

Application of Remote Sensing for Accelerating Early-Stage Geothermal Exploration in Canada

Wanju Yuan, Stephen. E. Grasby, Zhuoheng Chen, Di Lu and Zachary Dewis

Natural Resources Canada, Geological Survey of Canada, 3303 33rd Street NW, Calgary, Alberta, Canada

wanju.yuan@nrcan-rncan.gc.ca

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ABSTRACT

Early-stage geothermal exploration in Canada is challenged by remote terrain, harsh climate, limited infrastructure, and sparse subsurface data coverage, particularly in northern and underexplored regions. To address these challenges, this study develops a satellite-based remote sensing framework that quantifies geothermal heat flux contributions to land surface temperature (LST) derived from thermal infrared imagery. The method exploits the contrasting spatial–temporal characteristics of solar radiation and geothermal heat input to separate temporally invariant geothermal signals from time-dependent solar effects using a physics-based iterative decomposition workflow. The approach is applied across three contrasting geological settings in Canada, including the Mount Meager Volcanic Complex in British Columbia, a fault-controlled geothermal system near Burwash Landing in Yukon, and a carbonate-dominated Arctic environment on Cornwallis Island, Nunavut. Results demonstrate that the extracted geothermal-related LST anomalies form coherent spatial patterns consistent with geological controls across volcanic, structural, and Arctic settings. This remote sensing–driven framework provides an effective and transferable tool for early-stage geothermal target screening, significantly reducing exploration uncertainty in data-scarce and logistically challenging regions of Canada and beyond.

1. INTRODUCTION

Canada hosts substantial geothermal energy potential associated with its diverse geological framework, including volcanic belts, sedimentary basins, and Canadian shields (Grasby et al., 2012). However, geothermal resource exploration in Canada remains challenging, particularly during early-stage assessment. Much of the country is characterized by remote terrain, harsh climate, sparse infrastructure, and limited subsurface data coverage. Conventional geothermal exploration methods, such as drilling, detailed geophysical surveys, and extensive field campaigns, are often costly, logistically complex, and difficult to implement at regional scales. These constraints are especially pronounced in northern and remote regions, where short field seasons and limited accessibility significantly increase exploration risk. As a result, there is a strong need for efficient, low-cost screening tools capable of identifying prospective geothermal areas prior to detailed ground-based investigations.

Remote sensing technologies have been applied to broad geoscience research activity as complementary tools for regional-scale assessment (Booyesen et al., 2021; He et al., 2025; Badrakh et al., 2025). In geothermal application, satellite-based thermal infrared imagery enables systematic observation of land surface temperature (LST) patterns over large spatial extents, providing valuable insight into surface heat distribution. In addition to satellite platforms, airborne and unmanned aerial vehicle (UAV)–based thermal cameras could be used to detect localized thermal anomalies associated with hot springs, fumaroles, and geothermal discharge zones. Multispectral and hyperspectral imagery have the potential to further support geothermal exploration by facilitating the identification of hydrothermal alteration minerals, structural features, and surface manifestations linked to subsurface heat flow (van der Meer et al., 2014). These technologies offer the advantages of repeat coverage, consistent data acquisition, and applicability in areas where field access is limited or unavailable.

However, isolating geothermal signals from atmospheric effects, surface emissivity variations, and seasonal temperature fluctuations remains a major technical challenge. To address this, methodological frameworks have been developed to better interpret thermal anomalies by coupling satellite-derived LST with physical heat transfer concepts and geological controls (Chen et al., 2025). Building on these efforts, this study focuses on the systematic utilization of thermal bands from satellite imagery to identify geothermal anomaly zones. By developing a mathematical workflow to quantify geothermal heat flux contributions to observed surface temperature, this work aims to provide an effective remote sensing–driven approach for accelerating early-stage geothermal exploration across Canada’s diverse geological environments.

2. METHODOLOGY

2.1 General assumption

Land surface temperature derived from thermal infrared satellite imagery represents the integrated response of multiple surface and subsurface heat sources. From a geothermal exploration perspective, the observed LST signal is primarily controlled by two dominant energy contributions: solar radiation input at the land surface and geothermal heat flux (GHF) originating from the Earth’s interior (Fig. 1). Following surface energy balance principles, the temperature recorded by satellite sensors can therefore be conceptualized as the superposition of these two components, together with minor residual terms related to latent heat exchange and surface–atmosphere interactions (Eq. 1).

