—報告—
Report

Comprehensive report of the BELARE 2022–2023 meteorite reconnaissance expedition in the Sør Rondane area, East Antarctica

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(Received June 23, 2023; Accepted September 14, 2023)

Abstract: We provide a comprehensive overview of a reconnaissance expedition aimed at identifying new possible meteorite stranding zones in the surrounding of the Belgian Princess Elisabeth Antarctica (PEA) station in the Sør Rondane Mountains during the BELARE 2022–2023 field season. The team was composed of four scientists and one field guide. Several areas of interest were identified and daily searches occurred in two phases, first from a base camp and then from PEA. The first phase was in the Nils Larsenfjellet area, and a camp, accessible from the H.E. Hansenbreen (S72° 13.260' E22° 37.779'; altitude 1640 m), was set up from December 21 to 27, 2022. Systematic searches were performed in moraines and on blue ice areas (BIAs) during day trips, including the Verheyefjellet BIA, several BIAs surrounding an alignment of nunataks south of PEA, centered on S72° 18.403' E23° 13.191', and the Røysane nunatak at the eastern edge of Nils Larsenfjellet. Four meteorites were recovered during the first phase of the expedition, and another one in the second phase, also in the Nils Larsenfjellet area. In addition, nine surface ice samples and 18 kg of micrometeorite-bearing sediments were collected.

Preliminary classification, performed on-site using magnetic susceptibility, tentatively indicated H and L chondrites. The recovered meteorites were transported in frozen state to the Royal Belgian Institute of Natural Sciences in Brussels to be thawed in vacuum conditions and classified based on their mineralogy. The Nils Larsenfjellet is identified as a potential new Dense Collection Area.

Keywords: blue ice area, meteorites, Sør Rondane Mountains

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南極資料，Vol. 67，12–27，2023
Nankyoku Shiryô (Antarctic Record), Vol. 67, 12–27, 2023

1. Introduction

Since the 10th Japanese Antarctic Research Expedition (JARE-10) geological expedition in the Yamato Mountains in 1969 that recovered nine meteorites from a single patch of bare ice (Marvin, 2014; Yoshida *et al.*, 1971; Yoshida, 2010), accumulations of meteorites have been identified in numerous areas across Antarctica (Cassidy *et al.*, 1992). The general hypothesis for this local accumulation is related to the incorporation of meteorites into the ice after their fall and their transportation by glaciers toward the sea. However, in case a topographic obstacle is encountered, the movement of the ice is forced toward the surface. Over time, ice layers are ablated, exposing blue-colored ice (in contrast to most of the continent that is snow-covered) and the trapped meteorites are released and concentrated into a restricted (blue ice) area (Bintanja, 1999; Sinisalo and Moore, 2010). However, not all blue ice areas (BIAs) lead to meteorite accumulation (Zekollari *et al.*, 2019) and, in practice, field visits are needed to evaluate the presence of meteorites despite the logistic costs of Antarctic expeditions. In an effort to aid fieldwork missions, Tollenaar *et al.* (2022) used machine learning to combine satellite observations of physical parameters of the ice surface (radar backscatter data for snow cover, surface temperature, ice velocity, and surface slope) inherent to zones where meteorites are found. This approach yielded a probability index to find meteorites anywhere in Antarctica (see the website: http://wheretocatchafallingstar.science). Besides the large-scale concentration of meteorites due to glacier movements, secondary processes such as wind can create very localized high concentrations of meteorites (Folco *et al.*, 2002; Harvey, 2003). For example, meteorites below ~200 g can be displaced by the wind until they are caught in topographical depressions or moraines (Folco *et al.*, 2002). Those secondary, highly location-dependent processes render every BIA unique in their configuration and, hence, their potential to concentrate and distribute meteorites.

Field visits to the Nansen BIA located south of the Sør Rondane Mountains in East Antarctica have been extremely productive over the past 50 years, with almost 2000 meteorites collected by the JARE-29 in 1987−1989 (Naraoka *et al.*, 1990; Yanai *et al.*, 1993). All the meteorites recovered in this dense collection area (DCA) are named after the former Asuka Japanese research station. After the establishment of the Belgian Princess Elisabeth Antarctica (PEA) station in 2009, meteorite expeditions have resumed in the area. The JARE-51, with the participation of a Belgian scientist and the logistic support of PEA, collected 635 meteorites from the Mount Balchen area during the 2009−2010 field season (Kaiden *et al.*, 2010; Tsuchiya *et al.*, 2012). Subsequently, joint JARE and BELARE (Belgian Antarctic Research Expedition) missions were organized on the Nansen BIA by systematic searches on snowmobiles, yielding a total of 974 meteorites in the 2010−2011, 2012−2013 and 2019−2020 seasons (Goderis *et al.*, 2011; Goderis *et al.*, 2021; Imae *et al.*, 2015).

Following the successful searches of the Nansen BIA (see Goderis *et al.*, 2021, for an overview), the BELARE 2022−2023 expedition was intended as a reconnaissance field mission to evaluate the meteorite potential of other BIAs in the surrounding of PEA with the main goal to identify new DCAs for future missions. Based on the meteorite finding probability index map from Tollenaar *et al.* (2022), several points of interest were identified in the surrounding of PEA, reachable either by camp or daily trips (see Table 1 for a summary of the expedition log).

We summarize here the reconnaissance expedition for meteorite recovery during the BELARE 2022–2023 field season that found five meteorites. These will be named Asuka 22x and curated at the Royal Belgian Institute of Natural Sciences (RBINS), where they will first be dry-thawed and classified. Following a Letter of Intent accepted by all parties involved in the expedition, the expedition team members obtain priority access to the recovered meteorites for scientific research.

