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Fault Convection of Cold and Hot Waters in the Vicinity of Ittoqqortoormiit in East Greenland

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ABSTRACT

Geothermal springs in the neighborhood of the Ittoqqortoormiit settlement in E-Greenland were investigated during August of 2022. Of particular interest was Greenland's hottest spring, Uunartoq, 1 l/s of 60.1 °C. The Uunartaaji warm springs, located 2 km further east, measured between 32 and 45 °C. They had a minimum combined flow of 1.6 L/s on about 80 m long NW trending lineament, and likely double that rate when accounting for a 1200 m^2 open sea area spotted in mid-winter satellite images. Geothermal springs at Ittaajimmiit, 15 km west of Ittoqqortoormiit, were also visited. Their highest temperature was 15 °C and flow 1.6 L/s. A handful of large 3-6 °C cold springs were mapped, some flowing tens of L/s of fresh water coming out of fractures in the bedrock. This infers sizeable groundwater circulation in the area's bedrock, best explained by summer infiltration of meltwater at higher elevations and lower elevation discharge by faults. The water collected had neutral to basic pH, low in TDS while high in radon relative to springs in basaltic rocks. Seawater also percolates down, presumably near the hottest Uunartoq manifestation, where it mixes at depth with the fresh water infiltration before ascending to surface. Geochemical thermometers infer above 80 °C temperature at depth in Uunartoq. The geochemistry has a signature of chemical equilibrium with basalts, despite coming to surface within gneiss. This infers basaltic dykes, from the opening of the North Atlantic Ocean, still play a significant role in the geothermal convection.

We theorize that the mouth of Kangertittivaq (Scoresby Sound) is tectonically active. This allows for deep circulation of cold and hot waters. Northerly trending escarpment faults of the early rift are suspected as the primary geothermal fluid convection cells. If right, such systems have industrial scale cold and hot water production potential that can be developed for the local community and as a backbone for the region's growing travel industry. As a best-case scenario, a cogeneration of power and heat looks achievable at Uunartoq and Uunartaaji due to the 80 °C geochemical temperature at depth and access to the locally cold ocean as a heat sink. Carefully executed green energy development is expected to go hand in hand with the delicate and pristine flora and fauna at site, and without displacing arctic hares, seals, whales and polar bears that entertained the field crew during their August 2022 expedition.

1. INTRODUCTION

Warm springs are rare in Greenland. They are found primarily on the east coast, at a number of locations north and south of Kangertittivaq (Scoresby Sound). Additional thermal manifestations are mapped at several locations in Qeqertarsuaq (Disko Island), West Greenland. Outside these regions, only two occurrences of geothermal springs are known, at Uunartoq Island in South-Greenland and Ikasagtivaq on the southeast coast near Tasiilaq. See Figure 1 for their locations. The Greenland Glacier covers over 80% of the country and majority of hot springs and geothermal sites are believed to be ice covered. Logistics are challenging and snow cover limits reconnaissance work to only a few weeks per year.

This paper describes initial results from a week-long expedition to Kangertittivaq in E-Greenland in August 2022, focusing on geothermal springs in the neighborhood of Ittoqqortoormiit, a settlement with a population of about 350 people. Among them is Greenland's hottest geothermal spring at cape Uunartip Nuaa (Cape Tobin). Detailed studies on the geothermal potential of Greenland are scarce and serve mostly for reporting hot spring locations, flow and temperature, while lacking the conceptual model details necessary to better estimate the reservoirs' natures and possible development options. One of the authors of this paper, Hjartarson, has previously published Greenland overview reports at the World Geothermal Congress, besides visiting thermal manifestations on Qeqertarsuaq (Hjartarson and Ármannsson, 2005, 2010, 2015 and 2020). The Greenland East Coast basalts also have been of interest to members of the international geothermal community for decades, however inclined to past volcanology and petrophysics of intrusives within the basalts (Brikowski, 1995).

Being a close neighbor to Greenland, the Icelandic authors of this publication have for years looked for time and funds to visit the geothermal manifestations around Ittoqqortoormiit. Our curiosity is driven by its close proximity to Iceland, the logistical ease of having direct flights from Reykjavik to site, and our vision to assess if the hot spring locations near Ittoqqortoormiit have the potential to support a district heating geothermal project. The authors have in their previous carrier been partaking in many such hot water discoveries in Iceland and, furthermore, saw them through from green field exploration to long term operation (see for example Flovenz et al. 2000). We therefore know firsthand how district heating systems can improve the livelihood of local communities in the north, and may later serve as a base for new green energy development like spas, swimming pools and even power. Our acquaintance with Ittoqqortoormiit's civil engineer, Kristian Hammeken, was a major turning point in the effort, for logistical reasons and with his in-depth knowledge of the community infrastructure and potential use of geothermal fluids.

Figure 1 is a map of the survey area explored in the August 2022 expedition. The field crew was based in Ittoqqortoormit and sailed by small boats to locations A to D. Area E, on the other hand, was easily accessible at the estuary of the Kuuk River within Ittoqqortoormit. The field work consisted of mapping locations of anomalous temperature and/or flow, sampling seven spring locations with appropriate equipment and treatment, and taking long walks to check for temperature of numerous sites, in which water was flowing on surface during the dry days of the expedition. Despite fairly cold outside temperatures (2-6 °C), solar irradiation and snow melt was significant. Such melt waters were heated from 0 to 10 °C when flowing laterally only 30-50 m from a melting snow cap. Finally, one of the hotter thermal manifestations is located at a near vertical seaside cliff. A considerable effort was made to locate and sample its suspected submarine spring without success due to rough waves.

Following introduction, we outline in the paper the general geological settings, large and small scale from available literature. Then comes a section with descriptions of the thermal manifestations visited, their estimated flowrates, temperature, appearance, geological features and more. A detailed geochemistry of seven water samples is shown, their correlations made and deep reservoir temperatures estimated by geochemical models. Based on the available data, we put forward a conceptual reservoir model for cold, warm and hot springs. Based on the conceptual model, some preliminary development options are discussed prior to conclusions. Our plan was to accommodate the field campaign with high resolution thermal and optical orthomosaics by a drone; however, it was interrupted by a combination of Covid and cancelled flights.

