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Geothermal data from southeastern New Brunswick: Implications for potential geothermal energy projects and carbon sequestration in eastern Canada

Données géothermiques du sud-est du Nouveau-Brunswick : répercussions sur les projets éventuels d'énergie géothermique et la séquestration du carbone dans l'est du Canada

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Résumé de l'article

L'insuffisance d'information sur les gradients géothermiques a limité l'évaluation de la faisabilité des systèmes géothermiques avancés (SGA) au Nouveau-Brunswick. Les cartes existantes ont incorporé moins d'une douzaine de points de données, la majorité provenant d'investigations spécialisées et adjacente à des terres hautes centrales traversant la province du sud-ouest au nord-est. Pour compléter ces données, on a examiné les dossiers provinciaux faisant état des températures de fond des trous de forage d'exploration et on en a effectué un filtrage grossier pour repérer les données douteuses. La démarche a ajouté dans la moitié sud-est de la province plus d'une centaine de points de données qui ont été convertis en gradients géothermiques enrichissant les cartes antérieures. La carte géothermique mise à jour du sud-est du Nouveau-Brunswick indique que les gradients géothermiques dans la région correspondent en moyenne à environ 20,5 K/km, ce qui est inférieur à la moyenne mondiale de 25 K/km. Il existe toutefois des anomalies locales dans des endroits où les gradients sont très supérieurs à la moyenne mondiale. Les anomalies en question sont associées, en attendant une évaluation plus poussée, à des intrusions de sel à des profondeurs relativement faibles. Ailleurs, la présence de dépôts de sel d'une conductivité géothermique élevée a produit des « cheminées de sel » dans le cas desquelles des roches de subsurface sus-jacentes présentent des gradients géothermiques plus élevés que les régions adjacentes. En conséquence, bien que les valeurs moyennes des gradients géothermiques régionaux ne favorisent pas le recours aux SGA à grande échelle économiques utilisant les technologies existantes et puissent en plus abaisser le potentiel de séquestration économique de CO2 supercritique, l'emploi de systèmes géothermiques peu profonds, de température inférieure, pourrait être envisageable dans les endroits associés à des intrusions de sel, en particulier si une analyse plus poussée corrobore un effet de « cheminée de sel ».

Geothermal data from southeastern New Brunswick: implications for potential geothermal energy projects and carbon sequestration in eastern Canada†

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ABSTRACT

To date, assessing the feasibility of Enhanced Geothermal Systems (EGS) in New Brunswick has been limited by the lack of information pertaining to geothermal gradients. Existing maps have incorporated less than a dozen datapoints, mostly from dedicated investigations in and adjacent to the central uplands that cross the province from southwest to northeast. To supplement this data, provincial records that report Bottom Hole Temperatures from exploration boreholes have been reviewed and coarsely filtered for dubious data. This process has contributed over 100 additional datapoints in the southeastern half of the province that have been converted to geothermal gradients to supplement previous maps. The updated geothermal map of southeastern New Brunswick indicates that geothermal gradients across the region average ~20.5 K/km, which is below the global average of 25 K/km. Locally, however, potential anomalies exist where geothermal gradients are well above the global average. These anomalies, pending further assessment, are associated with relatively shallow-depth salt intrusions. Elsewhere, the presence of high geothermal conductivity salt deposits has produced "salt chimneys" whereby overlying, near-surface rocks have steeper geothermal gradients than adjacent regions. Accordingly, whereas average values for regional geothermal gradients are not conducive to economic large-scale EGS using current technologies and may also lower the potential for economic sequestration of supercritical CO_2, small-scale, lower temperature, shallow, geothermal systems may be feasible in localities associated with salt intrusions, particularly if further analysis supports a "salt-chimney" effect.

RÉSUMÉ

L'insuffisance d'information sur les gradients géothermiques a limité l'évaluation de la faisabilité des systèmes géothermiques avancés (SGA) au Nouveau-Brunswick. Les cartes existantes ont incorporé moins d'une douzaine de points de données, la majorité provenant d'investigations spécialisées et adjacente à des terres hautes centrales traversant la province du sud-ouest au nord-est. Pour compléter ces données, on a examiné les dossiers provinciaux faisant état des températures de fond des trous de forage d'exploration et on en a effectué un filtrage grossier pour repérer les données douteuses. La démarche a ajouté dans la moitié sud-est de la province plus d'une centaine de points de données qui ont été convertis en gradients géothermiques enrichissant les cartes antérieures. La carte géothermique mise à jour du sud-est du Nouveau-Brunswick indique que les gradients géothermiques dans la région correspondent en moyenne à environ 20,5 K/km, ce qui est inférieur à la moyenne mondiale de 25 K/km. Il existe toutefois des anomalies locales dans des endroits où les gradients sont très supérieurs à la moyenne mondiale. Les anomalies en question sont associées, en attendant une évaluation plus poussée, à des intrusions de sel à des profondeurs relativement faibles. Ailleurs, la présence de dépôts de sel d'une conductivité géothermique élevée a produit des « cheminées de sel » dans le cas desquelles des roches de subsurface sus-jacentes présentent des gradients géothermiques plus élevés que les régions adjacentes. En conséquence, bien que les valeurs moyennes des gradients géothermiques régionaux ne favorisent pas le recours aux SGA à grande échelle économiques utilisant les technologies existantes et puissent en plus abaisser le potentiel de séquestration économique de CO_2 supercritique, l'emploi de systèmes géothermiques peu profonds, de température inférieure, pourrait être envisageable dans les endroits associés à des intrusions de sel, en particulier si une analyse plus poussée corrobore un effet de « cheminée de sel ».

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INTRODUCTION

Greater environmental awareness of the impacts of burning fossil fuels is leading to an increased focus on renewable-energy alternatives such as geothermal energy or deep subsurface storage of captured CO_2 emissions (Michael *et al.* 2016; Vilarrasa and Rutqvist 2017; Oelkers and Gislason 2023). The economics of both alternatives are intricately tied to geothermal gradients. These gradients are due to the contrast between the hot core of the earth and its cooler surface (Fig. 1), coupled with crustal processes that (i) conductively transfer heat, such as volcanic activity and the decay of radioactive isotopes in intrusive igneous rocks, and (ii) convectively transfer heat, such as hydrothermal systems (hot springs, etc.) and petroleum migrations (Procesi *et al.* 2019; Goes *et al.* 2020).

