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DATA NOTE

Greenland 2022 GHOST project: Sampling Greenland geothermal springs - expedition report

[version 1; peer review: 3 approved with reservations]

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Abstract

This report describes the GRL22 expedition to Disko Island (West Greenland) to sample the thermal springs generated by residual heat associated with formation of the Icelandic hotspot. Despite the large number of springs present on Disko Island, our knowledge of the microbiology of these springs and how they relate to cycling of volatile elements and controls on their budgets is limited. The aim of the project is to understand the diversity of microbial communities brought to Earth's surface by spring fluids and to determine their role in biogeochemical cycling. The long-term goal of the project is to combine these data with hot spring data from East Greenland and Iceland. This approach will create a transect in "space and time" across the Icelandic hotspot track, that will allow us to evaluate the potential influences of the plume on the subsurface microbial communities. This leg of the expedition took place between July 25 and August 2, 2022, and nine distinct sites were sampled for microbiology and

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Any reports and responses or comments on the

geochemistry.

article can be found at the end of the article.

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Expedition report, Hot Springs, Arctic, Greenland, Disko Island, Icelandic Hotspot, Biogeochemistry

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Introduction

Volcanoes along Mid Ocean Ridges (MORs) are the primary conduits of mantle volatile to the surface of the planet (Bekaert *et al.*, 2021). The plutonic and volcanic complexes left in place into and onto the lithosphere (*e.g.*, intrusive vs. extrusive formations) by magmatic activity also contribute to the fertilization of the upper crust with metals and trace elements important for life (Edmonds *et al.*, 2018; Giovannelli, 2022; Giovannelli, 2023a; Hay Mele *et al.*, 2023). These complexes act to drive local geothermal circulation, sustaining hydrothermally derived springs and secondary geothermal manifestations over timescales of thousands to millions of years. As they slowly cool, the geochemistry and nature of the associated geothermalism change, altering the composition of fluids that influence the diversity of microbial communities in the subsurface.

While active volcanic complexes, such as those found along convergent margins, provide a means to access how subsurface communities respond to volatile degassing at the surface, hotspot volcanism may provide insight into mantle-crust interactions over long timescales. A hotspot is defined as a relatively stable area of the mantle where deep mantle plumes are believed to cause thinning and melting of the overlying lithosphere. Hotspots can be viewed as being stationary over geological timescales in an absolute reference frame, where overriding lithospheric plates ultimately create characteristic hotspot tracks as observed in Hawaii (Jiang *et al.*, 2021) and Yellowstone (Nelson & Grand, 2018).

Because the Iceland hotspot interacts with the North Atlantic Ridge, its track back in time is not characterized by a continuous and age progressed volcanic chain, in contrast to Hawaii for example. Volcanic rocks that characterize the Icelandic hotspot can be found in East and West Greenland and on the west coast of Scotland and Ireland as well as on the North Atlantic Ocean floor (Storey *et al.*, 2007), thus providing clear evidence for the opening of the North Atlantic Ocean (Figure 1).

The area in its entirety is known as the North Atlantic Large Igneous Province and has emerged from the Iceland mantle

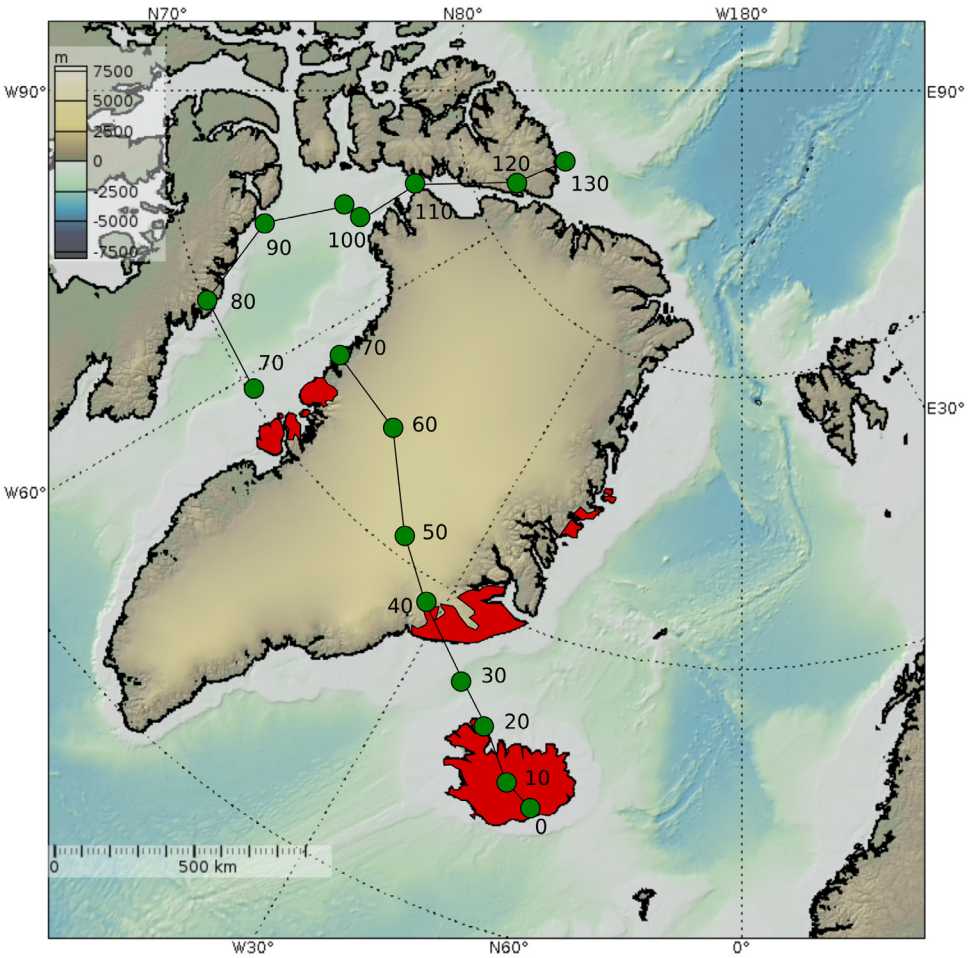


Figure 1. Map showing the reconstructed Icelandic hotspot track. On-shore igneous rocks are shown in red. Green circles represent the location of the Iceland mantle plume in 10 Ma increments. Image from (Ago, 2018), track from (Lawver & Müller, 1994). More recent evidence for a similar track can be found in Steinberger *et al.* (Steinberger *et al.*, 2019), while a more northward track is proposed by Martos *et al.* (Martos *et al.*, 2018). Modified from Lawver and Müller (1994).

plume activity over the last 70-80 Ma (Saunders *et al.*, 1997). Hotspot-related igneous extrusive rocks are found in East and West Greenland, where they, along with their intrusive counterparts, drive lower temperature thermal springs, comparable to those found on Iceland at present (Hjartarson & Armannsson, 2010). The highest temperature thermal springs in Greenland are found on the east coast, north and south of Scoresbysund, where recorded temperatures reach 62°C. In west Greenland the maximum recorded temperature of a thermal spring is approximately 18°C, on Disko Island (Figure 1).

Disko Island represents a unique location where 70 Ma basalts associated with the Icelandic hotspot are exposed on land and produce low temperature thermal springs. Thousands of springs are present on the island (Figure 2), with a large number of them known by the Innuit as Unatoq. The first mention of the springs in western literature is in 1852 (Rink, 1855). The flora and fauna in these springs were later investigated and found to have a more "southern composition" by Kristensen (Kristensen, 1987).

