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Re-evaluating Geothermal Potential in Resolute Bay, Nunavut: Implications for Energy Resilience in Canada's High Arctic

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INTRODUCTION

Given the harsh and extreme cold conditions of Arctic Canada, energy demand presents significant economic, environmental, and social challenges. Energy needs are typically met by expensive seasonal shipments of diesel and heating oil, by truck, ship and aircraft. Development of renewable, resilient, and reliable on-site energy solutions is required. Here we focus on one such community, Resolute Bay, Nunavut.

The second northernmost community in Canada, Resolute Bay is located on the southwestern tip of Cornwallis Island, Nunavut (Fig. 1). The remote community of < 200 residents has no road linkage to the south. Resolute Bay's annual heating load is reported at 5690 MWh (Miranda et al., 2023), which is moderate-low energy usage for a northern Canadian/remote community, and electricity demand is approximately 4500 MWh, both currently met with imported heating oil/diesel. The high latitude location experiences 24 hours of darkness for 89 days/year, and this coupled with common overcast conditions, results in a 29.4% possible annual sunshine rating, ranging from 0 to 41.4% monthly, greatly limiting solar energy potential. The mean annual air temperature of −15.1 °C (monthly means of −31.4 to +4.9 °C) also creates issues, such as icing of windmill blades and limits the efficiency of battery packs required to stabilise intermittent renewable power sources at low temperatures. Alternative renewable energy solutions are required to meet decarbonisation goals.

Resolute Bay has been identified as an area of higher thermal gradients based on shallow permafrost research wells (Misener, 1955). These observations have driven interest in examining geothermal potential to reduce the community's carbon footprint and address food insecurity through greenhouse heating (Kinney et al., 2019; Minnick et al., 2018; Miranda et al., 2023). We examined the geothermal resource potential to assess the feasibility of such development.

1 METHODS & RESULTS

1.1 Geologic setting

Cornwallis Island is underlain by Paleozoic strata deposited on the Franklin Margin, reaching >5 km thickness under Resolute Bay (Harrison, 2018). Unnamed Cambrian sandstones and shales are overlain by a thick succession of Cambrian to Upper Ordovician shallow water shelf and platform carbonates and evaporite units. Cornwallis Island is located within the Cornwallis fold belt, created by Late Silurian east-west compression that resulted in north-south oriented faults and anticline-syncline pairs. In the Late Devonian, the Ellesmere Orogeny compressed the region from north to south and created east-west oriented structures. The community of Resolute Bay is positioned between the Resolute Bay Syncline to the west and the Resolute Anticline to the east. Small faults and a small local anticline have been mapped near Resolute Bay. A petroleum exploration well drilled 3 km southeast of Resolute Bay 'Lobitos et al. Cornwallis Resolute Bay L-41' intersected 1475.2 m of Allen Bay Formation, Irene Bay Formation, Thumb Mountain Formation, and Bay Fiord Formation sediments.

During the Last Glacial Maximum ice load depressed Cornwallis Island. Rapid warming-initiated melting around 10,300 BP (Dyke, 1999; England et al., 2006) and postglacial isostatic rebound led to a relative sea level drop, as observed by raised beach terraces around Cornwallis Island. Land emergence initiated at least 9700 BP, with the highest well-developed marine strandlines situated 105 m vertically above modern sea level (Washburn and Stuiver, 1985).

Core and outcrop measurements were used to characterize the rock properties of the nine geological formations beneath Resolute Bay. Well log derived data was also used to derive shale volume (Vsh), total porosity (PHIT),

effective porosity (PHIE), and, where available, core-based permeability (Kmax) and porosity to support subsurface characterization.

Average shale volume varies across formations, ranging from 2% in the Baumann Fiord Formation to 55% in the Irene Bay Formation. Higher shale content in formations like the Irene Bay reflects the presence of mudstones interbedded with the carbonates, which reduces reservoir quality by decreasing both porosity and permeability. Average total porosity ranges from 0.9% in the Baumann Fiord Formation to 4.5% in the Irene Bay Formation. However, higher total porosity does not necessarily translate to reservoir-quality; the Irene Bay Formation, despite its high PHIT, shows a low average effective porosity of only 0.7% due to its elevated shale content. The Christian Elv Formation, despite its low shale volume (3%), exhibits a PHIT of 1.4% and an average effective porosity of just 0.2%, suggesting limited pore connectivity. The highest average effective porosity is observed in the Allen Bay Formation (1.9%), while several formations show values below 1%, indicating limited pore connectivity and storage potential.

