Field report on the vertical ground-coupled heat pump pilot project for the Forum building in Kuujjuaq (Nunavik, Canada)

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I. INTRODUCTION

The present field report describes the drilling of a geothermal exploration borehole and the installation of a ground heat exchanger for a pilot ground-coupled heat pump project led by Kujjuamiut Inc. as part of the Kuujjuaq Clean Energy Plan and funded by the "Indigenous Off-Diesel Initiative" of Natural Resources Canada. For this project, Borehole drilling was made by Avataa Rouillier Drilling, Geophysical well logging was made by Université Laval and ground heat exchanger installation was made by Induktion Géothermie. The Institut national de la recherche scientifique (INRS) collected and described the drilled core and kept track of the drilling process.

In 2021, a 240 m-deep well was drilled near the Kuujjuaq Forum building to assess the deep and shallow geothermal resource potential (Miranda and et al. 2022). Analysis results suggested that a 140 m-deep ground heat exchanger (GHE) located near the Forum could be used to extract about 9.8 MWh of thermal energy per year (Géotherma Solutions Inc, 2022). A pilot project was subsequently initiated with the goal of installing a GHE, which is expected to be connected to an experimental heat pump system by the end of March 2025. The heat pump system will heat office space in the Forum building and ultimately demonstrate the use of geothermal technologies in a subarctic climate.

The present report describes the field work carried from September to November 2024, during which the aforementioned borehole was extended to a depth of 450 m. The objectives were to evaluate the geothermal gradient and then to better characterize the subsurface at greater depth using various geophysical logs prior to installing the GHE. After a basic geographical and geological introduction, an overview of the drilling activities is presented, followed by a summary of the results of the well logs and finally a description of the installation of the ground heat exchanger.

1. GEOGRAPHICAL SETTING AND GENERAL CONTEXT

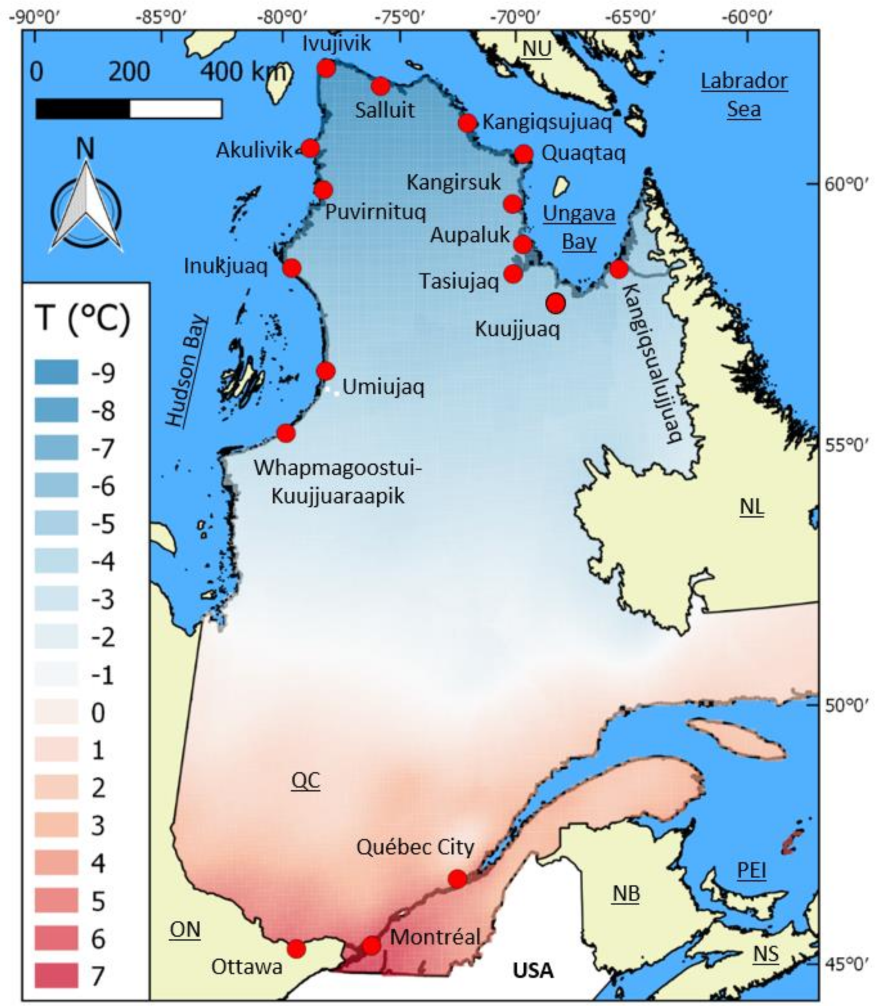

Figure 1 – Mean annual air temperature of all the province of Québec. Inuit-Cree northern remote communities are highlighted in red.

Nunavik is the Inuit territory of the Province of Québec standing north of the 55th parallel, where 14 communities mostly rely on fossil fuels (power plants and furnaces) to produce both electricity and heat (**Figure 1**). Kuujjuaq is the regional capital of Nunavik (Quebec, Canada). The population is 2,668 (2021) and is growing. The average population growth rate was 3.19% per year from 2011 to 2016. Moreover, there are currently about 973 residential dwellings in Kuujjuaq (Statistics Canada, 2021).

The mean annual air temperature in Kuujjuaq is -5.8 °C. The mean underground temperature from -10 to -100 m is about 1°C.

The presence of discontinuous but widespread permafrost is reported in Kuujjuaq (Allard and Lemay, 2012) and its presence is strongly dependent on local geological conditions (Lemieux et al., 2016; Giordano and Raymond, 2019). A temperature profile measured in groundwater Well 18 near the community of Kuujjuaq indicated the potential presence of permafrost at 20 m depth over a thickness of 20 m, but this permafrost layer is not always present below Kuujjuaq (Miranda et al., 2021). For example, no permafrost was detected below the Forum building.

2. GEOLOGICAL SETTING

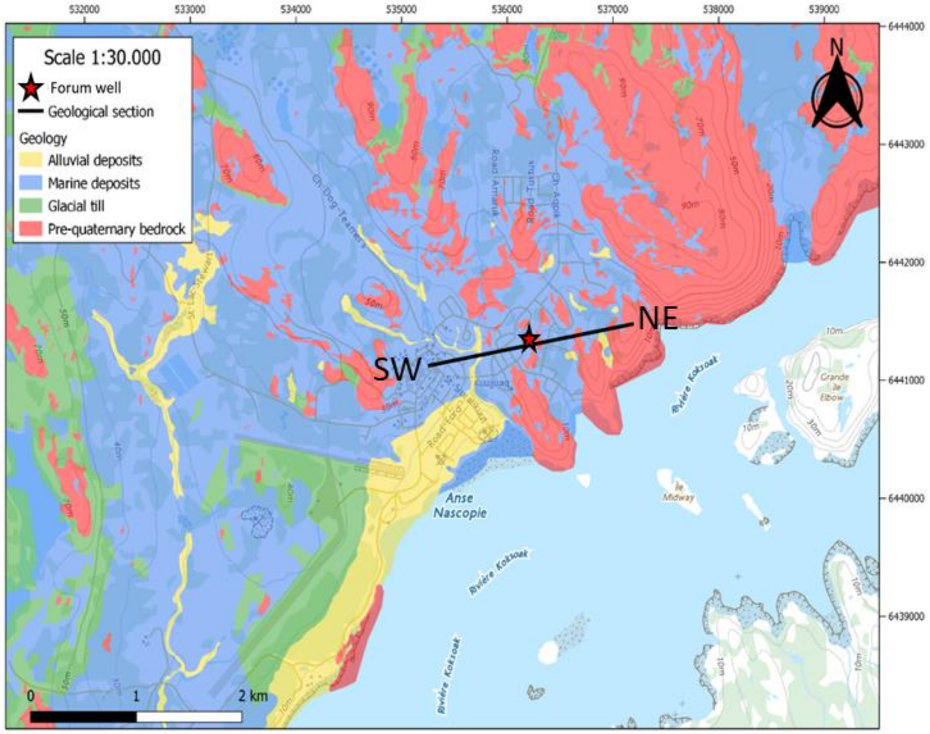

Figure 2 – Distribution of the Quaternary deposits in Kuujjuaq.