Table 1. Daily log of the BELARE 22–23 meteorite expedition

Date	Location	Meteorites recovered	Distance driven by snowmobile (km)	Comments
Dec 12 2022	Cape Town			Arrival of the team
Dec 13 2022	Cape Town			Polar gear reception at IPF
Dec 14 2022	Cape Town			ALCI briefing
Dec 15 2022	Cape Town			PCR test
Dec 16 2022	Cape Town			Flight D05 delayed
Dec 17 2022	Cape town to Novo to PEA			
Dec 18 2022	PEA			Snowmobile driving and crevasse rescue training
Dec 19 2022	PEA			Medical briefing and preparation for field camp
Dec 20 2022	PEA			Preparation for field camp and snowmobile driving
Dec 21 2022	PEA to Nils Larsenfjellet		48	PCR test
Dec 22 2022	Nils Larsenfjellet		30	Search in moraine
Dec 23 2022	Nils Larsenfjellet		26	Search in moraine
Dec 24 2022	Nils Larsenfjellet		38	Search in ice tongue and moraine + sediment collection
Dec 25 2022	Nils Larsenfjellet	3	72	Search on BIA
Dec 26 2022	Nils Larsenfjellet	1	10	Search in terminal moraine of ice tongue
Dec 27 2022	Nils Larsenfjellet to PEA		48	
Dec 28 2022	PEA			Bad weather
Dec 29 2022	PEA			Bad weather
Dec 30 2022	PEA			Bad weather
Dec 31 2022	PEA			Recovery of the 2 left behind sleds at the former camp site by Manu Poudelet and Henri Robert
Jan 01 2023	PEA			Too much wind
Jan 02 2023	PEA		52	Sediment collection in Wideroefjellet
Jan 03 2023	PEA		126	BIA surrounding aligned nunataks
Jan 04 2023	PEA		124	BIA at Verheyefjellet + sediment collection
Jan 05 2023	PEA	1	128	BIA at Røysane nunatak + sediment collection
Jan 06 2023	PEA			Sediment processing at PEA
Jan 07 2023	PEA			Sediment processing at PEA
Jan 08 2023	PEA			Packaging meteorites for travel
Jan 09 2023	PEA			Flight delayed
Jan 10 2023	PEA to Cape Town			
Jan 11 2023	Cape Town			Departure of the team
total		5	654	

2. Expedition members and their roles

The BELARE 2022–2023 meteorite expedition team consisted of four researchers working in the field of meteoritics, and one field guide/paramedic. The team was composed of: Vinciane Debaille (FNRS-Université libre de Bruxelles, Brussels, Belgium, under Belgian Science Policy (Belspo) funding, as the scientific leader of the team); Ryoga Maeda (Vrije Universiteit Brussel-Université libre de Bruxelles; Brussels, Belgium; under Belspo funding); Maria Schönbächler (ETH-Zürich, under ETH Zürich funding), Maria Valdes (The Field Museum of Natural History in Chicago; under Robert A. Pritzker Center of Meteoritics and Polar Studies and TAWANI Foundation funding); and Manu Poudelet (International Polar Guide Association; field guide and paramedic).

3. Scientific questions: definition of search areas and new dense collection area

It is well established that glaciers and ice movement concentrate meteorites in key areas that are usually associated with blue ice (*e.g.*, Cassidy *et al.*, 1992). However, the exact mechanism remains poorly constrained and likely depends on local conditions. Following the successful search of the Nansen BIA, recognition of new DCA in the surrounding of PEA is of utmost importance to continue recovering meteorites in the BELARE program.

Following the meteorite finding probability map provided by Tollenaar *et al.* (2022) (see: http://wheretocatchafallingstar.science), various areas were identified in the surrounding of PEA (Fig. 1), all with a probability index of more than 80% for finding meteorites.

The first site is located at Nils Larsenfjellet (No. 1 on Fig. 1.a). The area is composed of both BIAs and moraines (Fig. 1.b), and the local topography of the ice flow is promising, as the glacier divides into tongues finishing in topographical depressions and moraines. Because meteorites can easily be blown away by the wind, the goal was to investigate

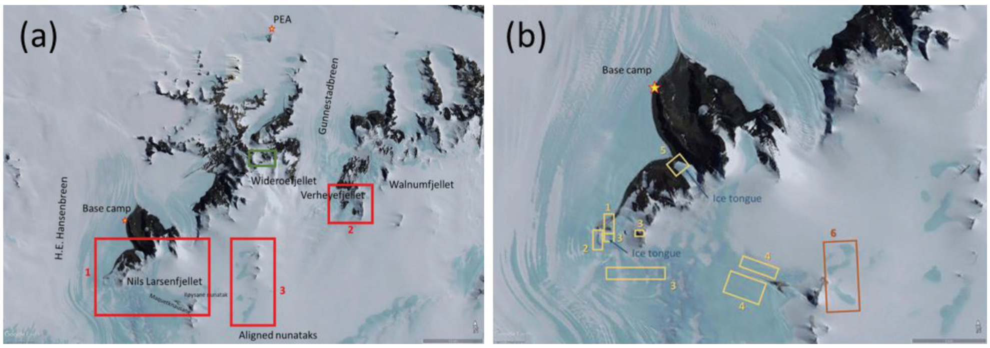

Fig. 1. (a) Sør Rondane Mountains map, with the location of PEA and the 3 different zones of interests based on the meteorite finding probability index map from (Tollenaar et al., 2022): 1: Nils Larsenfjellet; 2: Verheyefjellet; 3: aligned nunataks. (b) Zoom on the searching zone in Nils Larsenfjellet; 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).

moraines and topographical depressions as possible local meteorite traps. All the features were first identified using satellite images from Google Earth, and then in the field.