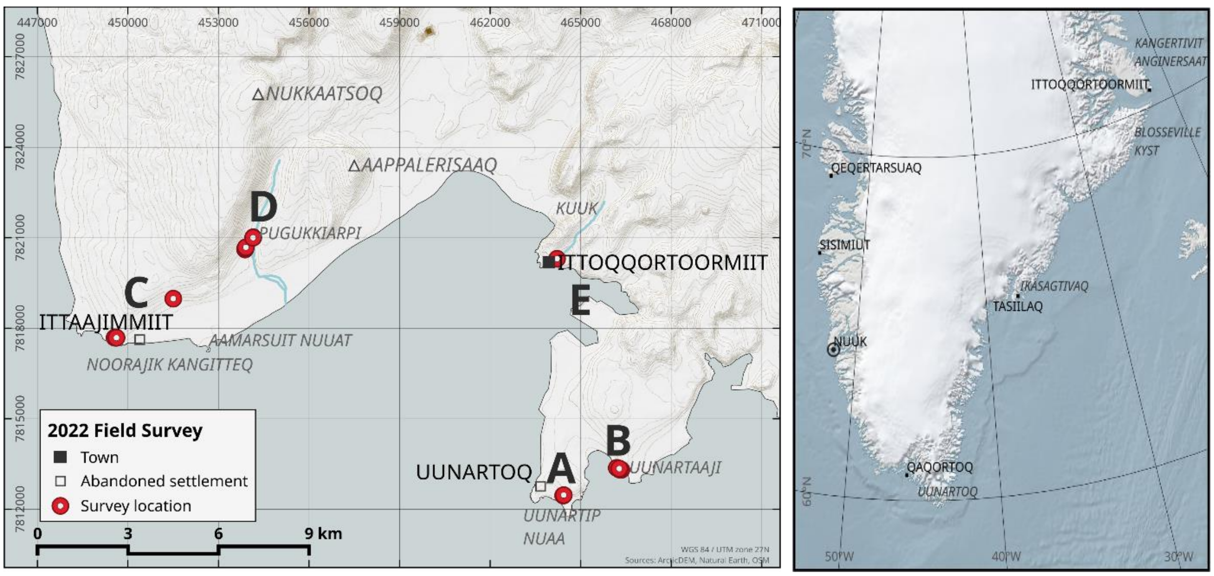

Figure 1: A map of the survey area and its location in Greenland

This paper made an effort to recognize local landscape names in text and maps. Table below links commonly used names of foreign influence to what is more appropriate for the local community. Map names are also supported by Higgins (2010) publication.

Table 1: Old and preferred local names in the survey area and beyond

Older name	Preferred local name
Kap Hope	Itterajivit/Igteravik locally and should be: Ittaajimmiit: meaning small houses
Kap Tobin	Ûnarteq/Uunarteq/Uunartoq (Uunartip for the actual cape)
Uunarteq	Is normally found on maps [older eastern dialect; Uunarder]. Today all locals are using Uunartoq meaning; something hot.
Uunarterajik	Uunartaaji: little hot [spring]
Gulfjeld	Locally called Aappalerisaaq meaning; reddish [could be mountain or area]
Bruddal	Pugukkiarpi – meaning; an area to collect black-berries
Basaltnæs	Aamarsuit Nuaat – meaning something like “coal headland”
Scoresbysund	Kangertittivaq
Ammassalik	Tasiilaq

2. GEOLOGICAL AND TECTONIC SETTINGS

The bedrock around Ittoqqortoormiit is the so-called Caledonian basement. It is made of Precambrian gneiss that got folded during the Caledonian orogeny in Ordovician - Early Devonian, 400-500 Ma. After that the Jameson Land Sediments were formed as a result of erosion of the Caledonian mountains in Upper Permian to Cretaceous. The next significant step in the geological evolution was the opening of the NE Atlantic Ocean in Palaeocene times, 50-60 Ma. It was accompanied by intense volcanism along the rifted continental margins. Figure 2 outlines some of the major geological and tectonic settings. Basalt formations that were formed in the time of the opening is found in East Greenland, in the Faroes and the British Isles and on the submerged Rockall Plateau, Jan Mayen Ridge and the Wöring Plateau (Larsen et al. 1989). The volcanic activity has continued along the Mid Atlantic Ridge since then and to the present time.
The opening history of the NE Atlantic Ocean is well documented. The initial rift of the opening was located close to the present coast of East Greenland, except in the region north and south of Kangertittivaq (Scoresby Sound), where it had a large deflection to the east. The spreading north and south of this deflection was simple and continuous throughout the period until present. The spreading in the Kangertittivaq area was on the other hand more complex, with repeated shifts in the position of the spreading axis. The first break up phase was due to activity in the Ægir Ridge and the second break up phase follows extinction of Ægir Ridge and initiation of the Kolbeinsey Ridge 22-24 Ma along with opening of a channel between the Kangertittivaq area and the Jan Mayen Micro Continent (Blischke, 2021).

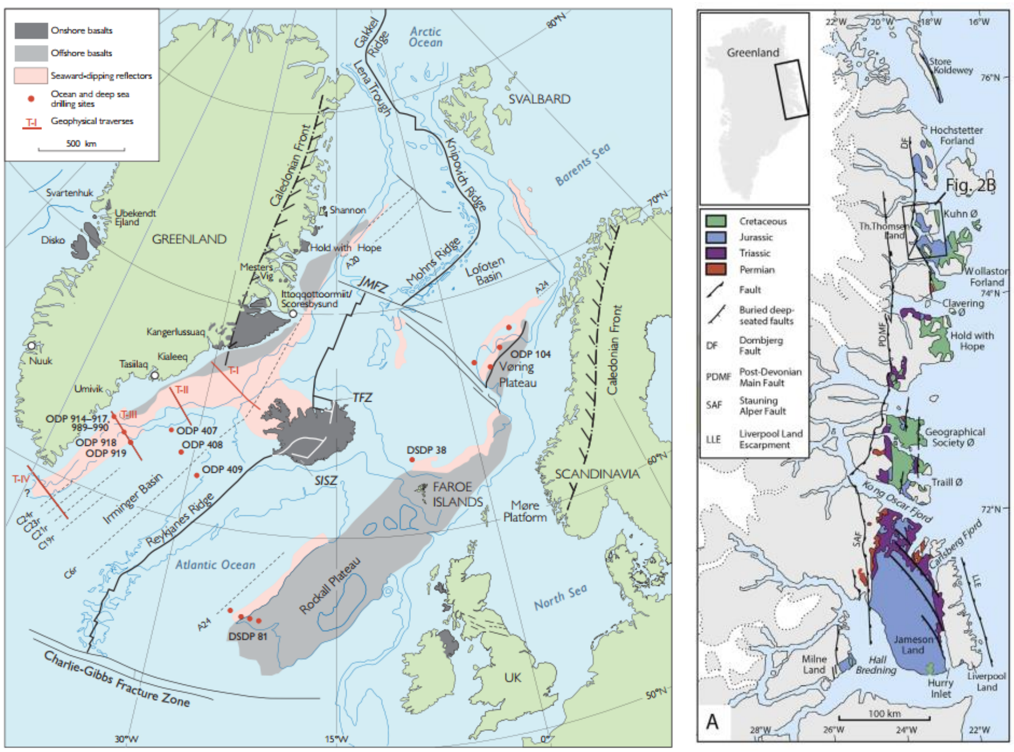

Figure 2: The North Atlantic and East Greenland tectonic and geological settings From Brooks, 2011 (left) and Kristensen et al., 2016 (right)

The geology south of Kangertittivaq is in some respects similar to the geology of Iceland, especially NW-Iceland, made up of a thick pile of flood basalt lavas. However, the basaltic pile is considerably older, from early Tertiary or around 60 Ma whereas the basaltic region of NW-Iceland is 14-16 Ma (Larsen et al. 1992). North of Kangertittivaq the bedrock is much older.

