Thermal History of the Liard Basin in Northern British Columbia and Western Northwest Territories (NTS 095B, 095C, 094J, 094K and 094N)

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Introduction

The Liard Basin in British Columbia (BC) and the Northwest Territories (NWT; Figure 1) is a prolific energy-resource area that hosts hydrocarbon reservoirs and anomalously high geothermal gradients (40–55 °C/km; Grasby et al., 2012). Due to the economic potential of geothermal resources, areas such as the Liard Basin are of increasing interest for exploration. This is an economic opportunity for diesel-dependent communities such as Fort Nelson, where the Tu Deh-Kah First Nation geothermal-energy project can upscale their economy by providing electricity and heat for greenhouse food production and district heating. However, unlike other well-known geothermal-resource areas in Canada (e.g., Mount Meager; Grasby et al., 2012), many questions remain about the geological processes that allowed the high geothermal gradients in the Liard Basin to develop. The aim of this project is to investigate the thermal history of the basin.

The Liard Basin is part of the Western Canada Sedimentary Basin (WCSB; Figure 1). Its history and stratigraphy are closely linked to orogenies (e.g., Klondike, Cordilleran; e.g., Mossop and Shetsen, 1994; Beranek and Mortensen, 2011), resulting in a wide range of depositional environments (e.g., deltaic, shelf, deep marine). Basement structures (e.g., Bovie Structure, Liard transfer zone) also influenced sedimentation and erosional patterns within the basin (e.g., Leckie et al., 1991; Cecile et al., 1997). The multiple phases of subsidence and erosion that are expected to have affected the basin are potentially linked to the development of the geothermal anomaly. The speed at which hot rocks at depth are brought to surface by uplift and erosion could result in a lack of time for isotherms to equilibrate. This disequilibrium, in turn, would manifest itself as high geothermal gradients in the shallow subsurface. The hypothesis being proposed is that the anomalously high geothermal gradients in parts of the Liard Basin are a consequence of the basin's erosional history. To test this hypothesis, low-temperature thermochronology is being carried out on outcrop and borehole samples from the Liard Basin.

The dataset comprises samples of different depositional age, depth and position in relation to the Cordilleran Fold-and-Thrust Belt. These characteristics enabled an examination of different time slices of the basin's history, which in turn can be used to build a more complete picture of the basin's history through time. The main questions of this project are 1) how is the heating and cooling of the Liard Basin related to major tectonic and erosional events that took place in western Canada? and 2) is there a spatial correlation between the thermal history of the Liard Basin and the geothermal gradients observed today? To answer these questions, 1) thermochronological analysis will be performed on 16 outcrop and 4 borehole samples from across the Liard Basin to constrain their thermal history; and 2) models will be developed that explain the different thermal histories within the region. Ultimately, a basin-wide model will be created that incorporates the different thermal histories, structures, stratigraphy and geothermal-gradient variations. Understanding the thermal evolution of the basin over time and in different regions is critical to understanding when and why the basin underwent heating events that led to the development of the hydrocarbon and geothermal, or potential geothermal, resources.

Geological Background

The WCSB is a wedge-shaped basin that records the long-lived history of the western margin of the North American continent (Figure 2; e.g., Mossop and Shetsen, 1994). Its stratigraphy overlies the Precambrian Canadian Shield and is defined by a Cambrian to Middle Jurassic passive-margin sequence (Figure 2) that evolved after the Neoproterozoic–Cambrian rifting. This sequence is overlain by an Upper Jurassic to Cenozoic foreland-basin sequence (Figure 2) that developed as the result of terrane accretion and collisional tectonics during the Klondike and Cordilleran orogenies (e.g., Beranek and Mortensen, 2011; Monger and Gibson, 2019).

The Liard Basin is part of the WCSB and is bounded to the east by the north-northeast-trending Bovie Structure (Fig-

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[1] The lead author is a 2024 Geoscience BC Scholarship recipient.