What constitutes geothermal energy is variably defined across Canadian jurisdictions (Huang *et al.* 2024). Herein, we use the terms as follows. Where crustal processes are active, high temperature "hydrothermal" (or conventional geothermal) resources have been used for steam-powered electricity generation for over a century (Gupta and Roy 2006). Elsewhere, most other industrial-scale geothermal potential lies in the "unconventional geothermal" or "Enhanced Geothermal Systems" (EGS), using heat-mining technologies to directly utilize stored thermal energy (Tester *et al.* 2007; Breede *et al.* 2013). To date, active large-scale EGS systems utilize temperatures of ~390 K (~120° C) or higher (e.g., Cloetingh *et al.* 2010; Blöcher *et al.* 2016; Lu 2018), although with technological and other advances, development of this "deep unconventional geothermal" resource currently appears possible with temperatures as low as ~330 K (Guo *et al.* 2018). Although heat energy is ubiquitous throughout the subsurface, being sourced from Earth's core, it requires extensive deep-drilling programs to access and exploit at a large (industrial or community) scale. At the scale of individual buildings and greenhouses, low-temperature (280–370 K), "shallow unconventional geothermal" resources are economically accessible at shallower depths and utilized through closed-loop geo-heat pumps, or through heat transfer of the "warm" groundwater via heat exchangers (Gupta and Roy 2006).

Effective subsurface sequestration of CO_2 is dependent on the captured CO_2 being stored in pore space as a supercritical fluid (i.e., as dense as a liquid, but flows like a gas and with no surface tension; Span and Wagner 1996). This state requires pressures of >7500 kPa, temperatures of >308 K, and suitable reservoir quality and volume. Current carbon storage projects often utilize existing infrastructure originally developed to extract oil and gas to pump back waste CO_2 that has been separated from natural gas or produced from burning the fossil fuels (e.g., at Sleipner in Norway and Weyburn in Saskatchewan, Canada; Ferguson 2013). Where such infrastructure is not available, deep-drilling programs similarly must be completed to access sufficiently high temperature and pressure subsurface reservoirs (saline aquifers).

For both EGS and sequestration in saline reservoirs to be economically viable, drilling costs must be minimized. Many interlinked factors impact costs, including operator and labour expenses and expertise; drilling-rig type, demand, and operational efficiency (e.g., number of casing-strings, drill-bit replacements, and loss-of-circulations), as well as geological conditions (rock properties, overpressures, undesirable gases, etc.) and depth (length if not drilled vertical) of the borehole (Kaiser 2007; Lukawski *et al.* 2014; Shamoushaki *et al.* 2021). Time-related factors, such as time to drill to target depth, is estimated to directly and indirectly account for about fifty percent of total costs (Lukawski *et al.* 2014). Steeper geothermal gradients that minimize required drilling depth are therefore advantageous.

For Maritimes Canada, subsurface temperatures and basic thermal models have been recorded in several academic and government reports over several decades (e.g., Jessop 1968; Hyndman *et al.* 1979; Reiter and Jessop 1985; Drury *et al.* 1987; Grasby *et al.* 2012). As reported in Keighley and Maher (2015), these data were reviewed for initial Canada-wide assessments for CO_2 storage and, in estimating the required depth to achieve supercritical CO_2, consensus was to assume a geothermal gradient of ~25 K/km or ~ 60mW/m^2, which globally is often reported (e.g., Allen and Allen 2013) as the average gradient for the upper continental crust. Thus, assuming a somewhat high average annual surface temperature of 283 K for New Brunswick, supercriticality would be achieved below ~1 km depth (Keighley and Maher 2015). At a similar gradient, industrial-scale EGS currently would be viable at below ~4 km depth. Most recently, Carey *et al.* (2023) used 0.8 km as the depth above which supercriticality was highly unlikely.

These earlier reports, however, have not incorporated all thermal data available for New Brunswick, such as those from the files of onshore petroleum and salt-potash exploration boreholes. Only now are more complete regional geothermal assessments from the Maritime Provinces (e.g., Comeau *et al.* 2020; de Luca *et al.* 2021; Skinner and Wach 2021; Raymond *et al.* 2022), and adjacent areas such as the Gaspé Peninsula of Quebec (Chabot Bergeron *et al.* 2016) being compiled. In this paper we provide a fuller assessment of the regional thermal gradients for the southeastern half of New Brunswick, where almost all the available subsurface data for the entire province is sourced; in the process, we provide an updated geothermal map for the study area and discuss the implications of this map.

GEOLOGICAL SETTING

Southeastern New Brunswick (Fig. 2) is underlain by a "basement" of various igneous, metamorphic, and sedimentary rock related to multiple peri-Gondwanan passive margin, volcanic arc, and back arc terranes (Miramichi, Annidale, St. Croix, New River, Brookville, and Caledonia) that were successively accreted against the Laurentian continental margin during the early Paleozoic, and their