Geothermal springs are found in a number of locations along the shore both north and south of Kangertittivaq (Figure 1). That is in the Blosseville coast south of Kangertittivaq and in the fjords north of it. The distance between the northernmost geothermal site in Kangertivit Anginersaat (Storefjord) and the southernmost sites in Johan Petersens Bugt is 350 km. The location and the tectonic setting of the geothermal sites may be related to the second break up phase and the separation of the Jan Mayen Micro Continent from East Greenland 22-24 Ma. It is noteworthy that the geothermal sites line up near the rifted continental margin of central East Greenland in the outer parts of the fjords next to the open ocean. The sites in Kangertittivaq are good examples, located near the mouth of the fjord. No hot springs are documented along the many hundred kilometres long beaches of the inner part of the fjord.

3. WARM AND HOT SPRING OVERVIEW

Warm springs have long been known near Ittaajimmiit. Th. Bjerring Pedersen (1929) mentioned them in his diary already in 1924-5. At least one of them, the Mosekilde, have been inspected and sampled. Figure 3 is taken from this manuscript. In the figure, *Varm kilde* is Danish for warm and hot springs. The map shows quite many additional geothermal locations than the most famous 60 °C spring at Uunartoq (K. Tobin). This map led the authors of this paper to speculate that the geothermal resource in the region is quite extensive and holds a potential opportunity for a geothermal district heating system for when explored in more detail. Apart from revisiting the hot springs at Uunartoq and Uunartaaji south of Ittoqqortoormiit, we therefore made considerable effort in mapping and sampling the locations shown on the west side of the 1925 map in Figure 3.

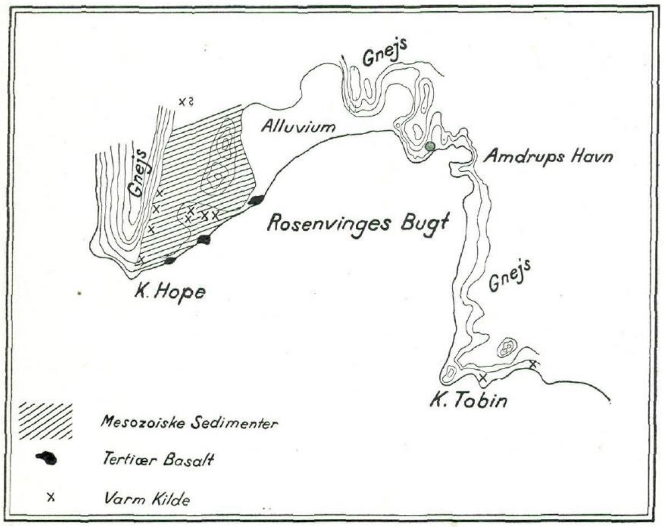

Figure 3: Pedersen (1929) sketch of Rosenvingens Bugt and its surroundings from 1925

3.1 Uunartoq Hot Springs in area A

The well-known Uunartoq (roughly translated as '*something warm'* in Greenlandic) hot spring area is located approximately 7.5 km south of Ittoqqortoormiit, around 1 km east of an abandoned settlement and weather station of the same name. The springs are about 260 m north from the seashore at 8-10 meters above sea level, in an area of rounded, loose boulders, gravel, and sand (Figure 4 and Figure 5). No vegetation is at the locality, but green algae thrive in the warm water runoff. The surrounding bedrock is gneiss that occasionally appears on the surface. The geothermal water issues in two springs, that are about seven meters apart. Additionally, a minor seepage was detected in between the boulders close by. The warm water melt impacts the snow cover in Figure 5.

The larger and warmer spring is of elliptical bowl shape, 2.0 x 1.3 m, and up to 27 cm deep. The hot water upflow is dispersed within the bowl. Temperatures are in a 58-60 °C range with a maximum of 60.1 °C. This is slightly lower than previously reported maximum (61.8 °C) and best explained by thermometer calibrations and variable ambient air temperature. Gas bubbles are steadily emerging within the hot water. The spring runoff, measured accurately by using a plastic pipe and a bucket, was 0.8 L/s. A smaller spring was positioned 7 m away in bearing towards N346 magnetic. Its maximum temperature measured 40.6 °C and eye estimated flowrate some 0.2-0.3 L/s. Finally, a tiny seepage was detected around 30 m upstream of the main springs, 20.5 °C. The total geothermal discharge at Uunartoq is therefore exceeding 1 L/s.

The runoff flows between the boulders towards the shore. The water has salty taste; faint smell of sulfur is in the air and a thin, transparent layer of steam rises from the water. White prominent precipitates are detected on rocks in the flow path. Faults and fissures are hard to see at the springs themselves. Fault exposures in the neighborhood prominently orient N147° magnetic. The geothermal site is pristine and not developed for bathing or other such common use elsewhere. It is nevertheless visited frequently by tourists. The hot water furthermore is used for cooking and cleaning skulls of musk ox, walrus and polar bears. Those meat leftovers attract polar bears as witnessed during expedition when a polar bear had to be scared away from the spring before sampling.

