite [β-FeOOH]. It is noteworthy that all Fe-bearing phases are affected by oxidation and contribute to the formation of these weathering products. However, FeNi metal is the mineral phase that is most susceptible to weathering, before sulphides and, finally, silicates. In the case of A10177, the witness sample MET-1 has been maintained under controlled climatic conditions since its recovery in Antarctica, preventing terrestrial alteration. However, the presence of Fe oxyhydroxide resulting from terrestrial weathering prior to the recovery on the field is obvious around most FeNi metal grain and filling veins (Fig. 4). Figure 19 shows that the Mössbauer spectrum of powder from MET-1 includes a doublet characteristic of Fe^{3+}-bearing oxyhydroxide. Table 3 shows that the hyperfine parameters IS (isomer shift) and quadrupole splitting (QS) match those of "mature" weathering products observed in Antarctic chondrites (Bland et al., 1998). It is not clear whether this material correspond to goethite or lepidocrocite, but it appears clear that akaganeite, which is usually the first corrosion product of FeNi metal in chondrites, is absent. This makes sense as lepidocrocite and goethite are common ageing products of akaganeite is Antarctic chondrites. As observed in figure 7, weathering products formed as a result of the weathering cycle 2. Their structure and chemistry suggest that these are Fe oxyhydroxides. Thus, we would expect the relative abundance of Fe^{3+} to be higher in MET-2 compared to MET-1, considering that our experiments oxidised FeNi metal to form metallic rust. However, the relative amount of the Fe^{3+}-bearing oxyhydroxides are identical in both MET-1 and MET-2. A likely explanation is that the signal of weathering products resulting from our experiments was obscured by the signal from weathering products that were present prior to the experiment. Indeed, in order to run one analysis, at least 1 mg of powder is necessary, requiring drilling out a significant quantity of material. This difficulty in identifying newly formed weathering products using Mössbauer spectroscopy prevented us from analysing more samples (i.e. MET-3, MET-4 and MET-5). The destructive nature of this technique in the present case further encouraged us to use non-desctructive Raman spectroscopy, a technique that is readily available and requires virtually no sample preparation.

The weathering of A10177 under laboratory conditions: Identifying weathering products resulting from our weathering experiments is critical to understand how alteration proceeds in ordinary chondrites under various climatic conditions. Previous studies have shown that terrestrial weathering result in a precise set of products that are common to certain types of climatic conditions, chondrite types and availability of reactive solutions (Benoit and Sears, 1999; Bland et al., 2006; Gooding, 1986, 1982; Jull et al., 1988; Lee and Bland, 2004; Losiak and Velbel, 2011; Velbel, 2014, 1988; Velbel and Gooding, 1990). Furthermore, minerals constituting ordinary chondrites show variable weathering susceptibilities and rates. When water is the main solvent interacting with chondrites, such as in the present study, the sequence of alteration is rather simple and is as follow: FeNi metal > troilite > mafic silicates. Products resulting from the alteration of these phases depend mainly on the elements released in the solution. The high susceptibility to weathering of FeNi metal with respect to other mineral phases results in ferruginous oxidation minerals as the most commonly observed weathering products. Gooding (1986) recognized two types of corrosion products in ordinary chondrites that are the “metallic” rust and the “sialic” rust. Metallic rust essentially results from the weathering of metallic iron-bearing phases, such as FeNi metal and troilite, whereas sialic (Fe-Si-Al) rust results from the alteration of mafic silicates. According to the sequence of alteration mentioned above, metallic rust is predominant during the first stage of alteration, whereas sialic rust becomes predominant at a late stage, when most (if not all) FeNi metal and troilite are lost and Fe^{2+} in mafic silicates is the main driver of ferruginous oxidation. Identified phases constituting metallic rust in ordinary chondrites include akaganeite [β-FeOOH], goethite [α-FeOOH], lepidocrocite [γ-FeOOH], and maghemite [γ-Fe2O3] (Buchwald and Clarke, 1989). Several studies have shown that regardless of the climate under which alteration takes place, akaganeite is a the key mineral phases to explain the corrosion of FeNi metal (Bland et al., 1997; Buchwald and Clarke, 1989). It has been suggested that the mechanism of akaganeite formation involves anodic metal going into solution and being replaced by Cl^- to maintain charge balance (Buchwald and Clarke, 1989). As weathering proceeds, akaganeite can decompose into goethite and/or lepidocrocite, releasing Cl^- ions that will further corrode Fe metal. For this reason, akaganeite is found at the interface with FeNi metal, which are areas exhibiting early-stage weathering, whereas late-stage weathering areas will more likely exhibit intergrowths of lepidocrocite and goethite. Identifying this set of minerals in our samples may allow reconstructing their weathering history.

Raman spectroscopy was used to identify the weathering products resulting from our experiments. This technique was preferred for several reasons: 1/ its availability at the RBINS; 2/ its ease of use, as it does not require particular sample preparation; and 3/ the study of spectral properties of the materials imply that only the weathering outgrowths are analysed, which is important to avoid analysing Fe oxyhydroxides that predates the experiments. Although this technique was not used to characterize weathering products in meteorites per se, it has been used in several studies as the main tool to characterize corrosion products of iron metal under laboratory and natural conditions (e.g. Cambier et al., 2014; Neff et al., 2004; Oh et al., 1998). Using reference spectra from the RRUFF online database (Lafuente et al., 2016), identified weathering products include lepidocrocite and goethite in MET-3 and MET-5, whereas only goethite was identified in MET-4. Interestingly, akaganeite was not identified. However, SEM survey of weathered areas show “cotton-ball” structures and “cigare-shaped” crystals typical of akaganeite, associated with structures and crystal habits typical of lepidocrocite and goethite (Fig. 12). Further to this, EDS analyses show areas with detectable Cl with concentrations up to 1.81 wt%, which is consistent with akaganeite and not lepidocrocite and goethite

(Table 2). Element maps also show that high-Cl contents are not ubiquitous in weathering products but are rather limited to “hot spots”, probably newly formed akaganeite (Figs. 14-16). Presence of S in weathering products of MET-3 and in some products on MET-5 suggest that troilite may have started being altered by the time the weathering cycle ended.

Apart from the weathering of metallic phases, another important aspect of the weathering of chondrites is the dissolution of mafic silicates and subsequent precipitation of weathering products, such Fe-rich phyllosilicates. In Antarctic meteorites, cronstedtite was observed as a weathering products of ferromagnesian silicates (Lee and Bland, 2004). For example, early-stage alteration of natural and meteoritic olivine is characterized by the presence of “wedge-shaped” dissolution features on the edge of the crystals (van Ginneken et al., 2016; Velbel, 2009). Such features are not observed using a SEM on olivine crystals of MET-3, MET-4 and MET-5. Some amount of Si and Mg are observed in EDS analyses of weathering products of MET-3 and MET-5. However, it is not clear whether this results from the alteration of ferromagnesian minerals or rather to the inclusion of underlying primary crystals due to a large interaction volume. Structures typical of phyllosilicates were not observed during SEM observations, and Raman spectra of weathered phases did not show peaks typical of phyllosilicates (Lafuente et al., 2016). We therefore assume that ferromagnesian mineral in our samples did not suffer from weathering, or at least to a very limited extent.

It appears that weathering products identified in MET-3, MET-4 and MET-5 exhibit the sequence of aqueous alteration typical of FeNi metal only. MET-2 exhibited similar weathering products, but only after going through the second cycle of alteration, along with MET-3. After the first cycle, involving changes of temperature while maintaining a fixed humidity, MET-2 did not show signs of weathering. This implies that rapid and large variations in humidity and/or very high humidity (cycle 4) result in a high risk of weathering. The shelled and tubular structures observed with SEM in figure 12 are identical to corrosion features observed on iron metal that was corroded in the natural environment (e.g., figure 4 in Selwyn et al., 1999). Such shelled structures occur when droplet of water react with iron metal, dissolving it to release Fe^{2+} in the solution. If Cl from the environment is present, the high surface tension of water droplets will result in the precipitation of Cl and Fe^{3+} resulting from the oxidation of Fe^{2+} to form akaganeite. Thus, it appears that the main driver of weathering during the experiment was liquid water in the form of microscale droplets rather that a uniform monolayer wetting the whole sample. More importantly, in cases of relatively low relative humidity, droplets condensation only occurred on the border of the samples. At 80% relative humidity, droplet condensation also occurs in the inner part of the sample.

