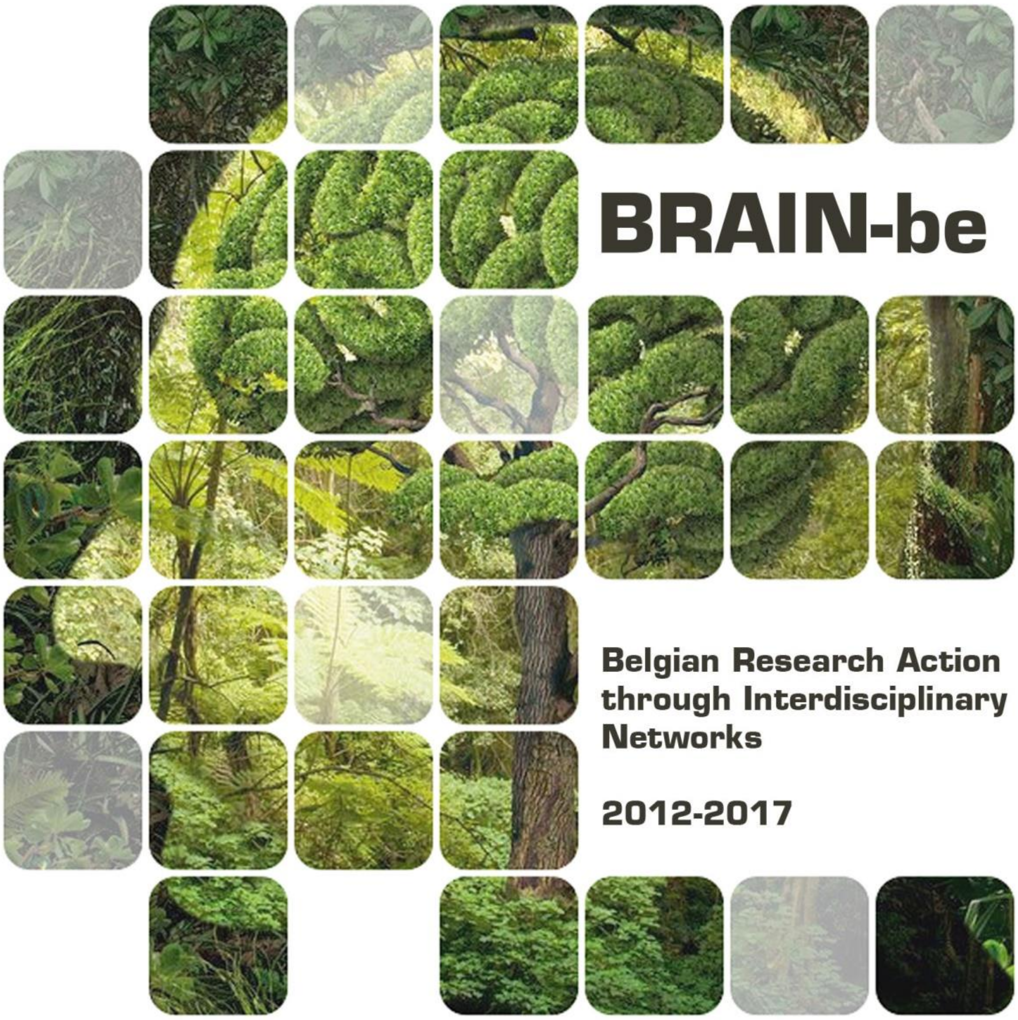

BAMM!

Belgian Antarctic Meteorites and Micrometeorites to document solar system formation and evolution

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NETWORK PROJECT

BAMM!

Belgian Antarctic Meteorites and Micrometeorites to document solar system formation and evolution

Contract - BR/175/A2/BAMM!

FINAL REPORT

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ABSTRACT

Since 2009, joint Belgian-Japanese missions in Antarctica have recovered more than 1200 highly pristine meteorites and >2500 micrometeorites from the blue ice fields surrounding the Sør Rondane Mountains. This Antarctic project aimed at extending the Belgian meteorite patrimony and stimulating meteorite curation and research at federal institutes and universities in Belgium, initially supported by the former BELAM (2012-2016) and AMUNDSEN (2016-2022) BELSPO projects. It built on and expanded the assembled expertise, and centered on a number of highly promising, but previously unexplored research opportunities provided by this valuable set of newly recovered extraterrestrial samples.

Meteorites constitute the most primitive objects in the solar system and represent the building blocks of the terrestrial planets. Their petrographic, chemical and isotopic study sheds light on the evolution of planetary materials in the early solar system and documents planetary differentiation processes. However, as (micro)meteorites represent highly fragile material, optimal preservation conditions are needed to provide a reliable understanding of their formational history. Antarctic (micro)meteorites constitute an enormous volume of extraterrestrial material that was preserved under excellent conditions thanks to a dry and cold climate, but may be lost in the future following the current climate change.

The objectives of the BAMM! project were to further constrain our understanding of the formation and evolution of solar system materials, investigating the meteorites and micrometeorites recently collected in the Sør Rondane Mountains of Antarctica, through two complementary approaches that converge by implementing state-of-the-art in situ isotopic analysis:

(1) A detailed study of micrometeorites and their igneous textures has been performed 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. One of the main focuses of this project has been to fully characterize a peculiar group of micrometeorites that, based on oxygen isotopes, does not appear to be represented among macroscopic meteorites.

(2) 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.

Another goal of the BAMM! project has been to further expand the Belgian Antarctic meteorite collection. As such, it encouraged a reliable, long-term protective curation program of Antarctic meteorites at the RBINS, which is now a key Antarctic (micro)meteorite curation center in Europe. Efforts were also made to disseminate the scientific results broadly, also towards a broad – non-scientific – audience.

Overall, the Sør Rondane Mountains deposits studied during the BAMM! project represent a rich, representative micrometeorite collection from East Antarctica that significantly contributed to better understand planetary differentiation processes. The scientific results have been valorized in a series of

important manuscripts, including top journals (including *Science Advances, Nature Astronomy, Geoscience Frontiers*).

The position of the RBINS as an internationally recognized meteorite curation center and expert in meteorite classification and studies has been consolidated during the BAMM! project, as testified by meteorite classification, exhibition and the new samples that entered the collection.

The BAMM! project emphasizes the importance of studies led on meteorites and micrometeorites to bring crucial information about planetary evolution. The continuation of the successful Antarctic program for collecting extraterrestrial material is of capital importance for the recovery of new material, the study of which ensuring the continuation of successful (micro)meteorite research at the national and international level.

Keywords

Antarctica, meteorites, micrometeorites, isotope anomalies, curation

1. INTRODUCTION

The BAMM! project has valorized the extraterrestrial material recovered from the surroundings of the Belgian Antarctic research station Princess Elisabeth (more than 1200 meteorites and >2500 micrometeorites so far) with the aim of 1) characterizing possibly unique extra-terrestrial parent bodies sampled only by micrometeorites, 2) investigating the measured isotopic discrepancy between primitive (and more evolved) asteroids sampled by meteorites and the terrestrial planets, which could reflect the effects of nebular and planetary processing of nucleosynthetic anomaly carrier phases, and 3) optimizing the curation of the extraterrestrial samples kept at the Royal Belgian institute for Natural Sciences by promoting the scientific value of this unique and large collection at the international level.

This research is part of a dense framework of national and international projects already dedicated to meteorites at one or more of the partner institutes. Among these, the BELAM project aimed at establishing a curation center dedicated to Antarctic meteorites at the RBINS. The Amundsen project was dedicated to provide best practices for meteorite curation in terms of curation conditions. Those projects converged to an optimal curation practices and the meteorite collection curated at the RBINS fully has supported the BAMM! needs. In addition, previous Antarctic campaigns have permitted the successful collection of unique micrometeorites that have been examined for the present project.

Besides, the BAMM! project fully complied with the expected output of the HORIZON 2020 COMPET-8-2014 program, which was funded to implement a European curation facility for and scientific publications on extraterrestrial material.

2. STATE OF THE ART AND OBJECTIVES

Most of the meteorite parent bodies first formed during the condensation of the solar nebula is now located in the asteroid belt between Mars and Jupiter. Among the large collection of highly diverse meteorites (>50,000 officially classified), the chondrite groups represent an especially important fraction because they have, in part, kept their primordial physical and chemical properties. Chondrites are amongst the most primitive objects found in the solar system, and represent an important constituent of the terrestrial planets. Studying chondrites and their components offers the opportunity to better characterize the initial composition of the solar nebula and its evolution, but even more importantly, the initial composition of the Earth and other terrestrial planets. Both the meteorite and micrometeorite populations are dominated by chondritic compositions. However, as delineated below, the nature and source regions for these materials could be different. For this purpose, this proposal clearly makes the distinction between micrometeorites and meteorites, with a cut-off value of 2 mm.

Antarctic meteorites represent a unique opportunity to study the formation and evolution of the solar system because they exhibit excellent preservation states with little terrestrial alteration fractions (e.g. Maeda et al. 2021; in press). The BAMM! project addressed two major questions related to the two different sizes. Each micrometeorite can be seen as the outcome of a micro-experiment involving melting, melt extraction, and evaporation of originally pristine meteoritic material. Therefore, these microscopic particles can also aid in the understanding of how planetary and nebular processes can affect the mineralogical, chemical and isotopic composition of their macroscopic counterparts.

During two of the Belgian-Japanese research expeditions in the vicinity of the Princess Elisabeth station (PES) (winters of 2010-2011 and 2012-2013), sedimentary deposits containing abundant micrometeorites have been collected alongside meteorites. However, the sampling locations were distinct. The meteorites were recovered from the Nansen Ice Field on the Antarctic plateau, while the richest micrometeorite deposits were sampled near the top of Sør Rondane Mountain peaks. Because of their small size (by definition < 2 mm, but mostly < 500 μm), entry velocity and angle, some micrometeorites have been less susceptible to destruction during their passage through the atmosphere. In addition, micrometeorites sample parent bodies different from meteorite samples, which are composed of roughly 90% ordinary chondrites and 2% carbonaceous chondrites (based on the collections worldwide). Although dependent on the size fraction, statistics on 135 cosmic spherules (fully melted micrometeorites) characterized for high-precision triple-oxygen isotope ratios, indicate a shift in the parent body population of micrometeorites, with >70% of all cosmic spherules in the fraction below 500 μm related to carbonaceous chondrites and <10% to ordinary chondrites (Folco and Cordier, 2015). So despite their small size, micrometeorites offer a new opportunity to study distinct parent bodies (e.g., Gounelle et al., 2009). This is for instance true for the group 4 (^{16}O-poor) micrometeorites defined on the basis of oxygen isotopic compositions not sampled in the classical macroscopic collections (e.g., Suavet et al., 2010; Cordier et al., 2011; Van Ginneken et al., abstract). The first aim of the present project is to fully study the Sør Rondane collection of micrometeorites, in particular the unusual particles (high Ca-Al, unmelted micrometeorites, etc.) and/or enigmatic groups (e.g., ^{16}O-depleted micrometeorites), in terms of their petrology, geochemistry, and origin.

At the same time, the more common Antarctic chondrites, in addition to rarer macroscopic Antarctic meteorites, offer the chance to study a broad and complete data set. Ordinary chondrites constitute the majority of all meteorites collected so far (~90%). In weakly-metamorphosed (type 3) chondrites, essential components attesting to the formation of the solar system can be recognized, with presolar grains and calcium-aluminium-rich inclusions as an example. Such objects have been shown to exhibit large isotopic anomalies. Isotopic anomalies are defined as deviations from terrestrial or bulk solar isotopic abundances that have resulted from processes other than radioactive decay or mass-dependent fractionation. For example, presolar grains, widespread in unequilibrated chondrites, are enriched in material derived from distinct nucleosynthetic environments (cf. summary in Goderis et al. 2016). In type 4 to 6 (or 7), “equilibrated” ordinary chondrites, these components have (partially) been destroyed by thermal metamorphism and can no longer be recognized (Armytage and Debaille, 2016). Yet, some bulk metamorphosed chondrites exhibit resolvable isotopic anomalies (e.g., Trinquier et al., 2009), suggesting that the carrier phases of nucleosynthetic isotope anomalies were not homogeneously distributed or destroyed. The second goal of this project was hence to study the nature of the carrier phases of the isotopic anomalies and how these phases were affected by nebular (e.g., Trinquier et al., 2009) or planetary (e.g., Goderis et al., 2015) processes.

The BAMM! project also aimed to continue and improve the efficient curation of all Antarctic meteorites at the RBINS. Thanks to meteorite recovery missions that took place within the framework of the BAMM! project, the size of the Antarctic RBINS collection increased significantly. In addition, the RBINS classification skills have been improved by developing in-house analytical procedures.