For daily searches from PEA, one target was identified at Verheyefjellet (No. 2 in Fig. 1.a). A second point of interest was also recognized around an alignment of nunataks (from north to south: Van de Canhamaren, Dillenberget, Goolsnuten, Swaabsteinen, and Caussinknappen, termed "aligned nunataks" in the following sections) (No. 3 in Fig. 1.a). All the geographical names have been used as in Shiraishi *et al.* (1997) and the Scientific Committee on Antarctic Research (SCAR) composite Gazetteer of Antarctica (https://data.aad.gov.au/aadc/gaz/scar/). For both sites, ESA Sentinel-2 images were used at PEA (from the website https://sentinel.esa.int/web/sentinel/sentinel-data-access) to determine and verify the recent snow cover before departure. Finally, since weather conditions and schedule were favorable, an extra day excursion from PEA focused on the Nils Larsenfjellet area, reaching the Røysane Nunatak and closely associated BIA (No. 6 in Fig. 1.b).

Because the BELARE 2022–2023 meteorite expedition is a reconnaissance field mission, it was therefore difficult to estimate the expected number of recovered meteorites.

4. Preparation for the expedition

4.1. Pre-expedition preparation

Discussions about international collaboration between Belgium, Switzerland and the USA were initiated in 2019, for a foreseen expedition during the 2020–2021 field season. However, due to the pandemic that started in the spring of 2020, notification of the cancellation of the field mission came in September 2020. Discussions resumed in the spring of 2021 (in a virtual meeting between the IPF, ULB, and VUB on April 22, 2021) and preparation actively started in the summer of 2021, for a field mission from ~ mid-January to ~ mid-February 2022. A general briefing was virtually organized on September 3, 2021. Due to the pandemic situation, a 10-day quarantine in Cape Town was mandated, and this was extended to 15 days in mid-December, advancing the departure by five days (December 28, 2021 instead of January 2, 2022, for a departure from Cape Town to PEA on January 12, 2022). Due to the COVID-19 situation at PEA, the expedition was finally cancelled on December 27, 2021. It is important to note that the extent of the snow cover on BIAs was observed to be exceptionally high during the 2021–2022 field season, which would have hindered the meteorite search.

Discussions then resumed in the spring of 2022 for the 2022–2023 field season. A virtual meeting was organized on July 28, 2022 between the IPF (Alain Hubert, Gigi Johnson-Amin, and Henri Robert), Vinciane Debaille, Maria Schönbächler, Maria Valdes, Steven Goderis, and Philippe Claeys to discuss the organization of the mission, including coordinates of the different zones to explore, and the logistics needed for the base camp in Nils Larsenfjellet. Advice was provided by Alain Hubert to identify potential zones to visit, combining scientific interests and safety concerns, and it was agreed that flexibility in the planning was required depending on the number of meteorites found in specific regions.

4.2. Dronning Maud Land Air Network (DROMLAN) flights

The Belgian, Swiss, and American team members flew to Cape Town (South Africa) using a commercial airline and met at Istanbul airport for the connecting flight to Cape Town on December 12, 2022. The DROMLAN flight D-05 from Cape Town to Novo Runway was planned for December 16, 2022 using an Ilyushin IL-76 aircraft. A virtual meeting was organized with the Antarctic Logistics Centre International (ALCI) on December 14 to prepare and organize the flight, including flight and safety procedures, cargo, and polar equipment bag. A PCR test for SARS-CoV-2 of the entire team was performed on the morning of December 15, which was negative for all expedition members. The same day, the team was informed that the flight to Novo was delayed because of the presence of snow on the runway. The departure finally took place on December 17. From Novo, after a connection of three hours, the team members flew to PEA with a Basler BT-67 turbo.

The return was organized from the Perseus airfield located 60 km away from PEA to Cape Town on January 9, 2023 by private jet. However, the return flight met a one-day delay due to the weather condition and thus the return was conducted on January 10, 2023.

4.3. *Safety trainings*

The pre-expedition safety training for the BELARE 2022‒2023 meteorite team took place immediately after arrival at PEA. On December 18, the morning was dedicated to snowmobile maintenance by Henri Robert and driving lessons by Manu Poudelet, and the afternoon to crevasse rescue training organized by Martin Leitl and Christian Herzog. All team members participated in the training taking place in a known crevasse close to PEA (S71° 55.012' E23° 35.317'). On December 19, a medical training was organized by the medical doctor of the station, Jeanne Picart, to discuss first aid rescue, the dangers of cold environments, and training on cardiac-pulmonary resuscitation and thermal isolation of a victim. The rest of the day and the morning of December 20 were used to plan and prepare the logistics for the base camp. A supplementary snowmobile driving exercise was provided on the afternoon of December 20.

4.4. *Clothing*

All personal equipment such as base layer clothing, snow boots, heavy jackets, goggles, gloves *etc.* were either brought by each team member individually or borrowed from IPF at the facility warehouse located in Cape Town, before departure to Novo. Outer pieces of equipment that were used during the meteorite search (snowmobile suits, helmets, and crampons) were provided directly at PEA.

4.5. *Nils Larsenfjellet base camp*

4.5.a: Logistics: Before the arrival of the team at PEA, the route to Nils Larsenfjellet was opened from the north, through H.E. Hansenbreen, and a pre-camp was set up by Alain Hubert, Martin Leitl, and Christian Herzog in a moraine area close to the BIA (S72° 13.260' E22° 37.779'). They left three sleds and mounted two New Dome five North Face tents (kitchen and toilet) and one Lowland mountain gear sleeping tent, and left fuel, insulated mattresses and food. The meteorite team left PEA on December 21 to the camp with three additional pulka sleds for personal gear, sleeping bags and extra food, and arrived after a three-hour drive on snowmobile (see Fig. 2.a). Another PCR test was conducted at PEA before deployment on the morning of December 21, which was negative for all meteorite team members.