The chloride in the weathering solution does not originate from the demineralized water used for the experiments, since it should contain only potential trace amounts of this ion. Chloride, which as mentioned above is a major corrosive agent for FeNi metal, may have originated from products of terrestrial weathering that were formed in the Antarctic environment prior to the experiment. Indeed, studies have shown that it is common for Fe-rich products of alteration resulting from the corrosion of FeNi metal to contain Cl content above 1 wt.% (Bland et al., 2006; Lee and Bland, 2004). As mentioned above, the relative humidity used during the experiments remained below 100%, meaning that condensation of water on the samples was theoretically not possible. However, hygroscopic materials are known for their capacity to absorb moisture from the air. Primary constituents of ordinary chondrites such as A10177 do not have hygroscopic properties, meaning that under the relative humidity conditions of the experiments, water should not condense on their surface. However, Fe oxyhydroxides minerals have hygroscopic properties and are known to present of potential risk of corrosion for metal exposed to the ambient air, even at relative humidity lower than 40% (e.g. Watkinson and Lewis, 2004; Watkinson and Emmerson, 2017; Yeşilbaş and Boily, 2016). Rapid changes in relative humidity are also known to enhance water condensation on Fe oxyhydroxides (Watkinson and Lewis, 2004). Condensation of water droplets on Fe oxyhydroxides resulting from terrestrial weathering in the Antarctic environment and subsequent release of chloride from these minerals seems like a probable mechanism explaining the corrosion of FeNi metal of A10177 during our experiments. Capillary condensation, which represents the ability of submicroscopic cavities to condense moisture at relative humidity below 100%, may explain the preferential corrosion observed at the interface between the Epoxy resin and samples MET-3 and MET-4 (Figs. 8 and 9). It is noteworthy that submicrometer pores represent the most numerous pore spaces in fresh ordinary chondrite falls. However, most pore spaces are efficiently filled with weathering products in chondrite finds, such as those from Antarctica (Britt and Consolmagno, 2003; Consolmagno S.J. and Britt, 1998; Li et al., 2019). It is clear from the SEM observations of A10177 that microscopic pores have long been filled with weathering products, preventing capillary condensation. In our samples, it is likely that water droplets originated from condensation on hygroscopic Fe oxyhydroxides mainly, with probable effects of capillary condensation where imperfect interface between the samples and Epoxy resin resulted in submicroscopic cavities. Water enriched in chloride started corroding FeNi metal, which in turn formed a new generation of akaganeite, lepidocrocite and goethite. Formation of new Fe oxyhydroxide probably promoted further condensation of water, resulting in the tubular structures observed. The high relative humidity during cycle 4 resulted in major contribution of condensation of water on Fe oxyhydroxides already present on MET-5, which may explain why this sample shows evidence of FeNi metal on most of its surface, compared to other samples.

4.2 Recommendations for the preservation of ordinary chondrites in meteorite collections

From their recovery on the field to their storage in museum or research institute collections, meteorites are carefully maintained under controlled environments to greatly reduce the effects of terrestrial weathering (e.g., Righter et al., 2014). This is particularly the case for Antarctic meteorites, which are usually recovered on the field at subzero temperatures. The collection and transfer of Antarctic meteorites to the curation facility of RBINS follow a precise protocol which involves their careful package in sealed plastic bags on the field, storage in a temperature of -20 °C during their shipment from Antarctic to the NIPR, and subsequent thawing at room temperature (~22-24 °C) under dry conditions to avoid interaction with liquid water (Yamaguchi et al., 2012). The meteorite are then sent to the RBINS, where they are stored in carefully controlled and stable temperature and relative humidity (De Ceukelaire et al., 2013). Failure to maintain stable environmental conditions can quickly damage meteorites, such as has been the case for meteorites from the 2003 ANSMET expedition. Indeed, the freezer in which meteorites were stored suffered a power loss for approximately 3 weeks, resulting in the formation of evaporites on the samples (“Antarctic Meteorite Newsletter . 19782006.,” 2006).

The present study has shown how important maintaining stable environmental conditions is for the preservation of ordinary chondrites, especially the H types containing the most FeNi metal. Rapid changes of temperature coupled with relatively low relative humidity (i.e. cycle 1) does not appear to affect FeNi metal grain at the microscopic scale. However, changing temperature and the relative humidity contemporaneously (i.e. cycle 2) appears to quickly result in the corrosion of metal grains. Changing humidity alone (i.e. cycle 3) result in less FeNi metal corrosion compared to changing both temperature and humidity, showing that temperature fluctuations should not be neglected when associated with changes in relative humidity. Storing chondritic samples in constant conditions of high relative humidity (i.e. cycle 4) result in severe corrosion on most of the samples, showing that such conditions should be particularly avoided. All in all, this work shows the importance of maintaining absolutely stable conditions of temperature and relative humidity, and especially that the latter parameter should be kept below 40%.

4.3 Long-term curation of the meteorite collection

In the frame of the AMUNSDSEN project, conservation and curation (including meteorite classification) of the collection was managed efficiently. Regular meetings with curators from several museum and institutes curating meteorites in Europe and members of the follow-up committee (during internal meetings) ensured the improvement of the curation and follow-up of the project itself.

In the future, more projects joining high level research in Belgium and missions in Antarctica will help in consolidating the role of BELSPO in Antarctica. This is ensured until at least 2024 thanks to the projects below.

A first project, introduced under Thematic axis 2, is entitled 'Belgian Antarctic Meteorites and Micrometeorites to document solar system formation and evolution' (BAMM!; belspo.be/belspo/brain-be/projects/BAMM_en.pdf; 01/01/2017 – 15/04/2022). This novel BRAINS project, gathering the same partners, builds on and expands the assembled expertise, and centers on a number of highly promising, but previously unexplored research opportunities provided by this valuable set of newly recovered extraterrestrial samples. (i) A detailed study of micrometeorites and their igneous textures will help to better document their parent body precursors (possibly not sampled by larger meteorites), quantify the continuum between unmelted and fully molten objects, and further constrain the effects of rapid melting, melt extraction and silicate-metal segregation on the petrological, chemical and isotopic characteristics of the precursor materials. (ii) A precise characterization of the isotope anomalies existing in bulk meteorite samples, and their counterparts in the constituent mineralogical phases measured by in situ mass spectrometry to better understand the presence and destruction of nucleosynthetic anomaly carrier phases during nebular and planetary processes. In addition, the BAMM! project further expands the Belgian Antarctic meteorite collection and encourages a reliable, long-term protective curation program of Antarctic meteorites at the RBINS, boosting at the same its position as a key Antarctic (micro)meteorite curation center in Europe. The Belgian meteorite classification expertise will be expanded, and implemented not only to Antarctic meteorites, but also to non-Antarctic samples. Last but not least, this project supports the preservation and, through its research output, the valorization of the Belgium museum collections and national heritage.

A second project, 'Tracing differentiation processes through siderophile elements, from meteorites to giant ore deposits' (DESIRED; belspo.be/belspo/brain2-be/projects/DESIRED_E.pdf;15/12/2019 - 15/03/2024) aims at expanding and improving the efficient curation of all Antarctic meteorites at the RBINS. Thanks to the two meteorite recovery missions planned within the framework of this project (2021-2022 and 2022-2023), the size of the Antarctic RBINS meteorite collection (>1300 specimens to date) is expected to increase substantially, ensuring sufficiently large meteorite masses needed to apply high-precision isotopic methods, as planned in the scientific tasks of the project.

5. DISSEMINATION AND VALORISATION

A lot of work was done regarding the diffusion and the valorisation of the results.

First, one can mention the major task dedicated to the digitizing of the thin sections. As main outcome, a new webpage about the different types of Antarctic meteorites and their microscopic view was designed and published.

Then, research activities can be evaluated thanks to the peer-reviewed papers and conference abstracts listed in the “6. Publications” section of this report. A specific paper is about the results from the AMUNDSEN project (Van Ginneken and al. 2022). During the Antarctic campaign, the chance is taken to investigate the relationship between the number of meteorites and the ice flux, and several micrometeorites were collected, leading to several publications using both micrometeorites and meteorites. One paper was published in “Science Advances” by Matthias Van Ginneken, the post-doc researcher hired for the AMUNDSEN project. The publication of this paper resulted in a broad dissemination of the activities lead in the frame of the project.

5.1. Digitizing of thin sections

The eight selected samples for digitizing illustrate the diversity of the collection at the RBINS : a chondrite type LL3 (specimen A09135), a chondrite type CM2 (specimen A09474), a chondrite type CK4 (specimen A1022), an achondrite type Ureilite (specimen A09317), an achondrite type Diogenite (sample A12144) and an achondrite type Eucrite (specimen A12223).

The corresponding thin sections were prepared in a dedicated laboratory in Italy and then sent to the Open University for digitizing by the team of “Virtual Microscope” https://www.virtualmicroscope.org/ . The thin sections were then sent back to the RBINS and are now part of the thin section collection.

As such, every meteorite features a virtual thin section so that one can study the mineral optical properties, grain size, shape and proportion, and also analyse the rock micro textures as if using a polarising microscope. The deliverable from the Open University was quickly published on the website of the RBINS: https://collections.naturalsciences.be/ssh-geology/thin-sections/Antarctic%20meteorites%20-%20microscopic%20view%20-%20different%20types

An introduction text about meteorite classification is provided on this page (Figure 24): “This digitalisation was realised by the team “Virtual Microscope” of The Open University, UK. https://virtualmicroscope.org BELAM (Belgian Antarctic Meteorites): since 2009, through a joint collaboration with the National Institute of Polar Research (NIRP) in Japan, Belgian scientists have carried out meteorite searches in the Sør Rondane region of Antarctica near the Belgian station Princess Elisabeth. The 2009-2010, 2010-2011 and 2012-2013 field seasons have yielded more than 1200 new meteorites, that are shared equally between the two countries. Stony meteorites can in general be divided into undifferentiated (chondrites) and differentiated meteorites (achondrites), which are further subdivided into classes, clans and groups. Chondrites are the most abundant meteorite group and constitute the most primitive solar system material. They formed around 4.56 billion years ago as part of the formation of their parent bodies and as such, they contain important information of the early solar system formation (e.g. physical-chemical properties of the protoplanetary disk region(s)). Most chondrites are characterized by the presence of abundant chondrules, which are mm-sized spheres consisting mainly of the silicate minerals olivine and pyroxene. Chondrites are further divided into three main classes: carbonaceous chondrites, ordinary chondrites and enstatite chondrites. Carbonaceous chondrites are of great interest because some contain up to 5% carbon in a variety of forms, including organic matter, carbonates, and minor amounts of “exotic” presolar grain material such as diamond or graphite. Achondrites are igneous rocks or breccias of rock fragments from differentiated planetary bodies (i.e. planetary bodies with a core and crust), such as Mars, the Moon or asteroids. Contrary to most chondrites, achondrites do not have any chondrules. They can further be subdivided into primitive achondrites and achondrites.”