3. METHODOLOGY

To reach the objectives, three work packages (WP) were considered in the present project:

WP1 Constraining the nature of the parent bodies of (melted) micrometeorites
WP2 Understanding the preserved nucleosynthetic isotopic signatures of chondrites
WP3 Implementing the meteorite curation facilities of the RBINS

The material investigated and methods used by work package are described here after.

3.1 Material

This project has valorized the more than 1200 meteorites recovered from the blue ice fields surrounding the Sør Rondane Mountains of Antarctica during three Belgian-Japanese recovery meteorite campaigns (2009-2010, 2010-2011 and 2012-2013) in the framework of the VUB-ULB SAMBA project (2009-2015). In the framework of the MICROMETA project (2010-2014) funded by the InBev-Baillet Latour fellowship, sediment with high concentrations of micrometeorites (up to 0.5-1 micrometeorites per gram of bulk sediment) has been recovered from cracks and fractures at the top of the Sør Rondane Mountains in Antarctica.

Within the BAMM! project, three additional Antarctic campaigns were organized to search for meteorites (2019-2020, 2022-2023) and micrometeorites (2017-2018). After finalizing the studies on the Nansen Blue Ice Field, focus was put on the moraine areas existing throughout and around the Sør Rondane Mountains (Fig. 1). This approach that was not used by the Japanese teams in the 1980s, was yet highly prolific in the Transantarctic mountains. In total, 66 meteorites for a total weight of 8.3 kg were collected on the Nansen blue ice field, area “C”, during the 2019-2020 field season and are currently hosted at the RBINS and at the Japanese National Institute of Polar Research (NIPR) (Goderis et al. 2021). During the 2022-2023 field season, five meteorites were collected in the Nils Larsenfjellet area. One specimen is of an exceptional weight at 7.6 kg. The recovered meteorites were transported in frozen state to the RBINS to be thawed in vacuum conditions and classified. The Nils Larsenfjellet is as such recognized as a potential new Dense Collection Area (Debaille et al., submitted; Fig. 1).

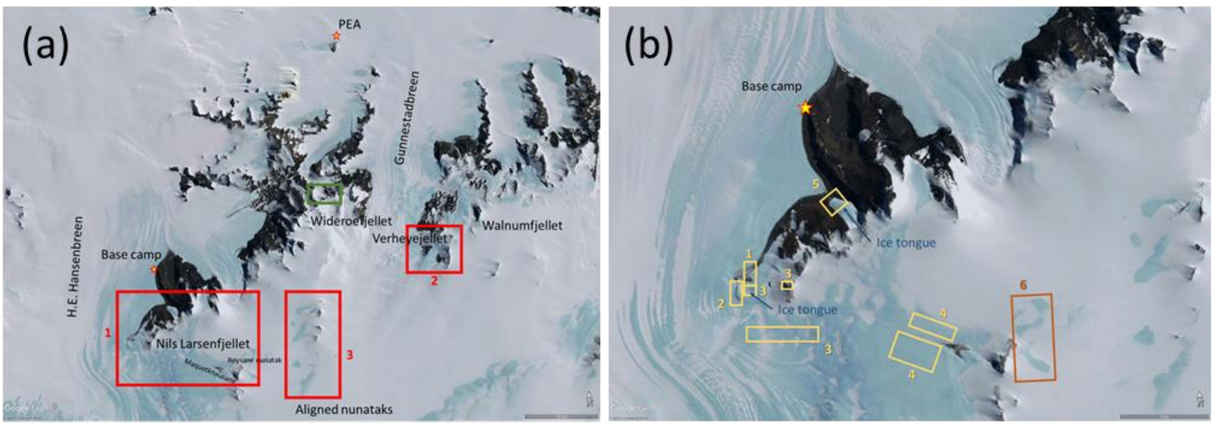

Figure 1. (a) Sør Rondane Mountains map, with the location of PEA and the 3 different zones of interests based on the meteorite finding probability index map from (Tollenaar et al. 2021): 1: Nils Larsenfjellet; 2:Verheyefjellet; 3: aligned nunataks. (b) Zoom on the searching zone in Nils Larsenfjellet; numbers refer to day 1 to 5 (see Table 1).

Number 6 refers to the daily trip from PEA in the Nils Larsenfjellet area at Røysane nunatak. Image based on Google Earth (US Geological Survey).

A 1-month field campaign to the moraines and mountain summits in the vicinity of the Princess Elisabeth station in the Sør Rondane Mountains of East Antarctica solely dedicated to the search of micrometeorites was completed successfully in February 2018. Three types of micrometeorite accumulation were targeted on the glacially eroded tops of the Vengen, Walnumfjellet, Widerøfjellet, Svindland and Smalegga mountain ridges and summits. The first type consisted of seven samples of soils and weathering products that may have been exposed for extended periods of times (up to several Myr). The second type comprised five samples taken in wind catchment areas, such as the base of large boulders or in cracks. Finally, the lee-side of three lateral and supraglacial moraines were also sampled, totaling eleven samples. In all cases, the sampled material with a total weight of approximately 80 kg, consisted of moderately sorted fine-grained rock detritus. An additional 1.5-month field campaign took place from January to mid-February 2020 allowed to collect meteorites from the Nansen C icefield as well as resample a few micrometeorite-containing sediments and target rocks, previously visited in 2018. Based on a variety of analyses, the sampled deposits likely contain on the order of 50,000 to 100,000 micrometeorites (Fig. 2), both melted and unmelted, but also contain other, more rare type of extraterrestrial materials (e.g., microtektites, particles from airburst events; Goderis et al. 2019; Soens et al. 2020, 2021, 2022; van Ginneken et al. 2021; Lampe et al. 2022).

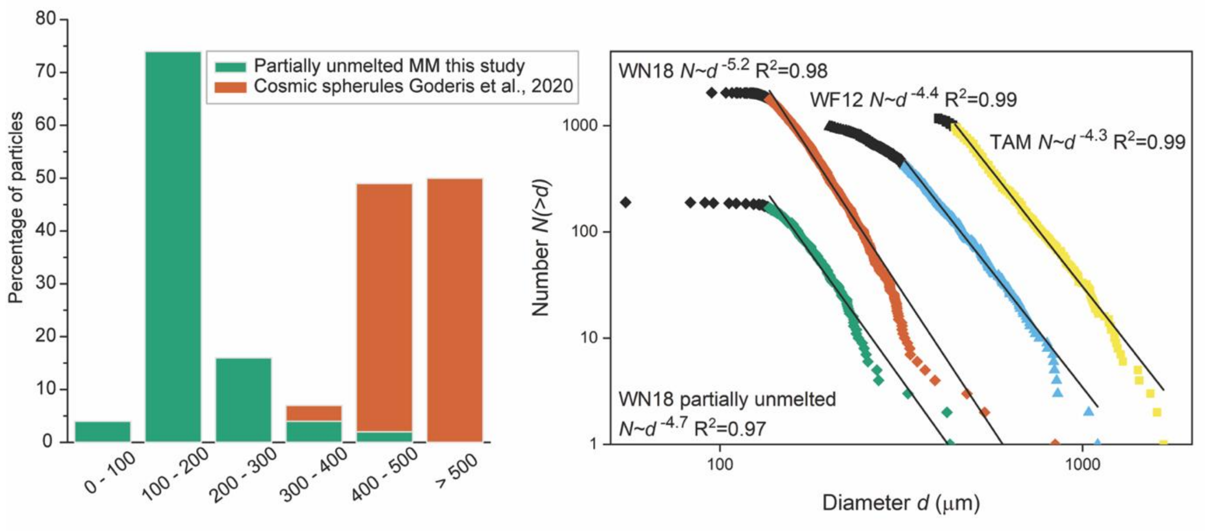

Figure 1. Left: Comparison of size distributions for scoriaceous and unmelted micrometeorites (n=49) characterized in this study and cosmic spherules extracted from the sedimentary deposits from the Sør Rondane Mountains (n=49; Goderis et al., 2020). Right: Cumulative size distribution for cosmic spherules (orange) and partially unmelted (green) particles from Walnumfjellet (WN) versus cosmic spherule fractions from Widerøefjellet (blue, WF) and the Transantarctic Mountains (>400 μm size fraction, yellow) collections. The slopes are calculated for the colored sections of the curves only. Data for Widerøefjellet from Goderis et al. (2020) and for the Transantarctic Mountains collection from Suavet et al. (2009). From Van Maldeghem et al. (2023, accepted).

3.2. Description of the methods according to the work packages

3.2.1. Work package 1 “Constraining the nature of the parent bodies of (melted) micrometeorites”

A first task of the work package has been to document the origins of and classify micrometeorites. Once the appropriate samples have been collected and selected, a general petrographic description of the observed textures and minerals of interest was carried out. Then a geochemical and crystallographic description of the minerals was completed at the RBINS, using the in-house equipment dedicated to mineralogical studies (SEM-EDS), including polished thick section preparation. Further petrological studies comprised cathodoluminescence observation and electron microprobe analysis (EMPA), microscopic X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), and laser ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) analysis, to document the repartition of elements within the different minerals. X-ray computed microtomography (CT) was used on samples of special interest to investigate their interior structure before any destructive analysis was performed. The measurement of the magnetic properties of micrometeorites is another non-destructive micrometeorites characterization tool that is used for selected samples (Suavet et al., 2009). Oxygen isotope ratios were obtained mainly by laser fluorination isotope ratio mass spectrometry (IRMS). Despite providing an excellent precision, laser fluorination requires a relatively large sample volume and is destructive. Consequently, high spatial resolution secondary ion mass spectrometry (SIMS and NanoSIMS), a non-destructive method, was also employed, even though this technique results in a lower precision.

3.2.2. Work package 2 “Understanding the preserved nucleosynthetic isotopic signatures of chondrites”

Concerning nucleosynthetic anomalies in chondrites, several samples were systematically studied for targeted nucleosynthetic anomalies in Sr using bulk rock samples, after chemical digestion or leaching experiments, element isolation, and measurement on the Nu Plasma MC-ICP-MS. Analytical issues were encountered and Ti isotopes could not be measured as initially planned. Major and trace elements were also measured in these fractions using ICP-MS and ICP-OES. Once selected, the samples have followed detailed petrological investigation using SEM, EMPA and LA-ICP-MS. Strontium nucleosynthetic analyses, focusing on the stable ratios $^{84}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$, have been performed at ULB on the Nu-Plasma 2 MC-ICP-MS. The existing protocol for Sr purification has been refined for allowing lower isobaric interference. Usually, ^{84}Sr is not considered while using MC-ICP-MS because of the interference with ^{84}Kr in the carrier gas (Moynier et al., 2012). However, we decided to work on both ratios. We could achieve precisions of 0.04-0.35 ‰ on the $^{84}Sr/^{86}Sr$ and of 0.09-0.36 ‰ on the $^{88}Sr/^{86}Sr$ by both standard-bracketing and Zr doping on synthetic and terrestrial standards. This is comparable to previous measurements on TIMS (e.g. Moynier et al., 2010), but is still 10 times higher than recent measurements performed using double-spike on TIMS (Charier et al., 2017). We had to stop this part of the project after the person in charge let for another project.

3.2.3. Work package 3 “Implementing the meteorite curation facilities of the RBINS“

Another task of the BAMM! Project was to pursue an efficient curation of Antarctic meteorites and establish the RBINS as a meteorite classification center. This can be realized by gaining a better experience in recognizing and curating the uncommon, scientifically highly valuable samples, classifying new meteorites, and increasing the collection existing at the curation center with new specimens.

Regarding classification, the development of meteorite classification through SEM quantitative analyses on olivines and pyroxenes at RBINS was proposed, first of all by developing an in-house standard. For the classification of rare types of meteorites, oxygen isotopic ratios (as well as nucleosynthetic isotope anomalies) can be determined. Finally, a magnetic classification developed by the CEREGE allow rapid, non-destructive and robust classification of meteorites, in particular ordinary chondrites (e.g., Rochette et al., 2003).

The increased size of the RBINS meteorite collection benefits from two missions in Antarctica (cf. above).

Besides, it was proposed to valorize the meteorite collection at the RBINS by new exhibition(s) and interviews to communicate about the ongoing research (including missions).

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1. Main results presented according to the work packages

All the scientific and administrative tasks of the defined work packages described in the project outline have been addressed, including three field campaigns (2017-2018, 2019-2020, 2022-2023), the detailed petrographic and chemical characterization of the collected materials, and set-up of analytical methods. The completed efforts can be summarized as follows, according to the work packages.