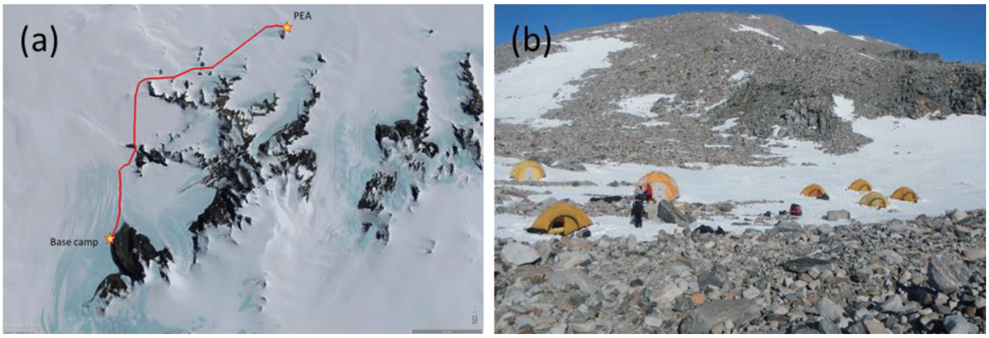

Fig. 2. *(a) Path used on snowmobiles to reach the Nils Larsenfjellet base camp from PEA. Image made using Google Earth (US geological survey). (b) Set up of the base camp at Nils Larsenfjellet. Five individual sleeping tents were pitched (4 on the right, one on the forefront left), in addition to two larger New Dome 5 North Face for kitchen (middle) and toilets (left). The first line of moraine is seen at the forefront of the picture. Picture credits: Vinciane Debaille.*

At arrival, four extra Lowland mountain gear sleeping tents were mounted, one per person (Fig. 2.b). Depending on the success of the exploration, one week was planned in the area, for thoroughly investigating moraines and BIAs. The team returned to PEA on December 27, after dismantling the camp, and packing six sleds, of which two were left on site for later pick-up.

4.5.b: Snowmobiles: Extra fuel was taken to the Nils Larsenfjellet base camp. Based on estimation, 400 liters (20 cans of 20 liters) were deposited by the initial reconnaissance team led by Alain Hubert before arrival of the meteorite team. Around 300 liters were used by the team to refuel the snowmobiles and the generators. Oil consumption was variable depending on the snowmobile power (two of 300 cc, and three of 550 cc), and on average, one liter of oil every three days was used per snowmobile (~10 liters in total).

4.5.c: Generators: Two Honda generators were present at the base camp (10i and 20i) for recharging personal electronic equipment and radio.

4.5.d: Food: Frozen dishes prepared at PEA were planned for five people for fifteen days, plus some fresh foods including bell peppers, tomatoes, onions. Eight frozen and sliced loaves of bread were also prepared for breakfast and lunch on the field. Cheese and vacuum-packed sliced charcuterie were prepared for lunch. Plenty of snacks (nuts, cereal bars, dried fruits, canned fruits ...), instant noodles, crackers, and chips were also packed into four boxes in total.

4.6. Daily searches from PEA

After returning from Nils Larsenfjellet base camp, daily expeditions from PEA were organized to the south of Gunnestadbreen, depending on the weather conditions (see Table 1), and all the logistics were organized from PEA with the help of Henri Robert. Snowmobiles were refueled on a daily basis. Lunch boxes were prepared at PEA.

5. Sample search and collection

Typically, the team drove in a row from the base camp or PEA to the search location, with adequate safety distances of about 30 meters between each member (Fig. 3.a). Then, snowmobiles were either parked or a V-shape was adopted for searching on blue ice (see paragraph 5.1.). The field guide was always equipped with a sled containing safety and emergency equipment (crevasse rescue kit, emergency tent, additional fuel, food ...). Because meteorites can be displaced by the wind, special attention was paid to moraines and topographical depressions, to verify whether these places could host secondary accumulations of meteorites.

5.1. At Nils Larsenfjellet

In moraines, the meteorite search was carried out on foot applying systematic swipes. The mixed patches of sandy areas with pebbles and ice (Fig. 3.b) required to use crampons.

On blue ice, systematic searches by snowmobiles were performed in a V-shape (Imae *et al.*, 2015), with the field guide at the front and two scientists on each side, separated by ~20 m. The search was divided into two parts, located south and north of the Maquetknausane moraine. Three meteorites were recovered on the Nils Larsenfjellet BIA, one showing exceptional flow lines (Fig. 4.a). Other zones of diluted moraines were searched by driving the snowmobiles slowly. Ice samples were also collected to obtain measurements of the H and O isotopic compositions as in Zekollari *et al.* (2019). These samples were obtained by removing the few upper centimeters of ice at the surface, after which ice below this surface (and therefore unaffected by surface processes) was crushed by a chisel and collected in small bottles. Dusty sediments were collected with a brush and dustpan at the top of Nils Larsenfjellet. Finally, the terminal moraine of an isolated glacier tongue (No. 5 in Fig. 1.b) was also investigated, during which a single meteorite was found and collected.