At the study site, we can expect to have 1-5 m of quaternary deposits overlying the bedrock. The unconsolidated Quaternary deposits mainly consist of littoral and pre-littoral sediments alternating with intertidal deposits related to different cycles of transgression and regression of the Iberville Sea **(Figure 2).**

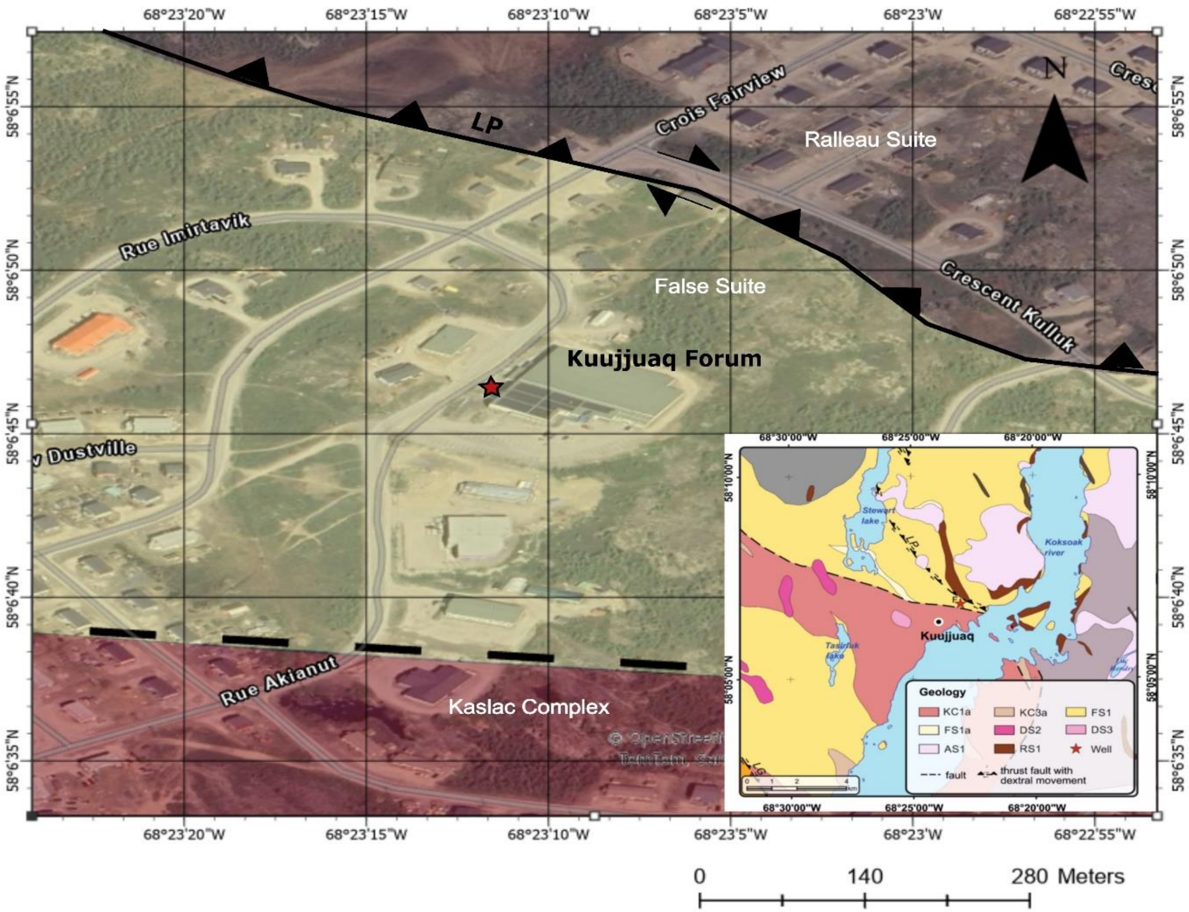

Figure 3 – Location of the Forum well and base map of bedrock geology in Kuujjuaq and the surroundings (Miranda et al., 2020). LP – Lac Pingiajjulik fault.

The main bedrock units present in Kuujjuaq, and the surroundings are diorites and gabbros from Ralleau Suite (RS1) and Kaslac Complex (KC1a) as well as granoblastic paragneisses of the False Suite (FS1) where the borehole was drilled (**Figure 3**).

3. DESCRIPTION OF THE EXPLORATION BOREHOLE

The Forum well is a vertical diamond drill hole. In 2021, the borehole was made until a depth of 240 m and drilling was executed by Avataa Rouiller Drilling using a diamond drill rig with core recovery. This drilling method is not common for GHE installations, so an initial attempt to install GHE failed at that time. The use of rotary drilling, a destructive drilling method, is more common for geothermal borehole. In continuation of the works done in 2021, the 2024 drilling activities were :

- to reenter the above 240 m deep hole;
- to remove the sand plug (S), then deepened the hole to 450 m;
- widened its diameter from NQ to HQ size from the surface to 168 m depth;
- and finally, to purge the well (F).

In the project timeline, the sequence of drilling lasted 19 days that incudes 9 hours of removing the sand followed by well logging and installation of the GHE (**Table 1**).

Project Task 2024	September				October																															November			
	27	28	29	30	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	4	5	6	7
Drilling					S	NQ	NQ	NQ	NQ	NQ	NQ	NQ	NQ	NQ	HQ	HQ	HQ	HQ	HQ	HQ	HQ	HQ	F																
Geophysical logging																								■	■	■	■												
Temperature measurement																													■		■		■						
GHE installation																																				■	■	■	■

Figure 4 – The vertical diamond drill hole next to the mechanical room of the Forum building in Kuujjuaq. B – Removal of the sand plug that was left due to the failure of the first ground heat exchanger installation attempt in 2021.

Several problems were encountered during drilling: the first four days (**Table 1**) were spent figuring out the tank and water supply. The water was delivered by the community's truck, thus depending on the availability of the truck long waits were often recorded, delaying drilling progress. The drilling consumed in average 6000 gallons a day and much more during the hole reaming. The latter operations also experienced some issues. Initially, the widening was planned before the hole was deepened. But due to the delay of delivery of the drilling rods, the driller decided to deepen first, knowing that sending drilling materials by plane to the north is difficult. Besides, the availability of the rods was limited by their condition. The average speed of drilling was about 3 to 45 m per day. A total of 109 hours were spent drilling, including 54 hours of reaming.

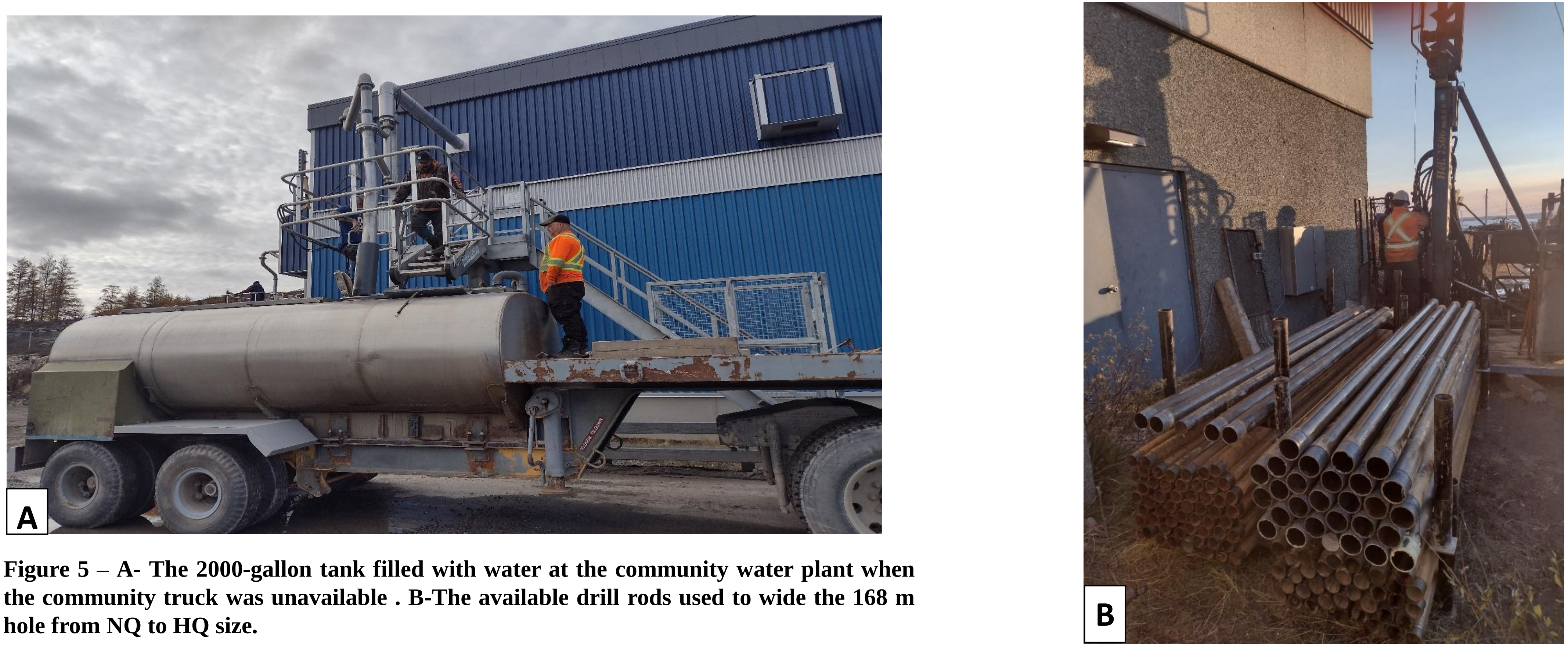

Figure 5 – A- The 2000-gallon tank filled with water at the community water plant when the community truck was unavailable . B-The available drill rods used to wide the 168 m hole from NQ to HQ size.