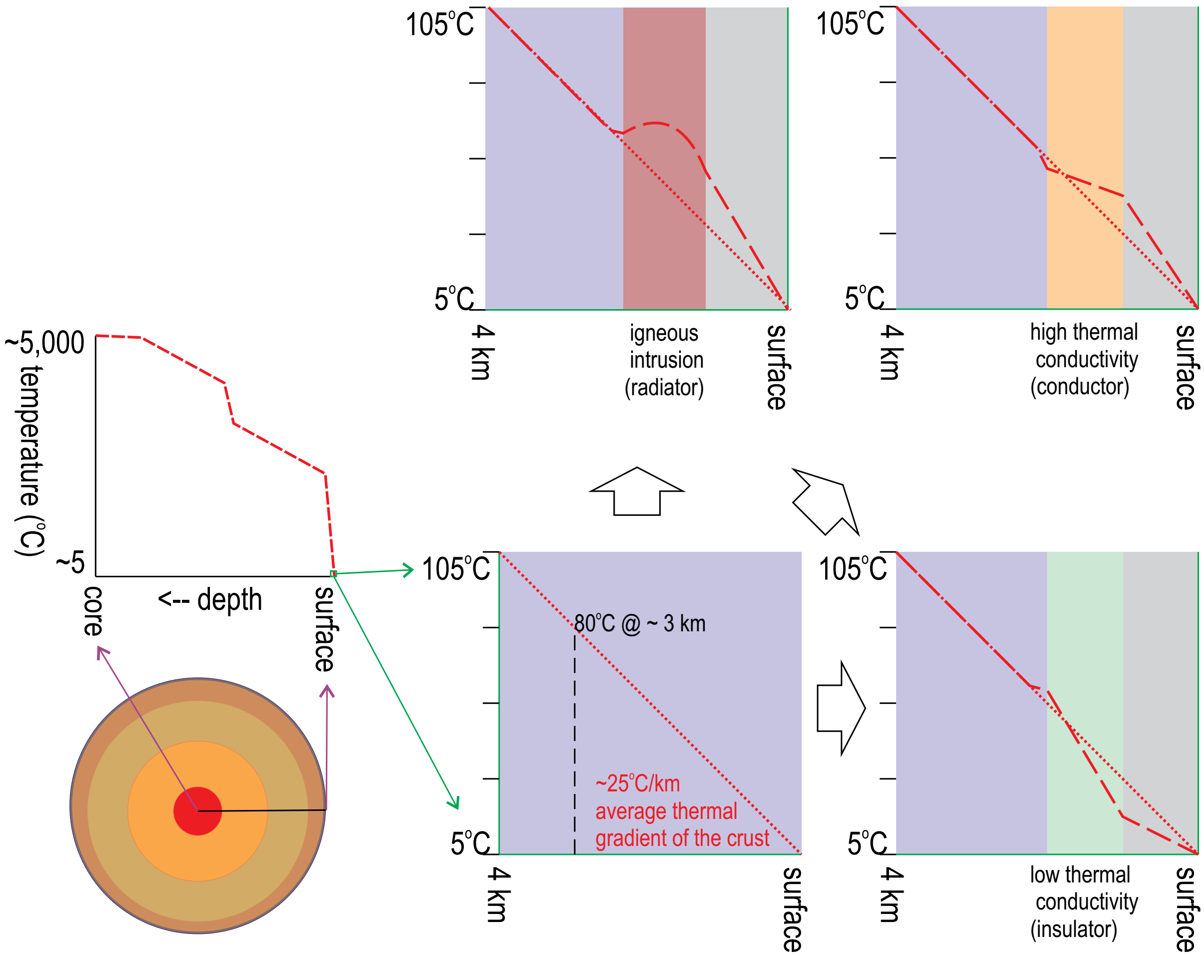

Figure 1. Diagrams to illustrate earth's geothermal gradient and how (near-surface) layers of rock of different composition, and hence thermal conductivity, can influence the gradient.

sedimentary cover sequences (Fyffe *et al.* 2011, 2023; Waldron *et al.* 2022). They occur within numerous fault-bounded linear belts that follow the regional SW-NE fabric imposed by the Acadian Orogeny and earlier accretionary orogenic events (Fyffe *et al.* 2011, 2023). Reactivation of these boundary faults in a transpressional setting during ongoing collision of Gondwana with Laurentia (Alleghanian Orogeny) uplifted and eroded these belts in the later Paleozoic. In contemporaneous areas of transtension, numerous pull-apart basins (in the study area these are the Cocagne Graben, Moncton, Sackville, and Cumberland basins; Fig. 2) accommodated the variably kilometres-thick succession of Devonian–Carboniferous pebbly to muddy clastic sediment shed from the uplifts (e.g., Keighley 2008; Craggs *et al.* 2017). Post-orogenic thermal relaxation resulted in a Pennsylvanian–Permian siliciclastic cover sequence (Greater Maritimes Basin) that blanketed the earlier, more localized pull-apart basins and many of the interspersed, eroded uplifts (collectively the Maritimes Basin Complex, Keighley 2008). Partly overlapping the southernmost areas are deposits of the Fundy Basin, which developed as one of a series of half-graben rift basins on some of the old terrane-boundary faults, possibly by the latest Permian and continuing through to the Jurassic (Sues and Olsen 2015). This rifting reflected break-up of Pangaea and was precursor to the opening of the Atlantic Ocean. Basin subsidence allowed for the accumulation of several kilometres of sediment and basalt flows associated with the latest Triassic to possibly earliest Jurassic Central Atlantic Magmatic Province (Kontak 2008; Withjack *et al.* 2009). Subsequently, only very localized, poorly consolidated Cretaceous sediment (Falcon-Lang *et al.* 2003) has been preserved in what has been primarily an erosive and otherwise generally inactive geological region for over 150 million years.

METHODS

Records examination and data limitations

Information is available from the New Brunswick Geological Survey pertaining to provincial drilling records of over 800 boreholes, mostly from wells drilled in southeastern New Brunswick. These well reports cover the years from 1909 to 2011 and are associated with a variety of commercial and public drilling projects. The records are therefore

