Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Expanding the Thermal Conductivity Assessment of the St. Lawrence Lowlands (Québec, Canada): A New Laboratory Dataset from Optical Scanning

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Keywords: Ground thermal properties, Geothermal mapping, Shallow geothermal energy, Scale effect, Anisotropy, Multiscale

ABSTRACT

Thermal conductivity (TC) assessments are critical for the design of ground-coupled heat pump systems. In the St. Lawrence Lowlands (SLL), Québec, previous regional TC mapping identified systematic overestimations in laboratory measurements (divided bar and needle probe) compared to *in situ* thermal response tests (TRTs). This discrepancy was attributed to the limited ability of small-scale laboratory samples to capture subsurface heterogeneities. Reservoir formations exhibited large differences between laboratory and field measurements, reaching up to 1.4 W/m·K. This study expands the SLL TC inventory with 101 new measurements obtained using a Thermal Conductivity Scanner (TCS), applying the optical scanning method to outcrop samples to improve spatial and lithological coverage. The results confirm previous trends, with the Cairnside and Covey Hill formations remaining the most conductive units (averaging 5.07 and 4.81 W/m·K in dry condition, and 6.17 and 5.80 W/m·K in saturated condition, respectively), while caprock units show lower values. In formations such as Theresa and Covey Hill, the inclusion of the new dataset increased the discrepancies between laboratory and TRT results, with differences up to 1.77 W/m·K in Covey Hill. These increases are attributed to the inclusion of measurements under saturated conditions, which raised dry TCS-derived values between 11% and 24% for Beauharnois, Theresa, Cairnside and Covey Hill formations. Other units exhibited no significant variation under saturated conditions. Thermal anisotropy was also observed, with higher TC parallel to bedding in 71% of the samples. Overall, although laboratory TC values remain higher than TRT values, except in Beauharnois samples, where fracture-related groundwater flow may enhance field-scale conductivity, the expanded dataset improves representativeness and highlights the influence of scale, moisture, anisotropy, and lithological variability. These results will support the update of the regional TC map and enhance the accuracy of geothermal design parameters in Québec.

1 INTRODUCTION

Thermal conductivity (TC) is the material property defining the ability to transfer heat, typically expressed in W/m·K. In geothermal heat pump systems, used mainly for space heating and cooling, the ground TC is a fundamental parameter because it determines the capacity of the subsurface to continuously deliver or absorb energy to or from the geothermal system, depending on whether it operates in heating or cooling mode (Raymond, 2018). Although the ground TC plays an important role in the performance of all geothermal systems, it is especially critical for closed-loop vertical ground-coupled heat pumps (GCHPs), one of the most widely used configurations in Canada, and especially in the province of Québec, where they account for about 85% of all geoexchange systems installed (Canadian GeoExchange Coalition, 2010). In these systems, no groundwater exchange occurs between the ground and the borehole heat exchanger, making conduction the dominant mechanism of heat transfer in the system. As a result, the ground TC directly controls the required dimensions of the borehole heat exchanger field. Higher TC values allow for shorter boreholes to satisfy a given energy demand, whereas lower TC values require longer boreholes. This has major cost implications for the overall system, since drilling typically represents 30–50% of the total initial cost (Blum et al., 2011; Giordano et al., 2019; Moreno et al., 2023). Therefore, accurate assessment of subsurface TC is essential for the proper design, sizing, and overall feasibility of GCHP systems.

Québec has one of the most renewable energy portfolios in Canada, largely dominated by hydropower, and is actively promoting the adoption of other sustainable technologies (MELCCFP, 2023; CAR, 2024). The province's most densely populated area is located within the St. Lawrence Lowlands (SLL) region, which includes major urban centers such as Montréal and Québec City (Figure 1a). This region has a significant proportion of the province heating energy demand that geothermal energy could help to sustainably meet. As a result, several

initiatives have been carried out in recent years to characterize and assess the geothermal potential of the SLL, including thermal property characterization studies (Bédard et al., 2018: Raymond et al., 2019), technical feasibility assessments (Raymond et al., 2012), and broader evaluations of geothermal resource potential (Bédard et al., 2020).

The SLL sedimentary basin forms part of the St. Lawrence Platform and is bounded by the Canadian Shield to the northwest and the Appalachian domain to the southeast. Its stratigraphic sequence reaches up to 3,000 m in thickness and is composed of slightly deformed Cambrian to Ordovician sedimentary rocks deposited in shallow to deep marine environments. At the base, the Potsdam Group (Covey Hill and Cairnside formations) consists of quartz- and feldspar-rich sandstones that are often considered reservoir units for geothermal exploration (Clark, 1972; Salad Hersi et al., 2002; Raymond et al., 2012). Overlying formations include the Beekmantown Group (Theresa and Beauharnois formations), composed mainly of dolomitic sandstones and dolostones (Clark, 1972; Globensky, 1987; Chi et al., 2000), followed by the Chazy–Black River–Trenton (Tr-BR-Ch) succession of limestones (Globensky, 1987). The stratigraphic column continues with the Utica Shale, a thick black shale unit, and is capped by the Lorraine, Sainte-Rosalie, and Queenston groups, composed primarily of shales, siltstones, and sandstones (Globensky, 1987) (Figure 1b).