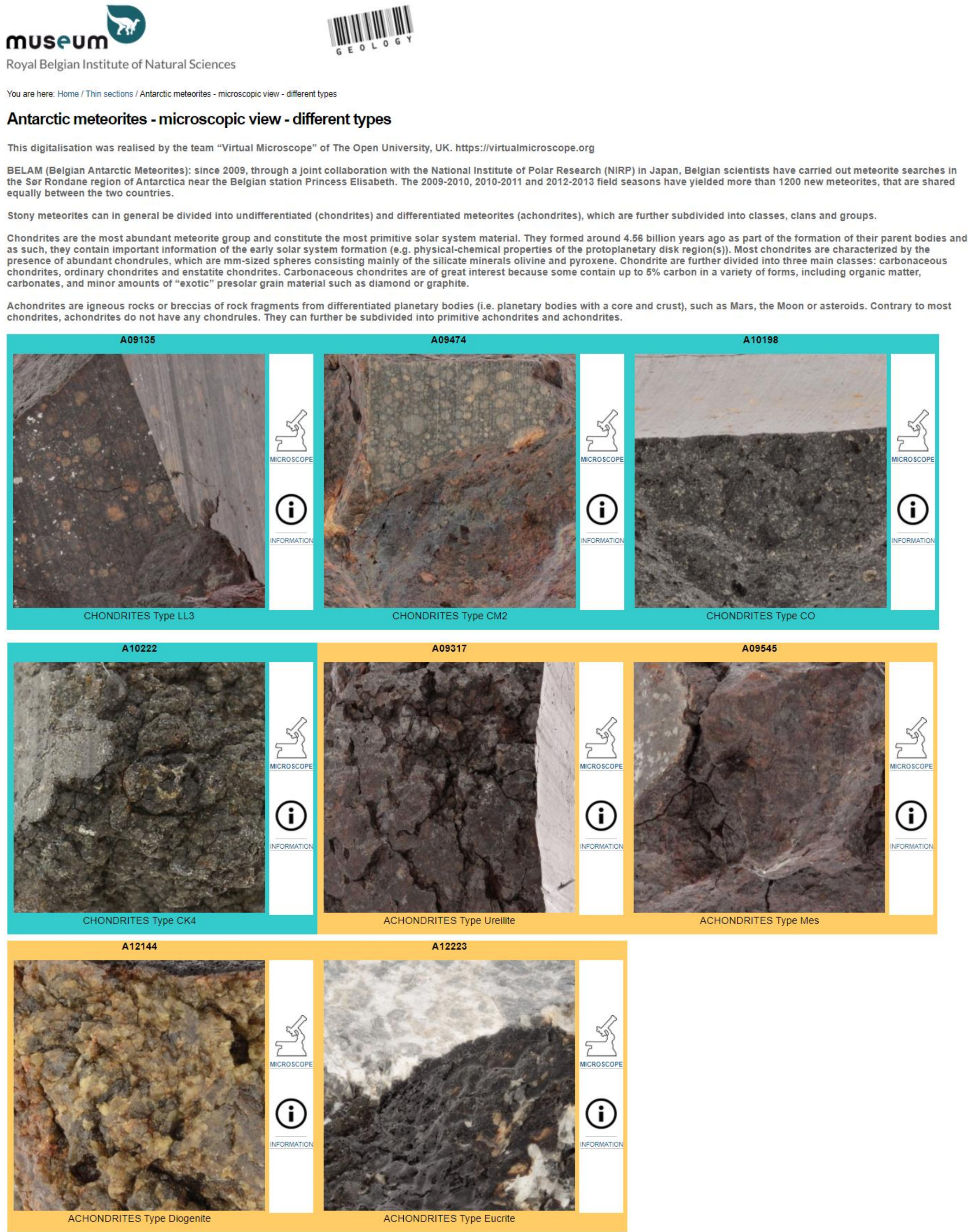


Figure 24. Screenshot of the web page illustrating the meteorites investigated for digitizing

For every specimen, one can see the digitized thin section, and virtually rotate the section around two or three rotation points, under plane polarised light and between crossed polars (Figure 25). It is also possible to get more information about the meteorite by clicking on the “information” icon (Figure 26).

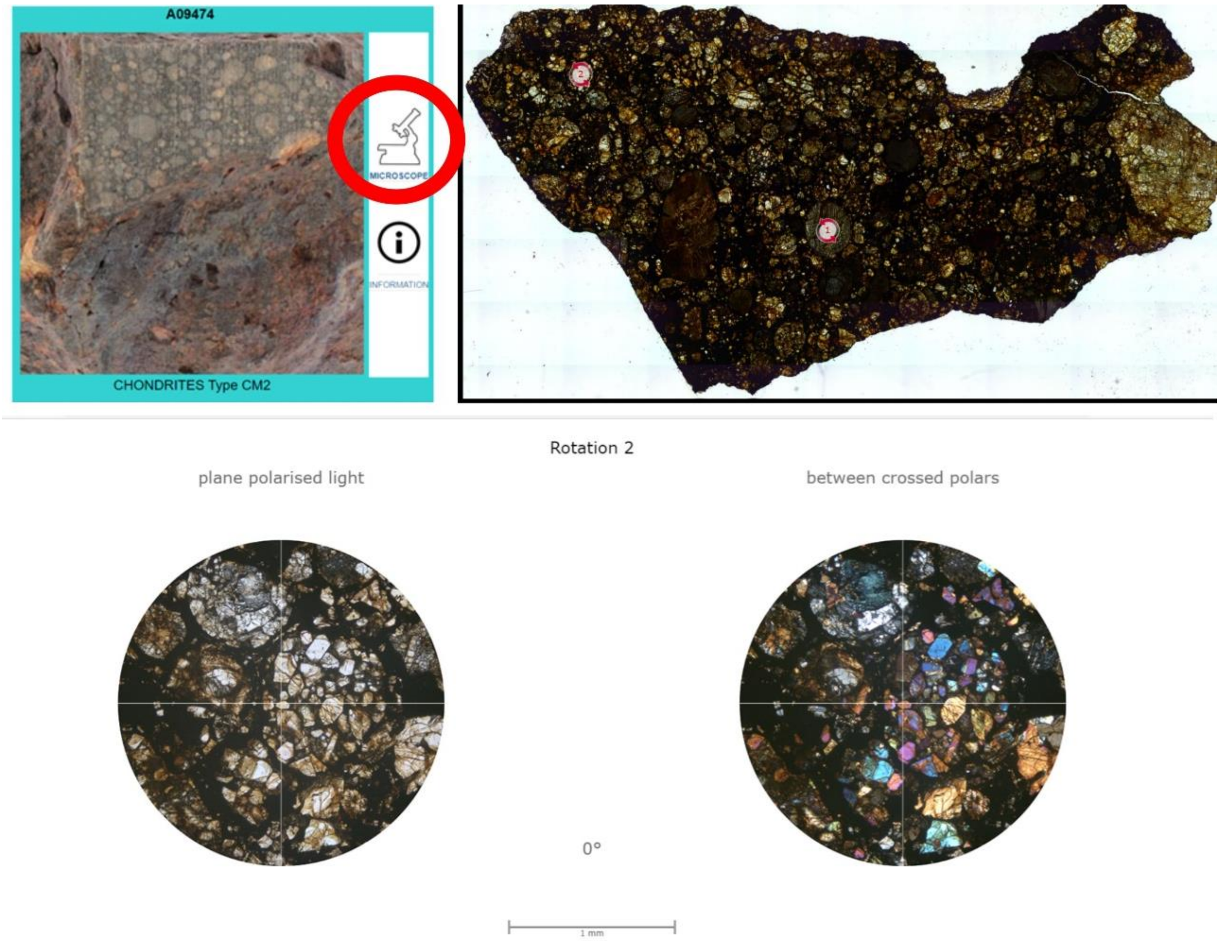


Figure 25. Screenshot of the page showing the thin section (sample A09474) under the virtual microscope

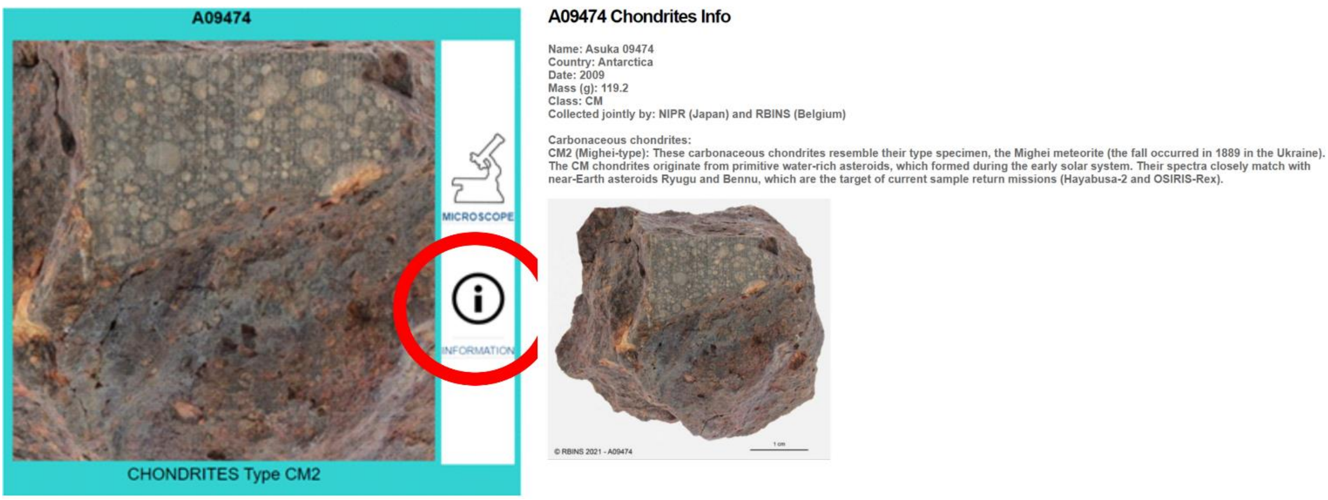


Figure 26. Detailed information about the digitized specimen (here sample A09474)

5.2. Paper in Science Advances – van Ginneken et al. 2021

Ground-breaking research on the collected material enhances the visibility of BELSPO at international scale regarding scientific works in Antarctica. One of the most striking examples is given by a paper published very recently (March 2021) in the journal *Science Advances* (Press release provided in Figure 7). This publication focuses on a large meteoritic event over Antarctica and the key role played by BELSPO (through the AMUNDSEN project) is clearly mentioned.