5.2. At Verheyefjellet

The BIA was searched on snowmobiles in a V-shape formation. The southwest part of

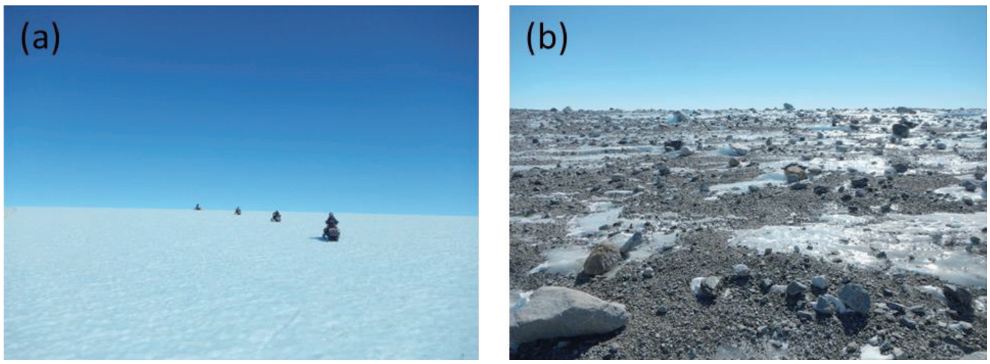

Fig. 3. (a) Team members driving on H.E. Hansenbreen in a line with safety distances between each other until reaching the search location. (b) Mixed patches of sandy areas and ice in the moraine area. Picture credits: Vinciane Debaille.

the BIA could not be accessed because of the increasing size and number of crevasses. The terminal moraine located at the north of the BIA was investigated on foot.

5.3. At aligned nunataks

The three different patches of blue ice were identified by visually inspecting the landscape, which was impeded by cloudy sky and thus limited visibility. The patches were searched on snowmobiles in a V-shape formation. No moraine was encountered.

5.4. At Røysane nunatak

The different patches of blue ice were searched on snowmobiles in a V-shape formation. A moraine on the flank of the nunatak was investigated, but the color of the terrestrial rocks was very similar to that of meteorites, complicating the search. One meteorite, with the exceptional weight of 7.6 kg, was found on the BIA (Fig. 4.b). Meteorites were collected and packed into polyethylene bags, avoiding direct contact with hand whenever possible. Provisional naming included the initial of the last name of the finder, then year, month, day, and number of the day, as in the previous expeditions (Goderis *et al.*, 2011; Goderis *et al.*, 2021; Imae *et al.*, 2015). The name was written directly on the ice with a permanent marker, or using a white dive slate and pencil in moraine areas. GPS locations were recorded with a handheld GPS. Aluminum foil was used for the 7.6 kg meteorite in order to facilitate its manipulation without directly touching it.

A total of 18 kg of fine-grained sediments were recovered from all searched areas: Nils Larsenfjellet summit, Verheyefjellet summit, Røysane Nunatak, and Widerøefjellet (which was visited solely for the purpose of collecting sediments for micrometeorites recovery). At Verheyefjellet, collected sediments are of poor quality due to the near absence of fine-grained sediments, strong winds while trying to collect dust, and the presence of snow. Sediments were dried at PEA and sieved using a 2 mm mesh. The sieved sediments were then divided between the team members according to the agreement outlined in the Letter of Intent.

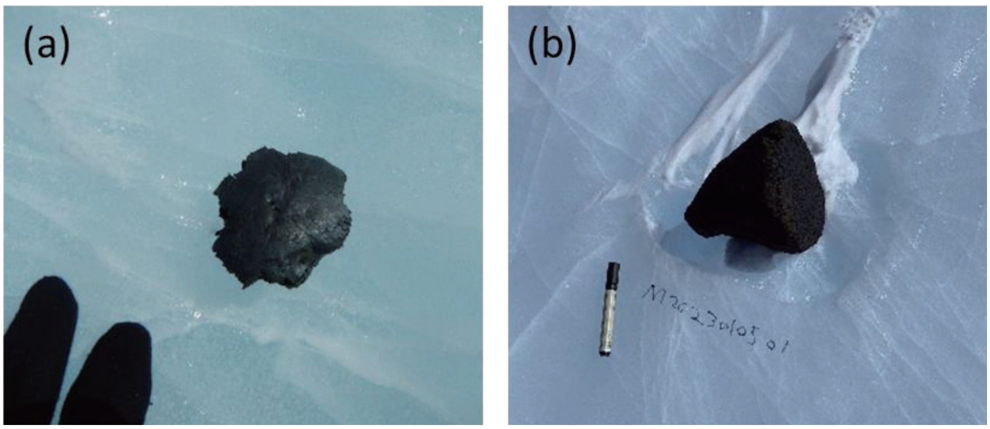

Fig. 4. (a) meteorite showing a flattened shape and flow line, picture credits: Vinciane Debaille. (b) Meteorite of 7.6 kg, picture credits: Maria Valdes.

5.5. Mass distribution

All recovered meteorites (n=5) were weighed using a portable scale at the camp in the evening. An industrial scale was used for the largest meteorite due to its heavy weight, after returning to PEA. The total mass of the collected meteorites was calculated as ~7800 g, with individual specimens ranging from 10 to 7600 g.

5.6. Magnetic measurements

Magnetic susceptibilities of the recovered meteorites were measured on each whole sample using a handheld A*METMET susceptibility meter developed at CEREGE (Aix-en-Provence) by Dr. M. Uehara, and refined for cold weather (suffix A*), as the battery is contained in a separate part that can be kept warm in a pocket. Magnetic susceptibility is expressed as the decimal logarithm of χ in $10^{-9}\,m^3/kg$ to account for the five orders of magnitude variation in rocks. Comparing the measured magnetic susceptibilities with those from an existing database (see Rochette *et al.,* 2003, for a summary) allowed a pre-classification on the field. Figure 5 presents the mass distribution vs. the magnetic susceptibility of the samples, the latter spreading between 4.7 (L chondrite) to 5.2 (H chondrite).