Figure 4: Uunartoq main spring, (A), the smaller 40.6 °C spring (B) and the Uunartoq gorge cutting the gneiss (C)

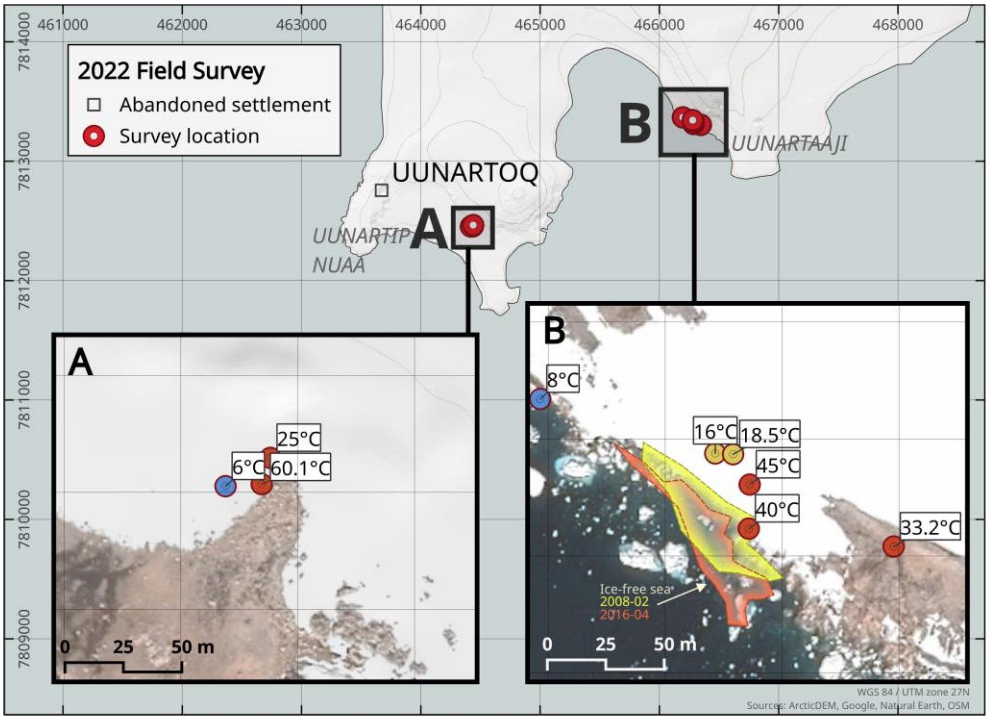

Figure 5: Warm spring locations in Uunartoq (A) and Uunartaaji (B)

3.2 Uunartaaji thermal springs in area B

The Uunartaaji (roughly translated as *'little warm [spring]')* site is 2 km ENE of area A (Uunartoq hot springs) and 7.5 km from Ittoqqortoormiit (Figure 5). The main spring is only 40 m from the shore, just above the high tide limit. All the springs can be considered to belong to the same upflow zone and supposedly line up on a single NW trending and 80 m long lineament.

Several small springs were mapped on a 20 m long line on a gravel ridge formed by the waves. The main spring is in a rounded bowl in the stony sand and gravel surface, 1.0 m in diameter and 10 cm deep. Maximum temperature in the main spring is 33.2 °C. This is close to what earlier measurements have given (Kristmannsdóttir 1998; Hjartarson and Ármannsson 2005, 2010). The total discharge is hard to estimate but seems just shy of 1 L/s. Gas bubbling is prominent. The water flows to the sea in many small seepages on the exposed gneiss bedrock making up the shoreline. Faults and fissures are prominent. The main fissure system has the same direction as the coastline, to the NW. Less prominent fissures are found perpendicular to the main one.

About 100 m NW of the main spring is a tiny seepage. It is only 8 °C and discharges 0.1-0.2 L/s. The expedition local field guides, Hjalmar and Kristian Hammeken, informed that there is a permanent opening in the sea-ice at the coast during winter, indicating a submarine spring and continuous geothermal flow. Google Earth winter images from February 2008 and April 2016 show this NW trending and elongated open water clearly (Figure 5, right). The opening is about 70 m long and 20 m wide, covering 1200 m^2.

After this discovery, Uunartaaji was revisited to better assess the nature of the seafloor hot spring. Temperature measurements were unsuccessful in pinpointing the hot water upflow and gas bubbles were not seen either. Thermal springs, however, were spotted in the upper littoral zone, near mean sea level, northwest of the 33 °C spring in Figure 5. A maximum temperature of 45.0 °C was measured there and runoff near 0.1 L/s. It has 12 °C higher temperature than previously reported in this location. The spring issues on a crosscut fissures bearing N115° and N35°. Close by and a little higher up was yet another spring, 18 °C and 0.5 L/s. The total runoff of geothermal water above sea-level from the NW trending lineament is therefore at least 1.6 L/s.

Back-of-the-envelope calculations on heat energy needed to maintain 1200 m^2 of open sea during cold winter months results in about 1.2 L/s discharge of 60 °C geothermal water. The number is expected to be conservative. Apparently, the Uunartaaji hot springs in area B therefore have higher thermal output than the Uunartoq springs in area A.

3.3 Ittaajimmiit cold and warm springs in area C

Ittaajimmiit (meaning small houses) is a small, abandoned settlement just east of a cape called Noorajik kangitteq (also known as Kap Hope) at the mouth of Kangerterajiva fjord (Hurry Inlet). It is 14 km west of Ittoqqortoormit.

The first spring mapped is some 700 m west of Ittaajimmiit (Figure 6 and Figure 7A). It was hosted within a cave the geothermal fluid melted into the thick snow pile above. The water comes from a sloping stony scree at 31 m above sea level, measured by a handheld GPS device. The surrounding rock is gneiss. Max temperature is 12.3 °C and the discharge is 0.5 L/s. The water is fresh. White precipitates are seen on stones.

Around 100 m further east, and lower in the slope, is another warm spring in the stony gneiss scree. Its maximum temperature is 15.3 °C and the discharge 0.6-0.8 L/s. Faults and fractures in the bedrock are oriented N50°. The temperature resembles the warm spring near Ittaajimmiit, mentioned by some authors as Mosekilden. The described location and moss was not found at the site however and remains as an outstanding issue in the area geothermal reconnaissance.

A prominent cold spring issues in a gneiss scree about 2 km northeast of Ittaajimmiit (Figure 7B). It was covered by a snow but possible to investigate in its snow cave. The water temperature was 6.1 °C and the discharge 20-25 L/s. Outside the arctic, this would be defined as a cold spring, but here, in the high arctic environment of Ittoqqortoormit it is definitely geothermal. The conductivity of the water and elements in solution indicate considerable water-rock interaction. The spring might be related to a prominent fault orienting N50° at the slope of the hill.