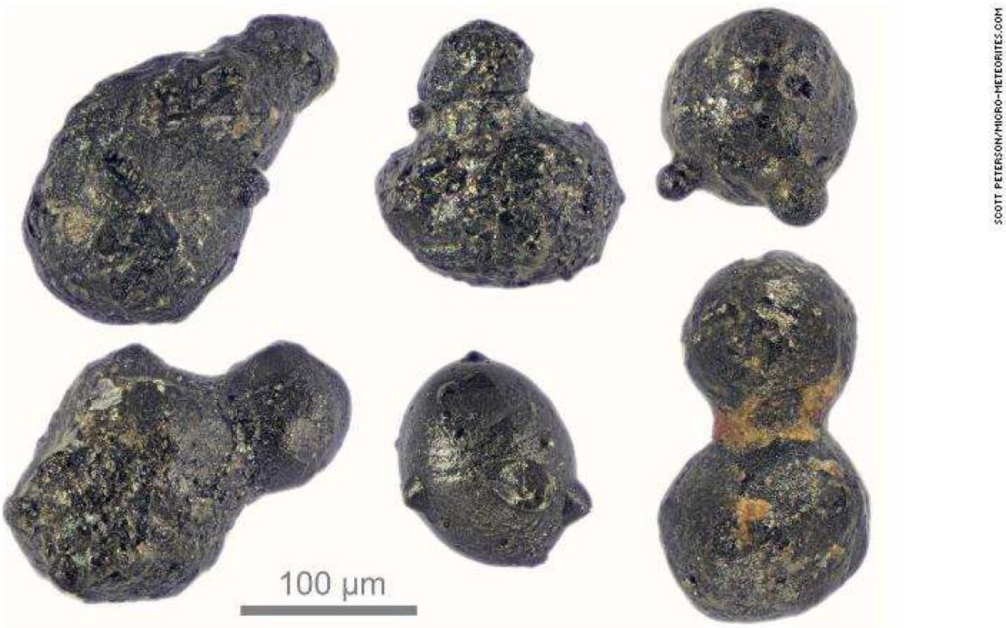
This paper was broadly advertised towards a large audience in media as diverse as CNN, National Geographic, Het Nieuwsblad, La Libre, Paris Match, RTBF, RTL, VRT, among others (see Figure 27 here below; the first page of a selection of articles are provided in Annex 1).

SPACE'S NEXT CHAPTER

A meteorite exploded in the air above Antarctica 430,000 years ago

CNN World

Updated 1800 GMT (0200 HKT) March 31, 2021



A micrograph of impact particles from the Sør Rondane Mountains, Antarctica, is shown here.

(CNN) — Tiny particles recovered from the summit of a mountain in Antarctica are clues that a meteorite more than 100 yards wide exploded in the sky 430,000 years ago, sending a fireball of vaporized extraterrestrial material to the icy surface, according to new research.

Such "airbursts" are thought to occur more frequently than falling meteors or much larger asteroids that leave craters in the ground -- such as the one that killed off the dinosaurs 66 million years ago. Identifying these space rocks, however, is much harder because they leave few traces in the geological record.

"Asteroids must be sufficiently massive to make it through the atmosphere and reach the ground with enough speed to form an impact crater. Smaller objects, which are much more abundant, explode in the atmosphere and do not form a crater," said Mark Boslough, a researcher at the University of New Mexico, who has studied meteorite explosions but wasn't involved in this latest study.

Matthias van Ginneken, a research associate from the University of Kent's School of Physical Sciences, collected the 17 dark black particles -- all smaller than 1 millimeter and invisible to the naked eye -- while on an expedition to the Sør Rondane Mountains, Queen Maud Land, in East Antarctica, where the Belgian Princess Elisabeth Antarctica station is based.

Figure 27. Article published by CNN about Van Ginneken's paper (Science Advances 2021)

6. PUBLICATIONS

6.1. Peer review papers

2019

- Zekollari, H., Goderis, S., Debaille, V., Van Ginneken, M., Gattacceca, J., Jull, A.J. T., Lenaerts, J.T.M., Yamaguchi, A., Huybrechts, P., Claeys, P. (2019). Unravelling the high-altitude Nansen blue ice field meteorite trap (East Antarctica) and implications for regional palaeo-conditions. Geochimica and Cosmochimica Acta 248, 289-310. doi:10.1016/j.gca.2018.12.035

2020

- Goderis, S., Soens, B., Huber, M., McKibbin, S., Van Ginneken, M., Van Maldeghem, F., Debaille, V., Greenwood, R., Franchi, I., Cnudde, V., Van Malderen, S., Vanhaecke, F., Koeberl, C., Topa, D., & Claeys, P. (2020). Cosmic spherules from Widerøefjellet, Sør Rondane Mountains (East Antarctica). Geochimica et cosmochimica acta, 270, 112-143. doi:10.1016/j.gca.2019.11.016
- Soens, B., Martin D. Suttle, M.D., Maeda, R., Frank Vanhaecke, F., Yamaguchi, A., Van Ginneken, M., Debaille, V., Claeys, Ph., Goderis, S. Evidence for the presence of chondrule- and CAI-derived material in an isotopically anomalous Antarctic micrometeorite. Meteoritics and Planetary Science 1-24. https://doi.org/10.1111/maps.13599

2021

- Soens, B., van Ginneken, M., Chernonozhkin, S., Slotte, N., Debaille, V., Vanhaecke, F., Terryn, H., Claeys, Ph., Goderis, S. (accepted). Australasian microtektites across the Antarctic continent: evidence from the Sør Rondane Mountain range (East Antarctica). Geoscience Frontiers 12, 101153.
- Van Ginneken, M., Goderis, S., Artemieva, N., Debaille, V., Decrée, S., Harvey, R. P., ... & Claeys, P. 2021. A large meteoritic event over Antarctica ca. 430 ka ago inferred from chondritic spherules from the Sør Rondane Mountains. Science advances, 7(14), eabc1008.

2022

- van Ginneken, M., Debaille, V., Decrée, S., Goderis, S., Woodland, A.B., Wozniakiewicz, P., De Ceukelaire, M., Leduc, T. and Claeys, P. (2022), Artificial weathering of an ordinary chondrite: Recommendations for the curation of Antarctic meteorites. Meteorit Planet Sci. https://doi.org/10.1111/maps.13818

6.2. Conference abstracts

2016

- B. Soens, S. Goderis, S. McKibbin, L. Pittarello, M. Van Ginneken, V. Debaille, P. Claeys 2016. Environmental control on Antarctic micrometeorite preservation state: The Wideroefjellet Mountain case study. 79th Annual Meeting of the Meteoritical Society, abstract n°6274
- B. Soens, S. Goderis, S. McKibbin, L. Pittarello, M. Van Ginneken, V. Debaille, P. Claeys 2016. A synthesis of triple-Oxygen isotope analyses on Antarctic micrometeorites. VIII SHRIMP Workshop 2016, Granada (Spain)

2017

- Debaille V., Gataccecca J., Rochette P., Pourkhorsandi H., Van Ginneken M., Leduc T., De Ceukelaire M., Goderis S., Claeys Ph. 2017. Classification of Antarctic meteorites by magnetic susceptibility. 8th Symposium on Antarctic meteorites, Tokyo, Japan.
- Soens B., Goderis S., Greenwood R. C., Mckibbin S., Van Ginneken M., Vanhaecke F., Debaille V., Franchi I. A., and Claeys Ph. 2017. Major, trace element concentration and triple-oxygen isotope compositions of g- and i-type spherules from the Sør Rondane Mountains, East Antarctica. 80th Meteoritical Society Annual Meeting, Santa Fe, USA. Vol. 52, p. 6288 (abstract).

- Soens B., Franchi I. A., Goderis S., Mckibbin S., Van Ginneken M., Debaille V., and Claeys, Ph. 2017. NanoSIMS Triple-Oxygen Isotope Analyses of Glass-Type Cosmic Spherules from the Sør Rondane Mountains, East Antarctica. Goldschmidt abstracts.
- Van Ginneken M., Mckibbin S., Ávila J. N., Ireland T., Holden P., Goderis S., Soens B., Claeys P., Debaille V., Folco L., and Rochette P. 2017. Identification of the parent bodies of micrometeorites: high-precision oxygen isotopic compositions with SHRIMP-SI. 80th Meteoritical Society Annual Meeting, Santa Fe, USA. Vol. 52, p. 6030 (abstract).
- Van Ginneken M., Mckibbin S.J., Avila J.N., Ireland T.R., Holden P., Goderis S., Soens B., Claeys P., Debaille V., Folco L. and Rochette P. Measuring oxygen isotopes in micrometeorites using SHRIMP. Goldschmidt 2017.