4.1.1. Work package 1 “Constraining the nature of the parent bodies of (melted) micrometeorites”

During the field campaign in February 2018 to the moraines and mountain summits in the vicinity of the Princess Elisabeth station in the Sør Rondane Mountains, three types of micrometeorite accumulation were targeted and sampled (see more detailed in section 4.1.3 of this report). A total of ~80 kg of sediments containing several thousands of micrometeorites was collected. The field campaign in 2020 allowed to collect meteorites from the Nansen C icefield and resample targets visited in 2018. The combination of these micrometeorite accumulations, and the measurement of cosmic-ray exposure ages in collaboration with Jérôme Gattacceca of the CEREGE, led to a better understanding of the concentration mechanisms of micrometeorites around the Belgian Antarctic Station. In its entirety, the current collection contains an estimated 50,000-100,000 micrometeorites and associated extraterrestrial material.

A subset of particles recovered during these field campaigns and during the 2012-2013 expedition has been characterized texturally, petrographically, chemically, and isotopically, and compared to recent urban micrometeorite collections. This has been done using in-house expertise and instrumentation (SEM-EDS, μXRF, and LA-ICP-MS), while a fraction of the recovered particles has also been characterized at partner institutes, using electron microprobe analysis (EMPA) at the Museum für Naturkunde in Berlin, in collaboration with Dr. Lutz Hecht (2018, 2019, 2020, 2021, 2022), and using secondary ions mass spectrometry (SIMS) at the CRPG in Nancy, collaborating with Dr. Johan Villeneuve (twice in 2019, once in 2021 & twice in 2022). In the case of the latter analytical technique, special focus has been put on placing important constraints on the “group 4”, ^{16}O-depleted micrometeorites that may relate to a new parent body, previously not sampled by classical, macroscopic meteorites. Additional focus was placed on unmelted micrometeorites, glass cosmic spherules, and highly evaporated micrometeorites following atmospheric passage. In 2020, a Europlanet 2024 research infrastructure proposal for transnational access to the NanoSIMS 50L at the Open University in Milton Keynes, United Kingdom was granted to study individual relict minerals of porphyritic cosmic spherules. Due to Covid-19, these analyses had to take place remotely, in close collaboration with the Open University colleagues led by Prof. Dr. Ian Franchi. The results were first presented at a Royal Astronomical Society meeting held online in Feb. 2022, and a manuscript is currently in preparation (to be submitted in the Summer of 2023).

Rare extraterrestrial particles have additionally been recovered from the collected sediment. These particles include Australasian microtektites that formed during a hypervelocity impact event on Southeast Asia approximately 790 kyr ago (Soens et al., 2021). In addition, spherules formed as the result of a unique touchdown airburst event over the east Antarctic ice sheet roughly 430 kyr were recovered. These particles display chondritic compositions with oxygen isotope signatures indicative of mixing between carbonaceous chondrites and Antarctic ice (Van Ginneken et al., 2021).

Several student dissertations have successfully been completed on the topics outlined in the BAMM! Proposal (for work package 1 and 2). KULeuven Earth Science MSc student Glen Peeters used non-destructive X-ray computed microtomography (CT) to retrieve spinel group minerals within the melted fraction of the Sør Rondane Mountains micrometeorites (i.e., cosmic spherules). This recovery was followed by a chemical characterization of these spinel group minerals to deduce solar system reservoirs from which these particles derive. Ghent University MSc student Flore Van Maldeghem worked on the petrographic, mineralogical and geochemical characterization of unmelted micrometeorites from the Sør Rondane Mountains collection using state-of-the-art synchrotron-based XRF and XRD. Flore continued her scientific studies as a PhD student in the VUB partner group working on this rare type of micrometeorites. Ghent University Earth science student Rémi Van de Merckt focused on the mineralogical characterization of unmelted micrometeorites. UGent student Seppe Lampe worked on the isotopic characterization of glass spherules using ns-LA-MC-ICP-MS. In the 2020-2021 academic year, Chemistry MSc student Kevin Vanbrusselen focused on the recovery and identification of particles from differentiated parent bodies.

Papers produced in the frame of the BAMM! project that comprise data on Antarctic micrometeorites include Schmitz et al. (2019), Tack et al. (2019), Goderis et al. (2020), González de Vega et al. (2020), Soens et al., (2020, 2022), and Lampe et al. (2022).

4.1.2 Work package 2 “Understanding the preserved nucleosynthetic isotopic signatures of chondrites”

Important achievement can be reported in developing and further optimizing the analytical protocols needed to tackle the main objectives of work package 2. Geneviève Hublet was hired in September 2018 to take care of the analytical aspect of the project, following her experience acquired in Japan in laser ablation techniques. She developed the high-precision Sr isotopes at ULB, including meteorites measurements, but changed position in September 2019. Due to the COVID-19 outbreak in March 2020, some delays were introduced in this work package. During the 2019-2020 academic year, VUB Chemistry MSc student Tom Boonants worked on a set of highly vaporized cosmic spherules combining major and trace element concentrations with oxygen isotope ratios. This student submitted a FWO proposal to continue the nucleosynthetic Sr isotope measurements, first on bulk samples and then later in situ by laser ablation coupled to MC-ICP-MS. Unfortunately, his application was not retained.

Through collaboration with JAMSTEC in Japan, publishable Ti (and Cr) isotope results on angrite Asuka 12209 and the meteoritic debris collected at Walnumfjellet, Sør Rondane Mountains, Antarctica have been obtained (van Ginneken et al., 2021). These results are expected to lead to two additional publications, one being published now, and the second one in preparation, on the angrite Asuka 12209. Nucleosynthetic isotope anomalies were also measured for the ungrouped iron meteorite Sirjan 001 (Pourkhorsandi et al. 2022), and a paper is currently being written up on this topic. Finally, a manuscript was produced on oxygen isotope ratios in angritic meteorites. These measurements indicate isotopic disequilibrium between the olivine xenocrysts and groundmass fractions from the Asuka 12209, Asuka 881371, and Northwest Africa 12320 meteorites (Rider-Stokes et al. 2023; Fig. 3). This isotopic disequilibrium can be explained by an impactor with a positive oxygen isotopic composition that collided with the angritic parent body (APB). Mixing of the two separate bodies then took place and relict olivine grains of the APB were affected by high-temperature events. Plutonic and dunitic angrites escape shock deformation and isotopic mixing due to their depth/distance from the impact site on the APB or due to being molten at the time of impact mixing.

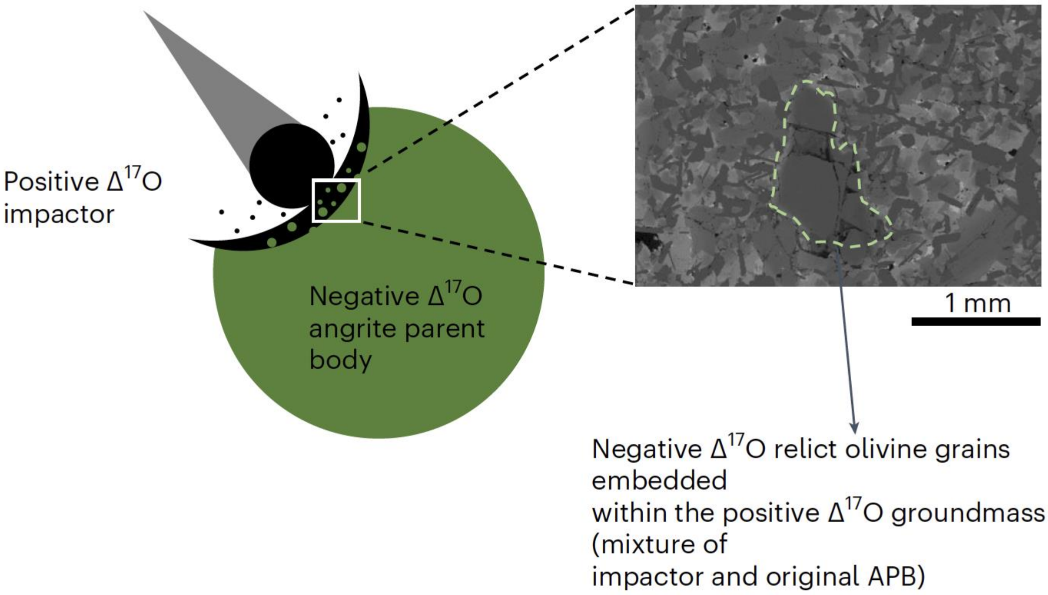

Figure 3. Schematic depicting a possible scenario that causes the oxygen isotopic disequilibrium in the quenched angrite meteorites.

Protocols for the in-situ isotopic characterization of selected Sør Rondane Mountain micrometeorites have been set-up and tested using the available ns-LA-MC-ICP-MS instrumentation at Ghent University. While the acquired precision previously did not approximate the requirements, the currently obtained accuracy and precision obtained using standard-bracketing and internal doping with Ni are in line with what is needed to differentiate mass-dependent isotope fractionation as the result of evaporation from mixing with atmospheric oxygen during atmospheric entry (González de Vega C. et al. 2020). Three additional papers on the cosmochemical interpretation of these results have been published (Chernonozhkin et al., 2021; Lampe et al., 2022; Soens et al., 2022).

4.1.3. Work package 3 “Implementing the meteorite curation facilities of the RBINS“

All objectives of WP 3 have been realized, with important steps carried out to consolidate the RBINS as an expert center in meteoritics and meteorite curation. Vinciane Debaille has presented the meteorite collection at RBINS at the first international meeting on curation of meteorites and extraterrestrial meteorites (10-13 September 2018, at the Astronomical observatory of the Vatican), in front of a worldwide audience of curators. The first Belgian achondrite that fell in the South of Belgium (Tintigny) in 1971 has now not only been classified, but also the meteorite entered the permanent exhibition of the RBINS in December 2018, after an official inauguration (see Fig. 4 and section 5 of this report). A scientific publication was produced on this: Pourkhorsandi et al., 2021.

MUSÉUM SCIENCE SERVICES QUI SOMMES-NOUS?

museum

Institut royal des Sciences naturelles de Belgique

Actualités Agenda Newsle

Une sixième météorite belge au Muséum

Accueil / Actualités » Une sixième météori ...

07/12/2018
post by
Reinout Verbeke

Une météorite découverte à Tintigny rejoint officiellement les cinq autres météorites belges conservées par notre Institut. Elle sera exposée au Muséum dès le 12 décembre 2018.

Il y a près d'un demi-siècle, une météorite rare est tombée à Tintigny, dans la province de Luxembourg. Les héritiers de son découvreur viennent d'en faire don à notre Institut. La météorite rejoint les autres spécimens exposés dans la Salle des Minéraux.

Un trou dans le toit

Février 1971. Eudore Schmitz, agriculteur à Tintigny, un village de la province de Luxembourg, entend un bruit étrange provenant de la grange : une pierre noire en a traversé le toit. Le lendemain, son fils apporte la pierre à l'école. L'instituteur Albert Rossignon, aujourd'hui curé de la paroisse, pense qu'il s'agit d'une météorite. Elle lui est confiée. Après plus de quarante ans, il demande à la famille Schmitz ce qu'ils veulent faire de la pierre. Le curé prend ensuite contact avec l'experte en météorites Vinciane Debaille (Université Libre de Bruxelles). Elle propose d'examiner et de conserver le spécimen au Muséum des Sciences naturelles.

Une pièce rare

On connaissait déjà cinq météorites belges : Saint-Denis-Westrem, Tourinnes-la-Grosse, Lesve, Hainaut et Hautes Fagnes. Tintigny vient d'être officiellement ajoutée à la « Meteorical Database ». Cette sixième météorite belge n'est pas une « chondrite ordinaire » (la variété la plus commune de météorite pierreuse) comme les cinq autres spécimens belges. C'est une « eucrite », une météorite pierreuse très rare (seulement 2 % des météorites retrouvées), qui témoigne de l'activité volcanique sur l'astéroïde Vesta. Seules huit autres eucrites sont connues en Europe.

Tintigny est donc une pièce unique que nous sommes fiers de présenter, avec les autres spécimens belges, dans une annexe de la Salle des Minéraux dédiée aux météorites. Le public peut venir l'admirer dès ce 12 décembre 2018.

Figure 4. Post published on the RBINS website about the Tintigny meteorite and the fact it entered the RBINS collection in December 2018.