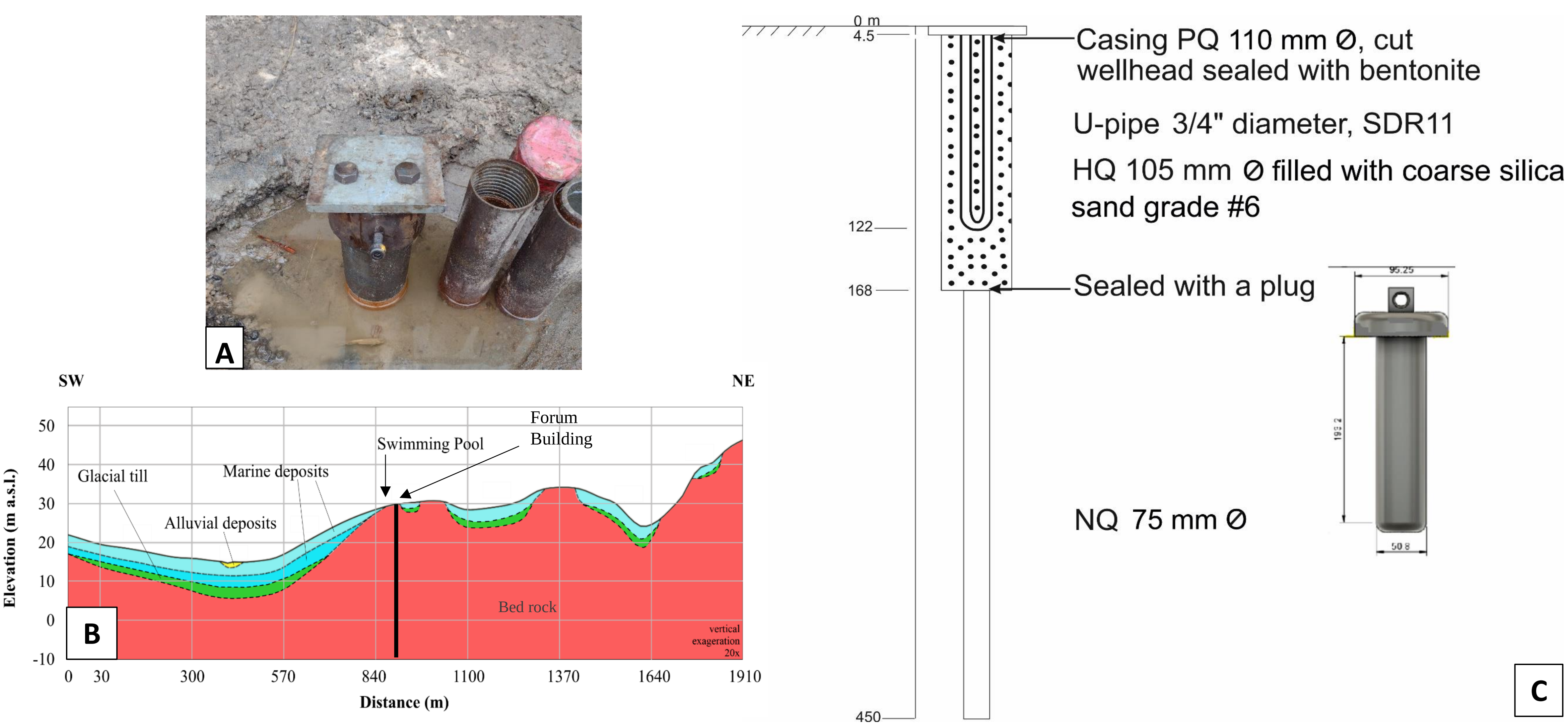

Figure 6 – A-Casing of the well before the GHE installation , B-Cross section near the study site (see Figure 2; Covelli, 2018) showing the location of the Forum well , C-Completion diagram of the 450 m exploration borehole and 122 m ground heat exchanger.

The casing with PQ size is 4.5 m in length and the seal plug was placed before the GHE was installed. The first 168 metres of the well are HQ size, into which the GHE was inserted, and the rest is NQ size.

4. DRILL CORE LOGGING

A total of 219 m of core was recovered from 237 m to 450 m depth in the Forum well, with good rock mass quality estimated for about 93%. The main lithologies are dominated by the alternation of paragneiss and diorite. The paragneiss is porphyroclastic or has augen-plagioclase texture. The diorite is biotite rich with siliceous veins.

The core was examined and about 30 samples were selected for further analysis (**Figure 7A-C**).

A graphical well log illustrating the lithologies was prepared and combined with other geophysical well logs as shown later in the report.

The core orienter REFLEX ACT III™ was used to orient the core. The bottomhole mark (red line) is drawn along the drill core (**Figure 7B**).

The alpha and beta angles were subsequently measured using the protractor (**Figure 7B**) and combined with the waveform sonic log in order to characterized the fracture plans.

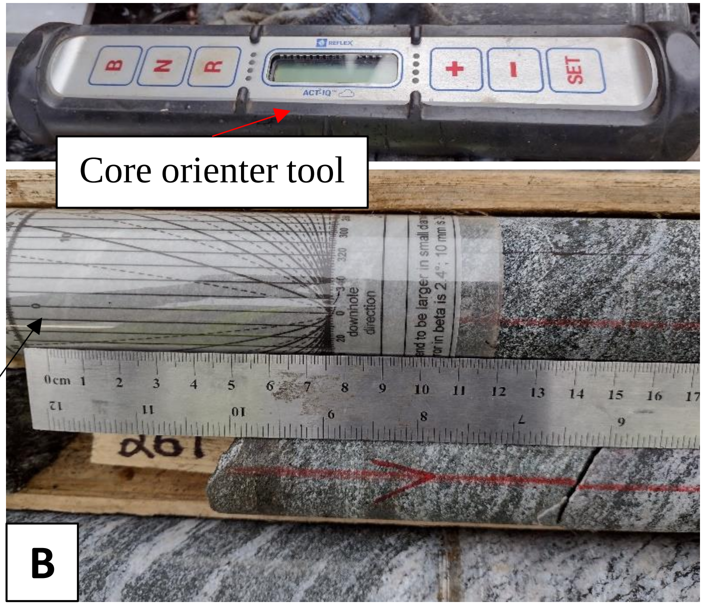

Figure 7 – Geological observation from core logging. A-drilling installation, B- Oriented drillcore C-drillcore sampling.

5. GEOPHYSICAL LOGGING

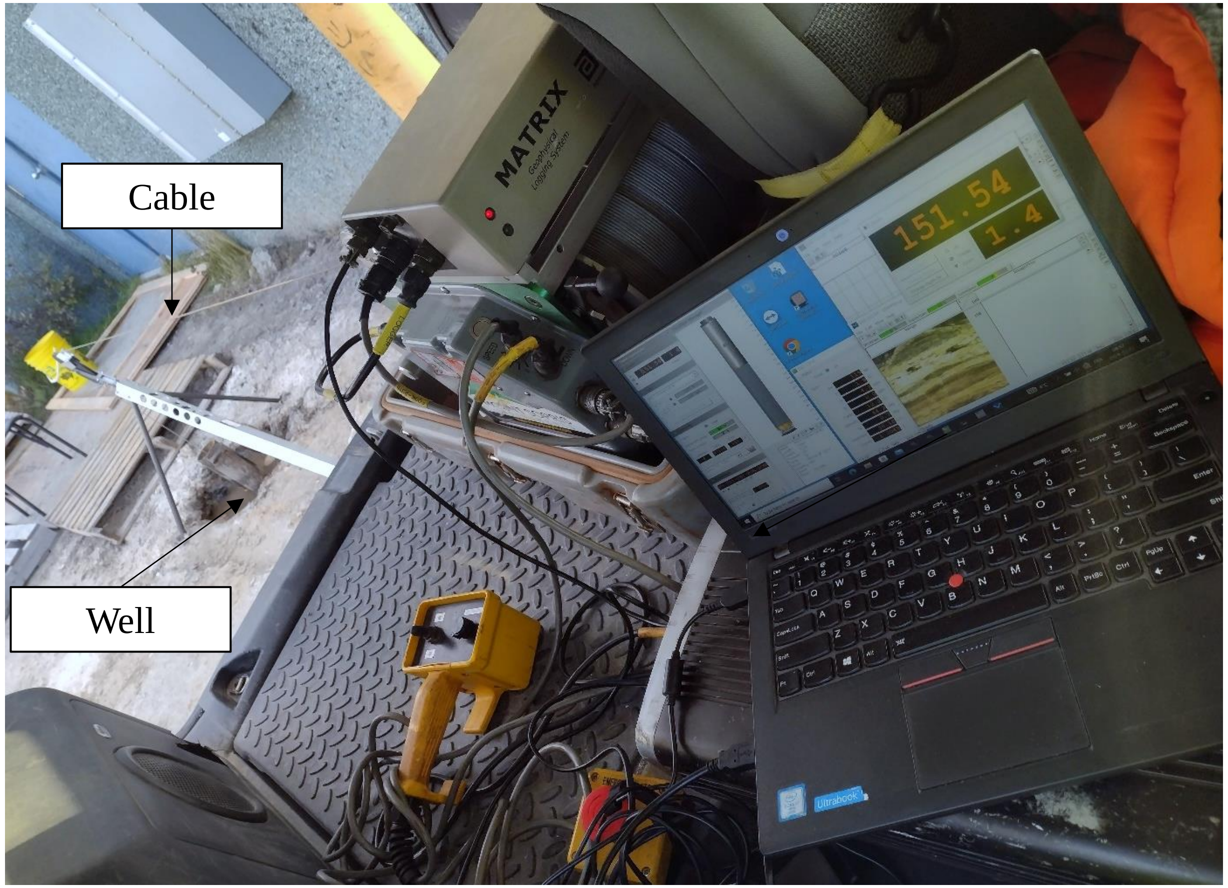

Figure 8 – Geophysical logging acquisition.