2018

- Goderis S., van Ginneken M., Soens B., Debaille V., and Claeys Ph. Micrometeorite accumulation in the Sør Rondane Mountains of East Antarctica. 2018. NIPR symposium abstract.
- Soens B., Peeters G., van Ginneken M., Debaille V., Claeys Ph., and Goderis S. 2018. Petrographic & geochemical characterization of a chondrule-like object preserved in an Antarctic micrometeorite. 2018. Goldschmidt abstracts.
- Van Ginneken M., Goderis S., Soens B., Debaille V., and Claeys Ph. 2018. Micrometeorites from the Sør Rondane Mountains, Antarctica. Workshop METEORITES – Understanding the origin of planetodiversity, Paris, 2018.
- Van Ginneken M., Goderis S., Soens B., Debaille V., and Claeys Ph. 2018. Micrometeorites from the Sør Rondane Mountains, Antarctica. Goldschmidt abstracts.

2019

- Van Ginneken M., Artemieva N., Claeys P., Debaille V., Decrée S., Hecht L., Yang S., Kaufmann F., Soens B., van Maldeghem F., Humayun M. and Goderis S. 2019. Meteoritic ablation debris from the Sør Rondane Mountains, Antarctica. 82d Meteoritical Society Annual Meeting, Sapporo, Japan.
- Pourkhorsandi H., Debaille V., Armytage R.M.G., Van Ginneken M., Rochette P. and Gattacceca J. 2019. The effects of terrestrial weathering on Samarium-Neodymium isotopic composition of chondrites. 82d Meteoritical Society Annual Meeting, Sapporo, Japan.
- Soens B., Villeneuve J., Van Ginneken M., Debaille V., Vanhaecke F., Claeys P. and Goderis S. 2019. Achondritic cosmic spherules from the Sør Rondane Mountains, East Antarctica: probing the asteroid belt beyond the meteorite inventory. 82d Meteoritical Society Annual Meeting, Sapporo, Japan.
- Soens B., Van Ginneken M., Debaille V., Vanhaecke F., Claeys P. and Goderis S. Microtektites from the Sør Rondane Mountains, East Antarctica: towards an extension of the Australasian strewn field? 82d Meteoritical Society Annual Meeting, Sapporo, Japan.

2021

- Van Ginneken M. et al. 2021. A large meteoritic event over Antarctica ca. 430 ka ago inferred from chondritic spherules from the Sor Rondane Mountains. Europlanet Science Congress 2021; Virtual meeting 13 – 24 September 2021

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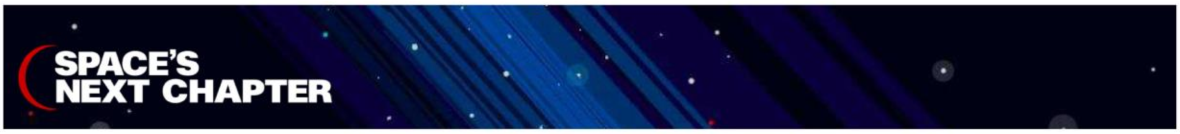
ANNEXES

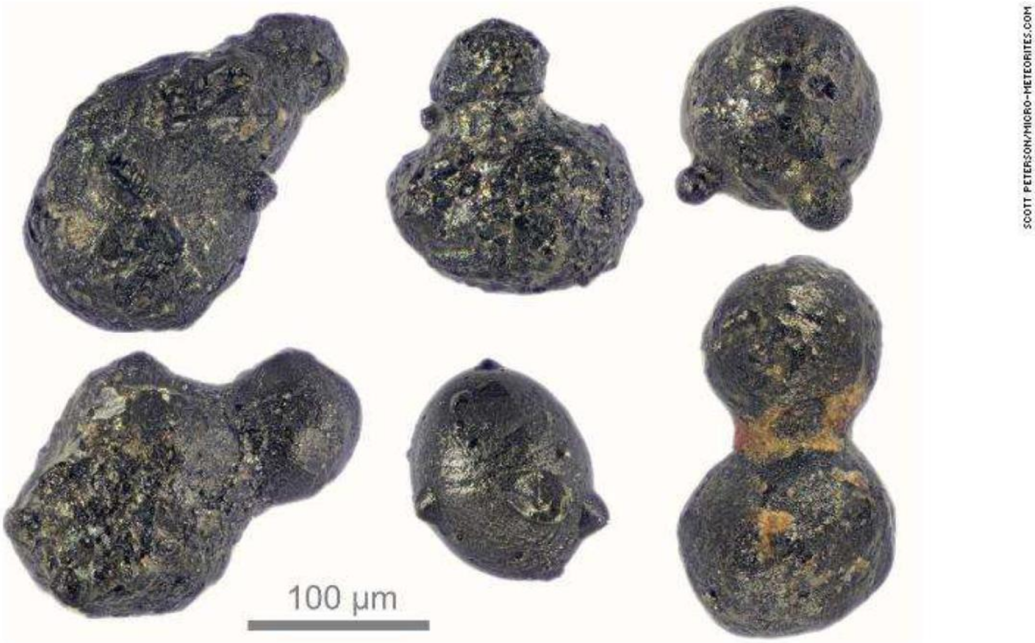
ANNEX 1. ADVERTISEMENT OF VAN GINNEKEN'S PAPER (SCIENCE ADVANCES 2021)



A meteorite exploded in the air above Antarctica 430,000 years ago

CNN World

Updated 1800 GMT (0200 HKT) March 31, 2021



A micrograph of impact particles from the Sør Rondane Mountains, Antarctica, is shown here.

(CNN) — Tiny particles recovered from the summit of a mountain in Antarctica are clues that a meteorite more than 100 yards wide exploded in the sky 430,000 years ago, sending a fireball of vaporized extraterrestrial material to the icy surface, according to new research.

Such "airbursts" are thought to occur more frequently than falling meteors or much larger asteroids that leave craters in the ground -- such as the one that killed off the dinosaurs 66 million years ago. Identifying these space rocks, however, is much harder because they leave few traces in the geological record.

"Asteroids must be sufficiently massive to make it through the atmosphere and reach the ground with enough speed to form an impact crater. Smaller objects, which are much more abundant, explode in the atmosphere and do not form a crater," said Mark Boslough, a researcher at the University of New Mexico, who has studied meteorite explosions but wasn't involved in this latest study.

Matthias van Ginneken, a research associate from the University of Kent's School of Physical Sciences, collected the 17 dark black particles -- all smaller than 1 millimeter and invisible to the naked eye -- while on an expedition to the Sør Rondane Mountains, Queen Maud Land, in East Antarctica, where the Belgian Princess Elisabeth Antarctica station is based.

"I first noticed that some of them looked like they had been stuck together, which would have had to have happened when they were molten. It would have meant lots of them interacting with each other when they were at a very high temperature. The only sensible way to explain this was a huge impact," said van Ginneken, the lead author of the study that published in the journal Science Advances on Wednesday.

NATIONAL GEOGRAPHIC LOGIN

An artist's depiction of a "touchdown" meteor impact over Antarctica.
ILLUSTRATION BY MARK A. GARLICK, MARKGARLICK.COM

SCIENCE NEWS

430,000 years ago a meteor exploded over Antarctica, leaving clues in the debris

Remnants from the space rock may help explain how often these cosmic explosions occur—and the threat they pose to Earth.

BY NADIA DRAKE

PUBLISHED MARCH 31, 2021 • 9 MIN READ

Ages ago, an asteroid about the length of a soccer field arced through the solar system on a collision course with Earth. It hurtled toward the planet's southern pole, aiming straight for an icy, unpopulated expanse: Antarctica.

It was 430,000 years ago, in the middle of the Pleistocene epoch. Elsewhere, some of the earliest Neanderthals were spreading across Europe, mammoths roamed the Northern Hemisphere, and Earth's ice sheets were growing thicker.

The space rock slammed into the planet's thick atmosphere. Friction tore it apart, and as the disintegrating meteor plummeted toward the Antarctic plateau, it left a flaming, incandescent trail in its wake. As it neared the ice, the meteor exploded in the sky, launching a superheated jet of gas and vaporized cosmic debris straight at the ground.

These kinds of mid-air explosions can cause immense amounts of damage, but they don't gouge craters in Earth's crust—meaning that finding their leftover fingerprints, and determining how frequently they occur, has been a bit of a guessing game.

Now, scientists studying tiny particles found in Antarctica have uncovered evidence of this ancient meteoritic airburst, and they used chemical clues locked in the particles to piece together what happened hundreds of thousands of years ago.