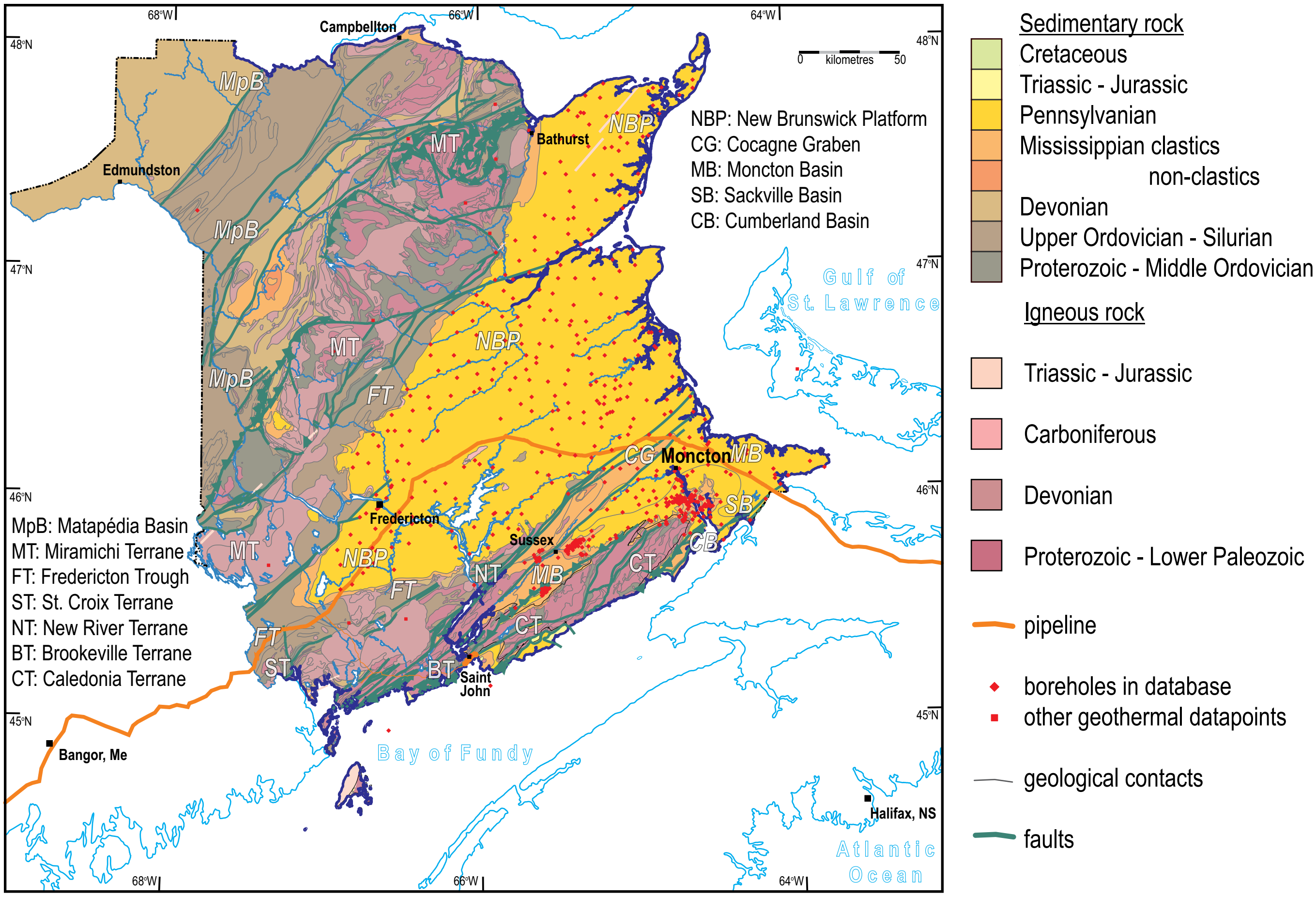

Figure 2. Geological map of New Brunswick with overprinted locations of existing geothermal data and locations of boreholes that were reviewed for information regarding bottom hole temperature. BT = Brookville Terrane, CB = Cumberland Basin, CG = Cocagne Graben, CT = Caledonia Terrane, FT = Fredericton Trough, MB = Moncton Basin, MpB = Matapedia Basin, MT = Miramichi Terrane, NBP = New Brunswick Platform, NT = New River and Annidale, Terranes, SB = Sackville Basin, ST = St Croix Terrane.

non-standardized and vary in the legibility, quantity, and reliability of information that they provide, thus introducing uncertainties into estimates of geothermal gradients (Kolawole and Evenick 2023). However, these sources provide the only additional temperature data available. We compiled each borehole's unique identifying number, longitude and latitude, elevation (ground or Kelly Bushing), total measured depth, degree of inclination (calculated or taken directly from the deviation survey), true vertical depth, and bottom hole temperature (BHT) in Microsoft® Excel spreadsheets. Borehole locations are shown in Figure 2. Many of the boreholes are extremely shallow (<100 m and thus likely subject to surface temperature fluctuations) or do not have a record of BHT; these boreholes are therefore excluded from the review. We assume that boreholes that do not have a record of any deviation have been drilled vertically. A few otherwise complete well records have been discarded because of contradictory data (e.g., two different BHTs lacking timestamps in different reports from the same well) or otherwise suspect data. For example, following Comeau *et al.* (2020), significantly elevated temperatures at depths of less than 300 m were rejected because seasonal surface temperatures might have affected the temperature reading, or because there was insufficient documented time allowed for the heat of the drilling bit to have dissipated before the temperature reading was taken (Bullard 1947; Blackwell and Spafford 1987). Some researchers in mid-continent North America also applied corrections to BHTs in those locations based on thousands of available records (e.g., Crowell *et al.* 2012), but we deemed this unworkable for our data because of the paucity of documented BHT readings, and times of readings. Indeed, we considered only 107 of the well records to have an "initially acceptable" value for construction of a more complete geothermal contour map of southeastern New Brunswick. Published data from twelve additional locations, such as the geothermal surveys noted in the introduction that included data from an onshore well nearby in western Prince Edward Island, are also included in the mapping (Fig. 2). The data are far from evenly distributed, with a predominance of drillholes south of Moncton (corresponding to the Stoney Creek oil and gas field) and around Sussex (McCully gas field and salt mining).

Geothermal calculations and mapping

For the "initially acceptable" boreholes, geothermal gradients are calculated by subtracting surface temperature ($T_{surface}$) from the BHT, then dividing by true vertical depth (TVD). The results are then multiplied by 1000 to achieve values for the average change in temperature per kilometre depth in units of K/km; thus:

Geothermal Gradient = 1000 (BHT – $T_{surface}$) / TVD

Note that geothermal gradients can also be estimated by dividing a measured heat flow, Q, in milliW/m^2, by an averaged thermal conductivity of the rock, k, in W/m·K, over that depth interval. Conversions included in this manuscript use k = 2.7 W/m·K following, e.g., Goes *et al.* (2020). There are also numerous ways of measuring Q, e.g., Clauser and Huenges (1995).

Average surface temperatures are known only for weather stations near the major urban centres in southeastern New Brunswick, and they vary only from 278 to 279.5 K (Government of Canada 2024). Accordingly, since surface temperature at a borehole location is likely some unknown value between these two temperatures and dependent on local microclimate, a constant 278.5 K is adopted as the surface temperature for all boreholes.

Once all subsurface thermal gradients were calculated, we produced a geothermal contour map using commercially available software (Surfer™ by Golden Software). Each datapoint on the map (Fig. 3) equates to one borehole, where longitude is assigned to the x-axis, latitude to the y-axis, and the calculated geothermal gradient to the z-axis. The kriging gridding method is used because of the widely uneven geographic distribution of datapoints, and no inferences are made outside of the main data hull (i.e., the map was left blank beyond the northwesternmost datapoints containing acceptable BHT data).

RESULTS AND DISCUSSION

For the 119 accepted datapoints, the mean value of the geothermal gradient for the uppermost crust in southeastern New Brunswick is ~20.5 K/km, with all except seven of the datapoints being within 12 K of this average (i.e., 9–32 K/km; Fig. 3), and only 27 lying at or above the global average of 25 K/km. The limited datapoints recorded across the Miramichi Terrane and New Brunswick Platform, all of which have low thermal gradients, skew the map representation (Fig. 3) and makes the below-global-average gradients for the uppermost crust appear even more extensive.