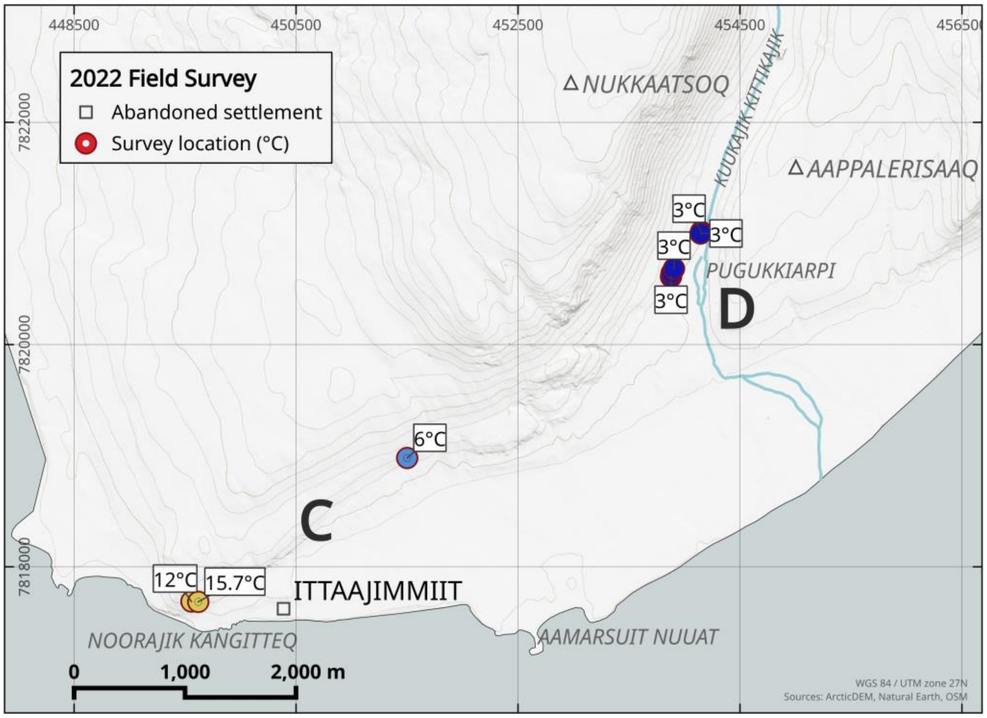

Figure 6: Cold and warm springs in areas C and D

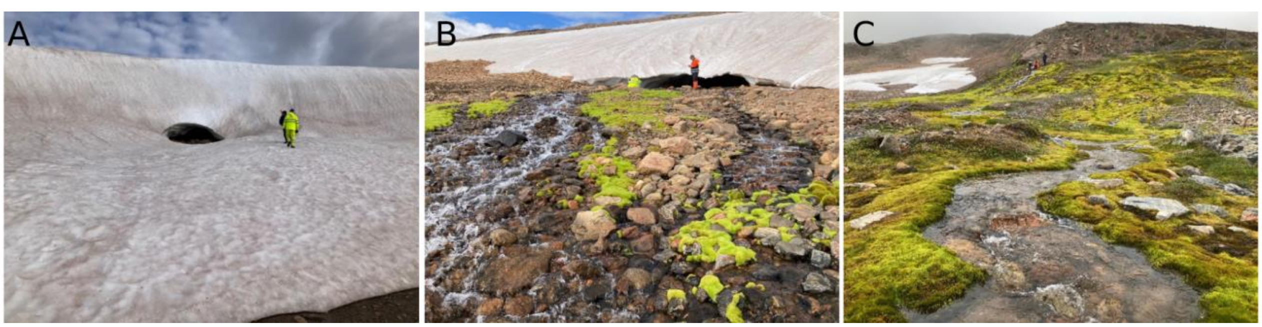

Figure 7: The Ittaajimmiit warm spring (A), the Ittaajimmiit cold springs (B) and the Pugukkiarpi cold springs (C)

3.4 Pugukkiarpi Cold Springs in area D

The river Kuukajik Kittikajik flows along the Pugukkiarpi valley, few kilometers northeast of Ittaajimmiit, between Mt. Nukkaatsoq and Mt. Aappalerisaaq. The expedition looked for possible warm springs in Pugukkiarpi, where Th. Bjerring Pedersen had marked some on his map in 1925 (Figure 3). No geothermal surface manifestations were found. Instead, prominent cold springs come out of the bedrock in the valley outer part, west of Kuukajik Kittikajik (Figure 6 and Figure 7C). They follow a 40 m long line in the gneiss bedrock, oriented N50° magnetic. The discharge was estimated near 30 L/s. Temperature is 3.0 °C at the lineament SW-end and 3.8 °C at the NA-end of the line.

This paper regards the occurrence of the large cold-water springs in area D as a significant discovery. First of all, it appears that many of the locations shown on the west side of Figure 3 are of cold-water origin, not geothermal. However, they seem to have sufficiently high flow and temperature to maintain depressions in the winter snow that may have been mistakenly interpreted as warm springs. Their occurrence on lineaments also indicates that the waters have infiltrated the bedrock at higher elevations before resurfacing. Such infiltration is only possible in summer time during solar irradiation and snow melt. Thirdly, these springs are likely to maintain sizeable flowrates during all seasons due to the winter depressions, hence a potential source for applications such as tap water or even mini-hydro.

3.5 Gorges

Three gorges or canyons eroded in the bedrock were investigated in the area between Ittoqqortoormiit and Uunartoq. The expedition inspected these as features of tectonic and geothermal significance. The first one is inside the Uunartoq settlement (Figure 4c). It is a remarkable cleft cut in the gneiss ridge forming the basement of cape Uunartip Nuaa (Cape Tobin). It is 40-50 m wide, bearing N-S (magnetic) with more or less vertical walls up to 20 m high. The length of the canyon is about 500 m. It hosts an elongated pond with run-off towards south. The gorge is likely the result of erosion by the oceanic waves and weathering along tectonic weaknesses in the bedrock.

Another two noteworthy and parallel gorges at the west dipping slopes between Ittoqqortoormit and Uunartoq were inspected. These are several hundred m long, 50 m wide and up to 12 m deep. These are also deemed as water erosional channels, presumably cut into tectonic weaknesses along glacier margins in late glacial times or early Holocene. Their bearing is NNE-SSW magnetic.

4. GEOCHEMISTRY OF SAMPLED SPRINGS

Seven water samples were collected for chemical analysis during the August 2022 expedition: Three samples from the hot springs near Uunartoq (areas A and B), three samples from cold and tepid springs near Ittaajimmiit (areas C and D) and one sample of surface water from the Kuuk river, that runs through Ittoqqortoormiit (area E). Results are presented in Table 2. The samples were collected from free flow using standard methods (Arnórsson et al., 2006) and cooled using a stainless-steel cooling spiral if the water temperature exceeded 30°C. Untreated sample fractions were collected for the analysis of silica and volatile species. Sample fractions for the analysis of anions, metals, TDS and stable isotopes were filtered through a 0.20 µm cellulose acetate filter using an inline PFA filter holder. The sample fraction for metals was acidified to 1% with concentrated ultrapure nitric acid. A peristaltic pump was used to pump water through the cooling spiral (when needed) and filtering apparatus. The concentration of H_2S was determined in the field by titration with mercury acetate using dithizone as an indicator. Sample fractions for the determination of CO_2, Rn, pH and conductivity were collected into air-tight glass bottles and were analyzed at the end of each day; pH and conductivity using electrodes, CO_2 (dissolved inorganic carbon) by potentiometric titration, and ^{222}Rn by alpha radiation detection (using a Durridge RAD7 system with the RAD H_2O accessory). The remaining chemical constituents were analyzed at the Iceland GeoSurvey laboratory using ion chromatography (anions), ICP-OES (metals and trace elements) and gravimetry (TDS). Stable isotopes of hydrogen and oxygen were determined at the University of Iceland Institute for Earth Sciences.