A series of papers in recent years by Kristensen and others described the tardigrade, rotifera and meiofauna populations found in these springs (reviewed in Funch & Sørensen, 2001; Meyer, 2013). The springs are described as homeothermic, such that their temperature remains constant throughout the

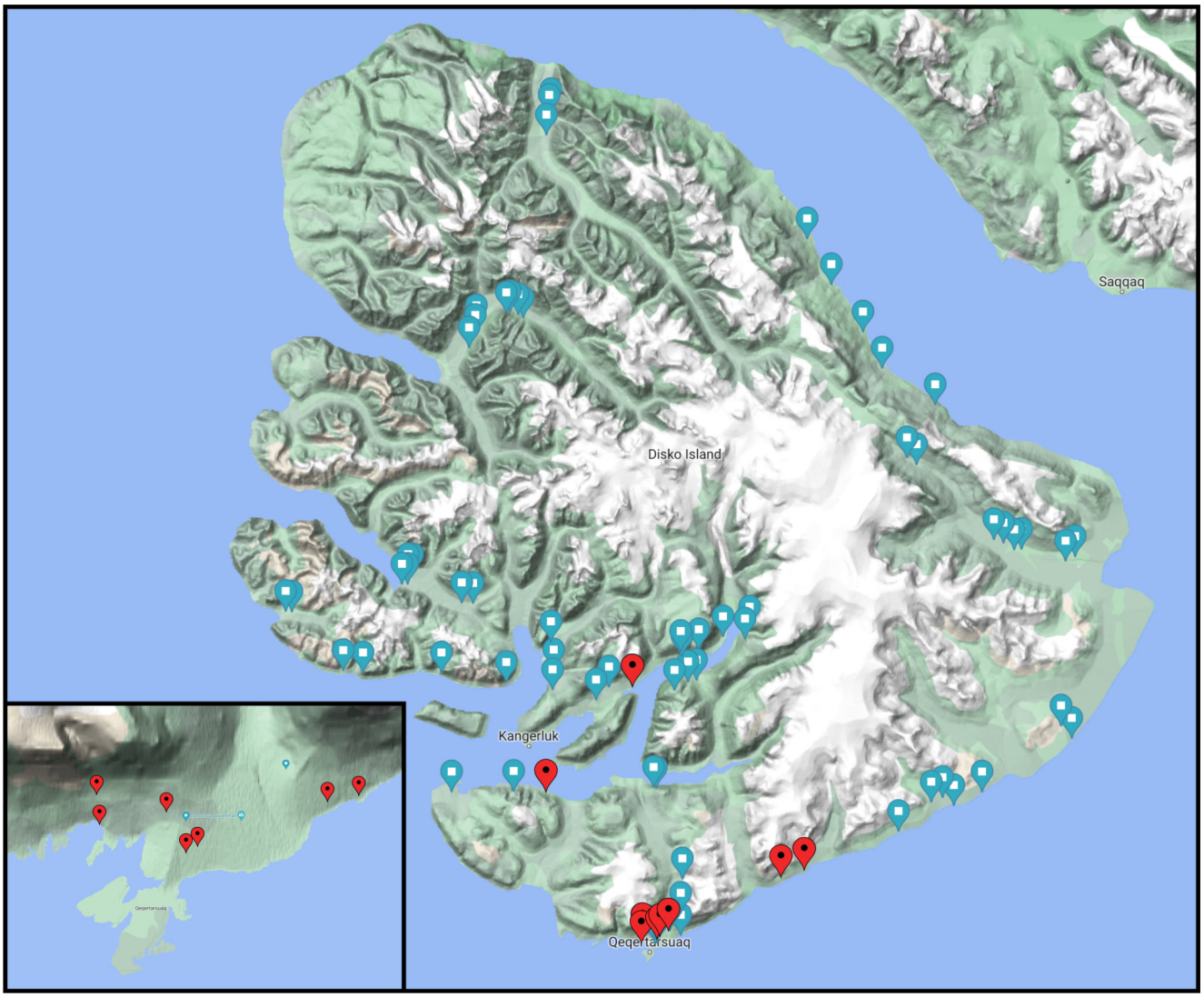


Figure 2. Topographic map of Disko Island with the location of known and putative geothermal manifestations on the island, including cold and warm springs and mud volcanoes on the northern fault system. The springs appear to be associated with the basaltic fault system present on the island, and emerge often at the contact between the underlying gneiss and overlaying tertiary basalt (see geological description). The insert in the bottom left corner shows a magnification around the Qeqertarsuaq settlement on the south coast of the island where the Arctic Station (University of Copenhagen) is located. Turquoise markers represent putative springs that appear in the literature with no exact coordinates. Red markers represent sampled springs during the GHOST Leg 1 expedition. The map was obtained from Google Maps, Imagery ©2023 TerraMetrics, Map data ©2023.

year, as opposed to the other surface springs in the area that freeze or dry out during the winter months due to the low temperatures and/or lack of meltwaters (Kristensen, 1987). Six springs in Disko were investigated for their geochemistry and potential geothermal utilization in 2005 (Hjartarson & Armannsson, 2010). No information is available regarding the microbial communities associated with these springs.

The aim of the GHOST project is to provide a glimpse into the microbial diversity associated with these deeply sourced springs. These springs are unique compared with several other geothermally sourced springs found globally, both in terms of their latitude, surrounding environment, as well as the driving rock geochemistry and composition. Additionally, comparing their diversity with the diversity of springs found in Eastern Greenland (sampled in August 2022) and in Iceland (sampled during past expeditions and to be sampled in the framework of the ERC CoEvolve project, https://www.coevolve.eu) provides a unique opportunity to track how the subsurface microbial communities respond to cooling (and differential leaching of metals and volatiles) of the volcanic rocks associate with the Icelandic hotspot. Sampling the hot springs in Disko will simultaneously provide: i) information on the unique diversity present in these springs, ii) information regarding the microbial community interaction with deeply sourced volatiles and biogeochemical cycling in the Arctic, and iii) a unique set of samples providing a transect across the movement of the plate over the Icelandic hot spot.

This report describes the sampling on Disko Island from July 25th to August 2nd, 2022.

Expedition team and logistics

The project team is composed of interdisciplinary scientists spanning the fields of microbiology, biogeochemistry, microbial ecology and gas geochemistry. The expedition was hosted by the Arctic Station (University of Copenhagen) located on the southern coast of Disko Island, West Greenland (69°15' N, 53°34' W). Access to the station was provided through the INTERACT III project (EU H2020 Grant Agreement No.871120) Transnational Access call. The Field Science Party was responsible for sample collection and field measurements. Given the remote location of the springs and the lack of roads and paths on the island, access to the springs was limited to a handful of locations within a 4 km radius of the Arctic Station. Two additional springs were sampled in the central part of the island using a small boat to reach the area. The Onshore Science Party was responsible for supporting the logistics and preparation of the expedition as well as collaborating on sample processing and analysis.

Field Science Party composition: Donato Giovannelli (Expedition Leader and PI of the project), Matteo Selci and James A. Bradley.

Onshore Science Party composition: Angelina Cordone, Luciano di Iorio, Monica Correggia, Margaret Cramm, Karen G. Lloyd, J. Maarten de Moor, Peter H. Barry, Shaunna M Morrison, Stefano Caliro, Sæmundur A. Halldórsson.

Geological and environmental settings

The Greenland Ice Sheet is the second largest reservoir of fresh water on Earth and ~80% of Greenland is ice covered. For these reasons, the subglacial thermal conditions, geology, and lithospheric structure of the continental interior are not well known and require indirect methods. Rock outcrops are only accessible near the coast, where direct access provides information regarding their petrology and geochemistry. Greenland is mainly composed of Precambrian provinces that collided during the Early Proterozoic (Braun *et al.*, 2007) (Figure 3). Even though Greenland is considered a stable craton, exposing some of the oldest Archaean rocks on the planet, its lithosphere has been affected by the passage of the Iceland hotspot in the last 90 Mya. Areas of hotspot-related magmatism have been identified based on geochemical signatures both in east Greenland and west Greenland around Disko Island (Figure 3).