The Antarctic martian meteorite A 12325 was added to the collection after classification by the Japanese NIPR and is currently studied at ULB and VUB (e.g. Debaille et al., 2019; Roland et al., 2021; Debaille et al., 2022). Another martian meteorite found in the Moroccan desert has been classified as well and deposited at the RBINS (NWA 12412). Classification using magnetic susceptibility, thanks to our collaboration with Jérome Gattaccecca, has been set up. The Antarctic meteorite collection has been screened for that parameters and results have been presented at the Antarctic meteorite symposium at NIPR in December 2017 (Debaille et al., 2017). This technique has been applied in the field during the Antarctic campaign of 2020. In addition, progress was made regarding the characterization of the ordinary chondrite H6 (collected during the Antarctic mission 2009-2021) – and more precisely, statistics on the chemistry of its pyroxene and olivine (~110 analyses, Fig. 5) – that will be used as in-house standard for silicate analyses and further meteorite classification at the RBINS, on the new SEM-EDS expected in 2023). Such analyses are critical to classify meteorites and will definitely assist in increasing the expertise in that field at the RBINS.

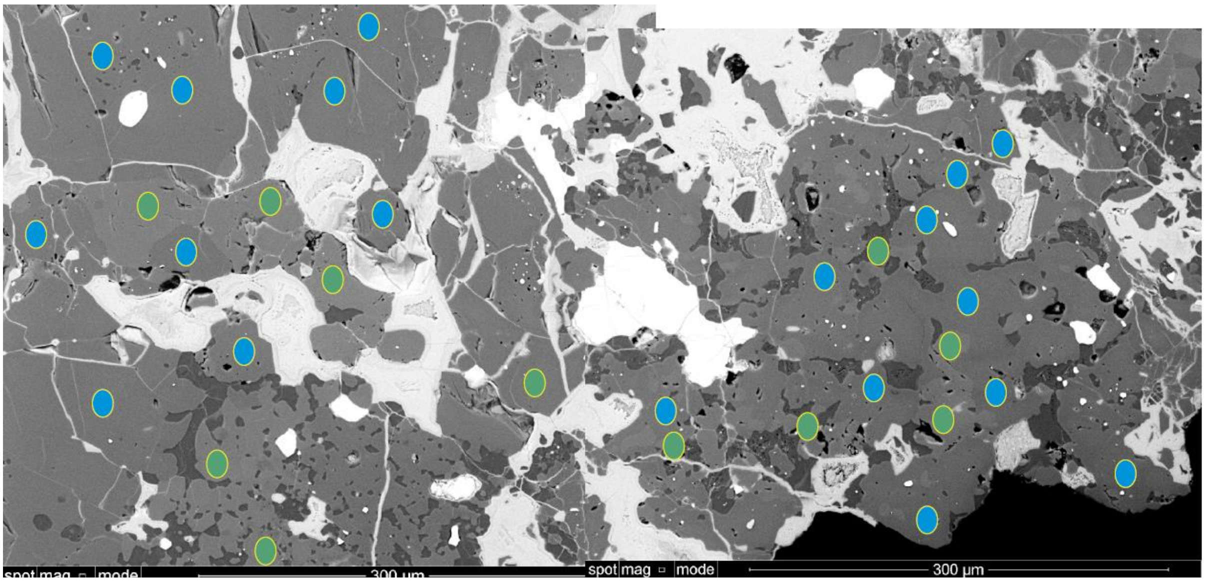

Figure 5. SEM-EDS picture of the ordinary chondrite H6 that was investigated and analysed to be used as standard. The green and blue circles represent measurement points.

A last aspect about curation at RBINS and the increase of the collection's size relates to the missions in Antarctica (Section 3.1 and Fig. 1). Several abstracts and papers were produced on the state of alteration of Antarctic meteorites, with recommendations for future meteorite preservation (Maeda et al., 2023), van Ginneken et al. (2022), and Debaille et al. (2022, abstract).

4.2. Recommendations

This project emphasizes the importance of the research led on meteorites and micrometeorites to better understand planetary evolution and differentiation processes.

The Sør Rondane Mountains deposits represent a rich, representative micrometeorite collection from East Antarctica that has fed the research objectives outlined above and led to the publication of a series of important manuscripts (see the list presented in section 6 of this report and Annex 1). Further projects will allow to investigate new areas in Antarctica, for instance by expanding the activities of the consortium to the Belgica Mountains. This is the scope of the recently funded BELSPO RTP-Polar project ULTIMO "UnLocking The scIentific potential of the Belgica MOuntains, East Antarctica". The continuation of the successful Antarctic program for collecting extraterrestrial material is of capital importance for the recovery of large volumes of new, excellently preserved micrometeorites, necessary to apply both semi- and fully destructive analyses and hence the continuation of successful meteorite research at the national and international level. This would also contribute to the continuous growth of the RBINS meteorite collection and meet the growing demands of the international research community. This would finally help to develop the optimal meteorite curation protocols and the consolidation of the RBINS as a meteorite curation center at the international level.

Concerning the latter aspect, a lot of analytical instrumentation and protocols are in place. Other ones should be optimized to expand future scientific goals, as for instance mineral chemistry of silicates (olivine, pyroxene) at the RBINS (to be developed in the second half of 2023, once the new SEM has arrived). Major efforts will also be placed in optimizing the recently acquired Teledyne Iridia 500 Hz 193 nm ArF eximer laser ablation system coupled to an Agilent 8900 ICP-QQQ for Advanced Applications, that was newly installed in AMGC in Feb. 2023 for determination of the major and trace element composition in a fast and semi-destructive manner. The visibility of the RBINS as an internationally recognized meteorite curation center will surely benefit from the organization of the Annual Meeting of the Meteoritical Society in 2024, in Brussels.

5. DISSEMINATION AND VALORISATION

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

First, the peer-reviewed papers and conference abstracts listed in the "6. Publications" section of this report testify for the valorisation of the research led for BAMM!.

Second, the curation program at the RBINS attracted significant media attention as the result of this Workpackage. Several news items on the arrival of martian meteorite A 12325, recovered from Antarctica during the joint Japanese-Belgian 2012-2013 expedition, to Belgium (26 June 2018), were advertised in Knack, het Nieuwsblad, bx1.be, RTL, RTBF, The Brussels Times, etc. The paper on the impact mixing among rocky planetesimals in the early Solar System from angrite oxygen isotopes received significant attention from the international media and reached an Altmetric score of 1161 (https://www.nature.com/articles/s41550-023-01968-0/metrics).

Another major event during this project is related to the Tintigny meteorite that entered the permanent exhibition of the RBINS in December 2018. An official inauguration (see Fig. 6 for the invitation) was organised in the frame of the BAMM! Project. These events have been widely discussed in the press (RTBF, TV journal of 11 December 2018), as illustrated here below with an article in Le Soir (Fig. 7).

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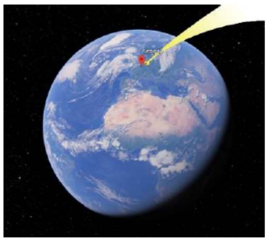

Le Muséum des Sciences naturelles et le Service Géologique de Belgique

vous invite à l'inauguration de

la météorite de Tintigny

en présence de la famille Schmitz,

le **mardi 11 décembre à 17h** dans la salle des Minéraux du Muséum (fin prévue à 19h).

Merci d'informer de votre présence avant le 7 décembre notre service de Géologie :
marleen.deceukelaire@naturalsciences.be ou au 02 788 76 37

La sixième météorite belge trouvera une place définitive au Muséum avant les vacances de Noël

Un jour de février 1971, **Monsieur Eudore Schmitz**, agriculteur à Tintigny (province du Luxembourg), voit une pierre noire trouer et traverser son toit. L'instituteur du village, Monsieur Albert Rossignon, aujourd'hui abbé, pense identifier une météorite. Pendant plus de 40 ans, cette pièce tombe dans l'oubli… jusqu'à ce que les enfants et petits-enfants de la famille Schmitz remettent la météorite sur la voie de son identification scientifique. Ils en font maintenant **don au Muséum des Sciences naturelles** afin que tous puissent voir ce spécimen de valeur venant de l'espace.

Au côté de cinq météorites belges déjà connues (St-Denis-Westrem, Tourinnes-la-Grosse, Lesve, Hainaut et Hautes Fagnes), la météorite de Tintigny est officiellement ajoutée à la « Meteorical Database ». Cette sixième météorite belge n'est pas une « chondrite ordinaire» (la variété la plus commune de météorite pierreuse) comme les cinq autres spécimens belges. Cette météorite a été classifiée comme « eucrite polymicte » (autre sorte de météorite pierreuse), ce qui en fait une météorite très rare (seulement 2 % des météorites retrouvées) et témoigne de l'activité volcanique sur l'astéroïde Vesta. Il n'y a actuellement que huit autres eucrites en Europe

« Tintigny » est donc unique à la fois historiquement et scientifiquement et nous sommes fiers de l'ajouter à notre collection des cinq météorites belges. Elles ont un espace qui leur est dédié dans la salle des Minéraux du Muséum.

Adresse du jour : Muséum des Sciences naturelles, 29 rue Vautier 1000 Bruxelles. Quelques places de parking sont prévues. Gare Bruxelles-Luxembourg, bus et métro à proximité.

Figure 6. Invitation for the inauguration of the exhibition of the Tintigny meteorite.

The BAMM! Project has also been advertised and presented through the Temporary Exhibition "Antarctica" (17/10/2019-03/01/2021). As mentioned on the RBINS website "*Antarctica is an immersive exhibition about the heart of the continent exclusively accessible to scientists. Superb films are projected onto big screens, including a final 360 ° projection, while infographics about the lives of animals help you discover the fascinating world of land and marine biodiversity in the South Pole*".

LE SOIR

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ACCUEIL • SOCIÉTÉ

Une météorite atypique entre au musée

La météorite de Tintigny est redécouverte après près de cinquante ans d'oubli. Elle devient une des premières « non primitives » à avoir été découverte chez nous.

Article réservé aux abonnés

Journaliste au service Société
Par **Marie Thieffry**

Publié le 10/12/2018 à 22:25 | Temps de lecture: 3 min

L'événement est exceptionnel, historiquement comme scientifiquement... » Pour la directrice générale de l'Institut royal des Sciences naturelles de Belgique, la météorite qu'elle accueille dans ses collections est des plus surprenantes.

Historiquement, d'abord. Février 1971, Eudore Schmitz, agriculteur à Tintigny dans la province de Luxembourg, s'affaire dans son étable. Un violent bruit le saisit : à l'étage, où il constate que le plafond vient d'être troué, un objet noir gros comme le poing gît sur le sol. Intrigué, il le ramène chez lui dans sa casquette pour ne pas se brûler. Le lendemain, un de ses fils le conduit à l'instituteur du village, Albert Rossignon, qui identifie une météorite. Avec les premiers succès d'Apollo sur la lune, la période est propice à ce genre de découvertes. Mais petit à petit, la pierre tombe dans l'oubli... Jusqu'à ce qu'enfants et petits-enfants de la famille Schmitz remettent la météorite sur la voie de son identification scientifique, près de cinquante ans plus tard.

Ils contactent une spécialiste, Vinciane Debaille, maître de recherches FNRS à l'ULB. Cette géologue de formation spécialisée dans l'étude des météorites de différentes origines a participé à plusieurs missions de collecte de météorites en Antarctique. Elle reconnaît dès les premières images une roche exceptionnelle, scientifiquement.

Deux familles

« Il existe deux grandes familles de météorites : les primitives et les non primitives, explique-t-elle. *Les premières sont de véritables échantillons des débuts du système solaire... Elles constituent un agglomérat de toutes les poussières qui se baladaient alors là-haut. On les appelle aussi des "chondrites" et elles constituent près de 95 % des météorites découvertes à ce jour. Celle de Tintigny, elle, est différente. Elle rentre dans les 5 % restants. C'est une "eucrite," une roche non primitive... »*

Des météorites de ce type, il n'y en a que huit en Europe. Chez nous, c'est la première du lot. *« Les eucrites sont issues d'astéroïdes qui ont connu de l'activité volcanique – comme Mars ou la Lune,* poursuit la chercheuse. *Elles sont facilement reconnaissables : derrière la couche noire brûlée lors de l'entrée dans l'atmosphère, elles ont un cœur très blanc. »*

Fragment de Vesta

Fragments d'astéroïdes ou de comètes, les météorites sont en général de petite taille. *« Elles proviennent principalement de la ceinture d'astéroïdes située entre Mars et Jupiter et sont donc de précieux indices sur la formation du système solaire,* explique Pham Le Binh San de l'Observatoire royal de Belgique. *En l'occurrence, la météorite de Tintigny est un fragment de l'astéroïde Vesta. »* Quatrième astéroïde découvert, il mesure plus de 600 km de diamètre.*« De quoi faire pas mal de météorites,* sourit l'experte. *Nous savons qu'elle provient de là car il est possible d'analyser à distance la composition des astéroïdes grâce à la réflexion de la lumière solaire. En fonction de la longueur d'ondes, qui varie selon le matériau de la surface, on peut retracer la "famille" de l'objet extraterrestre. »* Idem pour l'âge de la météorite : les roches contiennent naturellement de l'uranium qui devient, en vieillissant, du plomb. Plus la roche contient de plomb, plus celle-ci est âgée.