Matrix and fracture permeability measurements collected from slabbed core and hand samples using a handheld air permeameter offer a further indication of reservoir potential. However, they may significantly overestimate permeability as elevated stress, temperature, and fluid properties reduce effective permeability under reservoir conditions. Measured matrix permeability across the studied formations was generally low (< 1 mD (the lower detection limit of equipment used) to a maximum of 300 mD), consistent with the expectation for tight carbonates and shale. The Bay Fiord Formation has the highest permeability, but this is attributed to evaporite-rich intervals with high dissolution rates near the surface creating secondary pore space. These salts would likely become extremely tight and sealing under subsurface conditions. Excluding the Bay Fiord Formation, the highest matrix permeabilities were observed in the Irene Bay Formation, ranging from 35 to 170 mD, likely due to microfractures along bedding planes within shale and lime mudstone. Christian Elv Formation exhibited more modest matrix permeability, between 4 and 13 mD, while Cass Fjord ranged from 1 to 10 mD. The Eleanor River Formation showed slightly elevated but more variable matrix permeability, from 1 to 55 mD, reflecting localized heterogeneity.

The well history report for Resolute Bay L-41 records lost circulation zones at 544–558 m and 852–863 m within the Allen Bay Formation. The zones of lost circulation, particularly the deeper of the two, are associated with facies transitions within the Allen Bay Formation. In both cases, changes in lithology and/or diagenesis likely contribute to the loss of circulation, and there is additional potential for fracture development along these boundaries.

Analysis of regional lineaments on Cornwallis Island reveals a distinct conjugate fracture system with dominant NW-SE (~135°) and SW-NE (~45°) trends (Fig. 2A). Field measurements from outcrops of the Eleanor River Formation in the northwest central dome complement the remote sensing results, with 22 fracture directions and 112 spacing measured across four sites yielding an average fracture spacing of 0.43 m. Outcrop-scale fracture measurements provide ground-truth validation, showing a prominent NW-SE fracture set consistent with the regional trend (Fig. 2B). A second dominant, near north-south set observed at the outcrop may reflect localized fractures resulting from the strike-slip reactivation driven by the Ellesmerian compression or uplift of the central dome diapir. Together, these datasets demonstrate that Cornwallis Island hosts a complex fracture system that likely dominates fluid flow.

1.2 Thermal Gradients

Regional geothermal gradient data for the Canadian Arctic Archipelago, derived from petroleum well records (Chen et al., 2010) show a wide variation, with a 40 °C temperature range at 2000 m depth, most likely reflecting error in petroleum well data. A linear regression of temperature versus depth yields an average geothermal gradient of 23 °C per km for the Canadian Arctic Islands, with an r^2 value of 0.92.

Two petroleum exploration wells were drilled on Cornwallis Island: Resolute Bay L-41 (1.7 km east of Resolute Bay), and Cornwallis Central Dome K-40, 52 km north of Resolute Bay. Well history reports provide access to historic data, including BHT and DST records. We also examined data from five nearby exploration wells to obtain more depth-temperature data. A best fit line through the temperature data from local petroleum wells suggests a thermal gradient of 24.2 °C/Km (Fig. 3A).

A detailed temperature log taken after drilling, from 30 m below surface to the bottom recorded temperatures of ~+40 °C near the surface that then declined downhole (Fig. 3B). We discount the upper portion of the log as the well history report indicates that operators circulated 75 °C drilling mud through the hydril to avoid freezing

during drilling, explaining the anomalously high surface temperatures. The reported BHT of Resolute Bay L-41 (40 °C at 1473.6 m) was measured using a maximum-temperature recording thermometer, which is designed to record the highest temperature encountered – assumed to be at the bottom of the hole. However, we assume that the reported BHT reflects temperatures at the top, rather than at the bottom, of the well. A linear fit to the temperature–depth relationship for the lower part of the log provides a geothermal gradient of 14.9 °C/km.