Disko Island is the second largest island in Greenland after the mainland. The reworked basement of Disko Island is mainly composed of Cretaceous sandstone and Precambrian gneiss, with overlaying tertiary basalt flows visible all over the island dated more than 60 Ma (Figure 4). Geothermal activity is known in several places on Disko Island, with earlier reports dating back to 1852. The source of the geothermal heat and its relation to the stratigraphy and tectonics are unknown, but it seems to be connected to the early Tertiary volcanism associated with the Icelandic hotspot. Known geothermal springs are located along fault systems present on the island (Figure 2), and generally emerge at the contact between the gneiss basement and the overlying basalt (Figure 5).

The springs are characterized by a specific group of plants colonizing their surroundings. The majority of the visited spring showed a strong bright green color in the proximity of the source, mainly linked to the presence of moss and the biennial plant Angelica (*Angelica archangelica*), an edible wild relative of celery used in Greenlandic cuisine. The presence of this plant in proximity of homeothermic streams provides a useful bioindicator to recognize stable (*i.e.*, not influenced by seasonality) streams on Disko. Kristensen (1987) broadly classified the springs in three groups: 1) cold (0–3 °C) homeothermic springs low in nutrients and characterized by the presence of green moss; 2) warm (3–12 °C) springs low in nutrients and characterized by the presence of Angelica and Arctic willow; and 3) warm (12–18.5 °C) springs rich in nutrients and characterized by "southern" continental species such as orchids and ferns. The latter, he commented, are not recognizable from distance due to the lack of the characteristic bright green color in the surrounding vegetation. Despite the presence of this possible bioindicator, the homeothermic nature of the springs can only be confirmed by measuring their temperature both in the summer and winter, as accomplished in the past by Kristensen (1987). In winter, due to

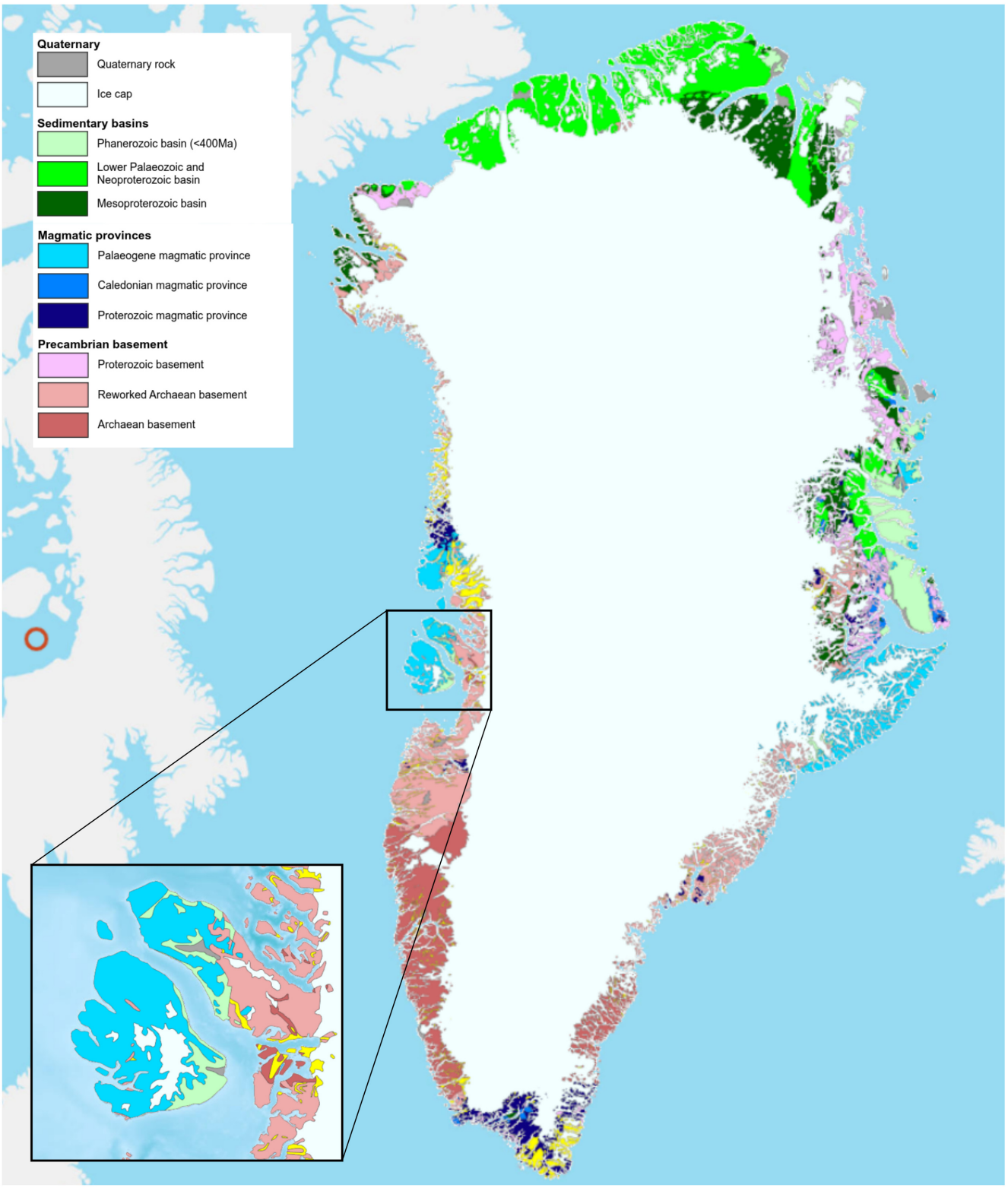


Figure 3. Geological map of Greenland (1:2,500,000) showing the location of the tertiary volcanic basalts (cyan color) on Iceland, East Greenland and West Greenland. The insert shows the composition of the geology of Disko Island. The geological map was obtained from the Geological Survey of Denmark and Greenland (GEUS) portal (https://maps.greenmin.gl/geusmap).



Figure 4. Basalt flow layers overlying the gneiss basement visible on the southern shores of Disko Island. Photograph taken by author DG for this publication.