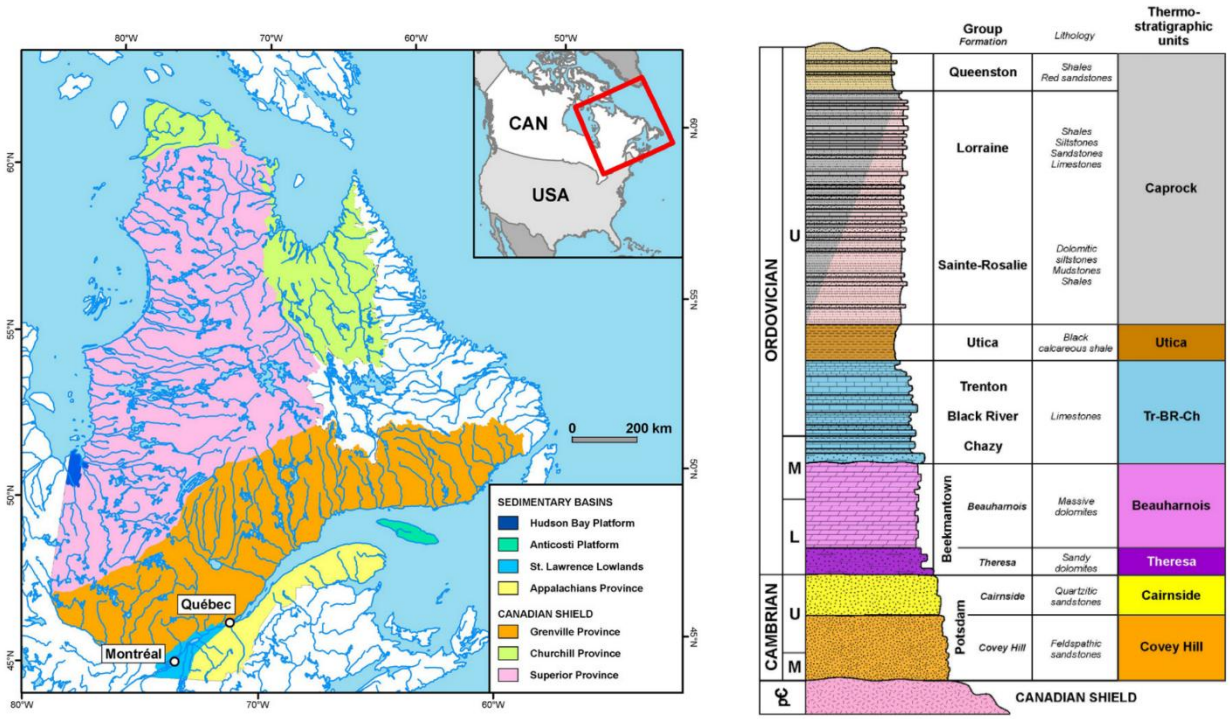


Figure 1. a) Location of the St. Lawrence Lowlands (SLL) sedimentary basin within the province of Québec; b) Stratigraphic column and thermostratigraphic units of the SLL. (Raymond et al., 2019).

Building upon this geological framework, Raymond et al. (2019) developed a regional map of bedrock TC for the SLL, based on an inventory that combined laboratory analyses, TRTs, and geophysical well log interpretations. Geological formations were grouped into thermostratigraphic units defined by their thermal properties (Figure 1b). The thermostratigraphic units of the SLL are divided into: (1) Caprock, comprising the Queenston, Lorraine, and Sainte-Rosalie groups; (2) Utica, including the Utica Formation; (3) Tr–BR–Ch, composed of the Trenton, Black River, and Chazy groups; (4) Beauharnois; (5) Theresa; (6) Cairnside; and (7) Covey Hill. This effort provided the first systematic dataset and spatial interpolation of bedrock TC in the basin, supporting geothermal system design at a regional scale. However, the study faced challenges related to the integration of TC values obtained from different measurement methods and scales.

Raymond et al. (2019) revealed that laboratory-derived values were systematically higher than those obtained from TRTs, except for the Beauharnois unit, with discrepancies of up to 1.4 W/m·K in reservoir units such as Cairnside and Covey Hill. The authors hypothesized that this overestimation was due to the inability of small-scale laboratory methods (divided bar and needle probe, for that paper) to capture heterogeneities that are present at the field scale. At the laboratory scale, features such as fractures, filled veins, or other discontinuities acting as barriers to heat transfer are often excluded, whereas TRTs inherently integrate these heterogeneities over a larger volume. These findings emphasized the need for improved laboratory measurements and processing capable of capturing heterogeneities to better represent field-scale heat transfer conditions.

To address the limitations identified in previous work, the objective of this study is to expand the TC inventory of the SLL with a new laboratory dataset obtained using a Thermal Conductivity Scanner (TCS). This optical scanning technique provides high-resolution, continuous measurements allowing the identification of heterogeneities within rock samples, thereby improving the representativeness of laboratory assessments. TCS measurements under both dry and saturated conditions were performed to quantify moisture effects on TC. Although some previous studies have reported measurements under saturated conditions using the TCS (Albert et al., 2017: Li et al., 2020), this experimental configuration remains relatively uncommon. The integration of the new dataset with existing laboratory and field data aims to evaluate methodological and scale-related discrepancies and to refine the regional understanding of TC in SLL bedrock. Ultimately, this work contributes to improving the spatial coverage and reliability of the TC inventory for the SLL, leading to more accurate and representative geothermal system design.