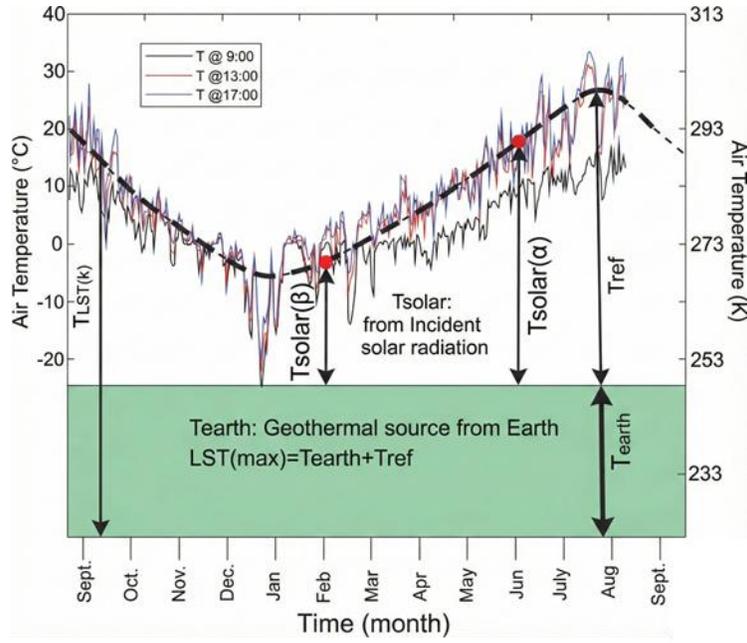


Figure 1. A diagram showing the two major sources of heat: time-invariant geothermal component and time-variant solar component, and their relationship to LST (modified from Chen et al., 2025).

$$T_{LST}(x, t) = T_{Solar}(t) + T_{Earth}(x) + \varepsilon_{Lat} \quad (1)$$

In addition, it is assumed that: the geothermal contribution from deep earth to LST is assumed to be spatially heterogeneous, reflecting variations in subsurface geological conditions such as heat flow intensity, permeability structure, fault distribution, and hydrothermal circulation pathways. However, this geothermal component is considered temporally stable over human time scales, exhibiting negligible seasonal variation. In contrast, the solar-induced component of LST is assumed to be spatially homogeneous at the regional scale of analysis, but strongly time dependent, varying with season, atmospheric conditions, and solar irradiance. Under these assumptions, the observed LST at any given pixel can be expressed as the sum of a temporally invariant geothermal temperature component and a temporally variable solar-driven temperature component, with residual effects treated as noise. This conceptual separation provides the physical basis for extracting geothermal-related thermal anomalies by exploiting the contrasting spatial–temporal behaviors of geothermal and solar heat inputs. By examining multi-temporal LST observations acquired under different solar forcing conditions, the stable geothermal signal can be progressively isolated from the dominant but transient solar background.

2.2 Imagery data acquisition and cleaning

Thermal infrared satellite imagery forms the core dataset for the proposed methodology. Land surface temperature products were acquired from the Landsat 8/9 missions, which provide consistent global coverage and thermal infrared observations suitable for regional geothermal reconnaissance. These platforms offer moderate spatial resolution thermal bands that are well suited for identifying spatially persistent temperature anomalies associated with geothermal processes.

To ensure data quality and comparability across time, standard preprocessing procedures were applied prior to analysis. This includes screening imagery for excessive cloud contamination, removing pixels affected by cloud, cloud shadow, and sensor artifacts, and using atmospherically corrected Level-2 LST products to minimize atmospheric distortion. All imagery was geometrically co-registered to ensure pixel-level consistency across multi-temporal datasets.

Because this section focuses on the general methodology rather than individual case studies, details such as the number of images, acquisition dates, or seasonal distribution are not specified here. Instead, the approach is designed to be flexible and transferable, allowing the same workflow to be applied to different geological regions, climatic settings, and temporal data availability. This generalization enables consistent comparison across volcanic, sedimentary basin, and Arctic geothermal systems examined later in the paper.

2.3 Imagery process algorithms

The extraction of geothermal heat flux–related LST anomalies follows a physics-based iterative workflow adapted from the method described in work by Chen et al. (2025). The workflow is designed to enhance persistent geothermal signals while suppressing transient thermal variations driven by solar radiation and environmental noise. Multiple LST images acquired under different solar conditions are first assembled into a temporal dataset. Among these, images representing relatively high and low solar forcing are used to approximate the dynamic range of solar-induced temperature variability. An initial estimate of the geothermal temperature component is generated based on the assumption that geothermal heat contributes to the lower-bound temperature field, while solar radiation dominates short-term temperature extremes.