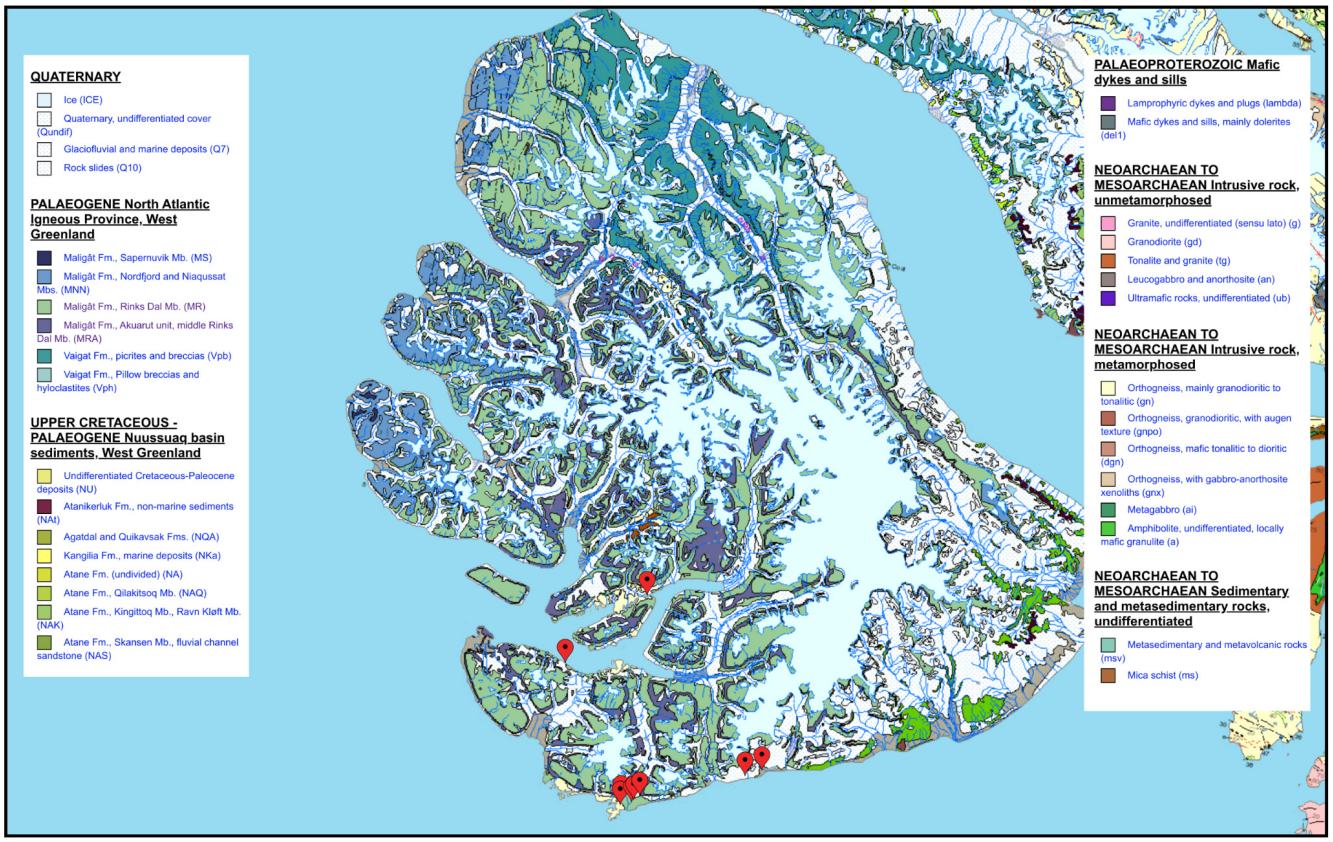


Figure 5. High resolution geological map (1:500,000) of Disko Island. The sample springs are associated with the contact between Paleocene basalts and the Neoarchaean gneiss. Sampling sites are marked with a red placemark. The geological map was obtained from the Geological Survey of Denmark and Greenland (GEUS) portal (https://maps.greenmin.gl/geusmap).

cold air temperatures, springs may be characterized by icings (sheet-like masses of layered ice formed by repeated flows of groundwater to the surface).

Sampling methodologies

Sample selection and environmental parameters

Fluids, sediments and background soils were collected from six locations identified based on the literature (Giovannelli, 2023b). The springs show characteristics compatible with the definition of deeply sourced seeps (Giovannelli *et al.*, 2022). At each sampling site, the main seep outlet was identified using a combination of previous data from literature, field observation, pH, conductivity and temperature measurement. The objective was to sample the pristine gases and fluids as they emerged from the subsurface, minimizing their mixing and interaction with the surface and the atmosphere. Background soil samples from the nearby area that did not show geothermal alterations. The rationale behind this type of sampling approach is to maximize the subsurface information that can be extrapolated from the data. Temperature, conductivity, pH, redox potential, total suspended solids and dissolved oxygen were measured directly in the field using a Hanna Multiparameter WP probe, regularly calibrated. Alkalinity and dissolved hydrogen sulfide were also measured in the field as described below.

Geochemistry samples acquisition

Dissolved gas geochemistry. Fluids for dissolved gas analysis were collected both for gas composition analysis and noble gas isotope systematics. Fluid samples for noble gas analysis were first flushed through silicone tubing and into 3/8-inch copper tubes. After sample flushing (*i.e.*, approximately 10x the volume of the tubing), stainless steel clamps were closed on each end of the copper tubes, trapping the sample inside of the copper tubing, between the clamps (Barry *et al.*, 2022). Fluids for dissolved gas composition were collected in pre-evacuated 250 mL Giggenbach bottles filled to ¾ of the volume taking care to avoid air contamination during collection (Barry *et al.*, 2019).

Aqueous and sediment geochemistry. For the characterization of the major dissolved ions, 0.22 µm filtered fluids were collected in a 50 mL conical tube. A duplicate sample was collected in acid-washed tubes and acidified with nitric acid (2% final concentration) for the analysis of trace elements. Filtered fluids (0.22 µm) were also collected in a 10 mL penicillin vial air-free for dissolved inorganic carbon isotope composition, and 6 mL of fluids were fixed with 2 mL 5% zinc acetate for the quantification of hydrogen sulfide. Sediment samples as close as possible to the fluid outlet point were collected into 50 mL acid-washed conical tubes.

Biological samples acquisition

At each site, sediments and fluid samples were collected aseptically for molecular analysis. Within each pool, the main inlet was identified by using a combination of field observation, pH and temperature analyses (Giovannelli *et al.*, 2022). The objective was to sample the pristine gases and fluids as they emerged from the subsurface. Sediments were collected in close proximity (within centimeters when available) to the inlet. Fluids for DNA extraction (2 L) were filtered in triplicate 0.22 µm Sterivex filter cartridges (MilliporeSigma) (Fullerton *et al.*, 2021). Filtration was achieved using a 3D-printed custom designed peristaltic pump (https://github.com/giovannellilab/Field_3D-printed_peristaltic_pump) connected to a battery powered portable drill. Sediments and background solid were collected in sterile 50 mL conical tubes. Sediments, background and filters were immediately frozen at the Arctic Station. Fluids were also collected in 2 mL cryovial preserved in 3% paraformaldehyde for cell counts. Glass vials (120 mL) were filled with biofilms and fluids for culturing and isolation purposes.

Sites and samples log

Details on the sampling locations are given in Table 1, while the measured environmental parameters are reported in Table 2 (Giovannelli, 2023b). The sampled springs range covers a narrow range of temperatures, with the pH fluctuating between neutral and alkaline conditions (Figure 6). Salinity

Table 1. Sampled springs coordinates and hosting rock type.

SiteID	CollectionID	Site name	Date	Latitude (°N)	Longitude (°E)	Altitude (m)	Rock type
OR	OR220726	Orpinguit spring	2022/07/26	69.257247	-53.518495	99.8	basalt
QW	QW220726	Qeqertarsuaq water	2022/07/26	69.262363	-53.533825	136	gneiss
UH	H220727	Unartorssuaq High	2022/07/27	69.265183	-53.5672	212	basalt
UK	UK220727	Unartorssuaq beach	2022/07/27	69.259692	-53.566644	4	gneiss
TQ	TQ220728	Tarajungistoq	2022/07/28	69.55685	-53.606526	60	gneiss
UN	UN220727	Unatorq	2022/07/28	69.432154	-53.890429	30	basalt
NJ	NJ220731	Naujánguit	2022/07/31	69.261233	-53.462571	99	basalt
KU	KU220731	Kuannit	2022/07/31	69.264886	-53.443278	20.3	basalt

Table 2. Main environmental characteristics of the sampled springs. Radioactivity levels and flow rate are from (Hjartarson & Armannsson, 2010).

SiteID	CollectionID	Temp (°C)	pH	ORP (mV)	DO (%)	DO (ppm)	SPC (mS/cm)	TDS (ppm)	Sal (PSU)	Alk (mg/L)	Flow (L/s)	Radio (Bq/L)
OR	OR220726	2.1	8.31	-42.3	105	12.98	0.53	265.00	0.26	53.3	20	NA
QW	QW220726	2.2	8.99	-50.3	109	13.5	0.275	140	0.14	80.0	35	NA
UH	H220727	3.8	9.5	-44.9	93	11.2	0.434	213	0.2	56.7	NA	NA
UK	UK220727	15	7.5	-21	43	4.39	1.315	658	0.66	113.3	3.1	NA
TQ	TQ220728	12.8	8.16	-16	0	0	3.037	1520	1.6	73.3	5	705
UN	UN220727	12	10.4	-25	86	8.8	0.512	255	0.25	86.7	7	61
KU	KU220731	5.67	10.01	-16	87.5	10.38	0.21	105	0.1	93.3	NA	NA
NJ	NJ220731	14	8.1	-10.3	95	9.8	0.114	57	0.05	60.0	NA	NA
QG	QG220801	7.9	7.27	-1.6	91.6	10.22	86	44	0.04	60.0	NA	NA