6. Expedition log

The mission was divided into two phases, the first one with a base camp and the second with daily trips from PEA (see Table 1).

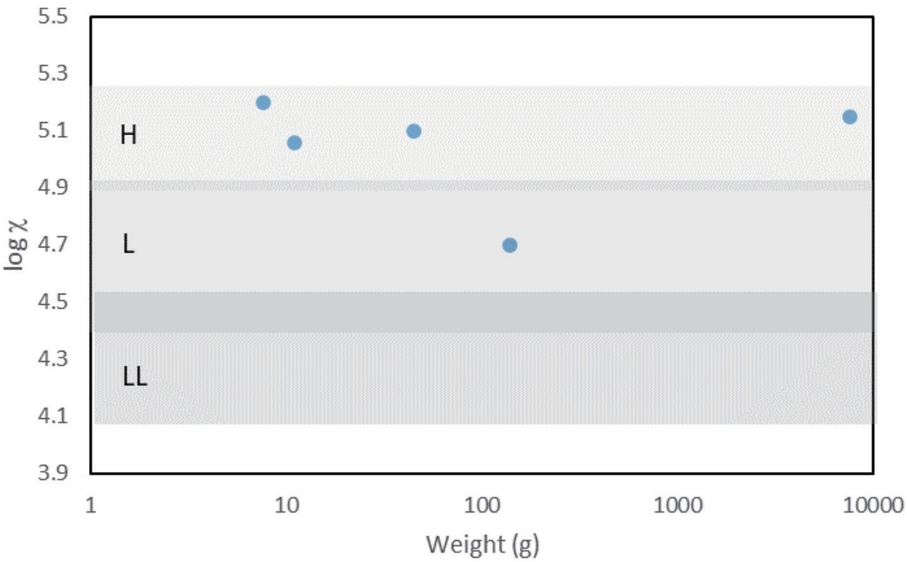

Fig. 5. Mass distribution vs log χ values (magnetic susceptibility) of the meteorites recovered in this expedition. Ranges for H, L and LL Antarctic ordinary chondrite finds from (Rochette et al., 2003).

6.1. Nils Larsenfjellet base camp

Five full days of searching were dedicated to this area, plus two days of driving in and out. Typically, the day started around 7:30 AM (local time), involving communication with PEA at 8 AM and weather measurements. The team generally left the camp around 9 AM, driving to the zones of interest in a row and then parking the snowmobiles or adopting a V-shape formation for systematic searches on blue ice. Lunch was around 1 PM, and return to the camp around 5 PM. After taking care of the snowmobiles (refueling, oil checks, and covering), free time was provided until dinner around 7 PM (during which the weighing and measuring of the magnetic susceptibility of meteorites took place), and communication with PEA was organised at 8 PM.

6.2. Daily searches from PEA

During good weather conditions, the team left PEA around 8 AM, to drive through Gunnestadbreen and reach the Verheyefjellet area, the aligned nunataks, or Røysane nunataks within two to three hours (typically ~50 km drive to destination). The search was usually finished around 4 PM, and then two to three hours of driving were necessary to return to PEA around 6–7 PM. The first task when back at PEA was refuelling and checking oil level of the snowmobiles.

7. Base camp

7.1. Nils Larsenfjellet base camp

The location of the base camp (S72° 13.260' E22° 37.779') was determined by Alain Hubert based on the previous expeditions. The place was already used by another scientific team in 2018–2019. The camp was located on snow, behind a first line of moraine from the H. E. Hansenbreen. A short walk on the first line of moraine was tracked with cairns. The snowmobiles were parked on a small patch of snow in front of the first line of moraine. Individual sleeping tents were provided for the team members, and two tents were set up for the kitchen and toilets (Fig. 2.b). A portable electric toilet was provided, using solar energy, as well as a pail toilet.

7.2. Evening briefings

Every evening, decisions for the next day's search were made based on the observations of the day. Magnetic susceptibility of the newly collected meteorites was determined after return from the field.

7.3. Weather observations

Weather conditions at the base camp and during the meteorite daily searches were measured twice a day (morning and evening) using a handheld weather station (Kestrel-4500). The base camp was partially shielded from katabatic winds, and the wind speed spanned between 1 and 8.9 m/s, temperature between −4.4 and −13.0°C, translating to a wind chill between −7.4 and −17.9°C. Conditions were slightly harsher on the field, more exposed to the wind, with wind speed between 1.7 and 10.9 m/s, temperature between −4.5 and −13.1°C, corresponding to a wind chill between −9.3 and −23.4°C. Searches were thus possible every day from the base camp. For the daily searches from PEA, locations were more exposed to the katabatic wind from the plateau due to higher altitude, and the temperature varied between −11.8 and −16.8°C; with wind speed between 2.7 and 7.4 m/s, leading to a windchill of −18.9 to −29.7°C.

8. Problems encountered

8.1. Weather

While the weather was exceptionally good during the time at the base camp on Nils Larsenfjellet, it degraded after December 27 with strong winds and consequential snow drift. Fortunately, the team was back at PEA, but had to wait until January 2, 2023 to resume field operations. Cloudy weather was encountered on January 3, 2023, making the visual reconnaissance of BIAs in the landscape challenging.