The geothermal contour map, however, reveals three "bullseye" areas with anomalously high subsurface temperature gradients; these areas are concentrated in two regions, one south of Moncton and two near Sussex. Both bullseye regions have well mapped, typically diapiric, salt deposits at less than 1.5 km depth (Wilson and White 2006). These deposits include anhydrite, halite, and potash, which are crustal rock types with some of the highest measured thermal conductivities (over 5 W/mK) and thus may be acting as localized "salt chimneys" (Zhuo *et al.* 2016; Canova *et al.* 2018), bringing warmer subsurface temperatures closer to the surface. For example, up to 16 K/km increase in thermal gradients are noted in Saskatchewan (Moore and Holländer 2020), and T of 25 K higher than enclosing strata have been noted in the Netherlands (Daniilidis and Herber 2017); however, Raymond *et al.* (2022), while noting gradients exceeding 40 K/km under the Magdalen Islands, cautioned that this effect is limited to shallow salt intrusions. Hitherto unidentified hydrothermal fluids circulating near the anomalies is another explanation, albeit speculative, that cannot be ruled out. Alternatively, the anomalies could represent additional examples of false BHT readings where insufficient time was allowed (but not clearly reported) for the heat of the drilling bit to have dissipated before the temperature reading was taken (Bullard 1947). If all twelve of the bullseye datapoints indicating geothermal gradients above 30 K/km are considered false readings and removed from the database, the mean value of the geothermal gradient would be revised downward to 18.4 K/km. Many of the remaining datapoints above the global average are also from the same salt-bearing regions and if they too are removed from the analysis, the mean geothermal gradient drops even further. A further screening of these bullseye anomalies, indeed all datapoints used to construct the map, requires additional investigations such as thermal modelling of each borehole. This is beyond the scope of the present contribution. At this stage, the bullseye anomalies are considered real and potentially indicative of shallow salt chimneys, but caution is strongly advised. Regardless, southeastern New Brunswick has predominantly low geothermal gradients that can be considered to extend into the rest of the Maritimes, given the similar geology in Prince Edward Island, Nova Scotia, and contiguous offshore regions. Indeed, in their assessment of the fewer borehole datapoints available in Nova Scotia, Comeau *et al.* (2020) indicated that the Springhill/Athol REI-B1-4 (P-104) borehole, less than 4 km southwest of mapped salt wells in the Cumberland Basin, has the highest corrected geothermal gradient of 28.18 K/km for that province.

The low geothermal gradients across southeastern New Brunswick and adjacent regions therefore conform with the fact that eastern Canada has been generally inactive tectonically for at least the last 150 million years, and that most major intrusive igneous bodies in the region are of Devonian or older age. As a broad approximation, global rates of heat flow at the surface decrease with increasing age of crust or increasing time since orogeny, e.g., higher values of 90–60 mW/m^2 (33.3–22.2 K/km) or more in currently tectonically active regions, lower values of 50–30 mW/m^2 (18.5–11.1 K/km) in Archaean cratons (Artemieva and Mooney 2001; Goes *et al.* 2020). Kolawole and Evenick (2023) recently suggested that the heat-flow values noted above are appropriate for new and old oceanic crust, but on continents lower geothermal gradients better correlate with increased crustal thickness. Further, they considered that sedimentary basins,