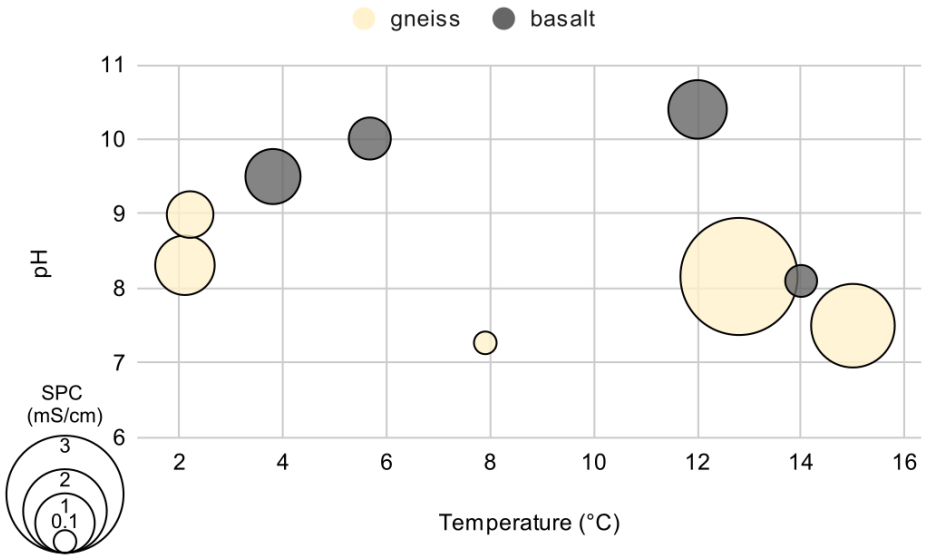


Figure 6. Graph showing the temperature (°C), pH, and conductivity (proportional to the size of the circles in µS/cm) of the sampled locations.

and total alkalinity (Figure 6 and Figure 7) did not vary systematically with temperature and pH. The description of each sampled location follows together with pictures useful for future identification of the site. A .kmz file containing the exact location of the sampled location is available on the online GitHub repository associated with this report (https://github.com/giovannellilab/GRL22_Leg1_Expedition_report; Giovannelli, 2023b).

Orpinguit spring (OR)

Orpinguit spring is located approximately 450 m north of the Arctic Station. The cold fluids seep from a fracture in the basalt dome (Figure 8). Fluids were sampled directly from the fracture at about 2.5 meters height. No visible sediments were present at the source, and orange and green biofilms coated the basalt wall influenced by the fluids.

Qeqertarsuaq water source (QW)

The drinking water supply to the town of Qeqertarsuaq is from one of the homeothermic springs located approximately 1.7 km north of the town. The site has multiple springs seeping from the gneiss outcrops (Figure 9), and the largest are channeled to provide water to the settlement. The characteristic bright green due to the growth of moss is visible in

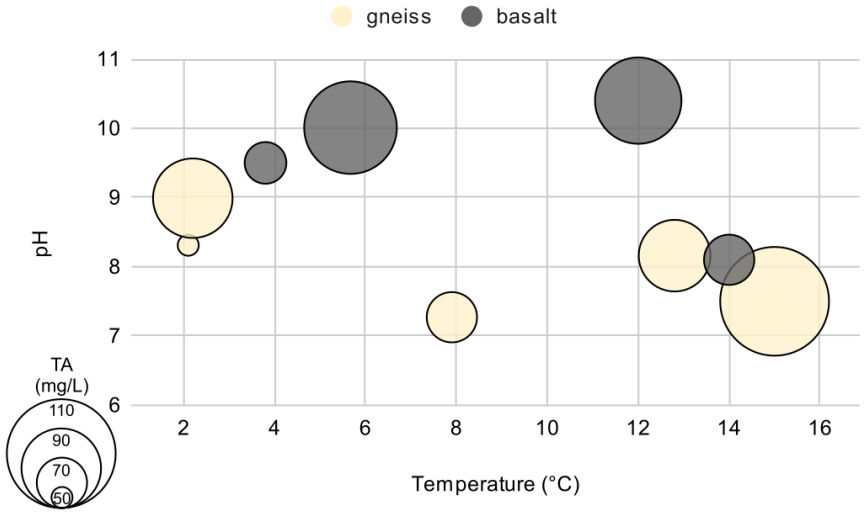


Figure 7. Graph showing the temperature (°C), pH, and total alkalinity (proportional to the size of the circles expressed in mg $CaCO_3$/L) of the sampled locations.

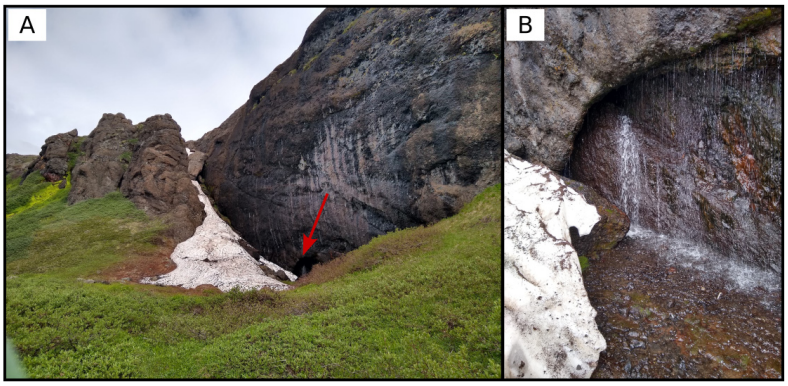


Figure 8. Orpinguit spring, located in a small cove on the side of a volcanic rock outcrop. A. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

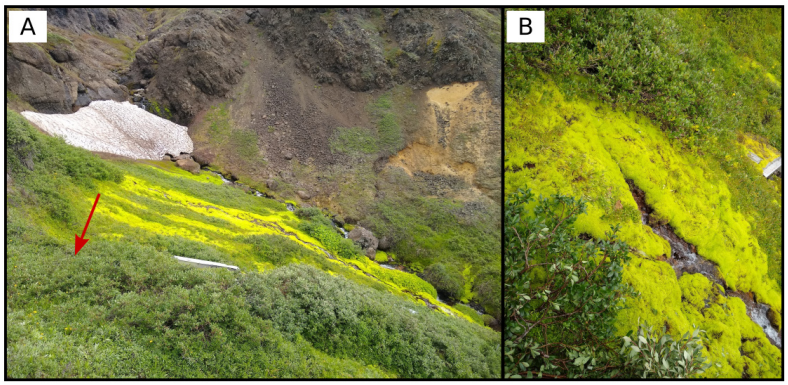


Figure 9. Qeqertarsuaq water source springs, located to the north of the town in the middle of the gneiss outcrops. Multiple springs were present on site. **A**. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

the area of fluid seepage. Samples were collected from the source free from the water supply tubes on the north wall of the area at the point of seepage.

Unartorssuaq high (UH)

A spring in Unartorssuaq, previously described by Hjartarson and Armannsson (2010) was seeping at the contact between the gneiss and the tertiary basalt. The cold spring was seeping from the base of a bush on the slope of the gneiss (Figure 10) and was surrounded by Angelica plants and connected with numerous other springs in the area. The area is characterized by several springs, and the complex terrain makes it difficult to access. A point source was identified for the seep described in Hjartarson and Armannsson (2010).

Unartorssuaq beach middle spring (UK)

The Unartorssuaq springs located on the beach of the bay are part of the warm springs sampled previously by Hjartarson and Armannsson (2010), and are the warmest springs sampled during this expedition. The fluids were seeping from the base of erratic gneiss rocks (Figure 11) before disappearing into the gravel of the beach. The waters re-emerge on the gravel before disappearing again. The middle seep was sampled during this expedition. The area, also known as Englishmen Harbor, is difficult to access from the plateau above - requiring hiking down a rockfall and grassy slopes and through a narrow canyon created by the mainstream channel.