8.2. Cryoconite-induced melting

The temperature at the surface of the ice is an important parameter for the probability of finding meteorites, both positively by increasing ablation on BIA, and, more importantly, negatively by increasing the amount of liquid water (and thus alteration of meteorites) and the potential disappearance of meteorites into the ice as they are heated and progressively melt the surrounding ice, sinking into it (Tollenaar *et al.*, 2022). This phenomenon is called cryoconite-induced melting. When visiting the moraine areas (location No. 1−3 in Fig. 1.b), despite temperatures well below freezing and strong katabatic winds, cryoconites and associated melting and sinking were observed to occur in large numbers, not only for dark rocks, but also for light-colored rocks and on patches of light grey silt (Fig. 6.a, b&c). Liquid water was commonly observed around large rocks in the ice tongue (No.3 in Fig. 1.b). Entire areas of light grey silt were sinking into the ice and were in some cases covered by another layer of ice (Fig. 6.b). These observations suggest a short residence time of pebbles at the surface. Therefore, although those moraines constitute clear accumulation of glacial debris, which may include meteorites either transported by the ice or deposited by the wind, the residence times are not favorable for meteorite accumulation at the surface. It should be noted that cryoconite-induced melting was extensive and widespread at an altitude of 1700 m (Fig. 6.a, b&c), but was also present at 2400 m (Fig. 6.d). Even at 2700 m, cryoconite-induced processing was observed (Fig. 6.e), sometimes assisted by drifted snow accumulation (Fig. 6.f).

9. Post-expedition matters

9.1. Retrieval of the base camp and return of food supplies and equipment

The base camp at Nils Larsenfjellet was completely dismantled on the morning of December 27 by the team members of the meteorite expedition. All the camping equipment was initially dried at the camp site, and then dried more extensively at PEA. The remaining food and materials were returned to the PEA station. Two sleds, with fuel, toilet kits, generators, insulated mattresses, solar panels, and a camping table and chairs were left on

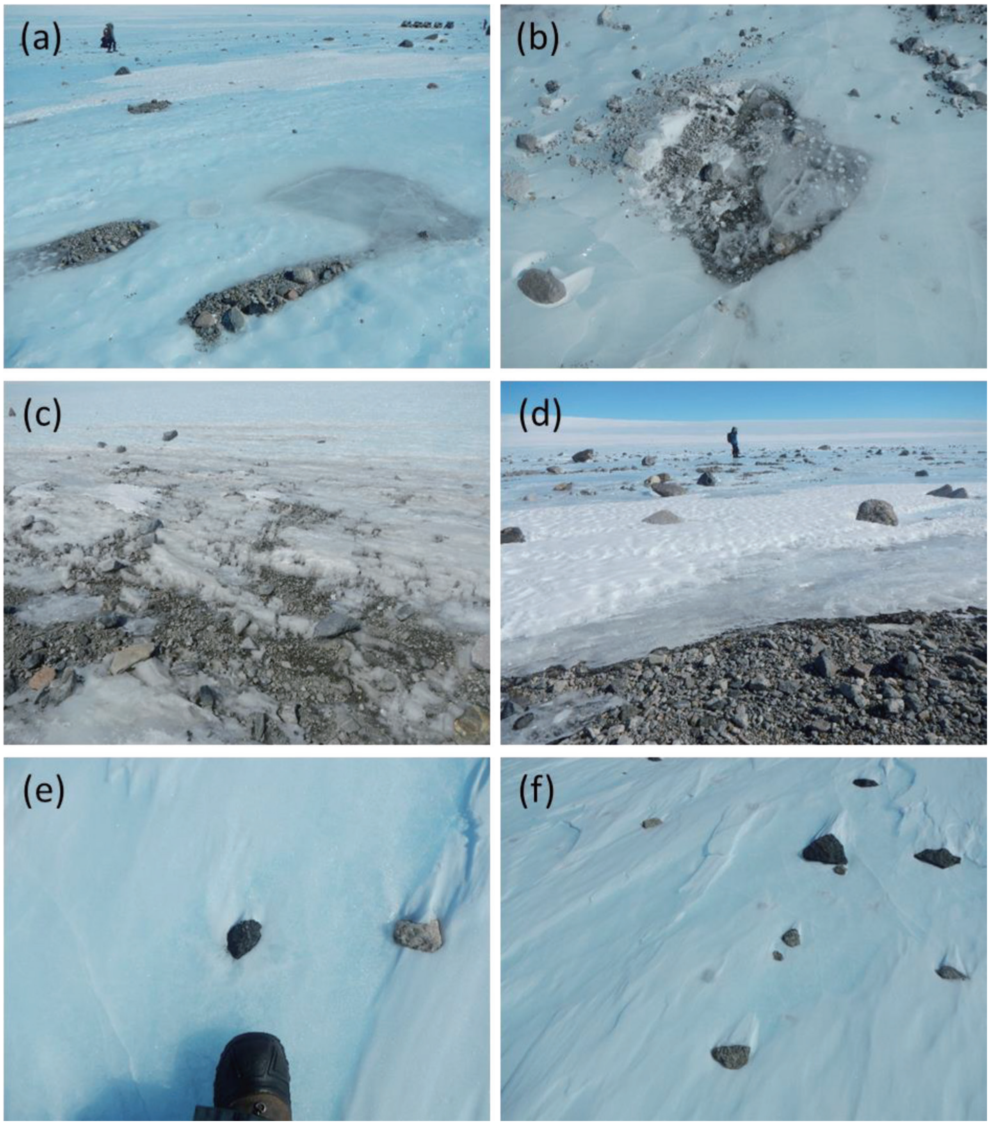

Fig. 6. Cryoconites observed in moraine areas. Areas of sand and pebbles, despite a light grey color, are slowly sinking into the ice and disappear under a new layer of ice and snow. (a), (b) and (c): Nils Larsen moraine at 1700 m. (d) Maquetknausane moraine at 2400 m. (e) & (f) Røysane nunataks at 2700 m. Picture credits: Vinciane Debaille.

site for later pick-up. This pick-up occurred on December 30 by Manu Poudelet and Henri Robert. All the items in those sleds were then put back in order at PEA by the scientific team later on the same day.