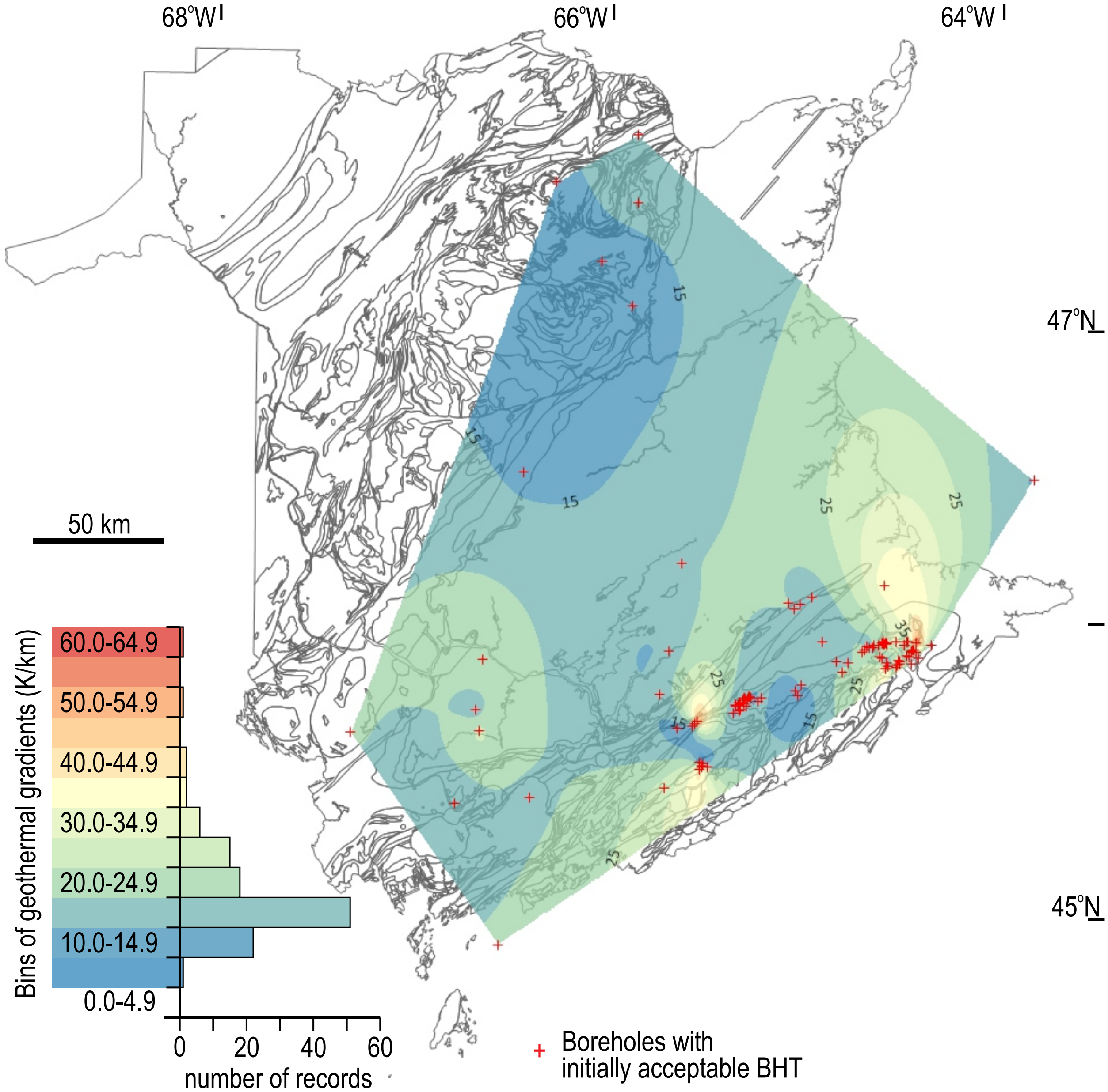

Figure 3. Histogram of geothermal gradients reported in New Brunswick from previous work or determined from bottom-hole temperatures (BHT), and same data reported geospatially using Surfer software (see text for data filtering and processing details).

such as the Maritimes and Fundy basins, exhibit distinct ranges of gradients that reflect their prevalent tectonic and geodynamic origins. Kolawole and Evenick (2023) also provided more supporting evidence to earlier studies suggesting that rates of heat flow will decline exponentially once a certain time interval has passed since active tectonism has occurred, rapid sedimentation or exhumation has ceased, or a certain crustal or lithospheric thickness is exceeded; these authors also noted that after ~50 million years values stabilize.

The New Brunswick data additionally indicate that, with current technologies requiring temperatures of ~390 K, industrial-scale EGS will only be available at greater than ~5.5 km depth (5.5 km @ 20.5 K/km average gradient, plus surface T of 278.5 K ≈ 391 K). Likely, technological improvements, which either reduce drilling costs and/or enhance heat extraction at lower temperatures, will be required before industrial-scale EGS can be widely developed economically in southeastern New Brunswick and adjacent areas. This does not preclude the economic development of shallower (lower temperature) small geothermal projects such as that investigated by the town of Sussex for development above its salt mine (Town of Sussex 2024), particularly if a "salt chimney" effect holds up to further scrutiny. Springhill in northern Nova Scotia has been extracting heat from mine waters since 1994 to aid with home heating.

Our findings have implications also for CO_2 sequestration potential in the region. Assessment values used to date, e.g., supercriticality at 1 km depth by Keighley and Maher (2015) and 800 m depth by Carey *et al.* (2023) likely overestimate the overall geothermal gradient and hence underestimate the depth at which CO_2 will be a supercritical fluid. With a 20.5 K/km geothermal gradient and average surface T = 278.5 K, a depth of ~1.44 km is required before T = 308 K and supercriticality is achieved. To counter the lack of CO_2 compressibility at shallower depths, a volumetrically much larger reservoir, for example, would be required. These implications further lower the sequestration potential for southeastern New Brunswick (central lowlands / New Brunswick Platform and the southeastern lowlands / Moncton–Sackville Basins), as well as the western Gulf of St Lawrence and Prince Edward Island, where declining porosities and permeabilities occur below 1 km depth (Lavoie *et al.* 2009). The revised estimate for the geothermal gradient may not affect the sequestration potential for the Bay of Fundy, where the Irving–Chevron *et al.* Cape Spencer No. 1 well, drilled near an anticlinal crest, contains two sands, 36 and 37 m thick, of very high porosity and permeability below 1.45 km depth (Keighley and Maher 2015).

CONCLUSIONS

A review of provincial borehole records has recovered BHT data for over 100 locations in southeastern New Brunswick. These data, publicly available although of highly variable quality and hence reliability, have been converted to geothermal gradients to supplement previous data-poor maps of the province. The updated geothermal map of southeastern indicates that geothermal gradients average ~20.5 K/km across the region, which is below the global average of 25 K/km. With current technology, such gradients are not currently conducive to economic large-scale EGS and may also lower the potential for economic sequestration of supercritical CO_2. Locally, potential anomalies that will require further verification exist where geothermal gradients are well above the global average and where development of small-scale, lower temperature geothermal systems may be warranted. These anomalies are associated with relatively shallow-depth salt intrusions that elsewhere, such as under the Magdalen Islands, have raised near-surface geothermal gradients to 40 K/km.

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REFERENCES

Allen, P.A. and Allen, J.R. 2013. Basin analysis: principles and applications. John Wiley and Sons Ltd., West Sussex, UK, 560 pp.

Artemieva, I.M. and Mooney, W.D. 2001. Thermal thickness and evolution of Precambrian lithosphere: a global study. Journal of Geophysical Research, 106, pp. 16 387–16 414. https://doi.org/10.1029/2000JB900439

Blackwell, D.D. and Spafford, R.E. 1987. Experimental methods in continental heat flow. *In:* Geophysics, part B, field measurements, Methods of Experimental Physics, 24. *Edited by* C.G. Sammis and T.L. Henyey. Academic Press, Orlando, pp. 189–226. https://doi.org/10.1016/S0076-695X(08)60599-2

Blöcher, G., Reinsch, T., Henninges, J., Milsch, H., Regenspurg, S., Kummerow, J., Francke, H., Kranz, S., Saadat, A., Zimmermann, G., and Huenges, E. 2016. Hydraulic history and current state of the deep geothermal reservoir Groß Schönebeck. Geothermics, 63, pp. 27–43. https://doi.org/10.1016/j.geothermics.2015.07.008

Breede, K., Dzebisashvili, K., Liu, X., and Falcone, G. 2013. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geothermal Energy 1, 27 pp. https://doi.org/10.1186/2195-9706-1-4

Bullard, E.C. 1947. The time necessary for a bore hole to attain temperature equilibrium. Geophysics Journal International, 5, pp. 127–130. https://doi.org/10.1111/j.1365-246X.1947.tb00348.x

Canova, D.P., Fischer, M.P., Jayne, R.S., and Pollyea, R.M. 2018. Advective heat transport and the salt chimney effect: a numeral analysis. Geofluids, 2378710. 18 pp. https://doi.org/10.1155/2018/2378710

Carey, J.S., Skinner, C.H., Giles, P.S., Durling, P., Plourde, A.P., Jauer, C., and Desroches, K. 2023. Preliminary assessment of geological carbon-storage potential of Atlantic Canada. Geological Survey of Canada, Open File 8996, 90 pp. https://doi.org/10.4095/332145

Chabot Bergeron, A., Raymond, J., Malo, M., and Comeau, F.-A. 2016. Évaluation du potentiel de génération d'électricité géothermique en Gaspésie: régions de la vallée de la Matapédia et de Gaspé (No. 1661). Institut national de la recherche scientifique - Centre Eau Terre Environnement, Québec, 69 pp.