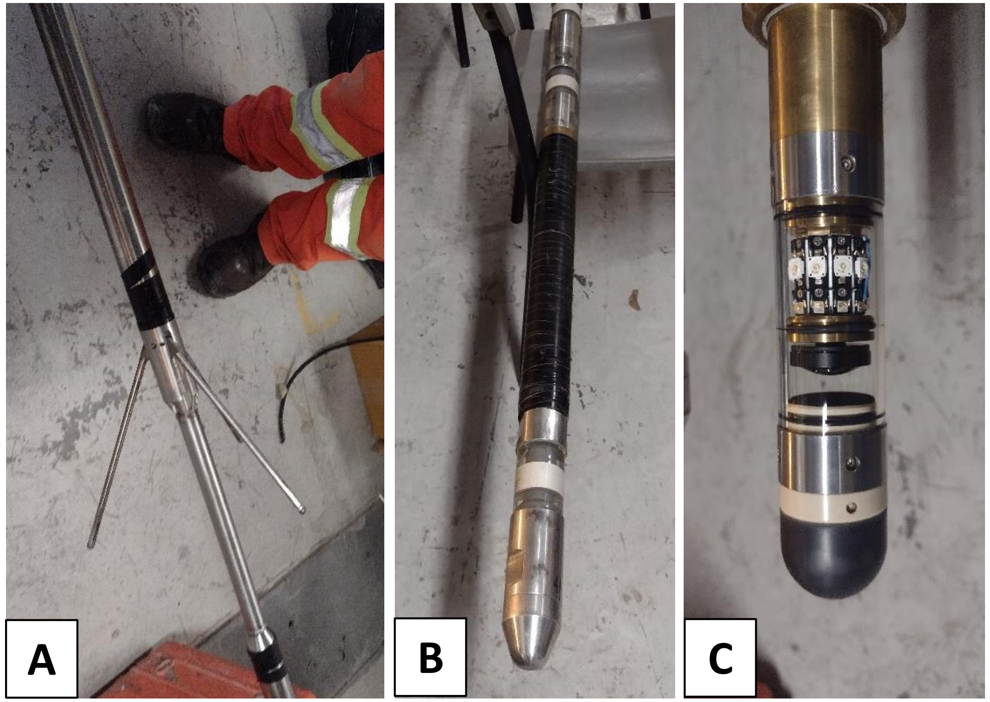

Figure 9 – Geophysical logging tools used for borehole logging. A- Caliper, B- Fluid temperature and electric conductivity FTC, C- Optical borehole imager.

One day after the completion of drilling, logging was conducted during four consecutive days (**Table 1**) using the following suite of tools: Caliper, FTC - Fluid temperature and electric conductivity - Normal resistivity - Full-Waveform Sonic - Optical Borehole Imager (OBI aka OTV) - Spectral Gamma and Acoustic Borehole Imager (ABI aka ATV).

Figure 10 –Temperature depth profile measurement. A-B- cable placed inside well ; C-RBR duet probe.

A RBR Duet probe with an accuracy of ± 0.002 ºC and ± 0.25 m was used to measure temperature depth profiles. The probe was placed in the well 20 minutes prior to the start of the recording to ensure thermal equilibrium between the probe and the groundwater in the well. Profiles were taken at a continuous temperature logging rate of about 1 m/10 sec, with the probe left for 10 minutes at every 50 m to calibrate the pressure sensor for depth. Three profiles were measured 10 days after completion of drilling. Measurements were taken every two days (**Table 1**).

6. GROUND HEAT EXCHANGER DESCRIPTION

In order to extract heat from the subsurface, a High-Density Polyethylene (HDPE) U-pipe has to be inserted in the well to convert the borehole into a GHE. The pipes are then connected to the heat pump allowing heat transfer between the ground and the building.

The current technical temperature limit of commercial heat pumps is near -7 °C. This means that a mixture water/antifreeze (e.g., 30 % of propylene glycol, freezing point -14 °C) is able to extract heat from a medium that is at a temperature near or below 0 °C. As shown later in the report, the average ground temperature T_0 measured in the Forum well and unaffected by seasonal variations is 1.5°C for a depth of 0 to 122 m, therefore hot enough to operate a heat pump system.

Géotherma Solutions Inc. estimated in its 2022 evaluation that a 145 m GHE can provide a minimum instantaneous thermal power of 6.76 to a maximum of 7.99 Wm^{-1} and a yearly average energy supply of 8.59 to 10.15 $MWh.y^{-1}$, which can be sustainably extracted over a 30-year period.

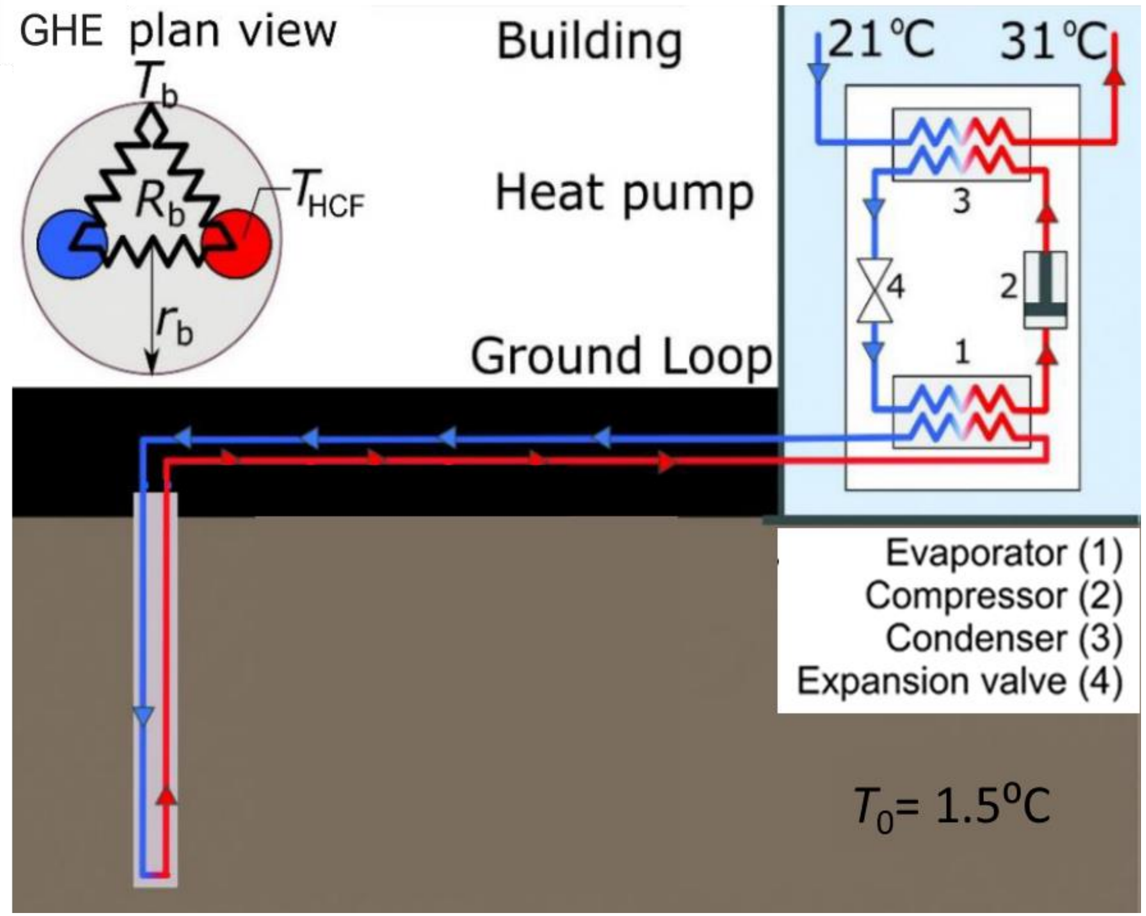

Figure 11 –Conceptual model of a vertical closed-loop ground heat exchanger and heat pump in heating mode. T_b and T_{HCF} are the temperature at the borehole wall and that of the heat carrier fluid, respectively, and R_b and r_b are the borehole thermal resistance and radius, respectively (modified from Raymond, 2018).

7.WELL LOG RESULT

With the description of the 219 m recovered oriented cores presented in **Appendix I**, the lithological well log from Miranda et al. (2022) report was extended to a depth of 450 m (**Figure 12**).

For the first 234 m , the paragneiss is the dominant lithology and is intersected by minor intrusions of mafic (diorite/gabbro) and felsic (tonalite/granite/granitoid) intrusive rocks. The average natural fracture intensity evaluated along the core is 0.96 fractures m^{-1} for a borehole that had a depth of 234 m (Miranda and et al. 2022). From 237 m to 450 m depth, the diorite becomes dominant and most of the fractures are believed to be induced by the drilling. The stick plot is a simple log that shows the location (i.e., depth) of each fracture intersected along the borehole. The stick plot provides a qualitative interpretation of the spatial arrangement of fractures, allowing qualitative identification of fracture clustering (**Figure 12**). The distinction between natural and induced fractures as well as their aperture will be better characterized with the sonic and acoustic tests.