Un impact météorique de 430.000 ans découvert au-dessus de l'Antarctique

Publié le 01-04-21 à 18h27 à Bruxelles (Belgique)

Une équipe internationale de géologues spécialisés dans les météorites a découvert sur la calotte glaciaire de l'Antarctique de nouvelles preuves d'un impact laissé par une météorite ayant explosé à basse altitude il y a 430.000 ans, a indiqué jeudi l'Université libre de Bruxelles (ULB) dans un communiqué. Matérialisées dans de petites particules d'impact et non un cratère, les preuves de tels événements restent rares.Lors d'une

expédition menée en 2017-2018 depuis la station belge Princesse Elisabeth, l'équipe, dirigée par le Dr Matthias van Ginneken de l'École des sciences physiques de l'Université britannique du Kent et ancien chercheur à l'ULB, la Vrije Universiteit Brussel (VUB) et l'Institut royal des sciences naturelles (IRSNB), a mis au jour des particules extraterrestres appelées "sphérules de condensation" dans la chaîne montagneuse de Sor Rondane, dans l'est de l'Antarctique. Ces particules sont liées à une explosion aérienne inhabituelle de météorite. Quand elles entrent dans l'atmosphère, les grosses météorites peuvent en effet s'écraser et former un cratère au sol, ou exploser en plein vol. Dans ce second cas, elles génèrent une onde de choc puissante et destructrice. Cela avait par exemple été le cas en 2013, rappelle l'ULB, lorsqu'une météorite avait explosé au-dessus de la métropole russe de Tcheliabinsk, projetant des éclairs incandescents dans le ciel et blessant près d'un millier de personnes dans cette région de l'Oural. Un siècle plus tôt, le 30 juin 1908, un astéroïde avait éclaté au-dessus de Toungouska, en Sibérie. Il avait détruit la forêt sur environ 20

Meteoriet explodeerde boven de zuidpool: kracht van 1.000 Hiroshima-kernbommen

31/03/2021 om 20:41 | Bron: BELGA - Print - Corrigeer (mailto:redactienbo@nieuwsblad.be?subject=Correctie%20-%20'Meteoriet%20explodeerde%20boven%20de%20zuidpool%3A%20kracht%20van%201.000%20Hiroshima-kernbommen'&body=https://www.nieuwsblad.be/cnt/dmf20210331_96744287)

Themabeeld (FOTO: IPF)

Onderzoek van VUB en ULB, in samenwerking met een internationaal team van onderzoekers uit verschillende universiteiten in Europa, Rusland en de Verenigde Staten heeft aangetoond dat 430.000 jaar geleden een grote meteoriet met een diameter van ongeveer 100 meter is ontploft boven Antarctica. De reusachtige meteoriet drong de dampkring binnen en explodeerde, nog voor hij het ijs van de Zuidpool bereikte, met een kracht vergelijkbaar met die van 1.000 Hiroshima-kernbommen.

"De explosie moet voor een vernietigende schade hebben gezorgd in een straal van tientallen tot enkele honderden kilometers rond de plek van de explosie", zegt VUB-prof Steven Goderis, die in 2018 de expeditie leidde die de ontdekkingen mogelijk maakte.

Goderis en zijn team trokken toen op zoek naar micrometeorieten in de Walnumfjellet, die deel uitmaakt van het Sør Rondanegebergte in het oosten van Antarctica. "De microscopisch kleine brokstukken van de ingeslagen meteoriet hebben een speciale samenstelling, waardoor ze goed te onderscheiden zijn van de gewone meteorieten en micrometeorieten die we op Antarctica vinden. Ze hebben een samenstelling die overeenkomt met die van meteorieten, maar reflecteren ook de zuurstofisotopische samenstelling van het Antarctische ijs."

De explosie kon gedateerd worden aan de hand van verschillende boorkernen die in de loop van de voorbije decennia in het poolijs zijn verzameld. In een aantal van die boorkernen vonden de onderzoekers ook sporen van de kosmische explosie.

"Waarschijnlijk komen dergelijke 'airburst-achtige' fenomenen geregeld voor, maar we vinden er meestal geen enkel spoor van terug", zegt Goderis. "In 2013 was er in het Siberische Chelyabinsk een gelijkaardige maar veel kleinere bijna-inslag, die toen veel schade veroorzaakte en waarbij wonderbaarlijk genoeg bijna uitsluitend materiële schade werd aangericht. Nog in Rusland, in Tunguska, werd in 1908 een gelijkaardige impact van een 100 meter grote meteoroïde beschreven. Waarschijnlijk moeten we rekening houden met een frequentie voor een inslag van die omvang van één keer om de duizend tot vijfduizend jaar."

Er blijft een kleine kans bestaan dat de meteoriet effectief het aardoppervlak heeft geraakt en dat de sporen daarvan in de loop van de voorbije vierhonderdduizend jaar letterlijk zijn ondergesneeuwd. In dat geval bevindt de impactkrater zich wellicht onder een flinke laag ijs. Toekomstig onderzoek kan daar eventueel uitsluitsel over geven. "De kans is redelijk klein", denkt Goderis. "Maar niet helemaal onbestaand. Waar we wel zeker van zijn, is dat we de sporen van de thermische impact die zo'n explosie heeft veroorzaakt beter in kaart zullen kunnen brengen. Ook de schokgolf die na de explosie volgde, zal waarschijnlijk ergens sporen zal hebben nagelaten."

Het onderzoek werd gepubliceerd in Science Advances onder de titel 'A large meteoritic event over Antarctica ca. 430 ka ago inferred from chondritic spherules from the Sør Rondane Mountains'. Hoofdauteur is Matthias van Ginneken, nu aan de Universiteit van Kent maar destijds voor het onderzoek verbonden aan de VUB. Het onderzoek werd mede mogelijk gemaakt door de logistieke ondersteuning vanuit het Belgische Prinses Elisabethstation op Antarctica, en de financiële ondersteuning door het federaal wetenschapsbeleid (Belspo).

ACCUEIL (HTTPS://PARISMATCH.BE) > TECHNOLOGIE (HTTPS://PARISMATCH.BE/LIFESTYLE/TECHNOLOGIE)

Un impact météorique de 430 000 ans découvert au-dessus de l'Antarctique

Rédaction Paris Match Belgique (https://parismatch.be/author/redactionwebbe) | Publié le 2 avril 2021 | Mis à jour le 2 avril 2021

Image d'illustration. | © Unsplash.

La découverte a été faite par une équipe de chercheurs de l'Université Libre de Bruxelles.

Une équipe internationale de géologues spécialisés dans les météorites a découvert sur la calotte glaciaire de l'Antarctique de nouvelles preuves d'un impact laissé par une météorite ayant explosé à basse altitude il y a 430 000 ans, a indiqué jeudi l'Université libre de Bruxelles (ULB) dans un communiqué. Matérialisées dans de petites particules d'impact et non un cratère, les preuves de tels événements restent rares.
Lire aussi > Une météorite martienne trouvée en Antarctique prouverait l'existence d'une vie sur la planète rouge (https://parismatch.be/actualites/401419/une-meteorite-martienne-trouvee-en-antarctique-prouverait-lexistence-dune-vie-sur-la-planete-rouge)

Un événement à la puissance destructrice considérable

Lors d'une expédition menée en 2017-2018 depuis la station belge Princesse Elisabeth, l'équipe, dirigée par le Dr Matthias van Ginneken de l'École des sciences physiques de l'Université britannique du Kent et ancien chercheur à l'ULB, la Vrije Universiteit Brussel (VUB) et l'Institut royal des sciences naturelles (IRSNB), a mis au jour des particules extraterrestres appelées « sphérules de condensation » dans la chaîne montagneuse de Sor Rondane, dans l'est de l'Antarctique.

INFO

Société

Des particules extraterrestres appelées "sphérules de condensation" identifiées dans l'est de l'Antarctique

(//app-eu.readspeaker.com/cgi-bin/rsent?customerid=7764&lang=fr_be&readid=id-text2speech-article&url=www.rtbf.be%2Finfo%2Fsociete%2Fdetail_des-particules-extraterrestres-appelees-spherules-de-condensation-identifiees-dans-l-est-de-l-antarctique%3Fid%3D10732892)

(#)

Steven Goderis (VUB) et Matthias van Ginneken (ULB) sur la chaîne montagneuse Sor Rondane en Antarctique. La moraine de fond et les sédiments près de la crête ont été échantillonnés et tous deux contiennent des micrométéorites. - © FRANS STEENHOUDT - BELGAIMAGE

RTBF avec Agences

Publié le jeudi 01 avril 2021 à 21h51

Une équipe internationale de géologues spécialisés dans les météorites a découvert sur la calotte glaciaire de l'Antarctique de nouvelles preuves d'un impact laissé par une météorite ayant explosé à basse altitude il y a 430.000 ans, a indiqué jeudi l'Université libre de Bruxelles (ULB) dans un communiqué. Matérialisées dans de petites particules d'impact et non un cratère, les preuves de tels événements restent rares.

Lors d'une expédition menée en 2017-2018 depuis la station belge Princesse Elisabeth, l'équipe, dirigée par le Dr Matthias van Ginneken de l'École des sciences physiques de l'Université britannique du Kent et ancien chercheur à l'ULB, la Vrije Universiteit Brussel (VUB) et l'Institut royal des sciences naturelles (IRSNB), a mis au jour des particules extraterrestres appelées "*sphérules de condensation*" dans la chaîne montagneuse de Sor Rondane, dans l'est de l'Antarctique.

Comme en Sibérie

Ces particules sont liées à une explosion aérienne inhabituelle de météorite. Quand elles entrent dans l'atmosphère, les grosses météorites peuvent en effet s'écraser et former un cratère au sol, ou exploser en plein vol. Dans ce second cas, elles génèrent une onde de choc puissante et destructrice. Cela avait par exemple été le cas en 2013, rappelle l'ULB, lorsqu'une météorite avait explosé au-dessus de la métropole russe de Tcheliabinsk, projetant des éclairs incandescents dans le ciel et blessant près d'un millier de personnes dans cette région de l'Oural. Un siècle plus tôt, le 30 juin 1908, un astéroïde avait éclaté au-dessus de Toungouska, en Sibérie. Il avait détruit la forêt sur environ 20 km2 et produit une onde de choc dont les dégâts étaient encore notables une centaine de kilomètres plus loin, avec une puissance estimée à près de 30 fois la bombe d'Hiroshima.