« Une météorite, c'est une sorte de mission spatiale low-cost, sourit Vinciane Debaille. *Grâce aux eucrites comme celle-ci, nous pourrons mieux étudier l'activité volcanique sur Vesta et ainsi mieux comprendre comment se forment les planètes. Peut-être finirons-nous par pouvoir prédire les mouvements de matériel rocheux dans le système solaire... jusqu'à celui qui pourrait nous menacer directement, comme l'impact ayant conduit à la disparition des dinosaures. »*

Figure 7. The Tintigny meteorite at the RBINS - a journalist paper published in Le Soir on December 10, 2018.

A short movie was shot with Matthias Van Ginneken acting and talking about the research led for the BAMM! Project (see pictures in Fig. 8 below). The paper on the recovery of debris from a large meteoritic event over Antarctica (van Ginneken et al., 2021) led to worldwide press attention and is in the top 5% of all research outputs ever tracked by Altmetric.

Equally important, the Meteoritical Society has chosen Brussels as the site for its annual meeting in 2023 (postponed to 2024 following the COVID-19 outbreak in 2020 and reorganisation of the international meeting schedule). This will lead to a fantastic exposure of the Belgian meteorite and micrometeorite collections and projects.

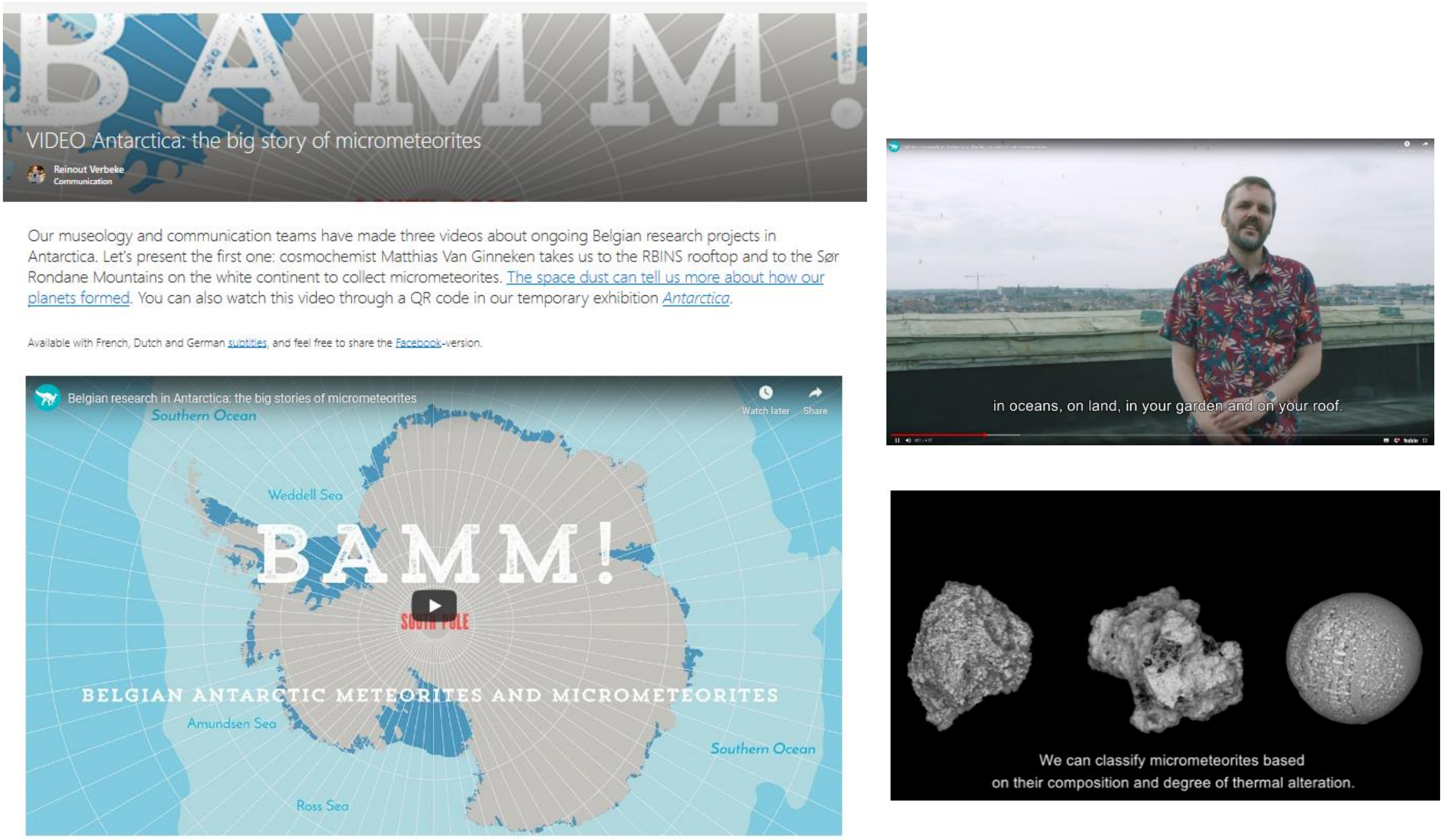

Figure 8. Pictures taken from the video dedicated to the BAMM! project for the temporary exhibition "Antarctica" at the RBINS.

6. PUBLICATIONS

6.1. Peer review paper

2023

- Maeda R., Goderis S., Yamaguchi A., Van Acker T., Vanhaecke F., Debaille V., and Claeys Ph. 2023. Fluid mobilization of rare earth elements (REEs), Th, and U during the terrestrial alteration of chondrites. Meteoritics & Planetary Science, accepted.
- Rider-Stokes B. G., Greenwood R. C., Anand M., White L. F., Franchi I. A., Debaille V., Goderis S., Pittarello L., Yamaguchi A., Mikouchi T., and Claeys Ph. 2023. Impact mixing among rocky planetesimals in the early Solar System from angrite oxygen isotopes. Nature Astronomy, in press 10.1038/s41550-023-01968-0
- Maeda R., Van Acker T., Vanhaecke F., Yamaguchi A., Debaille V., Claeys Ph., and **Goderis S.** 2023. Quantitative elemental mapping of chondritic meteorites using laser ablation-inductively coupled plasma-time of flight-mass spectrometry (LA-ICP-TOF-MS). Journal of Analytical Atomic Spectrometry 38, 369-381. doi.org/10.1039/d2ja00317a

2022

- Lampe S., Soens B., Chernonozhkin S. M., González de Vega C., van GInneken M., Van Maldeghem F., Vanhaecke F., Glass B. P., Franchi I. A., Debaille V., Claeys Ph., and Goderis S. 2022. Decoupling of chemical and isotopic fractionation processes during atmospheric heating of Antarctic micrometeorites, Geochimica et Cosmochimica Acta, 324, 221-239
- Van Ginneken M., Debaille V., Decrée S., Goderis S., Woodland A. B., Wozniakiewicz P., De Ceukelaire M., Leduc T., and Claeys Ph. 2022. Artificial weathering of an ordinary chondrite: Recommendations for the curation of Antarctic meteorites. Meteoritics and Planetary Science 57, 1247-1266.
- Soens B., Chernonozhkin S. M., González de Vega C., Vanhaecke F., Van Ginneken M., Claeys Ph. And Goderis S., 2022. Major, trace, oxygen and iron isotope compositions of achondritic cosmic spherules from Widerøefjellet (East Antarctica), Geochimica et Cosmochimica Acta 325, 106-128.
- Tollenaar V., Zekollari H., Lhermite S., Tax D., Debaille V., Goderis S., Claeys Ph. And Pattyn F. 2022. Unexplored Antarctic meteorite collection sites revealed through machine learning, Science advances 8 (4), eabj8138.

2021

- Pourkhorsandi, H., Debaille, V., Gattacceca, J., Greenwood, R., Leduc, T., De Ceukelaire, M., Decrée, S., Goderis, S, 2021. Tintigny meteorite: the first Belgian achondrite. Planetary and Space Science. Volume 209, , 105372
- Goderis S., Yesiltas M., Pourkhorsandi H., Shirai N., Poudelet M., Leitl M., Yamaguchi A., Debaille V., and Claeys Ph. 2021. Detailed record of the BELARE 2019-2020 meteorite recovery expedition on the Nansen Ice Field, East Antarctica. 2021. Antarctic Record 65, 1-20.

- Chernonozhkin S. M., González de Vega C., Artemieva N., Soens B., Belza J., Bolea-Fernandez E., Van Ginneken M., Glass B. P., Folco L., Genge M. J., Claeys Ph., Vanhaecke F., and **Goderis S.** 2021. Isotopic evolution of planetary crusts by hypervelocity impacts evidenced by Fe in microtektites. Nature Communications 12, 5646.
- Soens B., van Ginneken M., Chernonozhkin S., Slotte N., Debaille V., Vanhaecke F., Terryn H., Claeys Ph., and Goderis S. 2021. Australasian microtektites across the Antarctic continent: evidence from the Sør Rondane Mountain range (East Antarctica). Geoscience Frontiers, 101153.
- van Ginneken M., Goderis S., Artemieva N., Debaille V., Decrée S., Harvey R. P., Huwig K., Hecht L., Yang S., Kauffmann F. E. D., Soens B., Humayun M., Van Maldeghem F., Genge M. J., and 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, eabc1008.

2020

- Soens B., Suttle M. D., Maeda R., Vanhaecke F., Yamaguchi A., van Ginneken M., Debaille V., Claeys Ph., and Goderis S. 2020. Evidence for the presence of chondrule- and CAI-derived material in an isotopically anomalous Antarctic micrometeorite. Meteoritics and Planetary Science 1-24.
- González De Vega C., Costas-Rodríguez M., Van Acker T., Goderis S., and Vanhaecke F. 2020. Nanosecond Laser Ablation – Multicollector Inductively Coupled Plasma - Mass Spectrometry for in situ Fe Isotopic Analysis of Micrometeorites: Application to Micrometer-Sized Glassy Cosmic spherules. Analytical Chemistry 92, 3572-3580.

2019

- Goderis S., Soens B., Huber M. S., McKibbin S., van Ginneken M., Debaille V., Greenwood R. C., Franchi I. A., Cnudde V., Van Malderen S., Vanhaecke F., Koeberl C., Topa D., and Claeys Ph. Cosmic spherules from Widerøefjellet, Sør Rondane Mountains (East Antarctica). Geochimica et Cosmochimica Acta, 270, 112-143.
- Schmitz B., Farley K. A., Goderis S., Heck P. R., Bergström S., Boschi S., Claeys Ph., Debaille V., Dronov A., van Ginneken M., Harper D. A. T., Iqbal F., Friberg J., Liao S., Martin E., Meier M. M. M., Peucker-Ehrenbrink B., Soens B., Wieler R., and Terfelt F. An extraterrestrial trigger for the mid-Ordovician ice age: dust from the breakup of the L-chondrite parent body. Science Advances 5, eaax4184.
- Tack P., Baze B., Vekemans B., Okbinoglu T., Van Maldeghem F., Goderis S., Schöder S., and Vincze L. 2019. Investigation of (micro-)meteoritic materials at the new hard X-ray imaging PUMA beamline for heritage sciences. Journal of Synchrotron Radiation 26, 2033-2039.

6.2. Conference abstracts

2022

- Pourkhorsandi H., Debaille V., Kaskes P., Tornabene H. R., Bermingham K. R., Marocchi Y., Leduc T., and Goderis S. 2022. Sirjan 001: An ungrouped iron meteorite formed in a sulfur-rich environment. 85th Annual Meeting of the Meteoritical Society, Abstract.