2 METHODOLOGY

2.1 Fieldwork and sampling

Fieldwork was conducted in 2024 across the SLL sedimentary basin (Figure 1). A total of 78 new hand-sized rock samples were collected from outcrops of different geological formations, with particular attention to areas and units that were underrepresented in the existing SLL TC inventory reported by Raymond et al. (2019), such as the Covey Hill, Cairnside, Theresa, and Beauharnois formations. In addition, samples were collected from different lithologies within each formation to try to have the full range of lithological variations composing each geological unit. This approach aimed to evaluate whether improving lithological representativeness in laboratory analyses could help reduce the discrepancies previously observed between TRT and laboratory-derived TC values.

This strategy was particularly relevant because laboratory methods often require specific sample preparation, such as drilling cylindrical plugs for divided bar measurements, inserting small probes into the rock for needle probe tests, or cutting flat, polished surfaces for TCS analysis. As a result, field sampling tends to favor more competent and mechanically stable lithologies, which may not fully represent the diversity of subsurface materials. In contrast, weaker or highly fractured rocks, such as shales, slates, or laminated lithologies, which are common in the SLL study area, are rarely collected or tested due to their fragility. Consequently, laboratory datasets may overrepresent consolidated facies, potentially biasing the average TC values assigned to a geological unit.

2.2 Thermal Conductivity Measurements Using TCS

The TCS used to assess the TC of the new samples collected is a non-destructive optical device that employs a focused, mobile, near-point-like heat source combined with infrared temperature sensors. The sensors record surface temperatures before and after heating, and thermal properties are determined by comparing temperature differences measured on the rock surface with those obtained from standards (Popov et al., 1999; Popov, 2017) (Figure 2). The TCS enables rapid, high-resolution measurements at the millimetric scale, allowing the identification of heterogeneities and anisotropic features within the rock matrix (Jorand et al., 2013). In addition to the 78 new field samples, 23 rock samples previously analyzed using conventional laboratory techniques, such as the divided bar and needle probe methods, were remeasured with the TCS. In total, 101 samples were analyzed for thermal conductivity.

Rock samples showing evident bedding structures were measured in two orientations: parallel and perpendicular to the bedding planes. The heat flow generated by the TCS heat pulse propagates along the plane perpendicular to the scanning line (Popov et al., 1999), a scan line oriented perpendicular to the bedding represents the TC parallel to the lamination, whereas a scan line parallel to the bedding corresponds to a TC both perpendicular and parallel to the lamination (Popov et al., 1999; Jorand 2013). The final TC value assigned to each sample was taken as the average of these two measurements.

Considering that TRTs represent *in situ* saturated conditions, it was also essential to measure TC under saturated laboratory conditions to reduce discrepancies from differences in testing environments and to enable more meaningful comparisons between laboratory and field data, however, not all units were tested under saturated conditions. Saturation measurements were conducted only for those units meeting one of the following criteria: (1) A significant difference between the average TRT values reported by Raymond et al. (2019) and the dry laboratory results obtained in the present study (Table 1); or (2) The rock samples exhibited visible porosity at the macroscale. Based on these criteria, saturation tests were performed on all samples from the Beauharnois, Theresa, Cairnside, and Covey Hill formations, plus a few from the Tr–BR–Ch units.

Prior to measurement, all samples were cut to obtain flat and smooth surfaces suitable for optical scanning, avoiding weathered portions to preserve material integrity. The analyzed area was painted with a thin layer of black matte (acrylic) paint to ensure uniform absorption of the heat signal (Popov, 2017). Before testing, samples were conditioned for at least 24 hours in the same laboratory environment to achieve thermal equilibrium with ambient temperature. All measurements were performed in TC-mode with an accuracy of approximately ±3% (Popov, 2017).

Rock samples for saturated test conditions were cut into 3–5 cm thick sections to facilitate water penetration and were totally immersed in water for 48 hours prior to measurement although vacuum saturation is commonly recommended to ensure complete pore-space filling. While procedure for this study does not guarantee complete saturation throughout the entire sample thickness, the heat pulse generated by the TCS penetrates only up to 2 cm into the surface (depending on the thermal conductivity of the material; Popov, 2017; Li et al., 2020). Therefore, effective saturation within the near-surface zone was sufficient to influence the measured response. To minimize desaturation during testing and to prevent water leakage onto the instrument, samples were kept submerged except for the exposed flat surface. The TCS head was positioned upside down over the exposed area, and measurements were conducted with the scanner in direct contact with the water-saturated surface (Figure 2b).

Particular attention was given to ensuring proper positioning of the TCS on the sample surface, as any uneven contact or misalignment could introduce measurement errors. The reference standards were not saturated, only the rock samples. During preliminary tests, both water-based and oil-based paints were evaluated for their suitability. While water-based paints are typically easier to remove for subsequent analysis, they tend to form bubbles when exposed to moisture that could affect heat absorption and potentially bias the results. Conversely, oil-based paints provided more stable and uniform coatings without significant differences in measured TC values. Therefore, oil-based paint was used for all measurements.