The chemical composition of the samples allow for them to be divided into four categories: The hot waters at Uunartoq are Na/Ca-Cl type with pH ≈ 8 and TDS in the range 7-10 g/kg, the cold spring waters at Ittaajimmiit and Pugukkiarpi are Na/Ca-SO_4 waters with pH ≈ 9 and TDS of 70-80 mg/L, the tepid water of Mosekilden near Ittaajimmiit is slightly more mineralized with TDS = 110 mg/L, pH = 9.4 and a Na-Cl/sO_4 composition, and finally the very dilute water in the Kuuk river by Ittoqqortoormiit which is essentially precipitation with TDS ≈ 10 mg/L and neutral pH. This is apparent from the Piper diagram in Figure 8 (left). Stable water isotopes (Figure 8, right) show that the sample from the Kuuk river is the least depleted, with $\delta D \approx -105‰$, and those from Ittaajimmiit (area C) and Pugukkiarpi (area D) are the most depleted, with $\delta D \approx -130‰$. All fall very close to the global meteoric water line (Craig, 1961). The hot spring samples from Uunartoq and Uunartaaji fall between these two extrema, with δD ranging from -122‰ to -114‰. All three samples show a slight oxygen isotope exchange effect and are shifted from the meteoric water line by about 0.4-0.5‰. The $\delta^{18}O$ values reported for Kuuk river are in fairly good agreement with values given by Dansgaard et al. (1973) for precipitation from the Scoresbysund meteorological station ($\delta^{18}O \approx -14‰$). The isotope values show that the source of the groundwater flow near Ittaajimmiit is more depleted than precipitation in Ittoqqortoormiit and the groundwater that feeds the hot springs at Uunartoq, and hence belong to a different groundwater system sourced from further inland and/or at higher elevation.

Figure 9 shows the concentrations of boron and silica and the deuterium shift of all samples plotted against the chloride concentration. Boron, chloride and deuterium are assumed to be conservative constituents and can therefore be used to detect fluid mixing, whereas the concentration of silica in geothermal water is controlled by temperature-dependent water-rock equilibria and can therefore be used to deduce the reservoir temperature. The plots for boron and deuterium show that the hot springs at Uunartaaji (area B) fall on a mixing line between the Uunartoq (area A) and water from the Kuuk River and the silica plot also suggests that they may be mixed waters, although they don't fall directly on a mixing line. Therefore, it seems that the water emanating from Uunartoq represents the main geothermal source in the A-B area and that the hot springs at Uunartaaji are formed by dilution of that water with dilute surface water, which could have a similar origin to that of the water sampled from the Kuuk River.

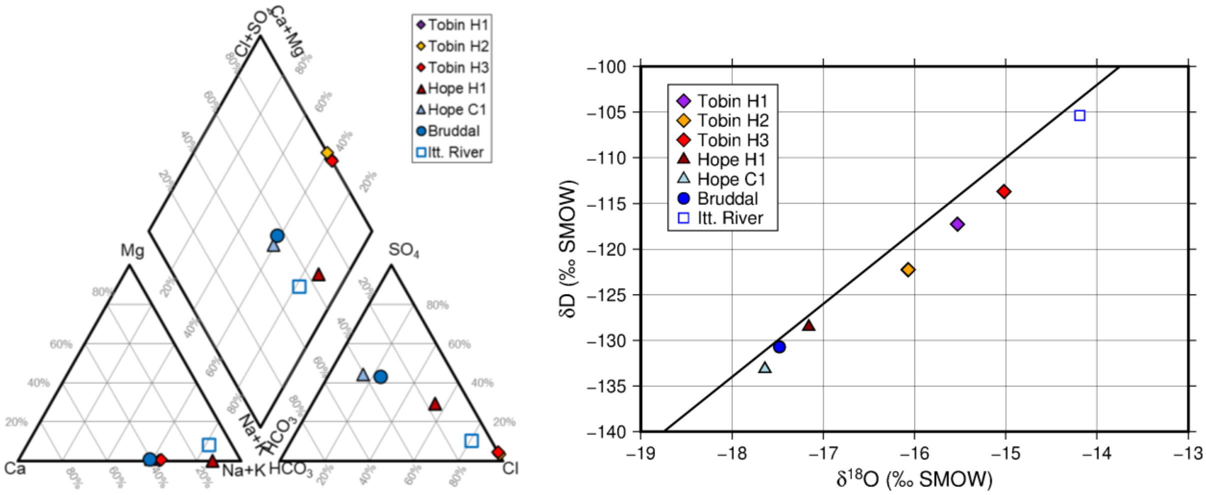

Figure 8. Piper diagram (left) and isotope delta plot (right) for the sampled waters. Also shown in the delta plot is the global meteoric water line (Craig, 1961)

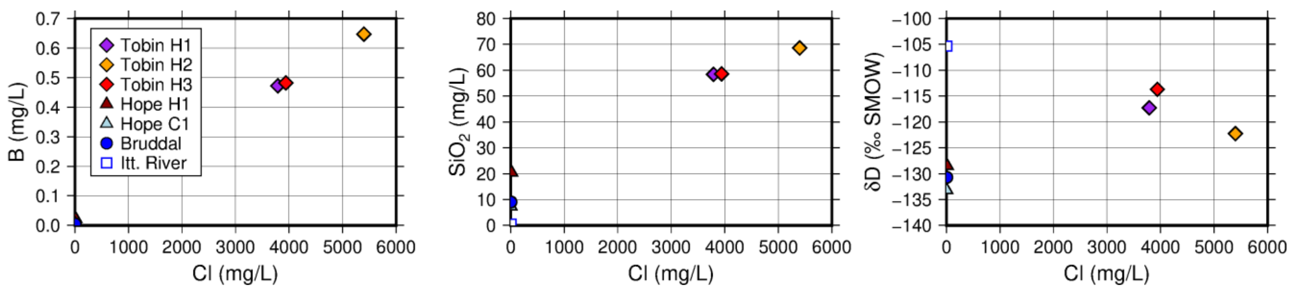

Figure 9. Concentrations of boron and silica, and deuterium value plotted against chloride concentration.