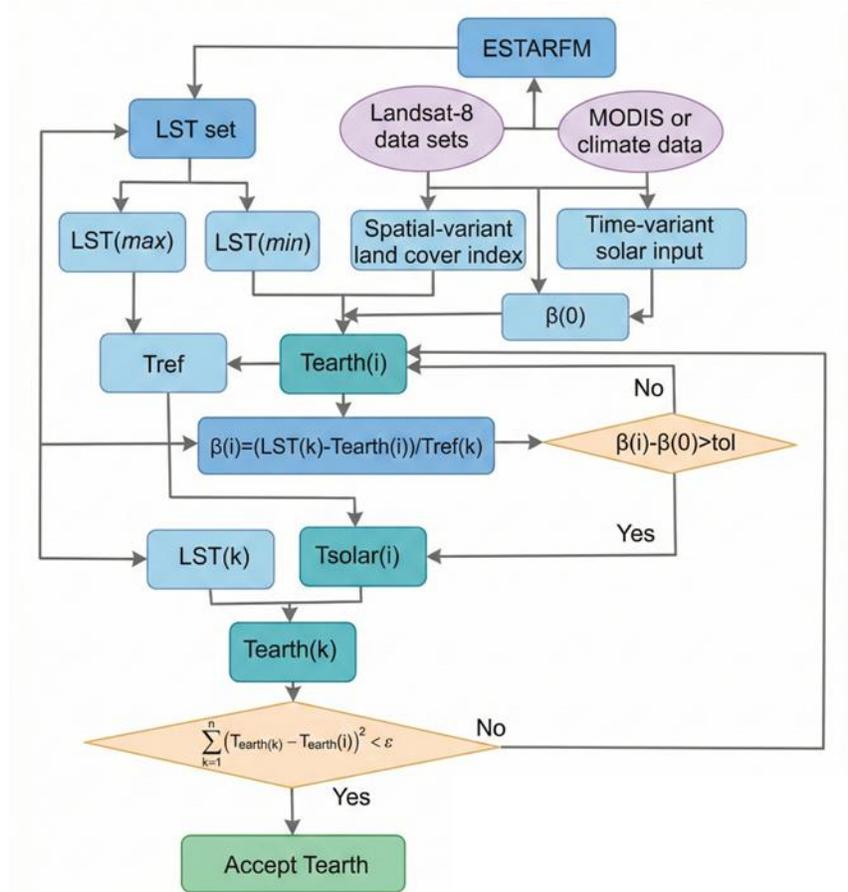


Figure 2. A flowchart for extracting GHF components from solar radiance dominated LST. ESTARFM stands for Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model (Zhu et al., 2010)

An iterative optimization process is then applied to decompose each LST image into its solar and geothermal components. For each iteration, the solar contribution is estimated as a fractional component of a reference temperature, while the geothermal component is treated as a spatially varying but temporally constant field. The difference between the reconstructed LST and observed LST is evaluated across all images, and the geothermal estimate is updated until convergence is achieved under predefined error thresholds and physical constraints. This process progressively minimizes solar-driven variability while reinforcing stable thermal patterns.

Following convergence, the resulting geothermal-related LST component represents the temperature field attributable to subsurface heat flux rather than surface heating. To further assess the robustness of detected anomalies, a probability-based approach can be applied by evaluating the recurrence of elevated geothermal-related temperatures across the image stack. Areas consistently exhibiting high geothermal temperature contributions are interpreted as candidate geothermal anomaly zones. This workflow enables the identification of geothermal thermal expressions that are persistent in space and invariant in time, providing a physically grounded method for early-stage geothermal target screening using satellite thermal imagery.

3. CASES STUDY

3.1 Mount Meager Volcanic Complex (MMVC) area, British Columbia

The Mount Meager Volcanic Complex (MMVC) is located in the Pacific Ranges of the Coast Mountains at the northern end of the Garibaldi Volcanic Belt in British Columbia, Canada. The region is characterized by strong environmental and topographic contrasts, ranging from densely forested low-elevation river valleys to rugged alpine terrain with extensive glacier cover. A transitional alpine zone composed of exposed volcanic bedrock and deposits occurs between these environments. Numerous meltwater-fed streams drain the volcanic massif and contribute to continuous surface reworking. The combination of steep relief, glaciation, and dense vegetation makes field-based geothermal exploration logistically challenging across much of the area.