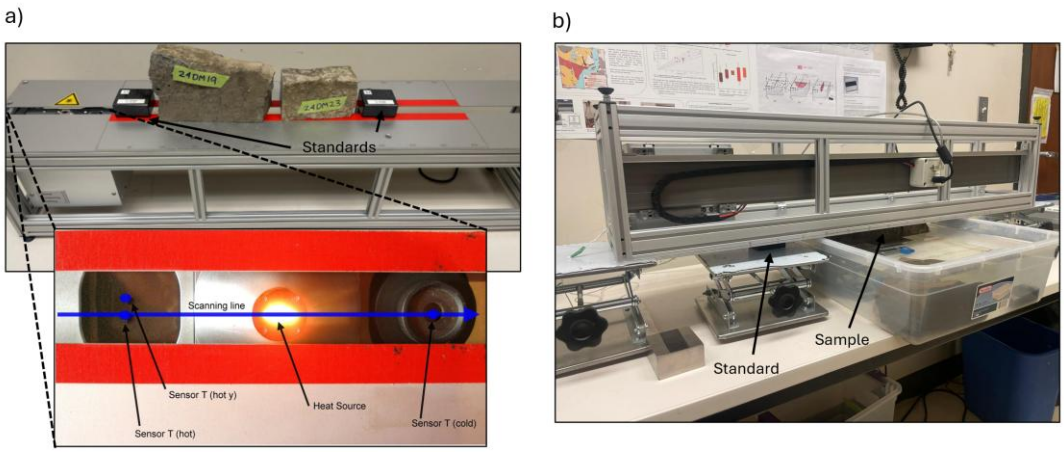


Figure 2. a) Thermal Conductivity Scanner (TCS) setup for measurements under dry conditions. b) setup for measurements under saturated conditions.

The TCS output includes several statistical parameters for each scan line: the mean, minimum, and maximum TC values, as well as G-factor, and inhomogeneity coefficient (β). The inhomogeneity coefficient is defined as $\beta = (TC_{max}-TC_{min})/TC_{mean}$. The G-factor is the ratio between the standard deviation and the mean TC value (Popov, 2017). Both parameters are dimensionless and express the degree of thermal heterogeneity in a sample along the scanned line. When β approaches zero, the sample is thermally homogeneous, meaning that TC variations along the scanned line are low. Conversely, higher β or G values indicate stronger thermal contrasts, caused by pores, fractures, mineralogical changes, or textural heterogeneity. These results provide a quantitative measure of heterogeneity within the rock sample and help assess the potential influence of textural or compositional discontinuities on the overall thermal conductivity.

2.3 Data Processing

The 2019 TC map of the SLL (Raymond et al., 2019) grouped the geological formations into thermostratigraphic units based on similarities in their thermal properties. In this study, the same classification was retained to ensure consistency with the previous inventory. However, for interpretative purposes, the results are also analyzed at the formation and lithology scale to highlight and better understand the variability within each

thermostratigraphic unit. This approach provides a more detailed understanding of how formation-scale heterogeneities and lithological distributions may influence the average TC values assigned to geological units.

To quantify the impact of water saturation on TC, results obtained under dry and saturated conditions for each sample and thermostratigraphic unit were compared using both the mean TC, G-factor, and inhomogeneity coefficient (β) derived from the TCS. These parameters allowed the identification of lithologies or units most sensitive to moisture content and helped determine whether saturation further influences the effect of heterogeneity of the samples in the measurements.

TC results obtained with the TCS were then compared and integrated with those from the 2019 laboratory inventor to finally contrast all laboratory results within situ TRTs. The comparison was conducted at the thermostratigraphic unit scale by computing the mean TC for each data source (TRT, previous laboratory (2019), and new laboratory data from TCS (2025)).

3 RESULTS AND DISCUSSIONS

3.1 Thermal conductivity measurements with the TCS

Location of the samples collected in 2024 and the 2019 thermal conductivity inventory, including both laboratory measurements and TRT data, are provided (Figure 3). Results for dry and saturated conditions are compiled (Table 1). The new dataset provides TC values for several formations and lithologies that were not represented in the 2019 inventory, such as the Lotbinière, Le Fonds, and Saint-Michel formations. Among them, the Lotbinière and Saint-Michel show average TC values comparable to those of other formations within their respective thermostratigraphic unit. However, the Les Fonds Formation exhibits the highest TC values within the Caprock unit, with an average of 3.28 W/m·K.

Medium to High TC values were obtained for the Beauharnois, Theresa, Covey Hill, and Cairnside formations, ranging averages from 3.40 to 5.07 W/m·K under dry conditions and from 3.78 to 6.17 W/m·K when saturated. In contrast, the Utica Shale and Caprock units showed the lowest TC values (2.40–2.44 W/m·K), consistent with their fine-grained, clay-rich composition. Overall, the TCS measurements confirm the general trends reported in the earlier inventory while expanding both the spatial and lithological coverage of the dataset across the SLL basin.