4.1 Geothermometry

Speciation calculations were carried out for the three hot water samples at Uunartoq and Uunartaaji using the WATCH software, version 2.4 (Arnórsson et al., 1982; Bjarnason, 2010), and the results used as input for several geothermometry equations. Results are given in Table 3 and seem to form two clusters, one which gives results in the range 80-90 °C (chalcedony, Na-K-Ca, Na/K, Mg/Li) and another which gives results close to 110 °C (quartz, K/Mg). It is not entirely clear which of the silica minerals controls the concentration of silicic acid in the geothermal reservoir; chalcedony is usually preferred at these temperatures in a basaltic setting, but it is not impossible that equilibrium with quartz would be obtained in the gneisses. The radon activity measured for those hot springs is higher than typical values from Icelandic basalt-hosted geothermal systems (Óskarsson and Ásgeirsdóttir, 2017) but similar to values reported by Hjartarson and Ármannsson (2005) for hot springs on Qeqertarsuaq (Disko Island), W-Greenland. Furthermore, the calculated saturation indices for selected minerals in the hottest spring at Uunartoq suggest that the water is close to equilibrium with several secondary minerals (including chalcedony) in the temperature range 80-100 °C (Figure 10). This allows us to draw two conclusions: (1) The water emanating from Uunartoq (area A) represents a partly saline geothermal system where the water has reached equilibrium with the host rock, i.e., the mixing between seawater and freshwater occurs before the water is heated up. (2) The chemical composition of the water suggests a reservoir temperature of at least 80 °C, which is considerably higher than the water temperature measured at surface.

Table 3. Geothermometry results (°C) for samples from the hot springs at Uunartoq

Geothermometer calibration	Tobin H1	Tobin H2	Tobin H3
Chalcedony (Fournier, 1977)	79	88	79
Quartz (Fournier and Potter, 1982)	109	117	108
Na-K-Ca (Fournier and Truesdell, 1973)	90	96	91
Na/K (Arnórsson et al., 1983)	77	83	79
K/Mg (Giggenbach, 1986)	112	109	102
Mg/Li (Kharaka and Mariner, 1989)	77	75	69

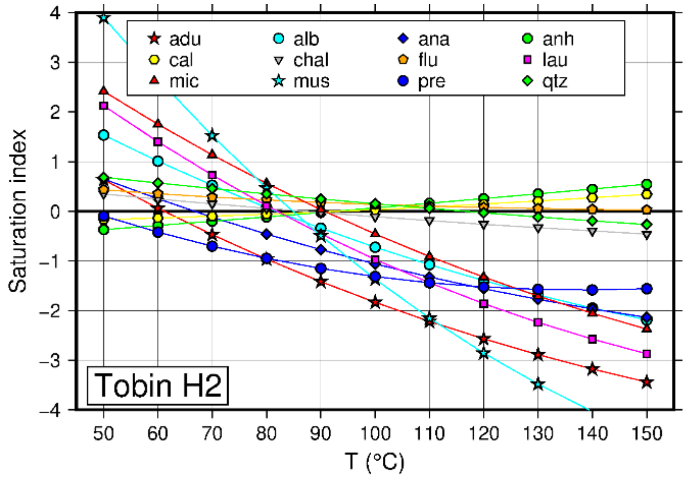

Figure 10. Saturation indices for selected minerals (adularia, albite, analcime, anhydrite, calcite, chalcedony, fluorite, laumontite, microcline, muscovite, prehnite, quartz) in waters from the hottest spring at Uunartoq.

Table 3: Results of chemical analyses for water samples. Concentrations are given as mg/L unless otherwise noted

Sample ID	20228001	20228007	20228002	20228003	20228004	20228005	20228006
Location	Uunarteraji nr. 1	Uunarteraji nr. 2	Uunartoq	Ittaajimmiit cold spring	Ittaajim-miit, Mose-kilden	Kuuk river	Pugukkiarpi cold spring
Area	B	B	A	C	C	E	D
Label	Tobin H1	Tobin H3	Tobin H2	Hope C1	Hope H1	Itt. River	Bruddal
N	70°25'23,2''	70°25'23,9''	70°24'54,4''	70°28'17,6''	70°27'34,3''	70°29'07.9"	70°29'12,0''
W	21°53'59,9''	21°54'07,1''	21°57'02,4''	22°18'01,9''	22°20'58,7''	21°57'35.3"	22°14'14,9''
Flowrate [l/s]	1	0.1	1	20	0.7	~10 m^3/s	30
Temperature [°C]	33	45	60.3	6.2	15.7	8.2	2.9
pH [pH/°C]	8.14 / 14.9	8.03 / 21.8	7.52 / 16.2	9.18 / 21.5	9.37 / 22.1	7.50 / 23.4	9.04 / 19.9
EC@25°C [µS/cm]	11430	11340	15540	180	168	27.2	120
CO_2	6	8.7	11.4	16.3	19.7	5	20.1
H_2S	0.05	<0.03	0.09	-	-	-	-
Rn [Bq/L]	66.9	30.5	13	6.52	4.54	0.084	5.32
B	0.472	0.482	0.647	0.00609	0.0221	<0.004	0.00484
SiO_2	58.4	58.6	68.6	7.41	20.5	0.472	9.03
Na	1580	1610	2050	11.4	30.6	4.51	13.7
K	36.2	35.8	51.3	0.838	1.23	0.144	1.24
Mg	4.09	7.98	10.5	0.0944	0.0208	0.249	0.133
Ca	813	787	1210	7	4.02	0.506	8.76
F	1.857	1.843	1.998	0.861	2.69	<0.01	1.18
Cl	3790	3940	5400	1.96	14	3.41	4.55
Br	7.4	7.72	11.1	<0.01	0.01	0.013	<0.01
SO_4	242	256	260	14.8	15.7	1.12	20.1
Al	0.0105	0.0056	0.003	0.00327	0.00854	<0.002	0.00278
As	<0.2	<0.2	<0.2	<0.01	<0.01	<0.01	<0.01
Ba	0.191	0.194	0.308	0.00211	0.0124	0.00224	0.0586
Cr	<0.08	<0.08	<0.08	<0.004	<0.004	<0.004	<0.004
Cu	<0.12	<0.12	<0.12	<0.006	<0.006	<0.006	<0.006
Fe	0.028	0.012	0.019	<0.002	0.00479	<0.002	<0.002
Li	0.312	0.306	0.453	0.00674	0.0136	0.00164	0.00646
Mn	0.149	0.111	0.14	<0.0005	<0.0005	<0.0005	<0.0005
Mo	<0.12	<0.12	<0.12	<0.006	<0.006	<0.006	<0.006
Ni	<0.02	<0.02	<0.02	<0.001	<0.001	<0.001	<0.001
Sr	21.8	21.4	36.8	0.0936	0.0808	0.0028	0.121
Ti	<0.4	<0.4	<0.4	<0.02	<0.02	<0.02	<0.02
Zn	0.0689	0.0852	0.227	<0.0005	0.00546	0.00163	0.00395
TDS	7100	7430	10190	70	110	10	80
δD [‰SMOW]	-117.27	-113.69	-122.25	-133.13	-128.51	-105.35	-130.72
$\delta^{18}O$ [‰SMOW]	-15.53	-15.02	-16.07	-17.64	-17.16	-14.19	-17.48