4/6/2021 Un impact météorique de 430.000 ans découvert au-dessus de l'Antarctique - RTL Info

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Un impact météorique de 430.000 ans découvert au-dessus de l'Antarctique

Agence Belga , publié le 01 avril 2021 à 18h27

(Belga) Une équipe internationale de géologues spécialisés dans les météorites a découvert sur la calotte glaciaire de l'Antarctique de nouvelles preuves d'un impact laissé par une météorite ayant explosé à basse altitude il y a 430.000 ans, a indiqué jeudi l'Université libre de Bruxelles (ULB) dans un communiqué. Matérialisées dans de petites particules d'impact et non un cratère, les preuves de tels événements restent rares.

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A LA UNE

Il neige et il va CONTINUER à neiger: voici les prévisions météo pour les prochains jours

Coronavirus en Belgique: le nombre de nouveaux cas baisse enfin, mais sera-ce assez vite pour éviter la saturation des soins intensifs?

L'épidémie de bronchiolite touche les plus petits avec 3 mois de RETARD: le phénomène inquiète, comment l'expliquer?

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vrt NWS

Wetenschap

Voorstelling van een asteroïde die op een besneeuwde vlakte neerkomt.
Mark Garlick / markgarlick.com

Belgisch onderzoek bewijst dat 430.000 jaar geleden een grote meteoriet ontplofte ne boven Antarctica

Een internationaal onderzoeksteam heeft nieuwe bewijzen gevonden voor het feit dat 430.000 jaar geleden een asteroïde van minsten 100 meter groot net boven de Antarctische ijskap uiteen is gespat. De bewijzen zijn buitenaardse deeltjes met een unieke samenstelling die eerder door een Belgische expeditie op de Zuidpool waren gevonden.

Luc De Roy
wo 31 mrt 20:25

De buitenaardse partikels in kwestie worden sferische gecondenseerde deeltjes genoemd en ze werden gevonden op de top van de berg Walnumfjellet in het Sør Rondanegebergte in Oost-Antarctica.

Dat gebeurde tijdens de 2017-2018 BELAM (Belgian Antarctic Meteorites) expeditie die georganiseerd werd vanuit het Belgische Antarctische Prins Elisabethstation, met fondsen van het federaal wetenschapsbeleid (BELSPO).

De partikels, die gevonden werden in sedimenten, wijzen op een ongewone ontploffing van een bijzonder grote meteoriet in de lucht.

De deeltjes zijn nu onderzocht en geanalyseerd in een nieuwe studie door een internationaal onderzoeksteam van planetaire wetenschappers, on leiding van doctor Matthias van Ginneken van de School of Physical Sciences aan de University of Kent, een voormalig onderzoeker aan de Vrije Universiteit Brussel (VUB), de Université libre de Bruxelles (ULB) en het Koninklijk Belgisch Instituut voor Natuurwetenschappen (KBIN).

ANNEX 2. PUBLICATIONS (ONLY THE FIRST PAGE IS PRESENTED, THE PAPERS ARE PROVIDED AS SEPARATE FILES)

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Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 248 (2019) 289–310

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Unravelling the high-altitude Nansen blue ice field meteorite trap (East Antarctica) and implications for regional palaeo-conditions

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Received 19 March 2018; accepted in revised form 23 December 2018; available online 4 January 2019

Abstract

Antarctic blue ice zones, the most productive locations for meteorite recovery on Earth, contain old ice that is easily accessible and available in large quantities. However, the mechanisms behind these meteorite traps remain a topic of ongoing debate. Here, we propose an interdisciplinary approach to improve our understanding of a meteorite trap in Dronning Maud Land (East Antarctica) on the Nansen blue ice field meteorite trap (2600–3100 m above sea level), where more than half of the Asuka meteorites have been collected. Based on 185 surface blue ice samples, one of the largest observed spatial patterns in oxygen isotopic variation to date is found. Relying on meteorites for which the terrestrial ages are determined using ^{14}C and ^{36}Cl, this surface ice is interpreted to date from the Last Interglacial up to the present-day. By combining state-of-the-art satellite derived surface velocities, surface mass balance modelling and ice flow modelling, we estimate that about 75–85% of the meteorites found on the ice field were supplied by ice flow after entering the ice sheet in an accumulation area of a few hundred square kilometres located south (upstream) of the ice field. Less than 0.4 new meteorites per year are supplied to the ice field through ice flow, suggesting that the hundreds of meteorites found 25 years after the first visit to this ice field mostly represent meteorites that were previously not found, rather than newly supplied meteorites. By combining these findings, the infall rate of meteorites from space is estimated, which is in line with values from the literature, but situated at the higher end of the range. A comparison of the oxygen isotopic variation of the surface blue ice to that of the European Project for Ice Coring

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https://doi.org/10.1016/j.gca.2018.12.035
0016-7037/

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Geochimica et Cosmochimica Acta
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Cosmic spherules from Wideroefjellet, Sør Rondane Mountains (East Antarctica)

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Abstract

A newly discovered sedimentary accumulation of micrometeorites in the Sør Rondane Mountains of East Antarctica, close to the Wideroefjellet summit at ~2750 m above sea level, is characterized in this work. The focus here lies on 2099 melted cosmic spherules larger than 200 μm, extracted from 3.2 kg of sampled sediment. Although the Wideroefjellet deposit shares similarities to the micrometeorite traps encountered in the Transantarctic Mountains, both subtle and more distinct differences in the physicochemical properties of the retrieved extraterrestrial particles and sedimentary host deposits are discernable (e.g., types of bedrock, degree of wind exposure, abundance of metal-rich particles). Unlike the Frontier Mountain and Miller Butte sedimentary traps, the size fraction below 240 μm indicates some degree of sorting at Wideroefjellet, potentially through the redistribution by wind, preferential alteration of smaller particles, or processing biases. However, the cosmic spherules larger than 300 μm appear largely unbiased following their size distribution, frequency by textural type, and bulk chemical compositions. Based on the available bedrock exposure ages for the Sør Rondane Mountains, extraterrestrial dust is estimated to have accumulated over a time span of ~1–3 Ma at Wideroefjellet. Consequently, the Wideroefjellet collection reflects a substantial reservoir to sample the micrometeorite influx over this time interval. Petrographic observations and 3D microscopic CT imaging are combined with chemical and triple-oxygen isotopic analyses of silicate-rich cosmic spherules larger than 325 μm. The major element composition of 49 cosmic spherules confirms their principally chondritic parentage. For 18 glassy, 15 barred olivine, and 11 cryptocrystalline cosmic spherules, trace element concentrations are also reported on.

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Evidence for the presence of chondrule- and CAI-derived material in an isotopically anomalous Antarctic micrometeorite

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Abstract–We report the discovery of a unique, refractory phase-bearing micrometeorite (WF1202A-001) from the Sør Rondane Mountains, East Antarctica. A silicate-rich cosmic spherule (~400 µm) displays a microporphyritic texture containing Ca-Al-rich inclusion (CAI)-derived material (~5–10 area%), including high-Mg forsterite (Fo_{98-99}) and enstatite (En_{98-99}, Wo_{0-1}). The micrometeorite also hosts a spherical inclusion (~209 µm), reminiscent of chondrules, displaying a barred olivine texture. Oxygen isotopic compositions of the micrometeorite groundmass ($\delta^{17}O$ = –3.46‰, $\delta^{18}O$ = 10.43‰, $\Delta^{17}O$ = –1.96‰) are consistent with a carbonaceous chondrite precursor body. Yet, a relict forsterite grain is characterized by $\delta^{17}O$ = –45.8‰, $\delta^{18}O$ = –43.7‰, $\Delta^{17}O$ = –23.1‰, compatible with CAIs. In contrast, a relict low-Ca pyroxene grain ($\delta^{17}O$ = –4.96‰, $\delta^{18}O$ = –4.32‰, $\Delta^{17}O$ = –2.71‰) presumably represents a first-generation silicate grain that accreted ^{18}O-rich gas or dust in a transient melting scenario. The spherical inclusion displays anomalous oxygen isotope ratios ($\delta^{17}O$ = –0.98‰, $\delta^{18}O$ = –2.16‰, $\Delta^{17}O$ = 0.15‰), comparable to anhydrous interplanetary dust particles (IDPs) and fragments from Comet 81P/Wild2. Based on its major element geochemistry, the chondrule size, and oxygen isotope systematics, micrometeorite WF1202A-001 likely sampled a carbonaceous chondrite parent body similar to, but distinct from CM, CO, or CV chondrites. This observation may suggest that some carbonaceous chondrite bodies can be linked to comets. The reconstructed atmospheric entry parameters of micrometeorite WF1202A-001 suggest that the precursor particle originated from a low-inclination, low-eccentricity source region, most likely either the main belt asteroids or Jupiter family comets (JFCs).