Tarajungistoq (TQ)

Tarajungistoq spring is located about 200 meters inland from the north coast of Disko Fjord. From the beach it is possible to follow the outflow channel upstream until a narrow source quickly opening up into a depression can be identified. The fluids precipitate white minerals on the rocks (Figure 12), and thick pink and white microbial biofilms, possibly representing anoxygenic phototrophs and sulfur oxidizers coat the outlet of the spring. The waters are saline, anoxic and radioactive.

Unatorq (UN)

The Unatorq spring is located 80 meters inland from the southern coast of Disko Fjord. Multiple small outlets converge into a larger channel (Figure 13). The bottom of the spring is

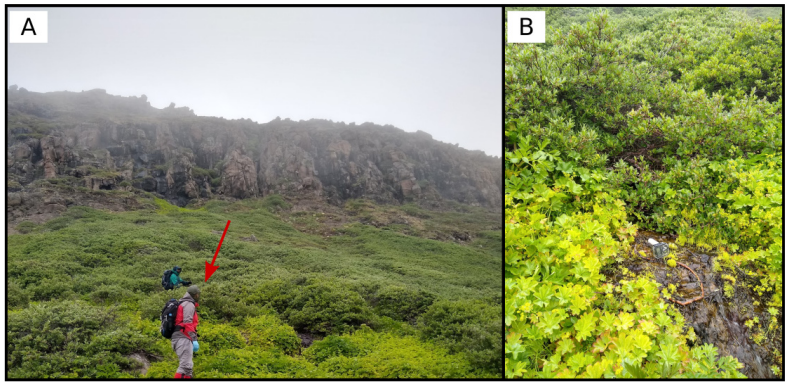


Figure 10. Unartorssuaq high spring, located at the base of the basalt outcrop in contact with the gneiss basement. Multiple springs were present on site. **A**. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

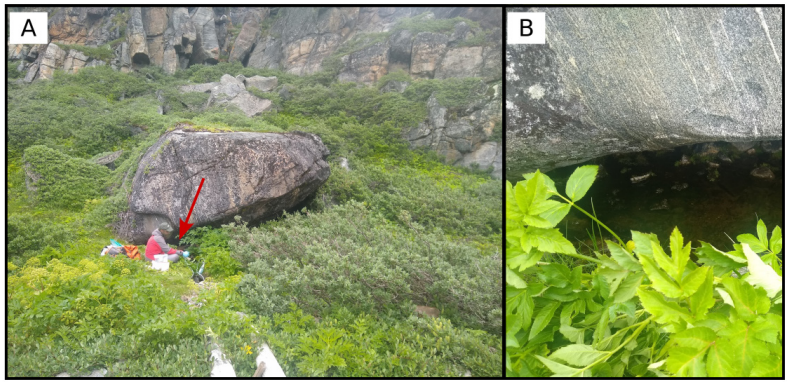


Figure 11. The middle spring, located in Unartorssuaq on the beach. Multiple springs were present on the beach, and the one that was sampled is located in the middle of the bay. **A**. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

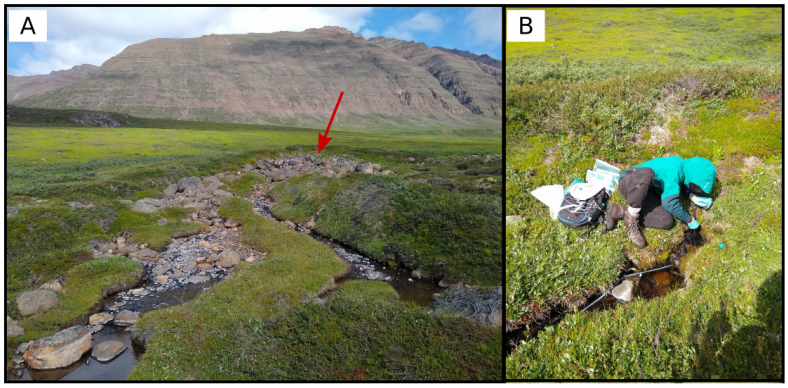


Figure 12. The Tarajungistoq spring, located in the northern coast of Disko fjord, 200 meters from the coast. A. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

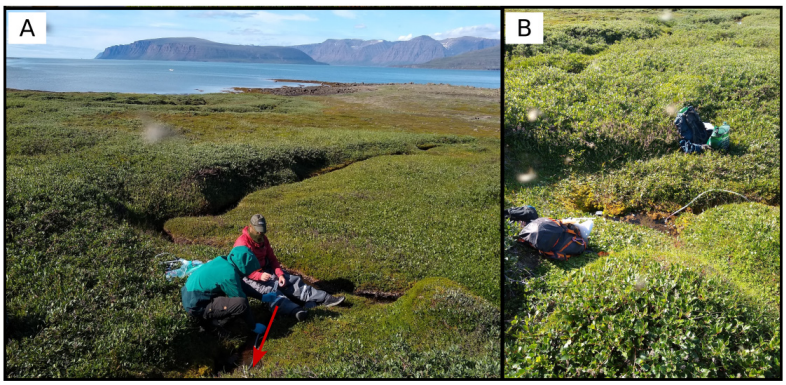


Figure 13. The Unatorq spring, located in the southern coast of Disko fjord, approximately 100 meters from the coast. A. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

coated with dark green and gray microbial mats, and occasional bubbles are released from the sandy bottom. Unfortunately, the stream of gas was too irregular to allow for sampling. A few locations where fluids were seeping from the spring floor were identified and the more upstream source was sampled. With a pH of 10.4, this is the most alkaline spring sampled.

Kuannit (KU)

The Kuannit area, located on the east of the Arctic Station at about 3.5 km, is characterized by spectacular columnar basalts. Contrary to the previously described locations, exact coordinates for the spring reported originally by Kristensen (1987) are not available, and after measuring basic physico-chemical parameters for a number of sources, a spring seeping directly from fractures in the columnar basalt wall was selected. The spring has a conductivity approximately twice as high as the other surface streams tested during this trip and a pH of 10.01, suggesting water-rock interactions. The fluids were sampled on the right side of the wall in a small crack (Figure 14), directly from the outlet to avoid air contamination. Large quantities of moss and Angelica were present in the area.

Naujánguit (NJ)

One of the springs in the valley of Naujánguit was sampled on the way back to the station from Kuannit. As for the previous one, no exact coordinates were available for the spring in the area. The spring lacked the characteristic bright green vegetation previously described by Kristensen (1987) (Figure 15) and potentially used as a bioindicator and, based on our initial interpretations, is considered a surface background sample with minimal mixing with deeply derived fluids.

Qeqertarsuaq gneiss spring (QG)

The last sampled spring is located in the gneiss formation on the backside of the Arctic Station and seems to be the primary source of the water used at the research station. The location of the spring was extracted from the map by Hjartarson and Armannsson (2010), however no description or previous data are available and therefore the location cannot be confirmed. Personnel at the Arctic Station confirmed that the spring used by the base as source water is a low temperature homeothermic spring available year around. However, the exact source of the fluids could not be identified since it emerged from underneath a large boulder field, and the

earliest surface appearance of the fluids between the rocks was sampled (Figure 16). At the source no characteristic vegetation was found, but bright green moss was present downstream.