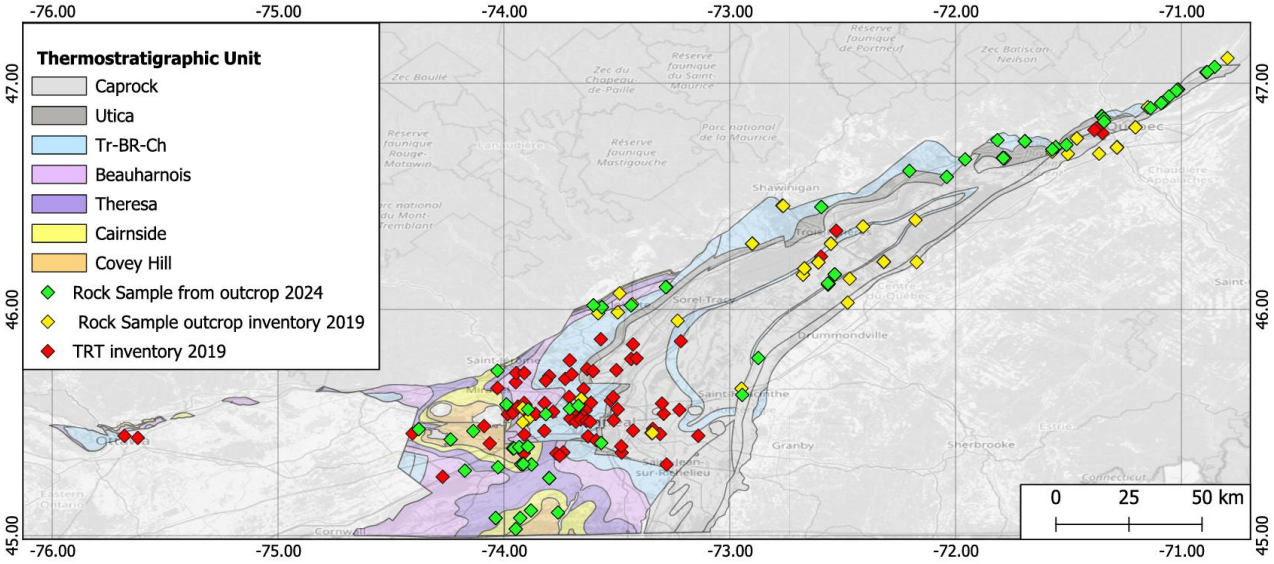


Figure 3. Map of the St. Lawrence Lowlands showing thermostratigraphic units and the location of TC data.

Table 1. Thermal conductivity measured exclusively with the TCS.

	W/m·K										
	Caprock	Utica	Tr-BR-Ch	Beauharnois		Theresa		Cairnside		Covey Hill	
	Dry	Dry	Dry	Dry	Sat	Dry	Sat	Dry	Sat	Dry	Sat
Average	2.40	2.44	2.81	3.40	3.78	3.83	4.76	5.07	6.12	4.81	5.80

Minimum	1.19	1.62	2.12	2.60	2.87	3.21	3.47	4.39	5.73	2.87	4.62
Median	2.57	2.56	2.81	3.34	3.69	3.50	4.68	5.02	6.08	4.95	5.79
Maximum	3.62	2.80	3.13	4.31	5.04	5.54	6.38	6.09	6.71	6.06	6.85
Standard deviation	0.62	0.39	0.22	0.65	0.68	0.77	0.97	0.50	0.33	0.98	0.71
Variance	0.39	0.16	0.05	0.42	0.60	0.59	0.94	0.25	0.11	0.96	0.50
Number of sample?	27	7	31	8		8		8		12	

Thermal anisotropy was identified, with TC values varying according to measurement direction. Results showed that in 71% of the scanned lines oriented perpendicular to the bedding (representing TC parallel to the lamination), TC values were higher than those measured with scan lines parallel to the bedding (TC perpendicular to the lamination), with differences reaching up to 0.5 W/m·K. These findings are consistent with those reported by Jorand et al. (2013), who also observed higher thermal conductivity parallel to the bedding than perpendicular to it. Overall, these results emphasize the importance of measuring in both orientations when analyzing laminated rocks.

A lithology-based analysis further highlights that lithological variability within the same formation can significantly affect average TC values. A notable example is the Theresa Formation, which includes quartzitic sandstones, dolomitic sandstones, and dolostones. Within this dataset, only one quartzitic sandstone sample was measured, showing particularly high TC values (5.54 W/m·K in dry and 6.38 W/m·K in saturated conditions), which strongly influences the overall average of the formation. A similar situation occurs in the Covey Hill Formation, composed of conglomerates, arkosic sandstones, and quartzitic sandstones. Arkosic sandstones yielded TC values closer to those observed in TRT results, around 3.0 W/m·K in TCS dry conditions, whereas quartzitic sandstones showed higher values, around approximately 5.0 W/m·K. Such variability underscores the importance of considering the relative proportions of each lithology when calculating representative TC values for the thermostratigraphic unit. Using simple arithmetic means may lead to over- or underestimations depending on which lithologies dominate the dataset. A weighted averaging approach, considering the proportion of each lithology within the formation, would yield more representative TC estimates, reducing potential biases when comparing laboratory and field measurements or integrating results into geothermal models.