5. A CONCEPTUAL MODEL FOR COLD AND HOT RESERVOIRS IN THE AREA

Figure 11 is an attempt to sketch a very simplified conceptual reservoir model for the cold and hot springs visited and sampled during the August 2022 expedition. The geological features are taken from the open literature (section 2 in this paper) while the flow cells and flow paths are the result of the current work. Based on the many linear features of cold and hot water occurrences and year-round discharge, the permeability in the region is presumed secondary and along steeply dipping faults. The hottest springs bear a signature of basalt reservoir water-rock interaction at depth, inferring that the water may be circulating along basaltic dykes within gneiss. The sediments are assumed to maintain matrix porosity and permeability despite age. Such formations can capture summer snow melt and convey to deeper formations. The gneiss is more likely only of secondary permeability, cut by basalt dykes since the opening of the N-Atlantic. The thermal gradient of 50 °C/km is speculative, however should be higher than a common 30-40 °C/km continent gradient due to the hot water upwelling in areas A and B. If right, the deep resource is residing at 1 km depth or more, possible with lateral flow along the faults, infiltration at higher elevations and outflow to the surface at the lower.

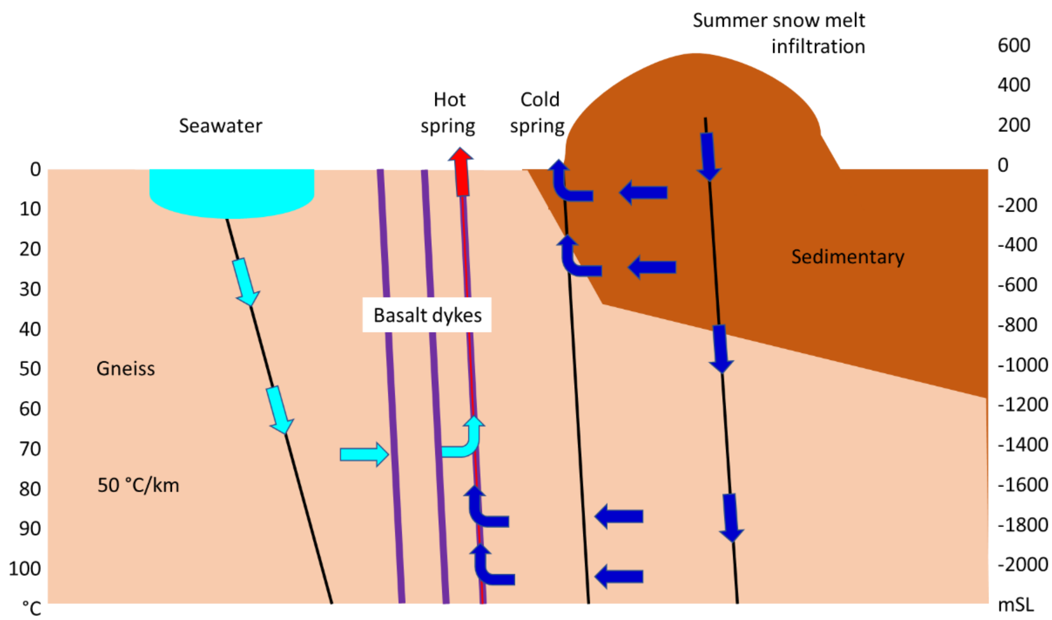

Figure 11. A very simplified conceptual reservoir model for hot and cold springs near Ittoqqortoormiit

6. SUGGESTED DEVELOPMENT OPTIONS

The work presented here is encouraging for green energy and sustainable geothermal development in the Ittoqqortoormiit region. This paper intentionally is unspecific on a suggested way forward strategy. Such decision making belongs to the local authorities and has to be adjusted to policies and community goals at each time. The below bullets are therefore just a suggestion, with the least expensive development at top and most expensive coming last.

- Build a nature spa using the free flow from the Uunartoq hot spring (Area A). Subject to seasonal snow pack and sea ice, select a location downstream from the spring. Build a facility made from local rocks to certify as a nature spa.
- Explore the Uunarteraji hot springs (Area B) in more detail, in particular the existence of a subsea hot spring. Capture the water and use for a nature spa.
- Pipe water from cold spring in area C for tap water use nearby. Apparently, there is limited local demand.
- Build a new 15 km long water facility for Ittoqqortoormiit from areas C and D. Couple with the thermodynamics of laying a long pipe in permafrost. Now the 6 °C Ittaajimmiit 20 l/s cold spring is of interest.
- Look at the economic feasibility of harnessing the cold spring in areas C and D for mini-hydro. Needs support of minimum 1 year of flowrate measurements, to verify the water is flowing in both winter and summer. A tap water pipe to Ittoqqortoormiit might run on this power.
- Initiate a full-scale geothermal exploration project at areas A and B. Should include additional surface exploration, shallow thermal gradient wells, intermediate depth well for district heating only and more than 1 km well for potential co-generation of power and heat, tapping 80 °C or more. Lay a 7 km hot water pipe to Ittoqqortoormiit and expand the existing, district heating system network to replace the fossil fuel power station.

7. CONCLUSIONS

This study infers a healthy subsurface flow of cold and hot water, fresh and saline, in the region of Ittoqqortoormiit. The location and tectonics of the geothermal sites in the Ittoqqortoormiit area, and in fact all of East-Greenland, are related to the separation of the Jan Mayen Micro Continent from East Greenland 22-24 million years ago. Permeability of the bedrock appears to follow secondary structures like faults and basalt dykes. The Gneiss are expected to be only of secondary permeability nature while the sediments may retain their primary porosity and therefore serve as a subsurface reservoir holding water and maintaining cold spring flow between summers and winters. All water systems seem to have higher elevation, fresh water infiltration, while the hottest waters also mix with seawater at depth and reach equilibrium condition before resurfacing in the hot springs. Geothermometry is suggesting 80 °C deep reservoir temperature or more, opening for the opportunity of the cogeneration of heat and power by drilling to 1 km depth or more.

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