Three subsequent logging runs were conducted in the upper portion of the well. These logs provide temperature measurements after thermal re-equilibration showing an average geothermal gradient of 20.2 °/km within the permafrost zone. Permafrost monitoring wells were also drilled 2.5 km from Resolute Bay. Misener (1955) showed that thermal disturbance of the well bore was re-equilibrated after 1 year and measured a near surface thermal gradient of 39.4 °C/km within the zone of permafrost. Initial heat flow estimates, calculated from the 39.4 °C/km thermal gradient of, were 121 mW/m^2. However, these wells were spudded on ground that was below the Holocene sea-level maximum, as defined by raised beach terraces. Emergence of shoreline due to glacio-isostatic rebound changed surface conditions from subsea (near 0 °C) to subaerial (mean annual air temperature of −15.1 °C), with a resultant propagation of a cold front into the ground. The net effect of glacial rebound was to produce an apparent transient thermal gradient much higher than it would be in equilibrium. The Resolute Bay temperature logs were reanalysed to account for the impact of post-glacial emergence on shallow thermal gradients (Lachenbruch, 1957). The steady-state correction of the thermal gradient was 25.5 °C/Km

In summary, the BHT and DST data from Resolute Bay L-41 DST are likely erroneous. We take the lower geothermal gradient of 14.9 °C/km from the detailed log of Resolute Bay L-41 as the most reasonable and conservative estimate but recognise potential for higher geothermal gradients similar to the regional average, taken as the Curie Point gradient (22 °C/km).

1.3 Thermal Properties

Thermal conductivity values were derived from 181 core-based measurements supplemented with published data where core was not available. Average thermal conductivity values for the geological formations beneath Resolute Bay vary considerably, reflecting differences in lithology and mineral composition. The Christian Elv Formation exhibits the highest measured thermal conductivity at 4.9 W/m K, based on core from the Sabine Bay A-07 well, closely followed by the Baumann Fiord Formation at 4.8 W/m·K (lithology-based estimate; Dalla Santa, 2020) and the Eleanor River Formation at 4.5 W/m·K, also derived from core at Sabine Bay A-07. These higher values are typical of anhydrite and dense, clean carbonate units. In contrast, the Cass Fjord Formation has the lowest measured conductivity at 2.4 W/m·K, based on core from the Cornwallis Central Dome K-40 well. Similarly, relatively low values are proposed for the Irene Bay Formation (2.8 W/m·K) and Cape Clay Formation (3.1 W/m·K), both estimated from lithology (Dalla Santa, 2020), which reflect increased shale or mudstone content. Intermediate values were observed in the Thumb Mountain Formation (3.2 W/m·K), Allen Bay Formation (3.7 W/m·K), and Bay Fiord Formation (3.7 W/m·K), determined from core in various wells. Overall, the range of thermal conductivity values spans from 2.4 to 4.9 W/m·K, with the majority of formations exhibiting values between 3.0 and 4.5 W/m·K, consistent with variably compacted carbonate and mixed siliciclastic compositions.

Heat generation was calculated from gamma ray log data. As is typical for sedimentary rocks the heat generation values are low, ranging from 0.15 to 1.9 μW/m^3 throughout the stratigraphic sequence. Regional stratigraphy suggests that deeper strata include thick Cambrian clastic sediments, which would be expected to have similarly low heat generation. Underlying basement is represented by Canadian Shield, largely metamorphosed granite. While heat generation values are sparse for the Canadian shield, they typically range from 0.2 μW/m^3 to 3.0 μW/m^3 with an average of 0.8 μW/m^3.