MMVC is one of the most well-documented high-temperature geothermal systems in Canada and has been investigated extensively over the past several decades. Previous exploration programs identified multiple geothermal prospects and led to the drilling of 47 geothermal wells, concentrated in the northern, eastern, and southern sectors of the complex (Nevin, et al., 1981; Shore and Schlax, 1982). Among these, only the South Meager area advanced to production testing. Subsurface temperature measurements and heat flow estimates confirm

the presence of a high-enthalpy geothermal system, with localized heat flow exceeding 1000 mW/m² and strong spatial variability controlled by geological structure and fluid pathways.

Two distinct geothermal systems have been recognized in the southern MMVC. A shallow geothermal aquifer is expressed at surface by hot springs and warm water seeps with temperatures exceeding 50 °C and was confirmed by shallow drilling along the Meager Creek valley (Lewis and Southern, 1978). In addition, a deep fractured geothermal reservoir, confined by faults and volcanic vents, exhibits temperatures greater than 200 °C at depths below 500 m (Lewis and Jossep, 1981). The availability of extensive subsurface temperature data, mapped hot and warm spring sites, high-resolution geophysical imaging, and surface temperature monitoring makes MMVC an ideal benchmark site for applying and validating satellite-based thermal anomaly detection methods prior to extending the workflow to less well-constrained geothermal regions.