- Boonants T., Goderis S., Soens B., Van Maldeghem F., Chernonozhkin S., Vanhaecke F., Claeys Ph. 2022. Elemental and oxygen isotopic fractionation recorded in highly vaporized cosmic spherules from Widerøefjellet, Sør Rondane Mountains (East Antarctica). 85th Annual Meeting of the Meteoritical Society, Abstract #6316.
- Debaille V., Maeda R., Pourkhorsandi H., Goderis S., Hublet G., and Claeys Ph. 2022. Effects of terrestrial alteration on meteorites from cold and hot deserts. The Goldschmidt 2022 Conference, abstract #10861.
- Lampe S., Soens B., Chernonozhkin S. M., González de Vega C., van Ginneken M., Van Maldeghem F., Vanhaecke F., Glass B. P., Franchi I. A., Terryn H., Debaille V., Claeys Ph., Goderis S. 2022. Decoupling of chemical and isotope fractionation processes during atmospheric heating of S-type micrometeorites. EGU General Assembly, EGU22-5656 (Abstract).
- Debaille V., Roland J., Goderis S., Hublet G. , Pourkhorsandi H. 2022. Asuka 12325: Expanding the Chemical Variety of the Martian Mantle Sampled by Shergottites. The Lunar and Planetary Conference, LPI Contributions 2678, 2433 (Abstract).
- Van Ginneken M., Goderis S., Maeda R., Wozniakiewicz P., Genge M., Folco L., Suttle M. D., Yamaguchi A., and Decrée S. 2022. A potential origin for 16O-poor cosmic spherules: a near-Earth source and parentage with CY chondrites. Royal Astronomical Society, abstract.

2021

- Maeda R., Goderis S., Van Acker T., Vanhaecke F., Yamaguchi A., Debaille V., Claeys Ph. 2021. The effect of fluid mobilization on the budget and distribution of rare earth elements in Antarctic chondrites. The 12th Symposium on Polar Science (Abstract).
- Tollenaar V. J. W., Zekollari H., Tuia D., Lhermitte S., Tax D. M. J., Debaille V., Goderis S., Claeys Ph., Pattyn F. 2021. A data-driven approach to quantifying Antarctic blue ice areas and the presence of meteorites. 19th Swiss Geoscience Meeting, Geneva (Abstract).
- Van Maldeghem F., Soens B., Kaufmann F. E. D., Van Ginneken M., Hecht L., Claeys Ph., Goderis S. 2021. Oxygen isotope variability in unmelted micrometeorites from the Sør Rondane Mountains, East Antarctica. The Goldschmidt Conference, Virtual.
- Roland J., Debaille V., Hublet G., Pourkhorsandi H., Goderis H. 2021. Geochemical and isotopic characterization of shergottite Asuka 12325. The Goldschmidt Conference, Virtual.

2020

- Maeda R., Goderis S., Debaille V., Pourkhorsandi H., Hublet G., and Claeys Ph. 2020. The effects on Sm-Nd and Lu-Hf systems in H chondrites by Antarctic alteration and sample heterogeneity. 4th National Polar Science Workshop (Abstract).
- Yesiltas M., Goderis S., Pourkhorsandi H., Shirai N., Poudelet M., Leitl M., Yamaguchi A., Debaille V., and Claeys Ph. 2020. 2019-2020 Antarctic (micro) meteorite search expedition: Collaboration of Belgium, Japan, and Turkey. 4th National Polar Science Workshop (Abstract).
- Shirai N., Goderis S., Yesiltas M., Pourkhorsandi H., Poudelet M., Leitl M., Yamaguchi A., Debaille V., and Claeys Ph. 2020. The BELARE 2019-2020 meteorite recovery expedition on the Nansen Ice Field, East Antarctica. The 11th Symposium on Polar Science, 275 (Abstract).

2019

- Debaille V., Hublet G., Roland J., Pourkhorsandi H., Goderis S. 2019. Asuka 12325: A new depleted shergottite. The Tenth Symposium on Polar Science 2019
- Soens B., Van Ginneken M., Debaille V., Vanhaecke F., Claeys Ph., and Goderis S. 2019. Microtektites from the Sør Rondane Mountains, East Antarctica: Towards an extension of the Australasian strewn field? The 82nd Annual Meeting of the Meteoritical Society, 6144 (Abstract).
- Van Ginneken M., Artemieva A., 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. The 82nd Annual Meeting of the Meteoritical Society, 6010 (Abstract).
- 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. The 82nd Annual Meeting of the Meteoritical Society, 6150 (Abstract).
- Van Maldeghem F., Goderis S., Laforce B., Soens B. De Pauw E., Suuronen J.-P., Van Ginneken M., Folco L., Debaille V., Vincze L., and Claeys P. 2019. Characterization of unmelted Antarctic micrometeorites using synchrotron-based X-ray analysis. Geologica Belgica 22, 95-96.
- Van Ginneken M., Artemieva N., Claeys P., Debaille V., Decrée S., Hecht L., Humayun M., Kaufmann F., Soens B., Yang S., and Goderis S. 2019. Meteoritic ablation debris from the Sør Rondane Mountains, Antarctica. 82nd Meteoritical Society Annual Meeting, Sapporo, Japan (abstract).
- Soens B., van Ginneken M., Debaille V., Vanhaecke F., Claeys Ph., and Goderis S. 2019. Microtektites from the Sør Rondane Mountains, East Antarctica: Towards an extension of the Australasian strewn field? 82nd Meteoritical Society Annual Meeting, Sapporo, Japan (abstract).
- Soens B., van Ginneken M., Debaille V., Vanhaecke F., Claeys Ph., and Goderis S. 2019. Achondritic spherules from the Sør Rondane Mountains, East Antarctica: Probing the asteroid belt beyond the meteorite inventory. 82nd Meteoritical Society Annual Meeting, Sapporo, Japan (abstract).
- Van Maldeghem F., Goderis S., Laforce B., Soens B., De Pauw E., Suuronen J.-P., van Ginneken M., Debaille V., and Claeys Ph. 2019. Unmelted Antarctic micrometeorites at the nanoscale. Goldschmidt abstracts.
- González de Vega C., Costas Rodriguez M., Van Acker T., Goderis S., and Vanhaecke F. 2019. Assessment of ns-LA Coupled to MC-ICP-MS for Fe Isotopic Analysis of Meteoritic Materials. Plasma Spectrochemistry, European Winter Conference, Abstract.

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ANNEXES

ANNEX 1. PUBLICATIONS (ONLY THE FIRST PAGE IS PRESENTED, THE PAPERS ARE PROVIDED AS SEPARATE FILE)

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ARTICLE

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Isotopic evolution of planetary crusts by hypervelocity impacts evidenced by Fe in microtektites

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Fractionation effects related to evaporation and condensation had a major impact on the current elemental and isotopic composition of the Solar System. Although isotopic fractionation of moderately volatile elements has been observed in tektites due to impact heating, the exact nature of the processes taking place during hypervelocity impacts remains poorly understood. By studying Fe in microtektites, here we show that impact events do not simply lead to melting, melt expulsion and evaporation, but involve a convoluted sequence of processes including condensation, variable degrees of mixing between isotopically distinct reservoirs and ablative evaporation during atmospheric re-entry. Hypervelocity impacts can as such not only generate isotopically heavy, but also isotopically light ejecta, with $\delta^{56/54}$Fe spanning over nearly 5‰ and likely even larger variations for more volatile elements. The mechanisms demonstrated here for terrestrial impact ejecta modify our understanding of the effects of impact processing on the isotopic evolution of planetary crusts.

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Cosmic spherules from Widerøefjellet, 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 Widerøefjellet 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 Widerøefjellet 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 Widerøefjellet, 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 Widerøefjellet. Consequently, the Widerøefjellet 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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—報告—
Report

A detailed record of the BELARE 2019–2020 meteorite recovery expedition on the Nansen Ice Field, East Antarctica

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2019–2020 年ベルギー南極観測隊による東南極ナンセン氷原における隕石探査報告

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(Received June 25, 2020; Accepted October 4, 2020)

要旨: 2019–2020 年の夏期に，東南極セール・ロンダーネ山地南部においてベルギー南極観測隊（BELARE）により隕石探査を実施した．ナンセン氷原には，2020 年 1 月 15 日から 2 月 6 日まで 23 日間滞在し，採取した隕石の総数は 66 個，合計重量は約 8 kg であった．ナンセン氷原での隕石集積機構を解明するために，隕石の他に氷，火山灰層や岩石の破片も採取した．採取した隕石は，凍結したまま国立極地研究所に輸送された．これら採取した隕石が国際隕石学会の隕石命名委員会に認可された後，分類データは Meteorite Newsletter で公開される．

キーワード: 隕石探査，南極隕石，ナンセン氷原

Abstract: This report summarizes the Belgian Antarctic Expedition (BELARE) 2019–2020 meteorite search and recovery expedition near the Sør Rondane Mountains of East Antarctica during the 2019–2020 field season. This expedition took place from 15 January to 6 February 2020 within the area defined as "C" of the Nansen Ice Fields (S72°38′–72°48′S, 24°35′–25°06′E). The expedition team consisted of four scientists and two field guides, who systematically searched the ice field area and collected 66 meteorites. The total weight of the meteorites was determined to be ～8 kg. In addition to meteorites, blue ice samples, volcanic ash layers, and wind-blown terrestrial rock fragments were collected from the area to study in detail the nature of the mechanisms concentrating meteorites on the Nansen Ice Fields. The recovered meteorites were transported in a frozen state to the National Institute of Polar Research, Japan for dry-thawing and subsequent classification.

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Nanosecond Laser Ablation–Multicollector Inductively Coupled Plasma-Mass Spectrometry for in Situ Fe Isotopic Analysis of Micrometeorites: Application to Micrometer-Sized Glassy Cosmic Spherules

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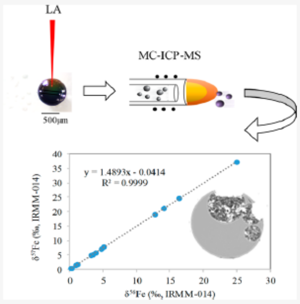
ABSTRACT: This work evaluates the use of nanosecond laser ablation–multicollector inductively coupled plasma-mass spectrometry (ns-LA–MC-ICP-MS) for Fe isotopic analysis of glassy cosmic spherules. Several protocols for data acquisition from the transient signals were compared, with the integration method, i.e., isotope ratios obtained by dividing the corresponding signal intensities integrated over the selected signal segment, providing the best precision. The bias caused by instrumental mass discrimination was corrected for by a combination of internal correction using Ni as an internal standard (coming from a conebulized standard solution) and external correction using a matrix-matched standard. Laser spot size and repetition rate were adapted to match the signal intensities for sample and standard within ±10%. For in situ isotopic analysis, the precision of the δ^{56}Fe values ranged between 0.02 and 0.11‰ (1 SD, based on 4 measurement sessions, each based on ablation along 5 lines for 30 s each) and 0.03–0.17‰ (SD, based on 3 measurement sessions) for glass reference materials and micrometeorites, respectively. Despite this excellent reproducibility, the variation of the isotope ratios along a single ablation line indicated isotopic inhomogeneity exceeding 1‰ in some micrometeorites. Isotopic analysis via pneumatic nebulization MC-ICP-MS, after sample digestion and chromatographic Fe isolation, was performed to validate the results obtained by in situ isotopic analysis, and good agreement was achieved between the δ-values obtained via both approaches and with those reported in literature for MPI-DING and USGS glass reference materials. Also for the glassy cosmic spherules, overall, there was a good match between the ns-LA–MC-ICP-MS and solution MC-ICP-MS results.



The characterization of extraterrestrial materials, such as meteorites and meteorite phases, e.g., glass, olivine, pyroxene, and Fe–Ni metal, and materials from sample-return missions, is a major driver for the development of novel and powerful analytical methods.[1] Advances in instrumentation, along with the parallel development of proper data acquisition and data-handling strategies, have given rise to a spectacular growth of analytical applications of mass spectrometric techniques in this context. For high-precision isotopic analysis, multicollector inductively coupled plasma-mass spectrometry (MC-ICP-MS) is the technique most commonly used nowadays, as it combines a high ionization efficiency and high sample throughput with sufficient precision to reveal the sometimes very small differences in isotope ratios caused by relevant processes.[2,3] Several works focused on the topic of Fe isotope geo- and cosmochemistry have been carried out using MC-ICP-MS already.[4,5] The isotopic composition of Fe was already determined in a wide range of Fe-bearing materials and matrices, including chondrites[6] and iron meteorites.[7,8] Dauphas et al.[9] obtained accurate Fe isotope ratio results for geological materials with a precision <0.03‰ on the δ^{56}Fe value using (pseudo-high mass resolution) MC-ICP-MS after sample digestion and target element isolation.