Summary

The expedition successfully sampled a number of springs, including confirmed homeothermic deeply sourced springs

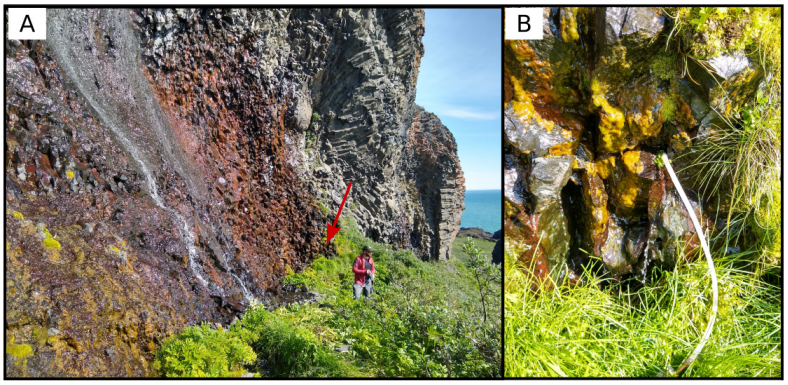


Figure 14. The fluids of Kuannit spring seeping from cracks in the columnar basalt wall. Fluids were sampled from a small crack on the right side of the outcrop, selected for the easy access to the seep. **A**. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

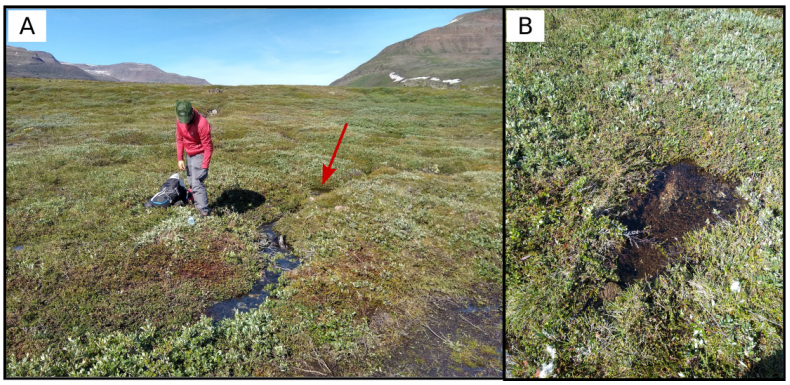


Figure 15. The surface spring is located in the Naujánguit locality in proximity of the yellow trail connecting Qeqertassuaq to Kuannit. A. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

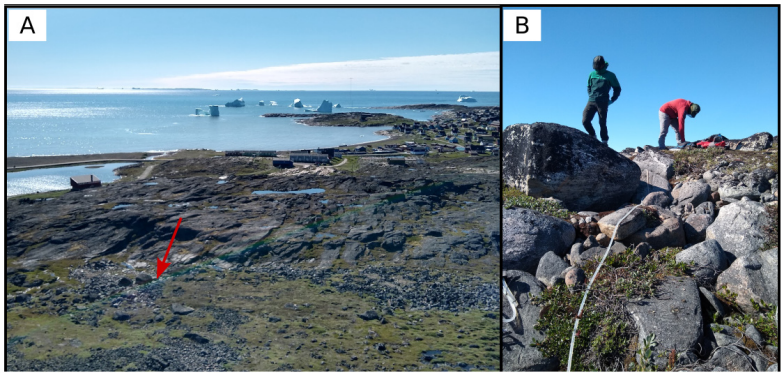


Figure 16. The surface spring is located in a gneiss formation on the backside of the Arctic Station and seems to be the primary source of the water used at the research station. A. Large view of the sampling site. **B**. Detail of the sampling location where the fluids were collected. The red arrow indicates the exact location of the sampling point shown in **B**. Photograph taken by author DG for this publication.

described in previous papers (Funch & Sørensen, 2001; Hjartarson & Armannsson, 2010; Kristensen, 1987). This is the first attempt to connect the microbiology of Greenlandic hot springs with the Icelandic hotspot source rocks. A number of other promising springs were too far away for easy access, and will eventually require a dedicated project, possibly in late winter to be able to minimize the influence of meltwaters. All the collected samples were brought back to our home laboratories in Italy, the UK, and the USA for analysis. The data obtained will be made public according to the FAIR Principles for scientific data management.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Underlying data

Zenodo: Underlying data for 'Greenland 2022 GHOST project: Sampling Greenland geothermal springs - expedition report', https://www.doi.org/10.5281/zenodo.10378679 (Giovannelli, 2023b)

This project contains the following underlying data:

- GHOST22 – Leg 1 – Expedition.kmz (the kmz file containing the location and the data from the sampled springs)
- GRL22_env_dataset – Table 2.csv (the file containing the data reported in Table 2 of the report)
- README.md

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0)

The expedition site and metadata have been uploaded to the CoEvolve Database (www.coevolvedb.org), and they have also been made available through a GitHub repository (https://github.com/giovannellilab/GRL22_Leg1_Expedition_report).

Acknowledgements

The authors wish to acknowledge the Arctic Station in Qeqertarsuaq for logistical support in the field and Kasper Broberg for logistic support in sampling some of the springs.

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Version 1

Reviewer Report 23 July 2024

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?

Jaime Alcorta
Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile, Santiago, Chile

The "Greenland 2022 GHOST project: Sampling Greenland geothermal springs - expedition report" data note is a well written report of the rationale to conduct the sampling expedition on the Disko Island (west Greenland), the selection of sampling sites and the used methodologies for geochemistry and microbiological analyses. It is noted the novelty of the expedition and the local difficulties that make these samples very valuable for the scientific literature. While some geochemistry parameters are given, the sampling methods for microbiological analyses (probably including next generation sequencing) are well suited and their descriptions will be waited with good expectations. Its indexing is recommended after minor comments and the improvements made with regards of the comments from other reviewers, which are well suited.

Figures 2, 3 and 5: As suggested by C. Rosen and J. Gong, please improve the map figures in terms of directionality and scales. While in Figure 3 and Figure 5, given the ratios (e. g. 1:2,500,000), a scale maybe is better for readers.

Figure 3: The colors are not so distinguishable from the legend to the map, and it is not know why some descriptions are in different colors (blue and purple). Maybe authors could highlight somehow the main features which are important in the text.

Figures 6 and 7: These figures are not understood why are separated as mentioned by S. Noell, and also could be aesthetically improved. Authors said from these figures that "Salinity and total alkalinity (Figure 6 and Figure 7) did not vary systematically with temperature and pH", therefore it would be suggested to show instead a correlation plot between these parameters (and/or others) to support the statement (as also said by previous reviewers).

Page 5/19: Maybe is worth mentioning the estimated temperatures of the shallow aquifers associated with these manifestations by Hjartarson & Armannsson (2010).

Page 5/19: As J. Gong mentioned, it is not explicit what GHOST does it mean. Furthermore, in the abstract is mentioned the expedition name GRL22 which is also not explained how it differs from

GHOST. Please mention the meaning of the acronyms at their first appearance.

Page 5/19: It is said "Known geothermal springs are located along fault systems present on the island (Figure 2)...", however the mentioned fault systems are not given in Figure 2. Authors can find a map with the fault systems in this or associated reports: Christiansen, F.G. et al. (2000 [Ref - 1]) : Petroleum geological activities in West Greenland in 1999. Geology of Greenland Survey Bulletin 186, 88—96.

Page 5/19: This phrase "The objective was to sample the pristine gases and fluids as they emerged from the subsurface" is a bit unconnected and redundant given the previous sections.

Page 5/19: As this is an expedition report, and no other results rather than primary analyses of the sites and their geochemistry are given. It would be valuable a supplementary table indicating the number of samples obtained for each type of analysis in each site. Of particular interest will be the numbers of samples for microbiological data, as it is highlighted as one of the main objectives of the project.

Page 9/19: In Orpinguit spring (OR), do authors have closer photographs of the orange and green biofilms? The descriptions are not well seen with the current distance of the photographs (as in the next comment).

Page 11/19: In Tarajungistoq (TQ), do authors have closer photographs of the biofilms in the precipitates? Furthermore, please provide a reference for this phrase "and thick pink and white microbial biofilms, possibly representing anoxygenic phototrophs and sulfur oxidizers coat the outlet of the spring".

Page 12/19: The site Naujánguit (NJ) is said "based on our initial interpretations, is considered a surface background sample with minimal mixing with deeply derived fluids", for this, which of the measurements could support this statement for authors? This sample would be important, because it is good to have a potential control sample with more influence of meteoric water than shallow thermal aquifers, to compare in the future the geochemistry and microbial communities.

Page 13/19: It is important in the Summary the number of successfully sampled sites.