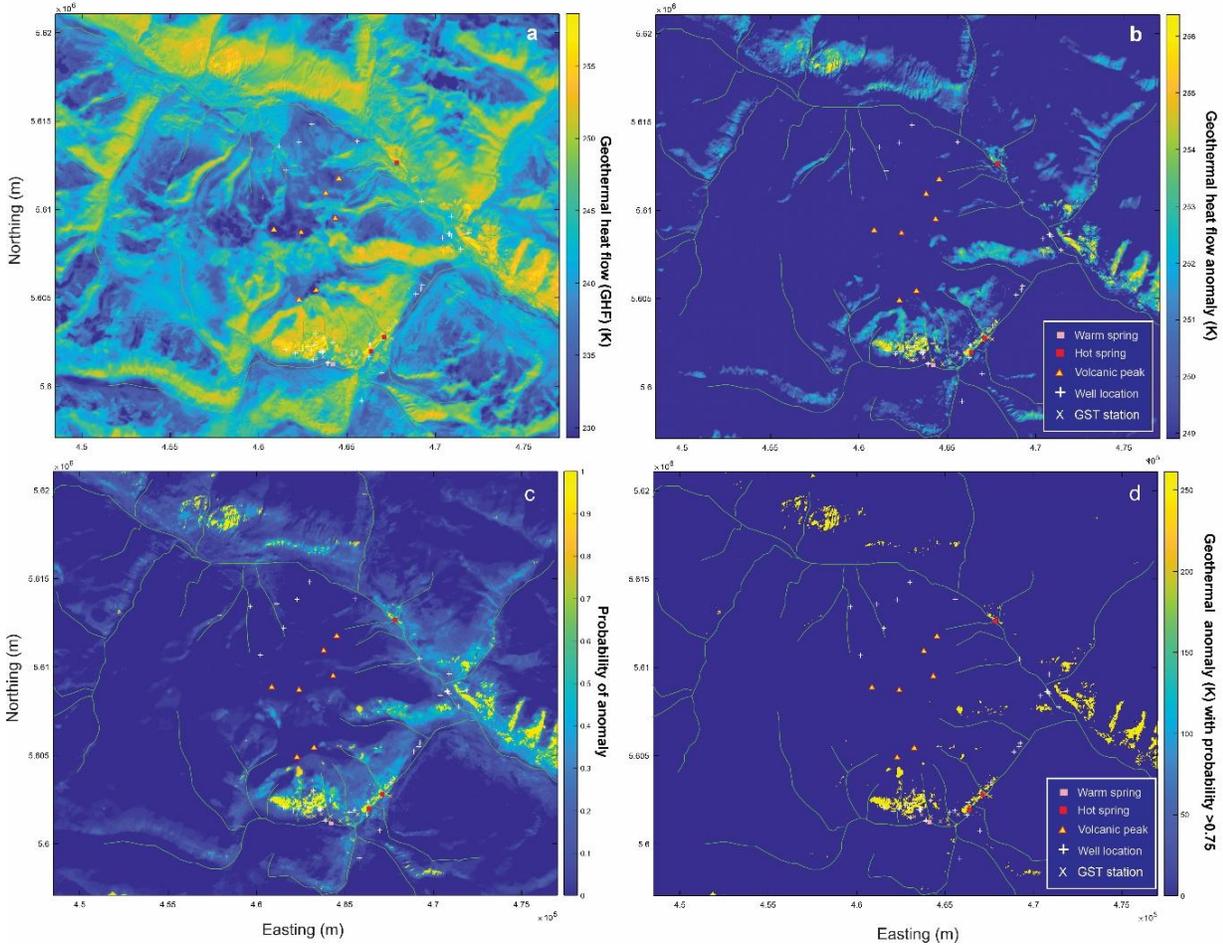


Figure 3. Maps showing the extracted GHF component (maps modified from Chen et al., 2025).

Application of the proposed thermal anomaly extraction workflow at the MMVC reveals four distinct types of temperature anomalies with different physical origins (Chen et al., 2025). The first category corresponds to geothermal surface manifestations, where elevated land surface temperatures spatially coincide with known hot springs and warm seep areas, reflecting shallow discharge of geothermal fluids. The second anomaly type is associated with zones of high subsurface heat flow confirmed by geothermal wells, representing deep, structurally controlled geothermal reservoirs whose thermal influence propagates toward the surface. A third group of anomalies is linked to surface geological processes, including landslides, scarps, and deeply incised drainage features, where enhanced heat transfer and groundwater seepage locally modify surface temperature patterns. The fourth anomaly type is related to anthropogenic activity, such as infrastructure and industrial facilities, which generate localized thermal signatures unrelated to natural geothermal systems. Together, these four anomaly types demonstrate that while satellite-derived thermal data can effectively highlight persistent heat sources, integration with geological and contextual information is essential for discriminating true geothermal targets from non-geothermal thermal anomalies.

3.2 Burwash Landing area, Yukon Territory

The Burwash Landing study area is located in southwestern Yukon within the broader Denali fault system, one of the most prominent crustal-scale strike-slip fault zones in northwestern North America (Fig. 4). The region is characterized by broad river valleys, glaciofluvial deposits, discontinuous permafrost, and relatively sparse vegetation compared to coastal or southern Canadian environments. The

geological framework is dominated by major fault strands, including the Denali Fault and associated splays along the Duke River valley and delta system, which play a critical role in controlling crustal permeability and fluid migration. These structural conditions, combined with limited infrastructure and challenging northern logistics, make conventional geothermal exploration difficult and highlight the need for regional-scale, cost-effective reconnaissance tools.

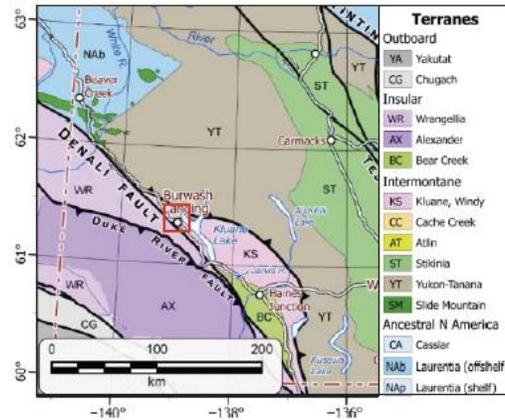


Figure 4. A geological map showing regional geological setting and location of the study area (Map modified from Government of Yukon, 2023).

Previous regional assessments have identified Yukon as a region with elevated geothermal potential, particularly where deep fault systems may facilitate upward migration of warm fluids. In the Burwash Landing area, multiple independent datasets provide evidence for structurally controlled heat flow anomalies. Ground surface temperature (GST) monitoring deployed across the area reveals localized zones with elevated winter temperatures and reduced seasonal amplitude, suggesting upward conductive or advective heat transport (Chen et al., 2024). These GST-derived temperature gradient trends are spatially consistent with major fault orientations, particularly along NNE–SSW and NW–SE structural trends associated with the Denali Fault zone. Complementary magnetotelluric (MT) models further identify near-surface and shallow conductive anomalies, interpreted as permeable zones that may act as pathways for warm groundwater circulation (Tschirhart et al., 2022).