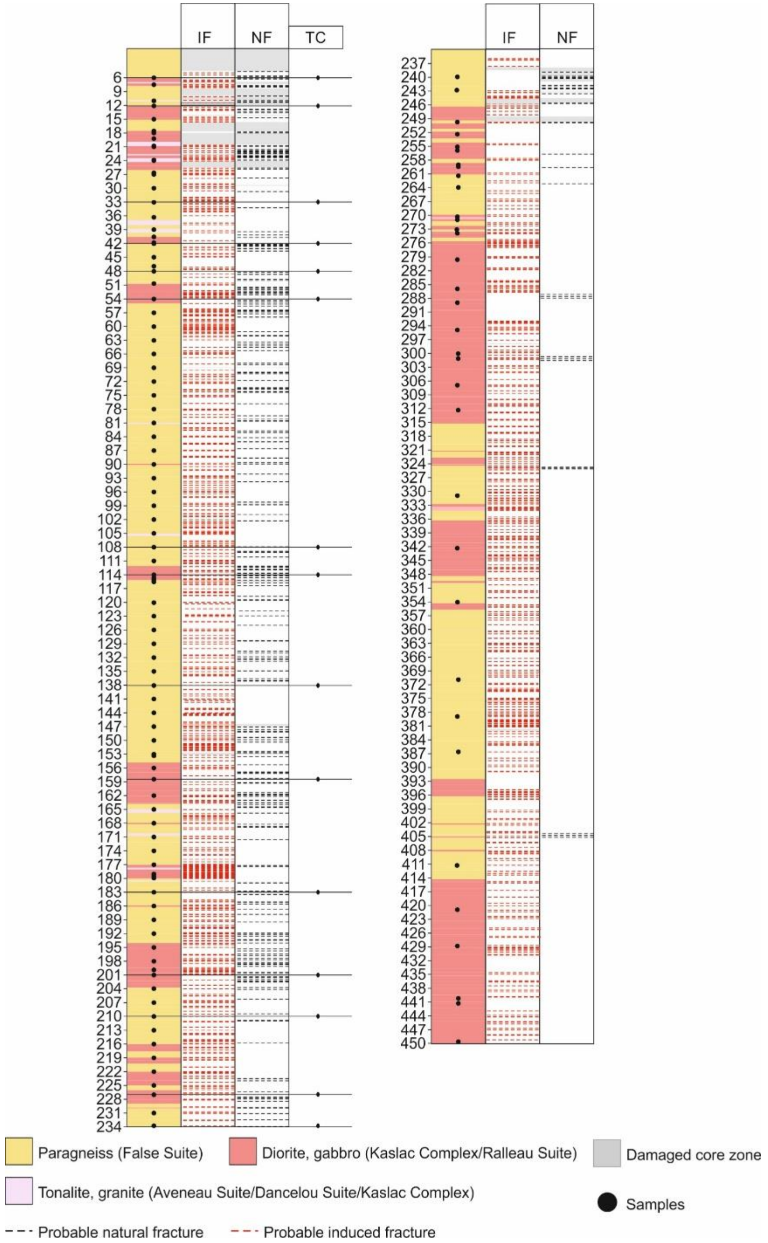

Figure 12 –Lithological well log. The stick plots produced for both induced (IF) and natural fractures (NF), the samples selected for thermal conductivity analysis (TC). Refer to Miranda et al. (2022) for full details of core analysis for the first 234 m depth.

8.GEOPHYSICAL LOGGING RESULTS

The geophysical logging results in **Figure 13** display selected logs giving an overview of the important information along depth. This includes the normal resistivity log which shows a significant decrease from 320 m depth, while the electrical conductivity of the fluid shows a significant increase close to 10000 uS/cm from 350 m. The fluid temperature is comparable to that measured with the RBR Duet probe. The caliper confirms the diameter size of the PQ, HQ and NQ sections. Finally, the spectral gamma ray log displays a significant contrast between depths of 0-245 m and 245-405 m. The 3D optical televiewer provides a good overview of the color contrast between the paragneiss, and the diorite rocks intersected along the borehole. Full and detailed results will be reported in a separate document prepared by Université Laval.

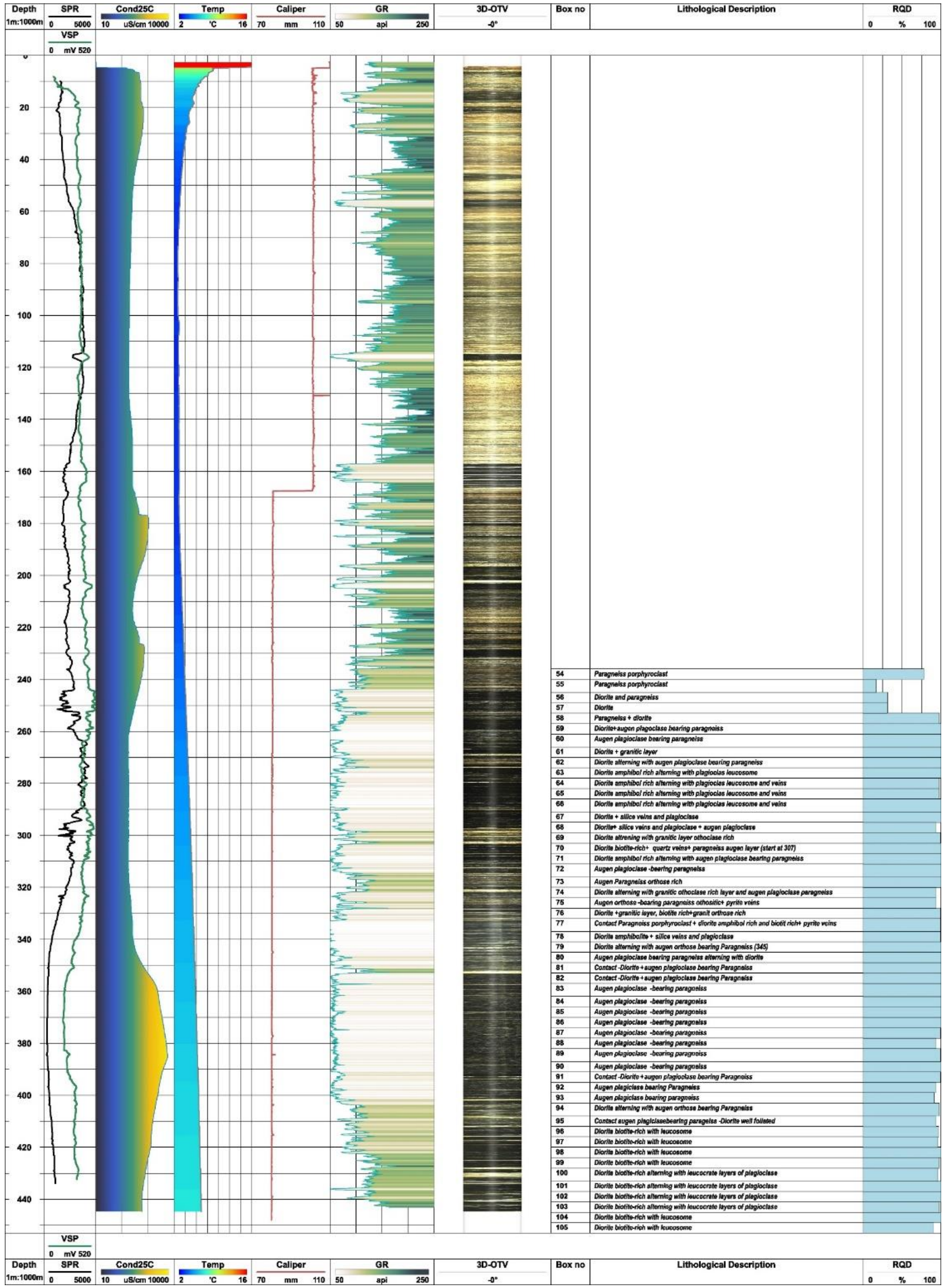

Figure 13 –Geophysical well logs

9. GEOTHERMAL GRADIENT ASSESSMENT

The water level is at 5.35 m depth below the ground surface. The Horner temperature shown by the black curve (**Figure 14**) is the temperature corrected for borehole friction and assumed to be in equilibrium with the subsurface temperature. With the Horner correction, the temperature ranges from a maximum of 7 °C at 10 m, to a minimum of 1 °C at a depth of 105 m. The well appears to show evidence of inflow at 110 m where the temperature increases to 1.3 °C. Then there is a linear increase of temperature below 125 m. For the operation of a heat exchanger, the average temperature over the depth equivalent to that of the U-pipe is 1.5 °C.
A Paleoclimate correction was used to assess the deep geothermal gradient. The equilibrium geothermal gradient is 19.7 °C km^{-1} evaluate at depth from 125 m to 433 m after correcting the temperature profile for both drilling- and paleoclimate-induced thermal disturbances (**Figure 14**).