INTRODUCTION

Chondrules are mm-sized, ferromagnesian objects formed by repeated flash-melting events in the solar nebula (Gooding et al. 1980; Wasson 1993; Hewins 1996; Rubin 2000a). As such, they represent a valuable archive recording the pre-accretionary history of the solar nebula. Various models have previously been proposed to explain chondrule formation, including gamma-ray bursts (McBreen and Hanlon 1999); nebular shock waves (Ciesla and Hood 2002; Desch and Connolly 2002); planetesimal collisions and impacts (Sanders and Scott 2012; Johnson et al. 2015); or, more recently, radiative heating from molten planetesimals or

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Research Paper

Australasian microtektites across the Antarctic continent: Evidence from the Sør Rondane Mountain range (East Antarctica)

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ABSTRACT

The ~790 ka Australasian (micro)tektite strewn field is one of the most recent and best-known examples of impact ejecta emplacement as the result of a large-scale cratering event across a considerable part of Earth's surface (>10% in area). The Australasian strewn field is characterized by a tri-lobe pattern consisting of a large central distribution lobe, and two smaller side lobes extending to the west and east. Here, we report on the discovery of microtektite-like particles in sedimentary traps, containing abundant micrometeorite material, in the Sør Rondane Mountain (SRM) range of East Antarctica. The thirty-three glassy particles display a characteristic pale yellow color and are predominantly spherical in shape, except for a single dumbbell-shaped particle. The vitreous spherules range in size from 220 to 570 μm, with an average diameter of ~370 μm. This compares relatively well with the size distribution (75–778 μm) of Australasian microtektites previously recovered from the Transantarctic Mountains (TAM) and located ca. 2500–3000 km from the SRM. In addition, the chemical composition of the SRM particles exhibits limited variation and is nearly identical to the 'normal-type' (i.e., <6% MgO) TAM microtektites. The Sr and Nd isotope systematics for a single batch of SRM particles ($n = 26$) strongly support their affiliation with TAM microtektites and the Australasian tektite strewn field in general. Furthermore, Sr isotope ratios and Nd model ages suggest that the target material of the SRM particles was composed of a plagioclase- or carbonate-rich lithology derived from a Paleo- or Mesoproterozoic crustal unit. The affiliation to the Australasian strewn field requires long-range transportation, with estimated great circle distances of ca. 11,600 km from the hypothetical source crater, provided transportation occurred along the central distribution lobe. This is in agreement with the observations made for the Australasian microtektites recovered from Victoria Land (ca. 11,000 km) and Larkman Nunatak (ca. 12,000 km), which, on average, decrease in size and alkali concentrations (e.g., Na and K) as their distance from the source crater increases. The values for the SRM particles are intermediate to those of the Victoria Land and Larkman Nunatak microtektites for both parameters, thus supporting this observation. We therefore interpret the SRM particles as 'normal-type' Australasian microtektites, which significantly extend the central distribution lobe of the Australasian strewn field westward. Australasian microtektite distribution thus occurred on a continent-wide scale across Antarctica and allows for the identification of new, potential recovery sites on the Antarctic continent as well as the southeastern part of the Indian Ocean. Similar to volcanic ash layers, the ~790 ka distal Australasian impact ejecta are thus a record of an instantaneous event that can be used for time-stratigraphic correlation across Antarctica.

1. Introduction

Tektites (and their submillimeter analogues microtektites) are natural, SiO_2-rich glasses that form during oblique hypervelocity impact of asteroidal or cometary bodies with the Earth's surface (e.g., Koeberl, 1994; Artemieva et al., 2002). They are distributed over large geographical areas (>100–1000 km) commonly referred to as 'strewn fields', which have previously been linked to large-scale impact cratering events in North America, Ivory Coast and Central Europe (Glass and Simonson, 2013).

The Australasian strewn field is among the largest (>10% of the Earth's surface) and most recent (788.1 ± 3.0 ka; Schwarz et al., 2016;

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SCIENCE ADVANCES | RESEARCH ARTICLE

PLANETARY SCIENCE

A large meteoritic event over Antarctica ca. 430 ka ago inferred from chondritic spherules from the Sør Rondane Mountains

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Large airbursts, the most frequent hazardous impact events, are estimated to occur orders of magnitude more frequently than crater-forming impacts. However, finding traces of these events is impeded by the difficulty of identifying them in the recent geological record. Here, we describe condensation spherules found on top of Walnumfjellet in the Sør Rondane Mountains, Antarctica. Affinities with similar spherules found in EPICA Dome C and Dome Fuji ice cores suggest that these particles were produced during a single-asteroid impact ca. 430 thousand years (ka) ago. The lack of a confirmed crater on the Antarctic ice sheet and geochemical and ^{18}O-poor oxygen isotope signatures allow us to hypothesize that the impact particles result from a touchdown event, in which a projectile vapor jet interacts with the Antarctic ice sheet. Numerical models support a touchdown scenario. This study has implications for the identification and inventory of large cosmic events on Earth.

INTRODUCTION

Remnants of hypervelocity impact on Earth's surface are mainly preserved as impact craters, generally circular depressions resulting from asteroids large and/or dense enough to reach ground level without suffering substantial atmospheric disruption (*1*). Crater formation is accompanied by the production of a characteristic set of shock-metamorphic effects (e.g., shocked quartz or shatter cones) and formation of high-pressure mineral phases (e.g., coesite and stishovite) in target rocks, resolvable geochemical anomalies, and ejection of target/projectiles materials with high velocity (e.g., tektites and microtektites) (*2*). Identifying hypervelocity impacts in the geological record is relatively straightforward if one or several of these features are identified. However, impactors several tens up to 150 m in size are totally fragmented and vaporized during atmospheric entry, resulting in a low-altitude airburst, similarly to the Tunguska and Chelyabinsk events over Russia in 1908 and 2013, respectively (*3*–*5*). Observation by direct eye witness accounts and indirect infrasound, seismic, video cameras, and numerical modeling of medium-sized airbursts have shown that these impacts represent a notable fraction of the extraterrestrial material accreted to Earth, with Tunguska-like events occurring once every 100 to 10,000 years, which is orders of magnitude more frequent than large crater-forming impacts (*6*). However, evidence of these events is scarce in the geological record, principally due to difficulty in identifying and characterizing potential residues (*7*). Finding evidence of these low-altitude meteoritic events thus remains critical to understanding the impact history of Earth and estimating hazardous effects of asteroid impacts. In recent years, meteoritic ablation debris resulting from airburst events have been found in three different locations of Antarctica. The material found at Miller Butte (Northern Victoria Land), Dome Concordia, and Dome Fuji all appears to have been produced during a Tunguska-like airburst event 480 thousand years (ka) ago (*7*–*9*). Here, we present the discovery of extraterrestrial particles formed during a significantly larger event recovered on the summit of Walnumfjellet (WN) within the Sør Rondane Mountains, Queen Maud Land, East Antarctica (Fig. 1). The characteristic features of the recovered particles attest to an unusual type of touchdown event, intermediate between an airburst and a crater-forming impact, during which the high-velocity vapor jet produced by the total disruption of an asteroid reached the Antarctic ice sheet.

RESULTS

The igneous particles studied in this work ($N = 17$) are dark black, subrounded to perfectly spherical. About half the particles are compound spherules consisting of two or more coalesced spherules (Fig. 2 and fig. S1). Scanning electron microscopy observations of polished sections of the particles indicate quench textures similar to S-type cosmic spherules (*10*). The mineralogy of the particles mainly consists of olivine and iron spinel, with minor interstitial glass. We subdivided the particles into four groups on the basis of their textures and spinel content: (i) spinel-rich (SR) particles ($N = 9$) characterized by abundant octahedral, cruciform and/or dendritic spinel (≥17% volume), and skeletal and/or euhedral olivine (Fig. 2, A and C, and fig. S1, A to F); (ii) spinel-poor (SP) particles ($N = 5$) characterized by large (>10 μm) skeletal or euhedral crystals of olivine with minor

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Artificial weathering of an ordinary chondrite: Recommendations for the curation of Antarctic meteorites

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Abstract–Meteorites are prone to errestrial weathering not only after their fall on the Earth's surface but also during storage in museum collections. To study the susceptibility of this material to weathering, weathering experiments were carried out on polished sections of the H5 chondrite Asuka 10177. The experiments consisted of four 100-days cycles during which temperature and humidity varied on a twelve hours basis. The first alteration cycle consisted of changing the temperature from 15 to 25 °C; the second cycle consisted of modifying both humidity and temperature from 35 to 45% and 15 to 25 °C, respectively; the third cycle consisted of varying the humidity level from 40 to 60%; and the fourth cycle maintained a fixed high humidity of 80%. Weathering products resulting from the experiments were identified and characterized using scanning electron microscopy–energy dispersive spectroscopy and Raman spectroscopy. Such products were not observed at the microscopic scale after the first cycle of alteration. Conversely, products typical of the corrosion of meteoritic FeNi metal were observed during scanning electron microscope surveys after all subsequent cycles. Important increases in the distribution of weathering products on the samples were observed after cycles 2 and 4 but not after cycle 3, suggesting that the combination of temperature and humidity fluctuations or high humidity (>60%) alone is most detrimental to chondritic samples. Chemistry of the weathering products revealed a high degree of FeNi metal corrosion with a limited contribution of troilite corrosion. No clear evidence of mafic silicate alteration was observed after all cycles, suggesting that postretrieval alteration remains limited to FeNi metal and to a lesser extent to troilite.

INTRODUCTION

Meteorites have been a subject of scientific scrutiny for centuries, even before the publication of Chladni's book in 1794 arguing that these unusual rocks came from space (Marvin, 2006; McCall et al., 2006). The fall of the Wold Cottage and L'Aigle meteorites in 1795 and 1803, respectively, was paramount to convince the scientific community that meteorites were indeed extraterrestrial in origin (Gounelle, 2006). Significant efforts around the world have focused on the acquisition of samples to establish meteorite collections ever since. The oldest and one of the biggest repositories of meteorites is held at the Museum of Natural History in Vienna, Austria, which was founded in the mid-18th century (Brandstätter, 2006). Following this trend, museums and research institutes all over the world started establishing their own meteorite

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