3.2 Effect of water saturation on thermal conductivity and thermal variability along the scanned profile

The influence of water saturation is reported in Table 2. In Beauharnois, Theresa, Cairnside and Covey Hill formations, the average TC increased by approximately +11.2%, +24.3%, +21.7%, and +16.6%, respectively, under saturated conditions. These results indicate that even rocks with low to moderate porosity, around 1.8-3% in Cairnside and 5-8% in Covey Hil (Konstantinovskaya et al., 2023) can experience a significant rise in TC once pore spaces are filled with water, improving the continuity of the conductive network (Popov et al., 1999; Jorand et al., 2015). In contrast, negligible changes were observed in formations such as Tr-BR-Ch, likely due to their dense, low-porosity textures. It should be noted, however, that this analysis was performed on hand-sized samples. At larger scales, the presence of secondary permeability features such as fractures or veins could enhance the influence of water content, again reflecting the importance of scale effects in TC measurements.

Table 2. Saturation effect by thermostratigraphic unit with thermal conductivity results under dry and saturated conditions, and inhomogeneity coefficient.

	Dry			Sat			
	TC (W/m·K)	G (%)	β	TC (W/m·K)	G (%)	β	Diff TC (Sat-Dry)
Tr-BR-Ch*	2.63	2.36	0.10	2.75	2.00	0.08	0.12
Beauharnois	3.40	2.47	0.10	3.78	2.41	0.10	0.31
Theresa	3.83	4.01	0.16	4.76	3.32	0.13	0.89
Cairnside	5.07	2.34	0.09	6.12	2.31	0.09	1.21
Covey Hill	4.81	2.94	0.11	5.80	2.46	0.10	0.89

* Only 5 samples of Tr-BR-Ch were measured.

When analyzed by lithology, expected trends were observed: sandstones exhibited a stronger response to saturation than compact carbonates. Although such behavior was expected for the Covey Hill and Cairnside sandstones, it is particularly interesting in the case of the Theresa Formation, where a pronounced increase in TC under saturated conditions was also observed, unlike the Beauharnois Formation, which showed lower changes despite belonging to the same Beekmantown Group and, in general, having a similar mineralogical composition. This difference may be attributed to the transitional nature of the Theresa Formation', located between the arkosic and quartzitic sandstones of the Potsdam Group, and the dolomite Beauharnois Formation (Globensky, 1987). Consequently, the Theresa Formation retains a higher proportion of sandstone facies and associated textural characteristics, making it more sensitive to saturation effects than the Beauharnois Formation, at least at the scale of compact laboratory samples.

The thermal inhomogeneity coefficient (β) and the G-factor were used to quantify the thermal variability along each scanned profile (Popov et al., 2003; Albert et al., 2017). According to the results, all formations showed a reduction in the G-factor under saturated conditions. A similar trend was observed for the β coefficient, except in the Beauharnois and Cairnside formations, where no significant change was detected. The lower values of these parameters suggest a decrease in internal thermal heterogeneity and a more uniform heat distribution when air in the pores is replaced by water, enhancing thermal connectivity within the rock matrix. This observation is consistent with previous findings by Popov et al. (2003) and Albert et al. (2017), who reported similar homogenization effects upon saturation. The consistent increase in TC under saturated conditions, together with the systematic reduction of β and similar trend for G-factor values, supports that the adopted immersion protocol was effective in altering the moisture state of sample measured by the TCS, even though complete saturation, particularly in the innermost parts of the sample, cannot be guaranteed.

These results highlight the importance of accounting for moisture conditions, especially in formations containing more porous or fractured lithologies, when comparing laboratory and field TC measurements. TRTs are conducted under saturated *in situ* conditions, laboratory tests performed in dry samples may underestimate TC of porous rocks. Aligning laboratory measurements with field moisture conditions provides a more realistic basis for assessing whether discrepancies between TRT and laboratory results truly arise from scale effects rather than from differences in testing environments.

3.3 Integration of laboratory datasets and comparison with previous studies

The complete laboratory dataset, integrating previous results from Raymond et al. (2019) with the new TCS measurements, is summarized in Table 3. For this integration, TC values obtained under saturated conditions were used for formations that exhibited a significant moisture effect, specifically, Cairnside, Covey Hill, Theresa, and Beauharnois, while dry-condition data were retained for Caprock, Utica, and Tr–BR–Ch. The inclusion of TCS data slightly modified the average TC of several thermostratigraphic units (Figure 4). Increases were observed in Tr–BR–Ch, Theresa, and Covey Hill (+5.93%, +6.28%, and +7.71%, respectively), whereas Caprock decreased by 3.85%. Utica, Beauharnois, and Cairnside remained nearly unchanged, with variations below ±1%. The higher increase TC values in Theresa and Covey Hill are attributed to the inclusion of saturated condition TCS measurements, which yield higher results than dry laboratory tests.

The integration of the new dataset also reduced the standard deviation and variance for the Trenton and Theresa formations, suggesting improved data consistency and reduced methodological bias. In contrast, minimal changes in the remaining units indicate that their variability mainly reflects intrinsic lithological heterogeneity. Nevertheless, Theresa and Covey Hill formations still display the highest standard deviation and variance, consistent with their transitional or lithological heterogeneity nature, Theresa being a transition between arkosic–quartzitic sandstones and dolomitic facies, and Covey Hill comprising conglomerates and quartzitic to arkosic sandstones.

Overall, the integration of TCS data did not alter the general hierarchy of TC among units, which remains consistent with Raymond et al. (2019). However, the expanded dataset refines the statistical representation and spatial coverage of the SLL inventory, enhancing its reliability for regional geothermal assessments.

Table 3. Compilation of all laboratory data regardless of the measurement method used.