9.2. Storage and transportation of meteorites

Each meteorite was stored in an individual Ziploc bag inside a freezer box at the base camp. Different sizes of 60 µm-thick non-sterile polyethylene Ziploc sample bags were brought on the field. It should be noted that a thickness of 100 µm would have been preferred but those bags were unavailable due to worldwide shortage at the time of preparing the expedition in December 2021. Food-grade aluminium foil was available in case of finding a carbonaceous chondrite to avoid direct contact with the plastic. Due to the large size of the 7.6 kg meteorite, aluminium foil was also used to manipulate the meteorite without direct contact. For travel (from base camp to PEA and from PEA to Belgium), Ziploc bags were individually wrapped in napkins to avoid shock between the plastic bags. This was particularly critical for the meteorite which displayed flow lines, as its edges are very sharp. Several bags were used for this specimen. Samples were transported in a frozen state from PEA using an insulated box and extra-cold packs. Upon arrival in Cape Town, samples were directly placed in a freezing facility at Cape Town airport. Then, the insulated box was transported by direct flight to Brussels airport, and directly put in a freezer. Upon arrival in Brussels, the packages were visually inspected and showed no melting of ice attached to the samples.

9.3. Identification of new DCA in the vicinity of PEA

Most of the investigated areas have an index of probability for the presence of meteorites of ca. 80% (Tollenaar *et al.*, 2022). However, no meteorites were recovered from the two locations located directly to the north of the Nansen BIA (Fig. 1.a, locations No. 2 and 3: aligned nunataks and Verheyefjellet). On the other hand, two days in the BIA of Nils Larsenfjellet led to the recovery of five meteorites. The configuration of the Nils Larsenfjellet area appears to be more complicated than the Nansen BIA, with blue ice flow surrounding the Røysane nunatak (see Fig.1.b) and flowing down towards the west to the Maquetknausane moraine, with a difference in altitude of ~300 m between the eastern and western side of Røysane nunatak. One hypothesis for the BIA located directly north of the Nansen BIA could be that the Nansen BIA acts as a funnel for all meteorites travelling into the ice, hence shielding BIA further north. As the Nils Larsenfjellet area is located on the west compared to Nansen BIA, this shielding would be less prominent, therefore allowing for the accumulation of meteorites at the surface. This underlines that the local topographical features are essential to understand meteorite stranding zones, rendering the generalization of this mechanism complicated.

10. Summary

During the 2022−2023 BELARE meteorite expedition, the team consisted of four scientists and one field guide. The goal of the mission was to identify new dense collection areas in the surrounding of PEA, based on the meteorite finding probability index developed by Tollenaar *et al.* (2022), and to retrieve meteorites. To this end, three main areas of interest were defined, one of which required a base camp (Nils Larsenfjellet), and two (Verheyefjellet and aligned nunataks) that were searched during daily trips from PEA. The eastern edge of Nils Larsenfjellet BIA surrounding the Røysane nunatak was also searched by a day trip from PEA.

The two regions of interest located directly north from the Nansen BIA (aligned nunataks and Verheyefjellet) did not provide any meteorites. On the other hand, the Nils Larsenfjellet BIA provided five meteorites, one of exceptional weight (7.6 kg) following two days of systematic searches. This implies that the Nils Larsenfjellet area, and notably its BIA, is a potential DCA, and a systematic search centered around the Maquetknausane moraine should be envisaged for the future. However, cryoconite-induced melting has proven to be an issue for losing meteorites back into the ice, even at altitudes as high as 2700 m. During the 2012–2013 meteorite expedition on the Nansen BIA (Imae *et al.*), a meteorite was retrieved half buried in the ice at 3000 m. It was thought that it was being excavated, but our new findings suggest that it might have been actually sinking into the ice. The five meteorites collected during this reconnaissance mission will be referred to as Asuka 22 meteorites. Several locations were also sampled for fine-grained sediments, and micrometeorites will be retrieved from those sediments in the laboratory.

The use of machine-learning approaches for identifying possible zones of interest as performed in Tollenaar *et al.* (2022) is an asset for identifying new search zones, as demonstrated by the identification of a new potential DCA around PEA. However, the experience acquired during the 2022–2023 BELARE meteorite expedition indicates that this approach only works to a first order. Local parameters such as topography and wind directions that can redistribute meteorites from BIAs into local meteorite traps have to be considered as well, that can be evaluated during field expeditions.

Acknowledgements

We gratefully acknowledge the support provided by the IPF at PEA. We are grateful to Alain Hubert, Martin Leitl and Christian Herzog for setting up the base camp, and to Alain Hubert for opening the routes to remote areas. Henri Robert is deeply thanked for his logistical and scientific support throughout the expedition. We are thankful to the IPF for the support provided since the first discussions a few years ago and despite the pandemic situation. The staff at PEA is thanked for the support in organizing the field searches. Quinten Vanhellemont is thanked for his help with the Sentinel-2 satellite images. The BELARE 2022–2023 meteorite search and recovery expedition was supported by the Belgian Science Policy (Belspo), projects DIABASE and BAMM to VD, SG and PC. VD thanks the FRS-FNRS for present support; VD, RM, SG, and PC acknowledge support from the Excellence of Science (EoS) project ET-HoME. MS acknowledges funding from ETH Zürich. MV and PRH are thankful for funding from the TAWANI Foundation and the Robert A. Pritzker Center for Meteoritics and Polar Studies. VT acknowledges funding as Research Fellow of the Fonds de la Recherche Scientifique (FNRS). We thank one anonymous reviewer and the associate editor at NIPR for helpful comments.

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