Clauser, C. and Huenges, E. 1995. Thermal conductivity of rocks and minerals. *In* Rock physics and phase relations: a handbook of physical constants. *Edited by* T.J. Ahrens. American Geosciences Institute, Shelf 3, pp.105–126. https://doi.org/10.1029/RF003p0105

Cloetingh, S., Van Wees, J.D., Ziegler, P., Lenkey, L., Beekman, F., Tesauro, M., Förster, A., Norden, B., Kaban, M., Hardebol, N., Bonte, D., Genter, A., Guillou-Frottier, L., Ter Voorde, M., Sokoutis, D., Willingshofer, E., Cornu, T., and Worum, G. 2010. Lithosphere tectonics and thermos-mechanical properties: an integrated modelling approach for enhanced geothermal systems exploration in Europe. Earth-Science Reviews, 102, pp. 159–206. https://

doi.org/10.1016/j.earscirev.2010.05.003

Comeau, F-A., Séjourné, S., and Raymond, J. 2020. Assessment of geothermal resources in onshore Nova Scotia. Report for the Offshore Energy Research Association, 214 pp.

Craggs, S., Keighley, D., Waldron, J.W.F., and Park, A. 2017. Salt tectonics in an intracontinental transform setting: Cumberland and Sackville basins, southern New Brunswick, Canada. Basin Research, 29, pp. 266–283. https://doi.org/10.1111/bre.12152

Crowell, A.M., Ochsner, A.T., and Gosnold, W. 2012. Correcting bottom-hole temperatures in the Denver Basin: Colorado and Nebraska. Geothermal Resources Council Transactions, 36, pp. 201–206.

Daniilidis, A. and Herber, R. 2017. Salt intrusions providing a new geothermal exploration target for higher energy recovery at shallow depths. Energy, 118, pp. 658–670. https://doi.org/10.1016/j.energy.2016.10.094

DeLuca, J., Keighley, D., Hinds, S., Park, A., Bateman, R., and Harris, A. 2021. New Brunswick geothermal maps and databases: an update. Exploration, Mining and Petroleum New Brunswick 2021 Conference. Abstract volume GR2021, p. 6.

Drury, M.J., Jessop, A.M., and Lewis, T.J. 1987. The thermal nature of the Canadian Appalachian crust. Tectonophysics, 133, pp. 1–14. https://doi.org/10.1016/0040-1951(87)90276-9

Falcon-Lang, H.J., Fensome, R.A., and Venugopal, D.V. 2003. The Cretaceous age of the Vinegar Hill silica sand deposit, southern New Brunswick. Atlantic Geology, 39, pp. 39–46. https://doi.org/10.4138/1048

Ferguson, G. 2013. Subsurface energy footprints. Environmental Research Letters, 8, 014037, 6 pp. https://doi.org/10.1088/1748-9326/8/1/014037

Fyffe, L.R., Johnson, S.C., and van Staal, C.R. 2011. A review of Proterozoic to early Paleozoic lithotectonic terranes in the northeastern Appalachian orogen of New Brunswick, Canada, and their tectonic evolution during Penobscot, Taconic, Salinic, and Acadian orogenies. Atlantic Geology, 47, pp. 211–248. https://doi.org/10.4138/atlgeol.2011.010

Fyffe, L.R., van Staal, C.R., Wilson, R.A., and Johnson, S.C. 2023. An overview of early Paleozoic arc systems in New Brunswick, Canada, and eastern Maine, USA. Atlantic Geology, 59, pp. 1–28. https://doi.org/10.4138/atlgeo.2023.001

Goes, S., Hasterok, D., Schutt, D.L., and Klöcking, M. 2020. Continental lithospheric temperatures: a review. Physics of the Earth and Planetary Interiors, 306, 106509, 18 pp. https://doi.org/10.1016/j.pepi.2020.106509

Government of Canada. 2024. Canadian climate normal and averages. URL <https://climate.weather.gc.ca/climate_normals/index_e.html>, 15 May 2024.

Grasby, S.E., Allen, D.M., Bell, S., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J., and Therrien, R. 2012. Geothermal energy resource potential of Canada. Geological Survey of Canada, Open File Report 6914, 301 pp. https://doi.org/10.4095/291488

Guo, X., Song, H., Killough, J., Du, L., and Sun, P. 2018. Numerical investigation of the efficiency of emission reduction and heat extraction in a sedimentary geothermal reservoir: a case study of the Daming geothermal field in China. Environmental Science and Pollution Research, 25, pp. 4690–4706. https://doi.org/10.1016/j.tecto.2017.01.024

Gupta, H. K. and Roy, S. 2006. Geothermal energy: an alternative resource for the 21st Century. Elsevier Science & Technology, 279 pp.

Huang, K., Dehghani-Sanij, A., Hickson, C., Grasby, S.E., Smejkal, E., Miranda, M.M., Raymond, J., Fraser, D., Harbottle, K., Torres, D.A., Ebell, J., Dixon, J., Olsen, E., Vany, J., Marci, K., Colpron, M., Wigston, A., Brasnett, G., Unsworth, M., and Harms, P. 2024. Canada's geothermal energy update in 2023. Energies, 17, 1807, 34 pp. https://doi.org/10.3390/en17081807

Hyndman, R.D., Jessop, A.M., Judge, A.S., and Rankin, D.S. 1979. Heat flow in the Maritime Provinces of Canada. Canadian Journal of Earth Sciences, 16, pp. 1154–1165. https://doi.org/10.1139/e79-102

Jessop, A.M. 1968. Three measurements of heat flow in eastern Canada. Canadian Journal of Earth Sciences, 5, pp. l–8. https://doi.org/10.1139/e68-006

Kaiser, M.J. 2007. A survey of drilling cost and complexity estimation models. International Journal of Petroleum Science and Technology, 1, pp. 1–22. https://doi.org/10.2118/98401-PA

Keighley, D. 2008. A lacustrine shoreface succession in the Albert Formation, Moncton Basin, New Brunswick. Bulletin of Canadian Petroleum Geology, 56, pp. 235–258. https://doi.org/10.2113/gscpgbull.56.4.235