The combination of solid sampling via laser ablation (LA) with MC-ICP-MS provides direct isotopic information, while avoiding sample pretreatment and reducing the sample consumption.[10] Previously, femtosecond (fs)-LA–MC-ICP-MS has been successfully applied for that purpose in a variety of mineral matrices,[11,12] e.g., iron metal, sulfides, hematite, siderite, goethite, magnetite, and silicates.[13] Oeser et al.[14] reported in situ Fe isotopic analysis of reference glass materials using fs-LA–MC-ICP-MS, proving that the spatial resolution and precision achievable were suitable to resolve the diffusion-generated Fe–Mg isotopic zoning in magmatic olivines. Also separate mineral phases of such samples can be studied. In this context, the Fe isotopic composition has already been used to

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Decoupling of chemical and isotope fractionation processes during atmospheric heating of micrometeorites

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Abstract

Micrometeorites experience varying degrees of evaporation and mixing with atmospheric oxygen during atmospheric entry. Evaporation due to gas drag heating alters the physicochemical properties of fully melted cosmic spherules (CSs), including the size, chemical and isotopic compositions and is thus expressed in its chemical and isotopic signatures. However, the extent of evaporation and atmospheric mixing in CSs often remains unclear, leading to uncertainties in precursor body identification and statistics. Several studies have previously estimated the extent of evaporation based on the contents of major refractory elements Ca and Al in combination with the determined Fe/Si atomic ratios. Similarly, attempts have been made to design classification schemes based on isotopic variations. However, a full integration of any previously defined chemical classification schemes with the observed isotopic variability has not yet been successful. As evaporation can lead to both chemical and isotope fractionation, it is important to verify whether the estimated degrees of evaporation based on chemical and isotopic proxies converge. Here, we have analysed the major and trace element compositions of 57 chondritic (mostly V-type) CSs, along with their Fe isotope ratios. The chemical (Zn, Na, K or CaO and Al_2O_3 concentrations) and δ^{56}Fe isotope fractionation measured in these particles show no correlation. The interpretation of these results is twofold: (i) isotopic and chemical fractionation are governed by distinct processes or (ii) the proxies selected for chemical and isotope fractionation are inadequate. While the initial Fe isotopic ratios of chondrites are constrained within a relatively narrow range (0.005 ± 0.008‰ δ^{56}Fe), the chemical compositions of CSs display larger variability. Cosmic spherules are thus often not chemically representative of their precursor bodies, due to their small size. As oxygen isotopes are commonly used to refine the precursor bodies of meteorites, triple oxygen isotope ratios were measured in thirty-seven of the characterized CSs. Based on the relationship between δ^{18}O and δ^{57}Fe, the evaporation effect on the O isotope system can be calculated, which allows for a more accurate parent body determination. Using this correction method, two 'Group 4' spherules with strongly variable

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Quantitative elemental mapping of chondritic meteorites using laser ablation-inductively coupled plasma-time of flight-mass spectrometry (LA-ICP-TOF-MS)†

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Fast elemental mapping using laser ablation-inductively coupled plasma-time of flight-mass spectrometry (LA-ICP-TOF-MS) was applied to a set of chondritic meteorite samples, more specifically H chondrites. LA-ICP-TOF-MS enables element distribution maps for both major and trace elements to be obtained at µm-order spatial resolution (5 × 5 µm square pixels in this study) in a (semi-)quantitative manner. To assess the reliability of the quantitative data as obtained using LA-ICP-TOF-MS mapping, the accuracy and precision as obtained using this fast elemental mapping approach were compared to those of the data obtained using the more conventional spot analysis with an electron probe micro analyzer and LA-ICP-sector field (SF)-MS for major and trace elements, respectively. The maps obtained using LA-ICP-TOF-MS visualize elemental distributions among the constituent minerals, while major and trace element abundances determined using LA-ICP-TOF-MS are overall in good agreement within up to 30% relative uncertainty with those obtained based on the spot analyses and with literature values. Yet, some analytical limitations of LA-ICP-TOF-MS mapping remain due to the limited ablated yield when using a small laser spot size for high spatial resolution mapping, while ICP-TOF-MS shows a lower sensitivity and narrower linear dynamic range than does ICP-SF-MS. On the other hand, the main host phase(s) of an element can be readily identified and the major and trace element abundances in the phase(s) can be quantified with an accuracy approaching that of the spot analyses. As such, this study demonstrates the potential of LA-ICP-TOF-MS for fast quantitative imaging of various types of samples, in particular geological samples.

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Introduction

In situ spot analysis and elemental mapping in geological and geochemical research are commonly based on electron probe micro analysis (EPMA), scanning electron microscopy in combination with energy-dispersive X-ray spectrometry, micro-X-ray fluorescence spectrometry (µXRF), or secondary ion mass spectrometry (SIMS). Most of these techniques are valuable in the context of major element concentrations (generally >0.1% m m^{-1} level) for both spot analysis and mapping, but their application is more limited in relation to trace element analysis due to their relatively high limits of detection. For the determination of trace elemental abundances, laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) is now widely used as a direct solid sampling micro-analytical technique.[1–3] The LA-ICP-MS technique not only determines the trace elemental abundances in mineral phases, but also provides spatially resolved information in the form of elemental maps for major, minor, and trace elements.[4,5] Recently, hardware developments focusing on low-dispersion ablation cells and aerosol transport systems, which reduce the duration of single pulse response profiles and boost the signal-to-noise ratio and speed of analysis, significantly improved the analytical capabilities of LA-ICP-MS elemental mapping.[6,7] Moreover, the launch of commercially available time-of-flight (TOF) based ICP-mass spectrometers, providing rapid quasi-simultaneous detection of nearly the entire elemental mass spectrum for each individual laser pulse, has boosted the use of LA-ICP-MS for elemental mapping applications in a wide variety of research fields. ICP-TOF-MS instruments can handle the short transient signals produced with low-dispersion LA setups and provide fast multi-elemental detection in contrast to sequential scanning-type ICP-mass

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METEORITICS & PLANETARY SCIENCE

Fluid mobilization of rare earth elements (REEs), Th, and U during the terrestrial alteration of H chondrites

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Tintigny meteorite: the first Belgian achondrite

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ABSTRACT

A late afternoon in February 1971, a meteorite impacted the rooftop of a house in Tintigny village in southern Belgium. Confirmed as a possible meteorite by the schoolteacher, the meteorite and its fall story did not leave the village. Finally, 46 years after the fall event, we got the opportunity to study and characterize this meteorite. In this work, we give a detailed report on its textural, mineralogical, whole-rock elemental and oxygen isotopic composition. Officially named as Tintigny, we classified it as an achondrite from howardite-eucrite-diogenite (HED) clan and more precisely a polymict eucrite. A brecciated basaltic rock believed to be originated from the surface of V-type asteroids namely the asteroid 4 Vesta. Tintigny has recorded the evidence of the impact metamorphism and metasomatism processes active on its parent body. Tintigny is one of the 39 eucrite falls known to date, and one of the 11 eucrites occurred in Europe. It is the fifth officially recognized meteorite and the first achondrite from Belgium. This report shows the importance of studying and accessing such a meteorite for further cosmochemical and planetary investigations and enriching our knowledge on the formation of HED meteorites and their parent bodi(es). In addition, it brings the attention to its importance as a scientific heritage that has to be properly understood and safeguarded for the generations of scientists, scholar, and amateurs to come.

1. Introduction

In February 1971 (precise date not recorded), Mr Eudore Schmitz was working in his barn in the village of Tintigny (southern Belgium, 49.683786°N, 5.532957°E) during the late afternoon when he heard a loud noise from the roof of the building. After going upstairs, he found a hole in a tile and a black stone on the barn floor. It was suggested that he burnt himself picking up the fragment, so he used some hay and then his hat to hold the stone. The schoolteacher of the village, Mr Albert Rossignon, confirmed that the stone was a meteorite and kept it, hoping that his identification would be confirmed during a subsequent investigation. The teacher later joined a religious seminary and became a priest. While he faithfully kept the meteorite and showed it from time to time to visitors and children, the stone and associated story never left the region. In 2017, after reading an article about recent Belgian meteorite recovery expeditions in Antarctica, he contacted Dr Vinciane Debaille, professor at the Université Libre de Bruxelles (ULB) and specialist in planetary sciences and meteoritics who recognized the stone as an achondritic meteorite. The meteorite was subsequently donated by Madam Germaine Mathus, widow of Mr Eudore Schmitz, and her children, Jean-Paul, Rita and Joseph Schmitz, to the Royal Belgian Institute for Natural Science (RBINS) and studied. While the meteorite is no longer complete due to handling of the stone by various people over the years, Father Rossignon affirms that the fusion crust was initially complete, with a piece of the tile originally stuck on the stone.

We have classified this meteorite as a polymict eucrite and Tintigny, its official name, has been approved by the Nomenclature Committee of the Meteoritical Society (Gattacceca et al., 2020). Tintigny is the fifth officially recognized meteorite and the first achondrite from the Belgian territory (Fig. 1). This meteorite is now on permanent open display at RBINS.

In this paper, details on the petrological, geochemical, and isotopic characteristics of Tintigny are reported and its formation processes studied.

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Impact mixing among rocky planetesimals in the early Solar System from angrite oxygen isotopes

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Angrite meteorites are thought to represent ancient basaltic igneous rocks that formed inward of Jupiter's orbit on the basis of their isotopic parameters such as ε^{50}Ti, ε^{54}Cr and Δ^{17}O in addition to Fe/Mn ratios of pyroxene. New bulk oxygen isotope measurements of nine angrites, and of olivine 'xenocrysts' and groundmass fractions from three quenched angrites, however, reveal clear isotopic disequilibrium, implying an impact melt origin. Groundmass fractions from Asuka 12209, Asuka 881371 and Northwest Africa 12320 quenched angrites demonstrate an average Δ^{17}O value of -0.003 ± 0.020‰. Here, excluding the bulk value and all groundmass fractions of Northwest Africa 12320, which is contaminated by an impactor, we determine a new well constrained average Δ^{17}O value for the angrite parent body (-0.066 ± 0.016‰). Microstructural investigations of Northwest Africa 12320 reveal the presence of both fully recrystallized and undeformed olivine xenocrysts, indicating that some xenocrysts underwent high-temperature processes. These results suggest that angrites bear signatures of impact-driven isotopic mixing, possibly in response to early giant planet migration. The evidence for impact mixing raises doubts about the utility of quenched angrites as a suitable Pb–Pb isotopic anchor, which in turn has consequences for accurately defining the timeline of other Solar System events.

Angrites are defined as a group of unshocked, alkali-depleted basaltic meteorites that are amongst the oldest igneous rocks in the Solar System[1,2]. On the basis of the mineral chemistry of pyroxene (Fe/Mn ratios) within angrites and the isotopic dichotomy between non-carbonaceous and carbonaceous chondrites, it is likely that angrites originate from the inner Solar System[3,4]. Evidence from Mn/Cr isotopic systematics indicates that the angrite parent body (APB) was larger than the asteroid 4 Vesta[5]. On the basis of differing textures and mineralogy, angrites have been principally divided into plutonic angrites (slowly cooled), with crystallization ages ranging from $4{,}560.74 \pm 0.47$ to $4{,}556.60 \pm 0.26$ million years ago (Ma), and quenched angrites (rapidly cooled), with crystallization ages ranging from $4{,}564.39 \pm 0.24$ to $4{,}562.2 \pm 0.7$ Ma

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SCIENCE ADVANCES | RESEARCH ARTICLE

PLANETARY SCIENCE

An extraterrestrial trigger for the mid-Ordovician ice age: Dust from the breakup of the L-chondrite parent body

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The breakup of the L-chondrite parent body in the asteroid belt 466 million years (Ma) ago still delivers almost a third of all meteorites falling on Earth. Our new extraterrestrial chromite and ^{3}He data for Ordovician sediments show that the breakup took place just at the onset of a major, eustatic sea level fall previously attributed to an Ordovician ice age. Shortly after the breakup, the flux to Earth of the most fine-grained, extraterrestrial material increased by three to four orders of magnitude. In the present stratosphere, extraterrestrial dust represents 1% of all the dust and has no climatic significance. Extraordinary amounts of dust in the entire inner solar system during >2 Ma following the L-chondrite breakup cooled Earth and triggered Ordovician icehouse conditions, sea level fall, and major faunal turnovers related to the Great Ordovician Biodiversification Event.

INTRODUCTION

During the past 500 million years (Ma), Earth has experienced three major ice ages (*1*). We live in the latest ice age that began in the Late Eocene, ~35 Ma ago, after more than 230 Ma of ice-free high-latitude continental regions. The preceding major ice age lasted from the Late Devonian to the mid-Permian, leaving behind extensive glacial deposits over ancient Gondwanaland. The oldest major Phanerozoic ice age peaked in the Late Ordovician, as indicated by glacial deposits in, e.g., North and South Africa and South America (*2*, *3*), but sea level records indicate that ice age conditions may have started already in the mid-Ordovician (*4*–*7*). Although much of Earth's short-term climate variability is astronomically paced, as expressed by the Milankovitch cycles, the fluctuations on a 10- to 100-Ma scale between greenhouse and icehouse climates are generally explained in terms of Earth-bound causes, such as the closing or opening of seaways, uplift of mountain chains, or changes in atmospheric CO_2 concentrations (*1*).