The satellite-derived geothermal-related land surface temperature (LST) component at Burwash Landing reveals the dominant anomaly trend oriented approximately NNE–SSW. This linear or curvilinear thermal feature forms coherent anomaly swarms that closely follow the regional geomorphic fabric expressed in the Duke River valley and delta system, as well as major lineament patterns visible in optical imagery. A prominent anomaly (upper panel in Fig. 5) occurs in the central portion of the Duke River delta, where concentrated high-temperature patches form an elongated zone consistent with localized structural segmentation within the river plain. A second major anomaly swarm (lower panel in Fig. 5) is observed in the area of planned geothermal drilling, characterized by clustered thermal highs aligned along linear surface features, suggesting focused upward heat transfer along fracture-controlled pathways. Together, these anomaly patterns indicate that the geothermal-related thermal signals extracted from satellite imagery are not randomly distributed, but instead organized into structurally coherent trends, highlighting areas where subsurface heat may be preferentially expressed at the surface.

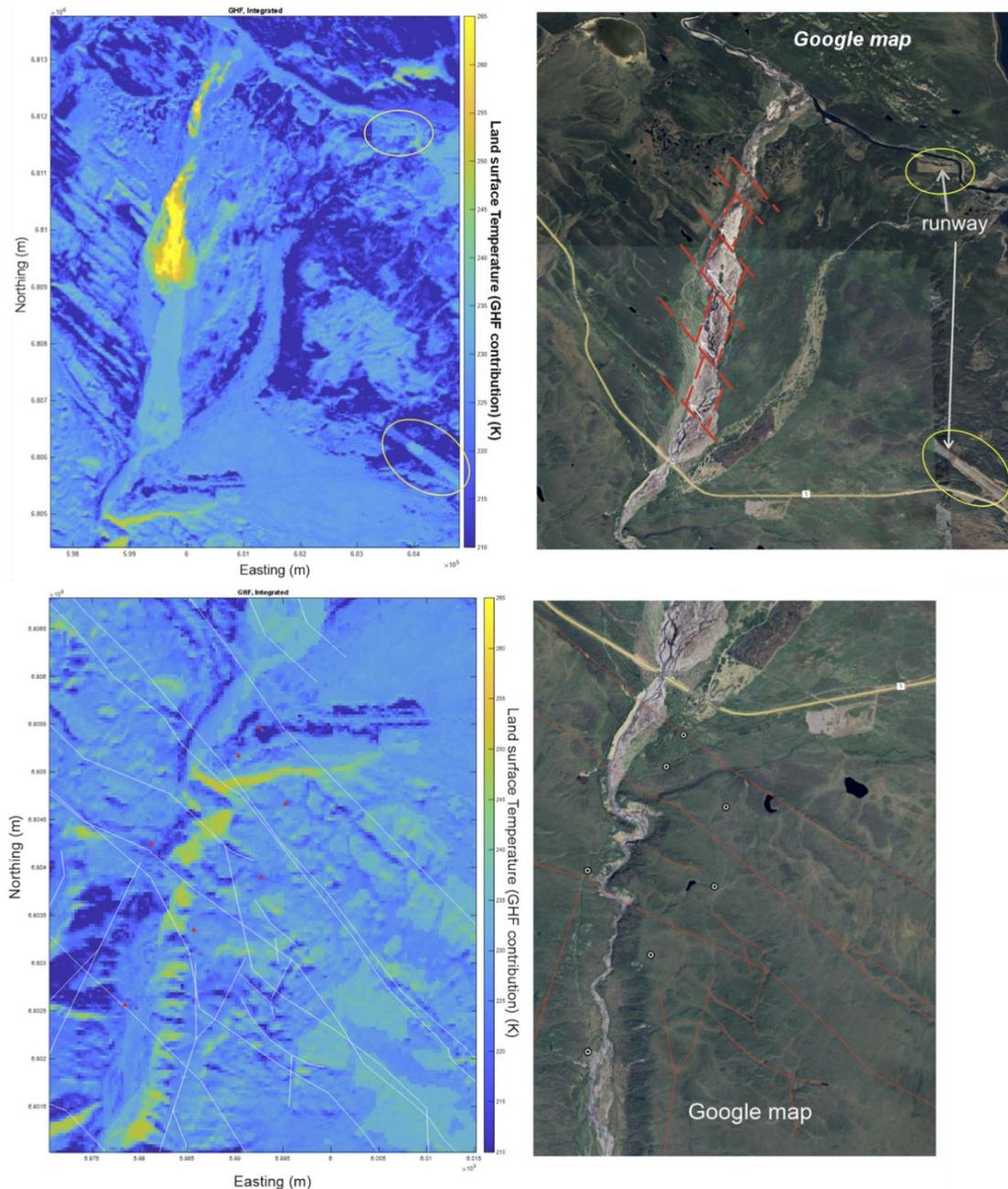


Figure 5. Comparison between satellite-derived geothermal heat flux component to LST and corresponding surface features interpreted from high-resolution Google Earth imagery.