	W/m·K						
	Caprock	Utica	Tr - BR- Ch	Beauharnois	Theresa	Cairnside	Covey Hill
Average	2.50	2.54	2.86	3.83	4.57	6.16	5.17
Minimum	1.19	1.62	2.12	2.87	3.08	4.99	3.07

Median	2.61	2.58	2.82	3.84	4.65	6.12	5.24
Maximum	3.62	2.88	4.15	5.04	6.38	6.90	6.85
Standard deviation	0.62	0.33	0.31	0.64	1.07	0.48	1.24
Variance	0.38	0.11	0.10	0.41	1.14	0.23	1.53
Number of laboratory analysis	44	13	40	15	9	15	22
TRT (Raymond et al., 2019)	2.4	2.4	2.6	4.2	3.6	5.0	3.4
Number of TRT (Raymond et al., 2019)	24	8	22	16	4	3	2

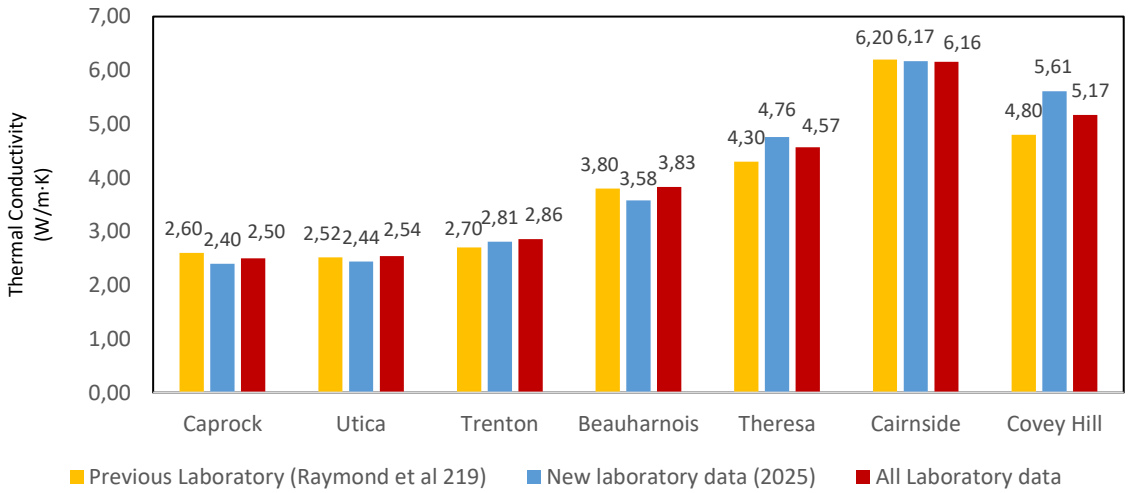


Figure 4. TC in previous laboratory dataset (Raymond et al., 2019), new dataset in TCS 2025, and all lab data integrated

3.4 Comparison between laboratory and field Measurements

The comparison between TRT results from Raymond et al. (2019) and all laboratory data and fieldwork is presented in Figure 5. In all cases except for the Beauharnois Formation, laboratory-derived TC values were higher than those obtained from TRTs. The largest discrepancies were observed in the Theresa, Cairnside, and Covey Hill formations, with differences reaching up to 1.77 W/m·K. These findings are consistent with those previously reported by Raymond et al. (2019), confirming the systematic overestimation of laboratory values compared to field data for these reservoir units.

The contrasting behavior of the Beauharnois Formation, where TRT values exceed those obtained in the laboratory, may be related to groundwater flow and saturation effects occurring at the field scale. Although saturated-state measurements were performed in this study, the influence of saturation on Beauharnois samples was found to be limited at the laboratory scale. At the regional scale, the Beauharnois Formation has been identified as a host rock for gas accumulations in the SLL (Bertrand et al., 2003; Lavoie et al., 2009). Studies have shown that porosities can locally reach values of up to 15%, and permeabilities on the order of 70 mD have been linked to dissolution processes occurring along fracture networks within the dolomitic units (Bertrand et al., 2003). While saturation effects appear minor at the sample scale, they likely become significant at the field scale, where groundwater circulation through fracture networks may strongly influence the effective thermal conductivity of the formation.

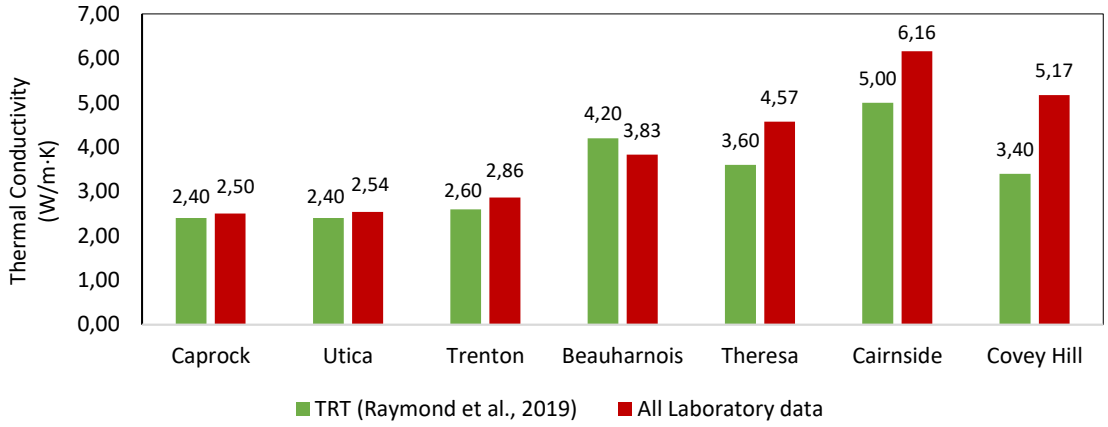


Figure 5. TC values obtained from TRTs and laboratory measurements.