2 DISCUSSION & CONCLUSION

Given generally low thermal gradients (~15-20 °C/km) in the Resolute Bay area we consider the potential for electrical generation limited. Depths > 5 km would be needed to reach suitable temperatures for even low efficiency generation (at least 75 °C for a binary system). The Resolute Bay area though does have two main loci of heat demand. One is the community itself, and the second is facilities at the airstrip ~ 5 km from the community (Fig. 1). Based on this and the geothermal conditions present at Resolute Bay we consider two potential resource plays for direct heat use: 1) conventional open hole system that could be drilled vertically in one or both locations (the distance is too great to transport thermal waters between them at surface); and 2) U-shape closed-loop geothermal connection between the locations in the subsurface. Shallow heat pump systems are not considered at this point because of the permafrost influence on the facility stability.

Based on the conservative 14.9 °C/km geothermal gradient derived from Resolute Bay L-41, a conventional geothermal system would have to reach depths between 1800–2500 m to obtain temperatures between 20 and 30 °C, or beyond 3000 m for temperatures > 40 °C. Stratigraphic correlation of the Resolute Bay area indicate that at the lower temperature range, the Eleanor River Formation would be intersected, followed by the predominantly evaporite Baumann Fiord Formation beyond ~1900 m. Penetration beyond ~3000 m would intersect the limestone and shale of the Cass Fjord Formation. For a conventional open hole geothermal system, the Bay Fiord Formation offers the highest porosity with zones of up to 10% PHIE whereas the deeper Eleanor River Formation would have reduced porosity of 1.5%. This may provide sufficient thermal resources for direct heat use assuming adequate production volumes could be achieved. While greenhouse heating has been modeled for Resolute Bay by Kinney et al. (2019) the geothermal gradient they use (35 °C/km) is significantly higher than what we demonstrate here. We also demonstrate that the very low permeability of the carbonate mudstones would greatly reduce potential production rates, unless fracture systems are intersected. Deeper wells penetrating the Baumann Formation evaporites would not be productive and even deeper wells would likely be too excessive to consider direct heat use with current technologies.

As an alternative to conventional systems, closed-loop geothermal (Yuan et al., 2021; Yuan et al., 2023) provides an interesting alternative for geologic settings with low porosity/permeability reservoirs. For these systems the thermal conductivity of the rock becomes a key parameter influencing system efficiency. In the case of Resolute Bay, the carbonate dominated stratigraphy generally has low thermal conductivity. However, the Early Ordovician Baumann Fiord Formation is the exception based on its mixed lithology of dominant evaporites with subordinate carbonate, in addition to its substantial thickness, making it a suitable target given the anticipated higher thermal conductivity of evaporitic rocks. One possible system would have two closed-loop geothermal wells connecting the two main areas of heat demand (the community and the district around the airstrip) (Fig. 1), with a ~5 km subsurface horizontal leg through either the lower or upper evaporitic member. Such an installation could have two well pairs allowing use of thermal syphons to reduce lifting costs and reduce heat loss or thermal insulation cost for the heat transported on the surface. A horizontal well would maximise exposure of the well bore to the high thermal conductivity evaporite units. In addition, drilling a horizontal leg through evaporite beds would be technically easier and lower cost. Potential heat generation from such an installation would require more detailed information on the range of thermal conductivity expected for the Baumann Formation.