References

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Is the rationale for creating the dataset(s) clearly described?

Yes

Are the protocols appropriate and is the work technically sound?

Yes

Are sufficient details of methods and materials provided to allow replication by others?

Partly

Are the datasets clearly presented in a useable and accessible format?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Extremophiles. Environmental microbiology. Metagenomics. Microbial ecology and evolution. Comparative genomics.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 18 July 2024

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?

Stephen E. Noell
University of Waikato, Hamilton, New Zealand
Caleb Rosen
University of Southern California, Los Angeles, California, USA

Giovannelli et al. present an expedition report from sampling of homeothermic springs in west Greenland. The report is well-written, providing a clear explanation and background for the sampling scheme. As someone with limited experience in geology, I cannot comment on the background information presented in the Introduction. However, the sampling methodology looks sound and the sampling locations are documented thoroughly. These samples look to be very unique and very challenging to acquire and will provide a fascinating insight into the microbiology of geothermal/subsurface waters over long distances.

I just have a couple of small comments:

1. A few times (Abstract and in the Introduction), you talk about "volatile elements" and "volatiles." As someone who doesn't come from a geological background, it would be helpful for me if you would quickly define what is meant by this, as it is a key part of what you are looking for. I assume these are the dissolved gases that you sampled for?

2. Typo on page 5: "The majority of the visited spring showed a strong bright green color..." should be "springs"

3. In the Methodology, under "Sample selection and environmental parameters," the sentence "Background soil samples from the nearby area that did not show geothermal alterations." seems orphaned. Did you collect background samples from the nearby areas that did not have geothermal alterations? I assume that's what is meant but the sentence just needs a re-write.

4. Under "Biological samples acquisition," just a quick clarification: did you filter 3X 2L samples onto separate filters? Or something else?

5. Table 2: It would help to have definitions of the abbreviations in the column names, preferably in the table legend.

6. What was the rationale for splitting Figures 6 and 7 into two figures? It would ease interpretation if they were two panels of one figure or if the information was somehow combined into one figure. Correlation plots of temp vs conductivity, pH vs conductivity, temp vs alkalinity, pH vs alkalinity might be one way, but at least combining the two figures into two panels of one figure would be preferable.

7. On Page 11, Tarajungistoq spring description: I would provide an in-text citation here for that radioactivity data to go along with the statement that the waters are radioactive, unless you are presenting new results.

Review from co-reviewer (Caleb Rosen):
This report, Greenland 2022 GHOST project: Sampling Greenland geothermal springs - expedition report, described the goal and setting for this sampling campaign: to survey the geochemical features and microbiological communities of a unique low temperature continental geothermal system on Disko Island, Greenland. The authors describe the geological setting of the geothermal system in the context of Iceland volcanic hotpot and broader Greenland geologic strata followed by a description of each hot spring sampled and the associated geochemical data.

Overall, this seemed like a well written and organized report. I want to commend the authors for their brief though notable inclusion of the Innuit knowledge in the second paragraph of page 4 and clarification that first western mention does not constitute discovery. I have a few minor comments, primarily regarding figures and tables. Many of these comments were also noted by Jian Gong (Reviewer 1) in the previous review.

Fig 1: As J. Gong mentioned, an indication of where Disko Island is located on Figure 1 would help orient the reader.

Fig 2: I agree with J. Gong that this figure needs both a north indicator and scale bar as well as a clearer indication of the inset region on the larger map. Also, this figure does nothing to place Disko Island within Greenland at large, which would not be an issue if we had an indication of where Disko Island was located in a previous figure.

Fig 3: Neither the larger map nor the inset have a scale bar and the figure does not have a north indicator, though this latter point is less of an issue given the recognizable shape of Greenland. On the far left side of the figure, there appears to be an anomalous orange circle. I was left wondering if this is significant in any way.

Fig 5: Again, no scale bar. Also, I concluded from this figure that the Maligat formation apparently contained the large basalt flows who’s contact with the gneiss is so significant for the presence of the hot springs. A mention of the formation in the text or an indication on the figure that these are the basalts referenced would be appreciated. All other figures, including the one above, refer to

basalt flows, but basalt is not mentioned anywhere in Figure 5.

Table 1: The final spring, QG, appears to be missing from Table 1. Also, I would appreciate if the previous figures, particularly Figure 2, were actually labeled with the SiteID so the reader can compare the data presented in Table 2 across space.

Table 2: Please switch the order of KU and NJ to match the order in Table 1.

With these relatively minor changes along with those suggested by J. Gong, I look forward to seeing this getting indexed and reading about the subsequent results of the microbiological survey.

Is the rationale for creating the dataset(s) clearly described?
Yes

Are the protocols appropriate and is the work technically sound?
Yes

Are sufficient details of methods and materials provided to allow replication by others?
Partly

Are the datasets clearly presented in a useable and accessible format?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Environmental microbiology, Microbial ecology, Microbial genomics; co-reviewer: geology, geobiology

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Reviewer Report 19 June 2024

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?

Jian Gong
University of Wyoming, Laramie,, WY, USA

The article "Greenland 2022 GHOST project: Sampling Greenland geothermal springs - expedition report" described the expedition to Disko Island (West Greenland), sampling deeply sourced

spring waters and associated microorganisms. As an expedition report, the article focused on explaining the motivation of the sampling (geologic history of the site), team members, detailed methodologies and the initial environmental measurements of each sampled springs, as well as associated ground-based images of each spring.

The report is overall clearly organized, motivating and with detailed protocols easy to follow (additional methods linked to the team's GitHub site). The datasets presented (Table 1 and 2), plus the GPS coordinates (kmz) and sampling data table (csv), were made available as a Zenodo dataset as well as a released GitHub data submission (v1.1) are well documented.

Here I list minor comments and editorial suggestions to further improve the article, as well as some corrections that should be made before indexing.

1. Title: what is the acronym for "GHOST"? This is not apparent and never appear to be explained anywhere in the article.

2. Page 3/14, Introduction, Line 5: Suggest to modify from "fertilization" -> enrichment. Fertilization has a strong bias with a underlying mechanism. Not all metals and trace elements are important/essential for life. Too much metals/trace elements can be detrimental.

3. Page 4/14, End of 1st paragraph: Figure 1 is referenced (Disko Island). However, nowhere in Figure 1 actually shows where Disko Island is. Suggest adding a label in Figure 1, showing Disko Island.

4. Figure 2 has several issues:
   a. The figure requires a North arrow, showing the map orientation.
   b. Names of Islands are way too small to see. Suggest increasing font size.
   c. We need a scale bar for both the map as well as the zoom-in region (Qeqertarsuaq). We need a clear call-out arrow showing where the zoom-in region is referring to. We need a location label for the Arctic Station in the zoom-in region.
   d. Better to show a legend describing what the small turquoise markers are about (putative springs from literature with no exact coordinates). If no exact coordinates, how would you then know the location?
   e. The article later described the fault systems (Page 5), referencing this figure. However, there are no faults described in this figure. Could you add some descriptions of the known faults?

5. Page 8/14, Sampling methodologies, first paragraph: Incorrect sentence (grammar mistake): "Background soil samples from the nearby area that did not show geothermal alterations."

6. Page 8/14, Sampling methodologies, overall comment: How would we know/ensure that the spring is indeed "deeply sourced" vs. a surface spring?

7. Page 8/14, Sampling methodologies, Sample selection and environmental parameters, first sentence: "Fluids, sediments and background soils were collected from six locations identified based on the literature (Giovannelli, 2023b)." The reference "Giovannelli, 2023b" appears to be the dataset of this exact publication. There is some circular logic here. Please cite the correct literature(s) for the site identification.

Is the rationale for creating the dataset(s) clearly described?
Yes

Are the protocols appropriate and is the work technically sound?
Yes

Are sufficient details of methods and materials provided to allow replication by others?
Yes

Are the datasets clearly presented in a useable and accessible format?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Geology, Geochemistry, Geobiology, Field sampling methods, Data Science.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.