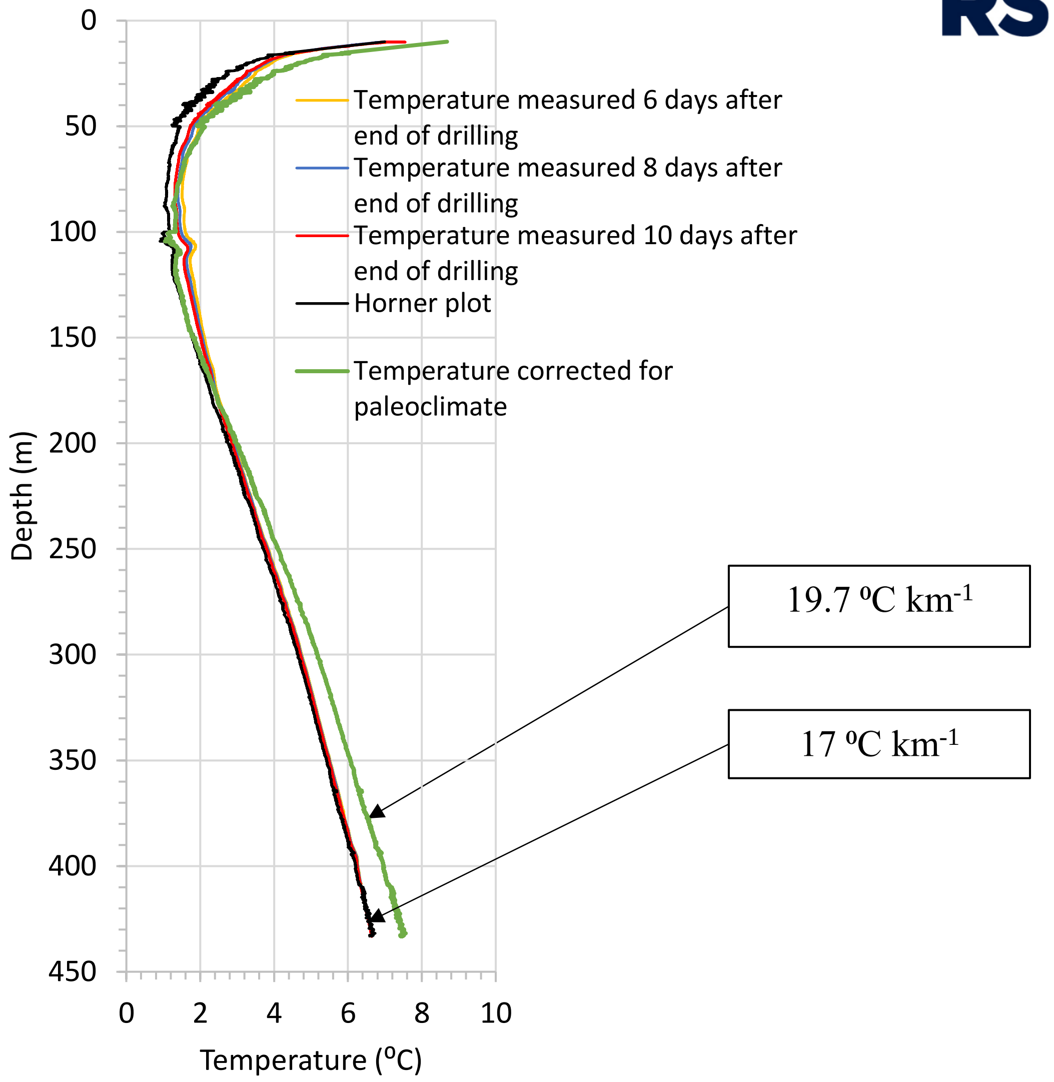

Figure 14 –Temperature profiles and geothermal gradient calculated.

10. GROUND HEAT EXCHANGER INSTALLATION

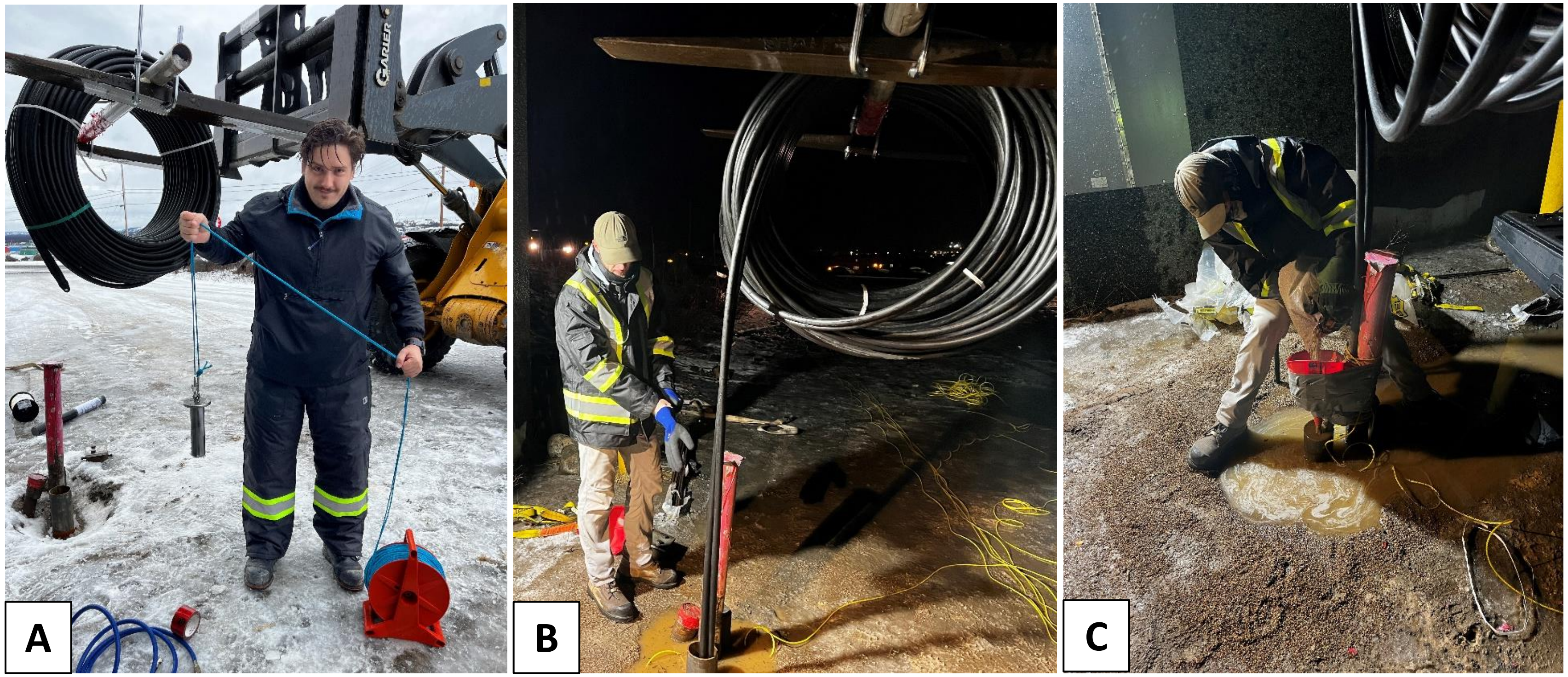

Figure 15– Vertical ground heat exchanger installation. A-A plug was inserted at the bottom of the NQ hole prior to B-the U-pipe installation, which occupies the 122 m depth of the upper part of the well , C-then the borehole was backfilled with coarse sand. Credits Induktion Géothermie.

A plug was designed to be placed at the bottom of the HQ section of the well (**Figure 6C** and **Figure 15A**) because the lower part with the NQ size of the well was only used for geophysical well logging. Then, the U-pipe (3/4" diameter, SDR11) was put into the upper portion of the borehole until a depth of 122 m (**Figure 15B**). This latter was backfilled with grade#6 coarse silica sand (**Figure 15C**). The U-pipe is to convert the borehole into a ground heat exchanger that will be connected to a heat pump. The U-pipe length is shallower than the borehole because of the difficulty of installing the pipe (**Figure 6C**).

The soil was excavated to an average depth of 1.2-1.5 m (**Figure 16A**) to bury the horizontal extension of the U-pipe leading to the mechanical room. The steel casing was cut, and the pipe was fused (**Figure 16B**).

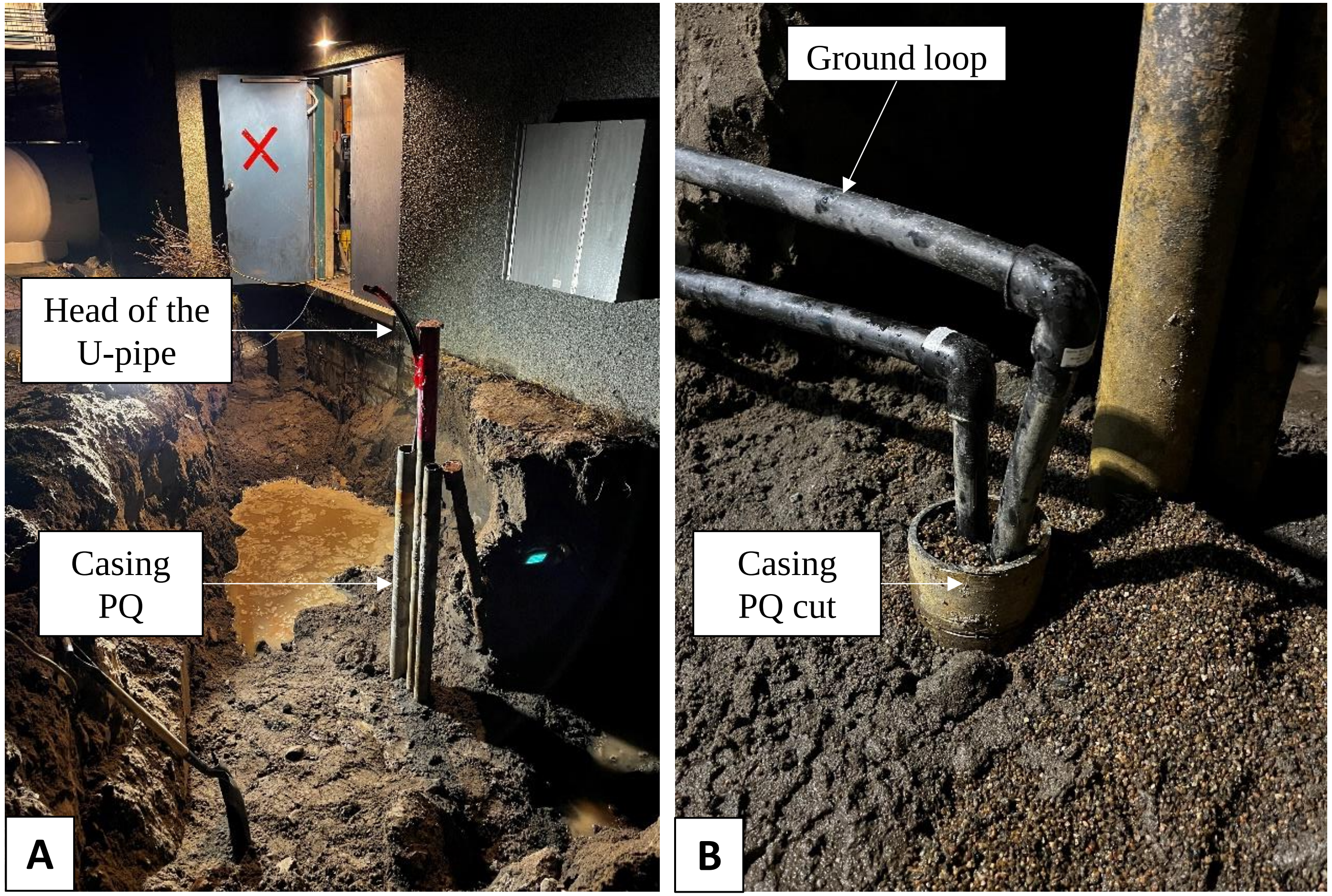

Figure 16 –Ground heat exchanger installed in front of the Forum basement where is the mechanical room entrance. A- Excavation of the soil, B- Connection between the head of U pipe and to horizontal pipes (IN and OUT of loop) extension. Credits Induktion Géothermie.