3.3 Cornwallis Island, Canadian Arctic, Nunavut Territory

Cornwallis Island is located in the Canadian High Arctic within the Sverdrup Basin, a large sedimentary basin that developed during the Paleozoic to Mesozoic in response to regional extensional tectonics (Grasby et al., 2025). The island is predominantly underlain by thick carbonate successions, including limestones and dolostones, interbedded locally with evaporites and clastic units. These carbonate formations commonly exhibit fracture networks and secondary porosity that can enhance fluid circulation. The region is characterized by continuous permafrost, minimal vegetation cover, and extremely cold climatic conditions, which strongly suppress surface thermal variability driven by solar radiation. As a result, surface temperature patterns are primarily controlled by subsurface thermal processes and heat transfer through the shallow ground, making Cornwallis Island a unique geological setting for evaluating geothermal-related thermal anomalies using satellite-based observations in a data-scarce Arctic environment.

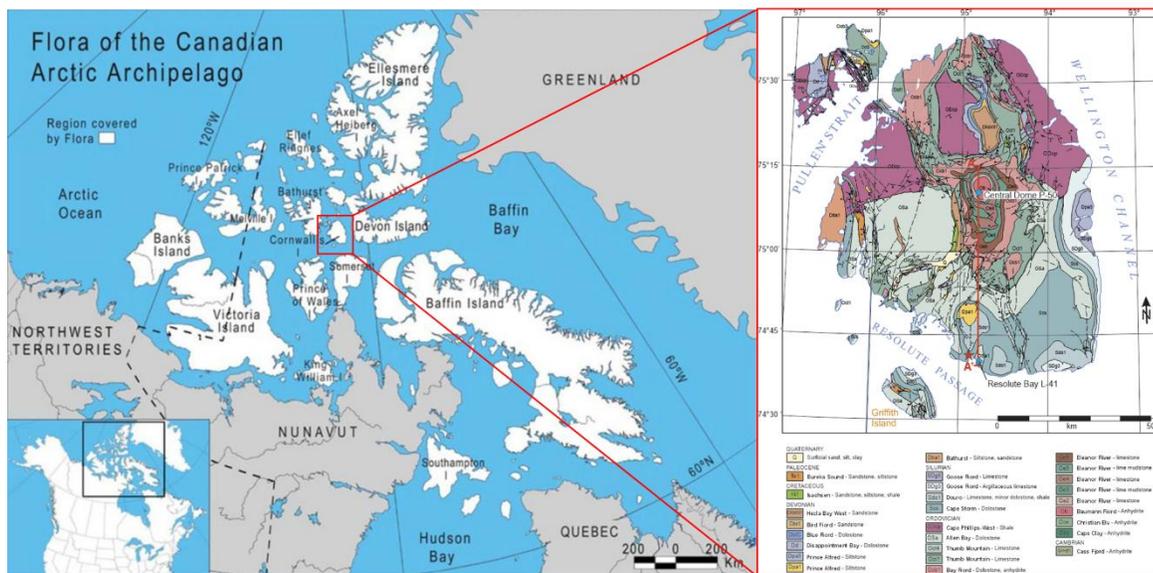


Figure 6. Map of Cornwallis Island in Canadian Arctic Archipelago area and its geology bedrock map.(View image from Canadian Museum of Nature, and bedrock map from Harrison et al., 2014).