Here, we focus on an interval of the geological record that has been proposed to represent the onset of the Ordovician ice age and where important faunal turnovers occurred worldwide (*4*, *8*). The interval has been studied in particular detail in Baltoscandia where many well-preserved sedimentary sections are exposed. In these sections, shortly following the transition between the regional Volkhov and Kunda stages (~466 Ma ago), one of the major steps in the so-called Great Ordovician Biodiversification Event (GOBE) is registered (*4*). Similar biodiversity changes are seen in coeval Laurentian sections, indicating a global event (*8*). The GOBE concept refers to a stepwise change over ~30 Ma from a world with relatively low marine invertebrate biodiversity in the Cambrian and Early Ordovician to near-modern levels at the end of the Ordovician (*9*). The literature discusses two seemingly opposing explanations for the faunal and climatic changes in the earliest Kundan (*4*, *10*). Schmitz *et al.* (*10*) showed that the changes appear to coincide with the breakup of the L-chondrite parent body (LCPB; diameter, ~150 km) in the asteroid belt, the largest documented breakup during the past 3 billion years. Besides the abundant L-chondritic meteorites still falling on Earth from this event, common fossil meteorites (1 to 20 cm large) in mid-Ordovician sediments attest to the breakup (*11*). Schmitz *et al.* (*10*) argued that recurrent asteroid impacts on Earth after the LCPB breakup may have spurred increases in biodiversity. This is consistent with the "intermediate disturbance hypothesis" that explains biodiversity increases in recent rain forests under mild stress (*12*). This proposed GOBE-LCPB relation has been challenged on the basis of oxygen-isotope temperature records, interpreted to indicate that the Ordovician biodiversity expansion, including the mid-Ordovician biota turnover, instead relates to a gradual cooling of Earth, culminating with the icehouse conditions in the Late Ordovician (*4*, *13*). Over the past decade, further evidence has accumulated in support of an increase in asteroid impacts during the extended period when the main phase of the GOBE took place (*14*). The craters from these impacts, however, are typically small (diameter, <10 km), and no direct links between these craters and faunal turnovers have been found. The debate about a possible causal connection between the LCPB breakup and GOBE has suffered from a lack

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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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Characterization of achondritic cosmic spherules from the Widerøefjellet micrometeorite collection (Sør Rondane Mountains, East Antarctica)

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Abstract

Achondritic micrometeorites represent one of the rarest (ca. 0.5–2.1%) particle types among Antarctic micrometeorite collections. Here, we present major, trace element and oxygen isotope compositions on five vitreous, achondritic cosmic spherules (341–526 µm in size) recovered from the Widerøefjellet sedimentary trap in the Sør Rondane Mountains (SRMs) of East Antarctica. We also present the first iron isotope data for four of these achondritic cosmic spherules. The particles were initially identified based on the atomic concentrations of Fe-Mg-Mn and their distribution in Fe/Mg versus Fe/Mn space, spanning a relatively wide range in Fe/Mg ratios (ca. 0.48–1.72). The Fe/Mn ratios cover a more restricted range (22.4–31.7), comparable to or slightly below the values measured for howardite-eucrite-diogenite (HED) and martian meteorites. One particle (WF1801-AC3) displays an elevated Fe/Mn ratio of ~78, comparable to the values determined for lunar rocks. The negative correlation observed between the CaO + Al_2O_3 contents and the Fe/Si ratios of achondritic spherules reflects both the mineralogy of the precursor materials, as well as the extent of volatilization experienced during atmospheric entry heating. This trend suggests that the primary mineralogy of precursor materials may have been compositionally similar to basaltic achondrites. Based on their distribution in Ca/Si versus Al/Si space, we argue that the majority of achondritic cosmic spherules predominantly sample pyroxene- and/or plagioclase-rich (i.e., basaltic) precursor bodies. Such precursor mineralogy is also inferred from their rare earth element (REE) patterns, which show resemblances to fine-grained basaltic eucrites or Type 1 achondritic spherules ($n = 3$ – av. $REE_N = 11.2–15.5$, $(La/Yb)_N = 0.93–1.21$), pigeonite-rich equilibrated eucrite precursors or Type 2 achondritic spherules ($n = 1$ – av. $REE_N = 27.9$, $(La/Yb)_N = 0.10$), and possibly Ca-phosphates from (primitive) achondritic bodies (n = 1 – av. $REE_N = 58.8$, $(La/Yb)_N = 1.59$). This is clearly demonstrated for particle WF1801AC-1, which was likely inherited from a fine-grained eucritic precursor body. The pre-atmospheric oxygen isotope composition was reconstructed through compensation of mass-dependent fractionation processes as well as mixing with atmospheric oxygen, using iron isotope data. Two particles (WF1801AC-2, WF1801-AC4) display corrected oxygen isotope compositions ($\delta^{18}O = 3.7–4.4‰$) largely consistent with HED meteorites and may thus originate from HED-like parent bodies. The corrected oxygen isotope compositions ($\delta^{18}O = 12.6–12.8‰$) of the remaining particles (WF1801-AC3, WF1801-AC5) do not

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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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Microtektites

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

GEOPHYSICS

Unexplored Antarctic meteorite collection sites revealed through machine learning

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Meteorites provide a unique view into the origin and evolution of the Solar System. Antarctica is the most productive region for recovering meteorites, where these extraterrestrial rocks concentrate at meteorite stranding zones. To date, meteorite-bearing blue ice areas are mostly identified by serendipity and through costly reconnaissance missions. Here, we identify meteorite-rich areas by combining state-of-the-art datasets in a machine learning algorithm and provide continent-wide estimates of the probability to find meteorites at any given location. The resulting set of ca. 600 meteorite stranding zones, with an estimated accuracy of over 80%, reveals the existence of unexplored zones, some of which are located close to research stations. Our analyses suggest that less than 15% of all meteorites at the surface of the Antarctic ice sheet have been recovered to date. The data-driven approach will greatly facilitate the quest to collect the remaining meteorites in a coordinated and cost-effective manner.

INTRODUCTION

Meteorites are parts of planetary bodies that formed and evolved throughout the evolution of the Solar System. These extraterrestrial rocks fell on Earth after surviving the passage through the atmosphere. Being directly accessible at the Earth's surface, meteorites provide important insight into nebular and planetary processes. Antarctic meteorites are especially important in this context because of their pristine states and the existing legal framework that ensures their availability for scientific research (*1*).

When meteorites fall on the surface of the Antarctic ice sheet, they typically become entrapped in the ice sheet's snow-covered accumulation area, which spans 98% of the continent (*2*, *3*). During the process in which snow accumulates, compacts, and transforms to ice, meteorites become embedded in the ice sheet (Fig. 1). These meteorites are then transported along with the ice that flows under gravitational forces toward the margins of the continent. Although most of the englacially transported meteorites end up in the ocean, a small fraction is brought back to the surface of the ice sheet in some of the continent's blue ice areas (BIAs) (*4*). In BIAs, the annual ablation exceeds the accumulation (*2*, *5*). If the ice within a BIA contains meteorites, these meteorites eventually become exposed through the removal of the ice by ablative processes (sublimation). Moreover, the absence of snow accumulation in a BIA implies that meteorites falling directly on a BIA can remain exposed at the surface. Thus, if the flow of the ice and specific geographical and climatological settings combine favorably, a BIA can act as a meteorite stranding zone (MSZ) (Fig. 1). In MSZs, meteorites are concentrated at the surface, where they can be easily recovered during field missions, as, thanks to their color, they contrast with the underlying blue ice. These MSZs make Antarctica the most productive region for collecting meteorites on Earth; to date, about 62% of all meteorites recovered on Earth originate from Antarctica (*6*).

A conceptual model for the mechanism behind MSZs was first proposed in the early 1970s, after a Japanese expedition found nine meteorites at a BIA in 1969 (*7*, *8*). Subsequently, many searches for meteorites were conducted, and the mechanism behind MSZs was studied at multiple individual ice fields (*9*–*11*). The concentrating mechanism has been generalized qualitatively, describing the various influencing factors, as well as the different settings in which meteorites are concentrated (*4*, *12*). For example, when the ice flow meets a submerged barrier (open MSZ) (Fig. 1) or an emerged barrier (closed MSZ) (Fig. 1), the flow is slowed down and redirected toward the surface due to a buttressing effect (*4*, *5*, *12*, *13*). The contribution of driving factors behind meteorite concentrations (e.g., direct infall, ablation, or ice flow) differs for individual MSZs. In MSZs, meteorites stay at the surface for up to thousands of years (*9*, *14*), during which they can be transported by the almost stagnant ice flow (and potentially wind), until they eventually reach the edge of the MSZ and (re-)enter the ice sheet.

Many of today's known MSZs were discovered coincidentally, and to date, the identification of new MSZs remains a very labor-intensive process that strongly relies on chance and past experience. Potential MSZs are typically identified through visual examination of remote sensing data of BIAs and their vicinity, after which candidate MSZs are visited by snowmobile or helicopter, to investigate whether a meteorite concentration is present (*15*). The discovery of meteorite concentrations thus partly depends on the expertise and experience of the persons examining maps and imagery, and largely on costly field reconnaissance visits. Because of this big human factor in the reconnaissance approach, it is most likely that major MSZs are still to be discovered.

Here, we combine the wealth of recent remote sensing observations and derived products over the Antarctic ice sheet with machine learning techniques to perform a continent-wide systematic analysis toward the detection of MSZs. A first attempt toward predicting areas containing concentrations of meteorites was recently performed by Evatt *et al.* (*14*). With a physics-based approach, they calculated the spatial flux of meteorite falls using data of

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research papers

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Investigation of (micro-)meteoritic materials at the new hard X-ray imaging PUMA beamline for heritage sciences

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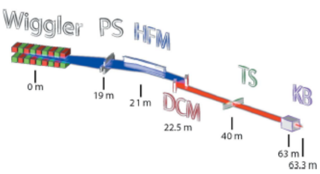
At the French synchrotron facility SOLEIL, a new X-ray imaging facility PUMA (Photons Utilisés pour les Matériaux Anciens) has been made available to scientific communities studying materials from cultural heritage. This new instrument aims to achieve 2D and 3D imaging with microscopic resolution, applying different analytical techniques including X-ray fluorescence spectroscopy (XRF), X-ray absorption spectroscopy (XAS), X-ray diffraction and phase-contrast imaging. In order to discover its capabilities a detailed analytical characterization of this beamline as an analytical and imaging tool is deemed necessary. In this work, (confocal) XRF and XAS analyses are demonstrated using the Seymchan pallasite meteorite and an Antarctic unmelted micrometeorite as case studies. The obtained spatial resolution (2 µm × 3 µm) and sensitivity (detection limits <10 p.p.m. for 1 s acquisition at 18 keV) show that PUMA is a competitive state-of-the-art beamline, providing several high-profile and high-in-demand analytical methods while maintaining applicability towards a wide range of heritage-oriented sciences.



1. Introduction

Investigation using X-ray based methods (on the microscopic scale) of ancient materials, *e.g.* in the fields of archaeology, palaeontology, paleo-environmental and conservation sciences, is usually performed at synchrotron radiation facilities owing to the non-destructive character of the analyses (Bertrand *et al.*, 2012; Schalm *et al.*, 2016; Grieten *et al.*, 2017; Brun *et al.*, 2016; Tack *et al.*, 2016; Monico *et al.*, 2015; Alfeld *et al.*, 2010; Vanmeert *et al.*, 2015; Salomé *et al.*, 2013; Fayard *et al.*, 2013; De Pauw *et al.*, 2018). However, access to these facilities is often limited. Furthermore, ancient materials research often has to compete for beam time with other research fields and regularly requires the investigation of complete sets or large sample series, requiring significant amounts of beam time. For this purpose, a new beamline has been constructed at the SOLEIL synchrotron (Gif-sur-Yvette, France) dedicated to the investigation of ancient materials, and developed in collaboration with the IPANEMA platform (Institut Photonique d'Analyse Non-destructive Européen des Matériaux Anciens; Bertrand *et al.*, 2011). The PUMA (Photons Utilisés pour les Matériaux Anciens) beamline is a hard X-ray imaging beamline optimized for the scientific communities of the heritage sciences and allows for 2D and 3D imaging capabilities with a microscopic spatial resolution, applying several analytical techniques including X-ray fluorescence spectroscopy (XRF), X-ray absorption spectroscopy (XAS), X-ray diffraction (XRD) and phase-contrast imaging.

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