Since the diameter of the borehole was unconventional for geothermal drilling, it was not possible to obtain well seals like those commonly used in the south of Quebec. The bentonite therefore acts as a plug to seal the well head and the trench is insulated with rigid insulating panels (**Figure 17A**).
Because the borehole is at Forum basement level, the pipes could therefore not enter the mechanical room under the floor slab, as a frost wall was present.
In such circumstances, it is possible to bring the pipes out of the ground. However, to prevent the heat transfer fluid from freezing, an insulation box must be installed at the pipe entry point (**Figure 17 A**).

In **Figure 17B**, the hole was drilled through the foundation so that the pipe enter the mechanical room ready to be connected to the heat pumps.

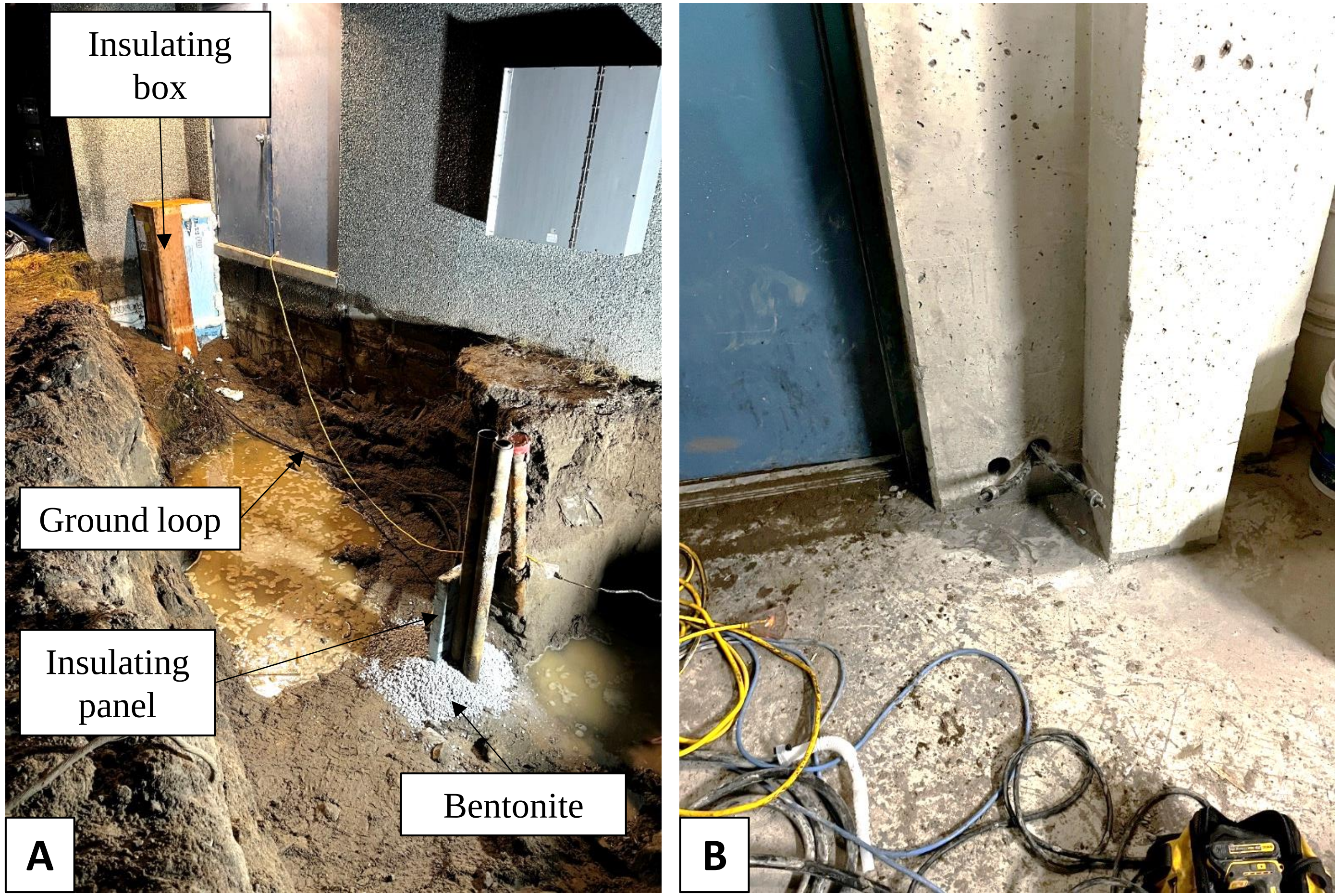

Figure 17 – A- The insulation box protects the U-pipe (IN and OUT loop) entering the basement mechanical room and the bentonite covers the connection between the head of the U-pipe and the horizontal pipe, B- U-pipe (IN and OUT loop) ready to be connected to the heat pump. Credits Induktion Géothermie.

IV. CONCLUDING REMARKS AND RECOMANDATIONS

Despite the high cost of drilling in Nunavik and the lack of expertise in geothermal heat pump system installation, this pilot project aimed to demonstrate the viability of geothermal energy in subarctic regions of Canada, from drilling to the operation of the heat pump system.

This first borehole heat exchanger was installed in Kuujjuaq (Nunavik, Canada) in the Fall 2024 in order to connect a heat pump that will heat office spaces in the Kuujjuaq Forum building. Drilling is a critical step before any geothermal system installation and represents the most expensive part of the installation budget. Knowing that the water supply in the remote Kuujjuaq region is prioritized for community use, the drilling company should use a water recycling system to reduce its water consumption. A full-scale geothermal heat pump system would require dozens of boreholes, and the destructive drilling would be more efficient than diamond drilling, which is more appropriate when core recovery is needed.

By extending the depth to 450 m, the calculated geothermal gradient is 19.7 °C km^{-1}, which is similar to that obtained previously when the well was drilled to 240 m (20.9 °C km^{-1}). The selected core samples will be analyzed for their thermal properties in order to calculate the heat flow. Inventoried fractures on drill cores combined with sonic test logging will better characterize fracture networks.

An experimental heat pump system is planned to be installed in March 2025. Geothermal energy extracted from the ground could provide a reliable heating source that can be combined with photovoltaic solar panels to decarbonize northern community buildings.

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APPENDIX I - core

Figure A1.1. Core box #54 -#58 – drilling depth 237-255 m.

Figure A1.2. Core box #59 -#63 – drilling depth 258-276 m.

PS: the Box #64 was skipped by the driller but the depth is correct

Figure A1.4. Core box #65 -#69 – drilling depth 285-303 m.

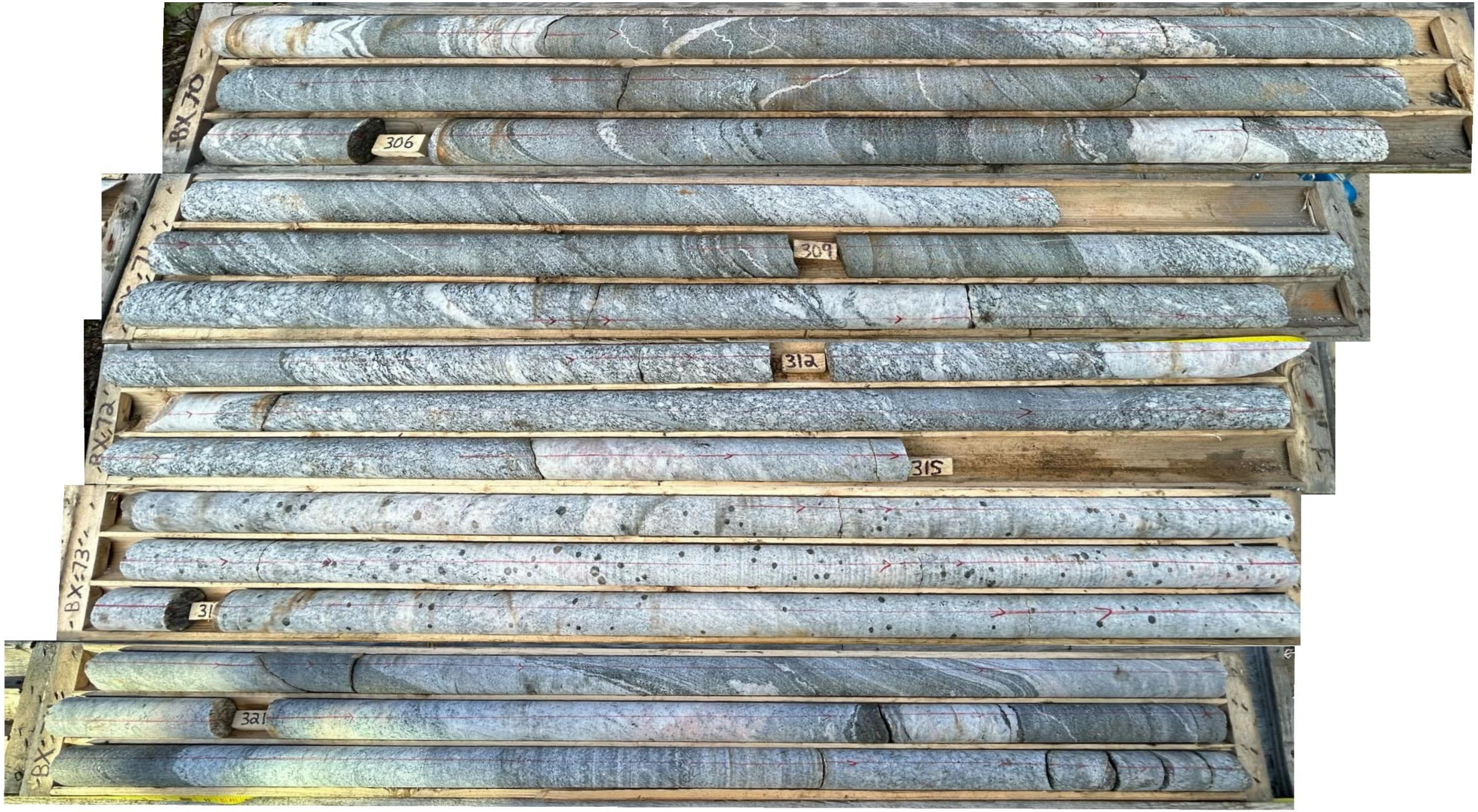

Figure A1.5. Core box #70 -#74 – drilling depth 306-321 m.