The inclusion of the new TCS dataset further increased the discrepancies between laboratory and TRT results in formations such as Tr-BR-Ch, Beauharnois, Theresa, Cairnside and Covey Hill. This may be attributed to three main factors: (1) Scale effects between laboratory and field measurements, due to the inability of laboratory analyses performed on small, homogeneous samples to capture larger-scale heterogeneities, such as fractures or filled veins, that can act as barriers to heat conduction, whereas TRTs integrate these effects over a much larger rock volume; (2) Differences in testing conditions, as the present study incorporated measurements under saturated conditions, while not all previously collected laboratory samples, were tested under the same moisture condition and, (3) Data availability, since the limited number of TRT results for formations such as Theresa (n=4), Covey Hill (n=3), and Cairnside (n=2) reduces the statistical robustness of the comparison, precisely the units that exhibit the largest discrepancies between laboratory and laboratory-derived TC values.

Despite these discrepancies, the overall trends remain consistent and provide valuable insights into the relative thermal behavior of the SLL formations. The results also highlight the importance of integrating multiscale datasets, combining laboratory and field measurements, to achieve a more comprehensive understanding of conductive heat transfer in heterogeneous geological media.

For units such as the Caprock, Utica and Tr-BR-Ch, the overall discrepancies with TRT data remained small. This stability suggests a reliable thermal characterization for these units, as they exhibit lower variability and reduced uncertainty in both laboratory and field datasets. These formations also correspond to the most extensive geological units within the SLL and possess the largest number of both laboratory and TRT data points, further reinforcing the confidence in their representative TC values.

4 CONCLUSIONS

This study expanded the thermal conductivity (TC) inventory of the St. Lawrence Lowlands (SLL) by integrating 101 new laboratory measurements obtained using a Thermal Conductivity Scanner (TCS), including 78 new field samples and 23 reanalyzed samples. The TCS proved to be an effective and precise method for high-resolution TC measurements, enabling the detection of heterogeneities and improving the representativeness of laboratory analyses.

Results show that the inclusion of TCS data refined the spatial and lithological coverage of the SLL inventory and provided new information for previously unsampled formations. The expanded dataset also captures thermal anisotropy in laminated rocks, where conductivity parallel to bedding exceeds that measured perpendicular to it, emphasizing the need for directional measurements when characterizing such facies. Water saturation produced a significant increase in TC in formations containing more porous or heterogeneous lithologies, particularly Theresa, Covey Hill, Cairnside and Beauharnois (+11% to +24%). The reductions in β and G-factor under saturated conditions further indicate a homogenizing effect, as water improves thermal connectivity by replacing air in pore spaces. These results highlight the importance of conducting or correcting laboratory measurements to moisture conditions that better approximate in-situ TRT environments. Additionally, future work should incorporate direct measurements of porosity, bulk density, and elastic wave velocities on the analyzed samples to enable a more quantitative evaluation of the relationship between pore structure and the observed increase in TC under saturated conditions.

When integrated with previous datasets, the new measurements slightly modified the average TC values of several units but preserved the overall hierarchy reported in earlier studies. However, laboratory-derived TC values remain systematically higher than those from TRTs, except for the Beauharnois Formation, highlighting possible influence of scale effects. At the laboratory scale, heterogeneities such as fractures or mineralized veins are difficult to capture in small, intact samples. At the field scale, however, these features may act either as barriers to heat transfer, as is believed to occur in the Theresa, Cairnside, and Covey Hill formations, where laboratory TC exceeds TRT values; or as preferential pathways that enhance heat transfer, as suggested for the Beauharnois Formation, where TRT values are higher than laboratory measurements.

Overall, the expanded and updated dataset provides a more robust foundation for future regional analyses and supports ongoing efforts to update the thermal conductivity map of the SLL. These results contribute to improving the accuracy of geothermal models and the design of ground-coupled heat pump systems in Québec's most populated region.

Based on the findings of this study, future work aimed at updating the bedrock thermal conductivity map of the SLL should consider calculating weighted average TC values for each geological unit, accounting for the relative proportion of lithologies reported in previous studies. Using simple arithmetic means may lead to over- or underestimations depending on which lithologies dominate the dataset. A weighted averaging approach would yield more representative TC estimates, reducing potential biases when comparing laboratory and field measurements. Future analyses should also include a more detailed evaluation of scale effects using large-size rock samples to better quantify the influence of heterogeneity and discontinuities on effective thermal conductivity at different observation scales. Additionally, increasing the number of TRTs values, particularly for units with limited existing data such as the Theresa, Cairnside, and Covey Hill formations, will be important to strengthen the statistical robustness and improve correlations between laboratory and field datasets.

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