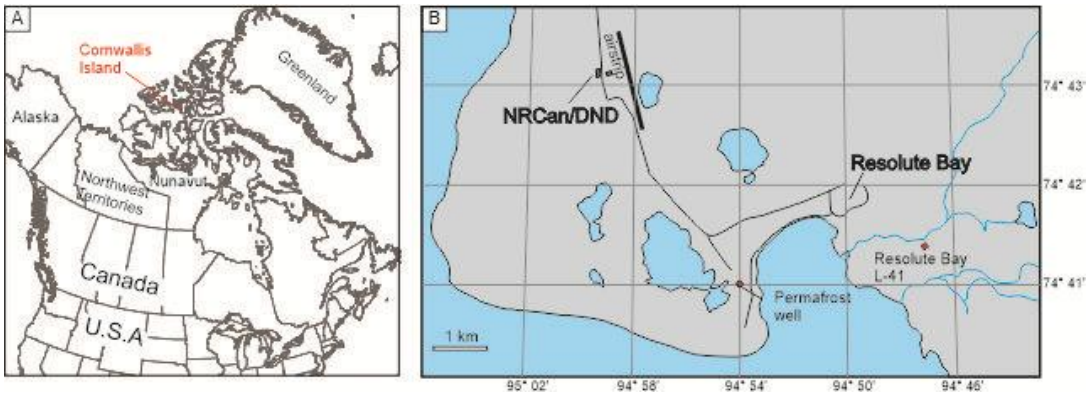


Figure 1. A) Map of Canada showing location of Cornwallis Island, B) Map of southwestern Cornwallis Iland showing location of the town, airstrip, government facilities (NRCan/DND), and drilled wells.

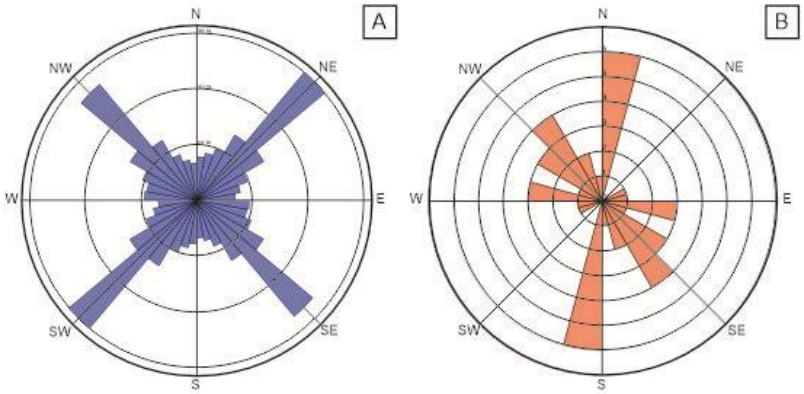


Figure 2. A) Rose diagram of processed linear terrain features of Cornwallis Island. B) Rose diagram of measured fractures direction in outcrops.

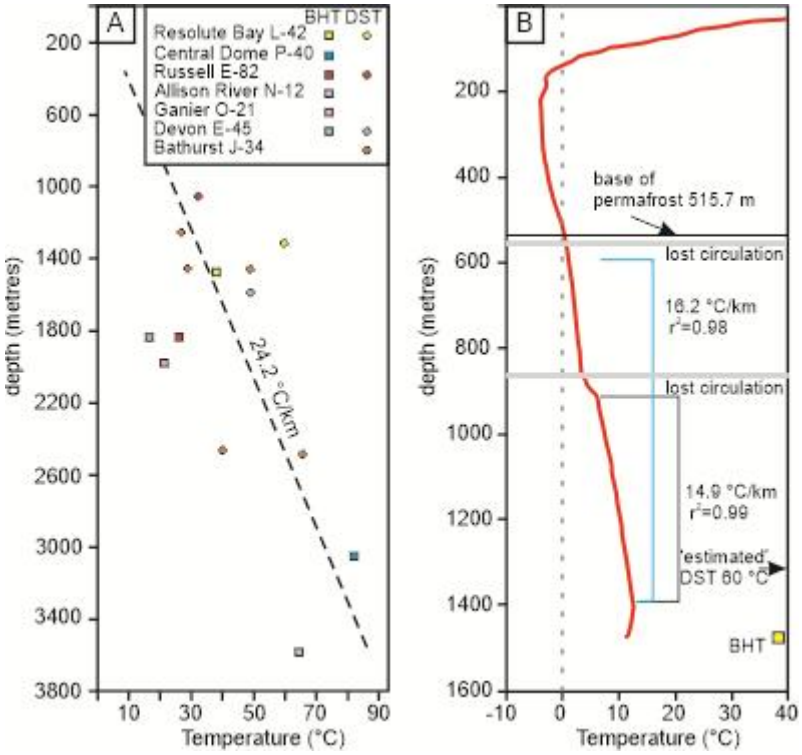


Figure 3. A) Bottom hole temperature (BHT) and drill stem test (DST) temperatures derived from petroleum wells. B) Continuous temperature log from the Resolute Bay L-41 well.

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