On Cornwallis Island, the satellite-derived geothermal anomaly patterns show a notable spatial association with areas of relatively high normalized difference vegetation index (NDVI). In the High Arctic environment, vegetation growth is extremely limited and strongly constrained by temperature availability; therefore, locally elevated NDVI values may indicate zones with comparatively warmer ground conditions. These areas of enhanced vegetation development may reflect increased near-surface heat availability, which can promote soil thawing and moisture retention during the short growing season. In addition, several thermal anomaly zones coincide with specific geological formations, suggesting that lithological properties—such as weathered carbonate units, fracture networks, or fault-related permeability—may facilitate subsurface fluid circulation and upward heat transfer. Given the unique climatic conditions, continuous permafrost, and carbonate-dominated geology of the region, the mechanisms linking vegetation distribution, subsurface heat flow, and surface thermal expression remain complex. Further investigation integrating geological, thermal, and environmental data is therefore required to fully understand the origin and significance of these observed geothermal-related anomalies in the Arctic setting.

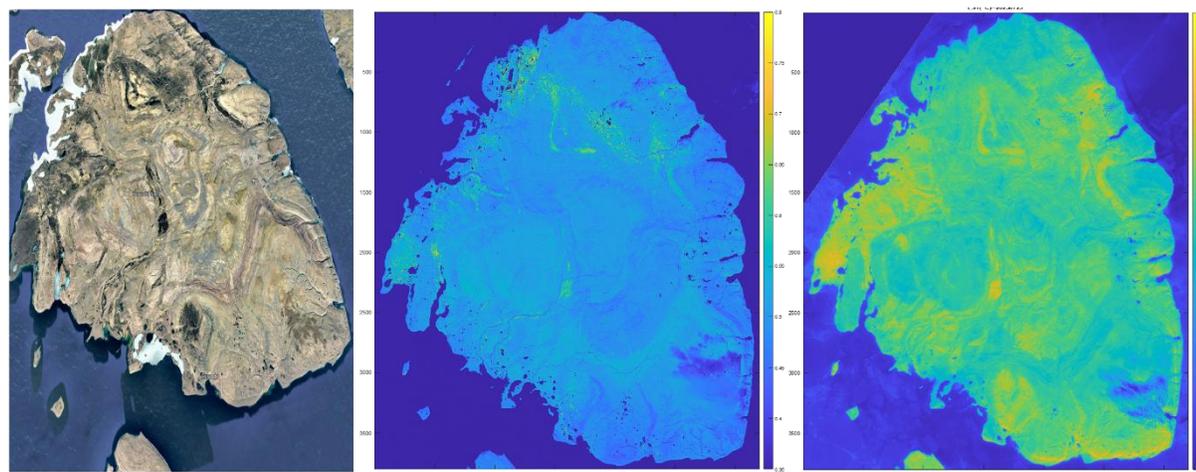


Figure 7. Comparison of surface morphology and satellite-derived thermal indicators over the study area. Left: Satellite Imagery of Cornwallis Island; Middle: NDVI image of Cornwallis Island on Aug. 25, 2023. Right: Land surface temperature on Aug. 25, 2023.

4. CONCLUSION

This study presents a remote sensing-driven framework for accelerating early-stage geothermal exploration across Canada’s diverse geological environments. By decomposing satellite-derived land surface temperature (LST) into temporally variable solar components and spatially heterogeneous, time-invariant geothermal components, the proposed methodology enables identification of geothermal-related thermal anomalies using widely available thermal infrared imagery. The approach provides a physically grounded and transferable

screening tool that can be applied in regions where conventional geothermal exploration is constrained by limited access, high cost, or sparse subsurface data.

Application of the workflow to three contrasting geological settings demonstrates its adaptability. In the Mount Meager Volcanic Complex, the extracted geothermal anomalies capture both shallow surface manifestations and deeper high-temperature geothermal systems, while also highlighting non-geothermal thermal sources that require geological discrimination. In the Burwash Landing area, satellite-derived geothermal LST anomalies form coherent linear trends that reflect structurally controlled thermal expression within a fault-dominated sedimentary environment. On Cornwallis Island in the Canadian High Arctic, geothermal-related anomalies exhibit spatial associations with elevated NDVI zones and specific carbonate formations, illustrating the unique surface–subsurface thermal coupling that can occur under extreme climatic and permafrost conditions.

Together, these case studies demonstrate that satellite thermal imagery, when interpreted through a physics-based decomposition framework, can significantly enhance regional geothermal target identification. While the method does not replace detailed field investigations, it provides an effective first-pass exploration tool to prioritize prospective areas and reduce early-stage exploration risk. Future work should focus on integrating additional environmental corrections, improving quantitative heat flow estimation, and coupling satellite-derived thermal anomalies with geological and geophysical datasets to further refine geothermal resource assessment in data-scarce regions of Canada and beyond.

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