Keighley, D. and Maher, C. 2015. A preliminary assessment of carbon storage suitability in deep underground geological formations of New Brunswick. Special Series: Environmental Geosciences. Atlantic Geology, 51, pp. 269–286. https://doi.org/10.4138/atlgeol.2015.011

Kolawole, F. and Evenick, J.C. 2023. Global distribution of geothermal gradients in sedimentary basins. Geoscience Frontiers, 14, 101685, 18 pp. https://doi.org/10.1016/j.gsf.2023.101685

Kontak, D.J. 2008. On the edge of CAMP: geology and volcanology of the Jurassic North Mountain Basalt, Nova Scotia. Lithos, 101, pp. 74–101. https://doi.org/10.1016/j.lithos.2007.07.013

Lavoie, D., Pinet, N., Dietrich, J., Hannigan, P., Castonguay, S., Hamblin, A.P., and Giles, P. 2009. Petroleum resource assessment, Paleozoic successions of the St. Lawrence Platform and Appalachians of eastern Canada. Geological Survey of Canada, Open File 6174, 273 pp. https://doi.org/10.4095/248071

Lu, S-M. 2018. A global review of enhanced geothermal system (EGS). Renewable and Sustainable Energy Reviews, 81, pp. 2902–2921. https://doi.org/10.1016/j.rser.2017.06.097

Lukawski, M.Z., Anderson, B.J., Augustine, C., Capuano, L.E., Jr, Beckers, K.F., Livesay, B., and Tester, J.W. 2014. Cost analysis of oil, gas, and geothermal well drilling. Journal of Petroleum Science and Engineering, 118, pp. 1–14. https://doi.org/10.1016/j.petrol.2014.03.012

Michael, K., Whittaker, S., Varma, S., Bekele, E., Langhi, L., Hodgkinson, J., and Harris, B. 2016. Framework for the assessment of interaction between CO_2 geological storage and other sedimentary basin resources. Environmental Science Processes and Impacts, 18, pp. 164–175. https://doi.org/10.1039/C5EM00539F

Moore, K.R. and Holländer, H.M. 2020. Feasibility of low-temperature geothermal systems: considerations of thermal anomalies, geochemistry, and local assets. Applied Energy, 275, 115412. 13 pp. https://doi.org/10.1016/j.apenergy.2020.115412

Oelkers, E.H. and Gislason, S.R. 2023. Carbon capture and storage: from global cycles to global solutions. Geochemical Perspectives, 12, pp. 179–349. https://doi.org/10.7185/geochempersp.12.2

Procesi, M., Ciotoli, G., Mazzini, A., and Etiope, G. 2019. Sediment-hosted geothermal systems: review and first global mapping. Earth-Science Reviews, 192, pp. 529–544. https://doi.org/10.1016/j.earscirev.2019.03.020

Raymond, J., Langevin, H., Comeau, F.A., Malo, M. 2022. Temperature dependence of rock salt thermal conductivity: implications for geothermal exploration. Renewable Energy, 184, pp. 26–35. https://doi.org/10.1016/j.renene.2021.11.080

Reiter, M. and Jessop, A.M. 1985. Estimates of terrestrial heat flow in offshore eastern Canada. Canadian Journal of Earth Sciences, 22, pp. 1503–1517. https://doi.org/10.1139/e85-156

Shamoushaki, M., Fiaschi, D., Manfrida, G., Niknam, P.H., and Talluri, L. 2021. Feasibility study and economic analysis of geothermal well drilling. International Journal of Environmental Studies, 78, pp. 1022–1036. https://doi.org/10.1080/00207233.2021.1905309

Skinner, C. and Wach, G. 2021. Geothermal potential of positive temperature anomalies above salt structures in Nova Scotia. Abstract, First European Association of Geoscientists and Engineers Workshop on Geothermal Energy in Latin America, August 2021, v. 2021, pp.1–3. https://doi.org/10.3997/2214-4609.202182005

Span, R. and Wagner, W. 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. Journal of Physical and Chemical Reference Data, 25, pp. 1509–1596. https://doi.org/10.1063/1.555991

Sues, H-D. and Olsen, P.E. 2015. Stratigraphic and temporal context and faunal diversity of Permian–Jurassic continental tetrapod assemblages from the Fundy rift basin, eastern Canada. Atlantic Geology, 51, pp. 139–205. https://doi.org/10.4138/atlgeol.2015.006

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, M.N., Veatch, R.W., Baria, R., Augustine,C., Murphy, E., Negraru, P., and Richards, M. 2007. Impact of enhanced geothermal systems on US energy supply in the Twenty-First Century. Philosophical Transactions: Mathematical, Physical and Engineering Sciences, 365, pp. 1057–1094. https://doi.org/10.1098/rsta.2006.1964

Town of Sussex, 2024. Geothermal feasibility study. URL <https://sussex.ca/documents/geothermal-feasibility-study/>, 15 May 2024.

Vilarrasa, V. and Rutqvist, J. 2017. Thermal effects on geologic carbon storage. Earth-Science Reviews, 165, pp. 245–256. https://doi.org/10.1016/j.earscirev.2016.12.011

Waldron, J.W.F., McCausland, P.J.A., Barr, S.M., and Schofield, D.I. 2022. Terrane history of the Iapetus Ocean as preserved in the northern Appalachians and western Caledonides. Earth-Science Reviews, 233, 104163, 75 pp. https://doi.org/10.1016/j.earscirev.2022.104163

Wilson, P. and White, J.C. 2006. Tectonic evolution of the Moncton Basin, New Brunswick, eastern Canada: new evidence from field and sub-surface data. Bulletin of Canadian Petroleum Geology, 54, pp. 319–336. https://doi.org/10.2113/gscpgbull.54.4.319

Withjack, M.O., Schlische, R.W., and Baum, M.S. 2009. Extensional development of the Fundy rift basin, southeastern Canada. Geological Journal, 44, pp. 631–651. https://doi.org/10.1002/gj.1186

Zhuo Q.G., Meng, F.W., Zhao, M.J., Li, Y., Lu, X.S., and Ni, P. 2016. The salt chimney effect: delay of thermal evolution of deep hydrocarbon source rocks due to high thermal conductivity of evaporites. Geofluids, 16, pp. 440–451. https://doi.org/10.1111/gfl.12162

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