Figure A1.6. Core box #75 -#78 – drilling depth 324-339 m.

Figure A1.7. Core box #79 -#82 – drilling depth 339-354 m.

Figure A1.8. Core box #83 -#87 – drilling depth 360-378 m.

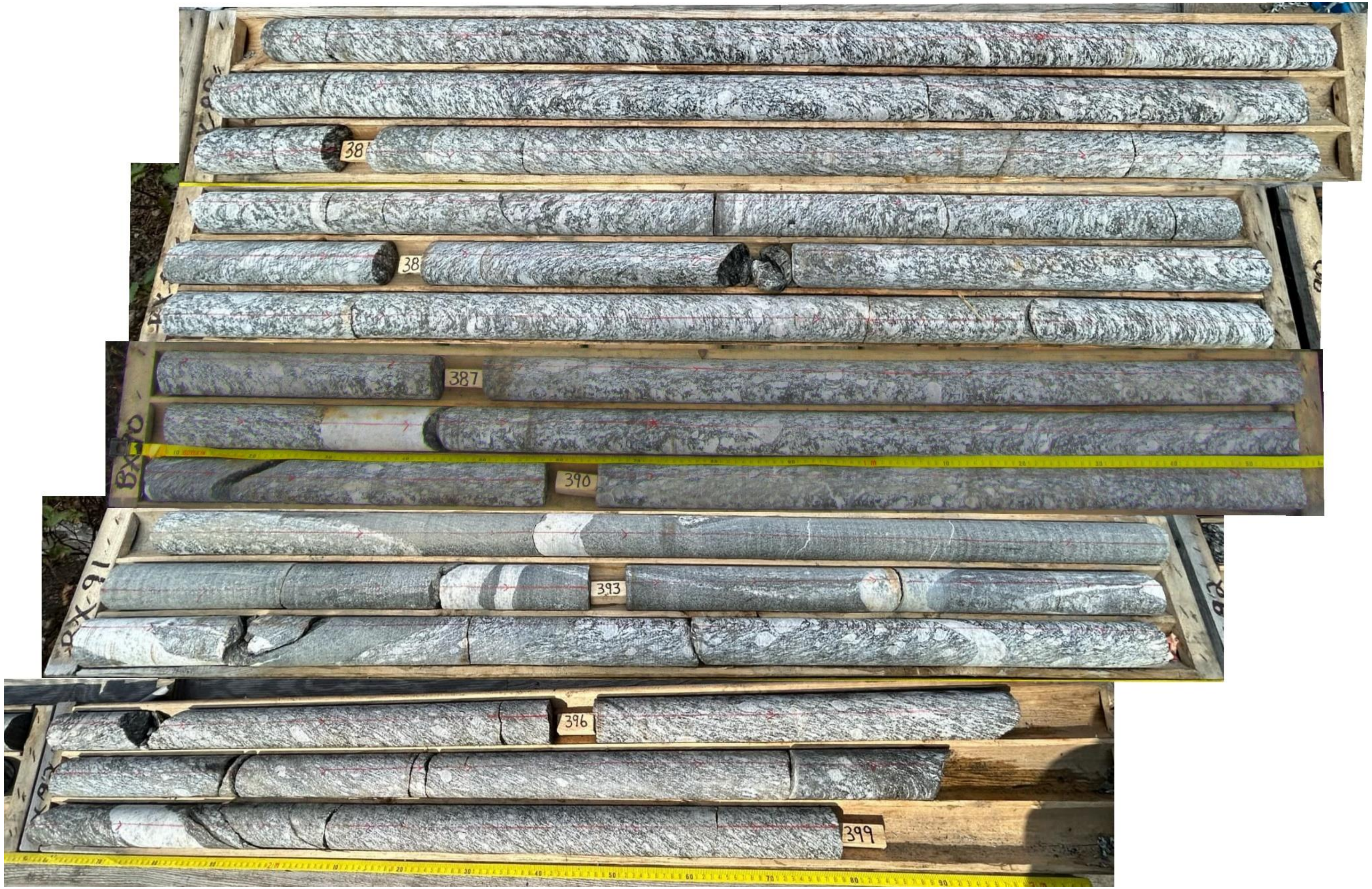

Figure A1.9. Core box #88 -#92 – drilling depth 381-399 m.

Figure A1.10. Core box #93 -#97 – drilling depth 402-417 m.

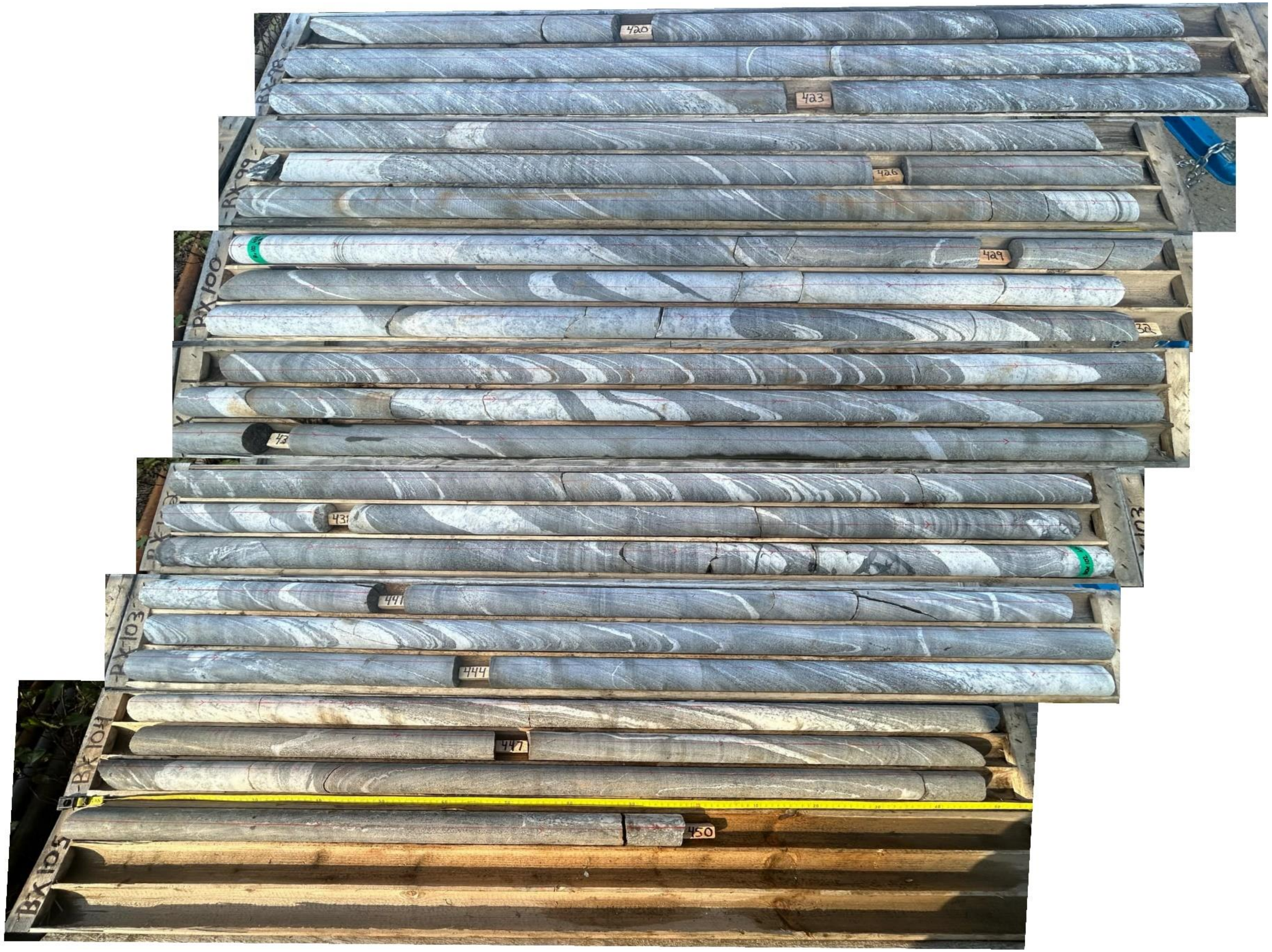

Figure A1.11. Core box #98 -#105 – drilling depth 420-450 m.