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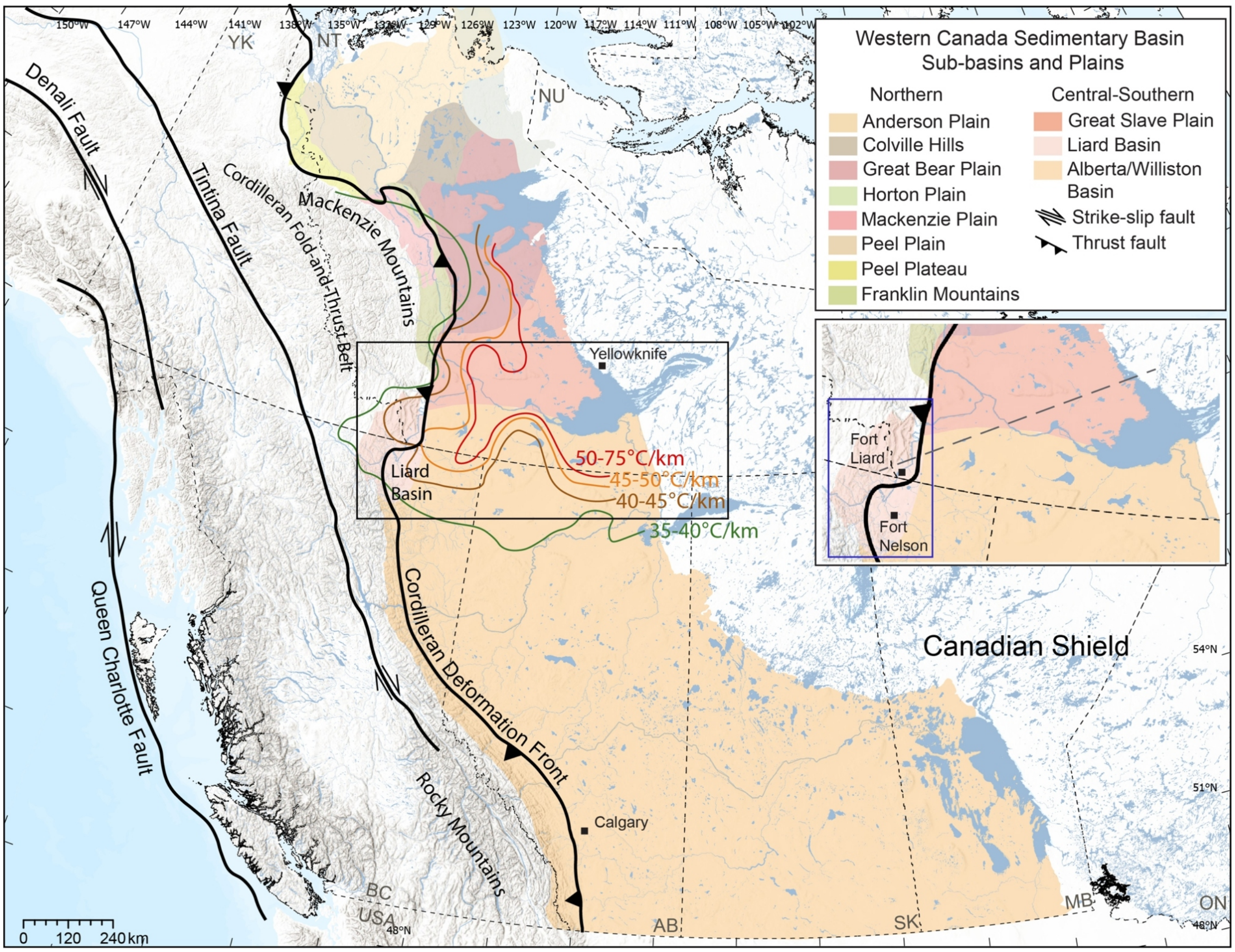

Figure 1. Western Canada Sedimentary Basin, with the study area marked by the blue box. Basins and sub-basins after Mossop et al. (2004). Schematic geothermal-gradient contours after Grasby et al. (2012). Dashed grey line on the inset map indicates the location of the schematic cross-section shown in Figure 2. Base map was created using ArcGIS® software by Esri. ArcGIS® is the intellectual property of Esri and is used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit <https://esri.ca/>.

ure 2), which is a fault that extends to the basement, and to the west by the Cordilleran Fold-and-Thrust Belt (Figures 1 and 2). The Bovie Structure was reactivated several times during the Phanerozoic (Leckie et al., 1991; MacLean and Morrow, 2004), which resulted in the deposition of anomalously thick upper Paleozoic and middle Cretaceous strata (Leslie-Panek and McMechan, 2021). For instance, the Carboniferous (Mississippian–Pennsylvanian) Mattson Formation is more than a kilometre thick in the Liard Basin, whereas it is only a few metres thick on the Great Slave Plain, east of the Bovie Structure (Figures 1 and 2; Leckie et al., 1991; Wright et al., 1994).

The Liard Basin is also known for its hydrocarbon resources. Examples of hydrocarbon source rocks are the Devonian Road River and Triassic Toad-Grayling formations, and examples of reservoir rocks are the Devonian Nahanni and Cretaceous Chinkeh formations (Rocheleau and Fiess, 2014). They underwent at least two phases of heating within the oil-maturity window, one in the Devonian and the other between the Triassic and Cretaceous (e.g., Morrow et al., 1993; Jiang et al., 2021). This information sheds light on the complexity of the thermal history of the basin, where multiple phases of heating occurred. The timing of such events is not fully constrained, nor is the cause of such heating.

Geothermal Systems

Heat in the upper crust is generated by decay of radioactive elements (e.g., U, Th, K) and also originated from primordial heat related to Earth's formation (e.g., Grasby et al., 2012). Geothermal systems are generally characterized by enhanced heat flows accompanied by thermal blanketing to trap heat. In Canada, the heat flows in the Canadian Shield and Canadian Cordillera are approximately 30 MW/m^2 and 60 MW/m^2, respectively (Jessop, 1990). However, several locations in western Canada have much higher values, such as the Garibaldi Volcanic Belt region (Mount Meager,

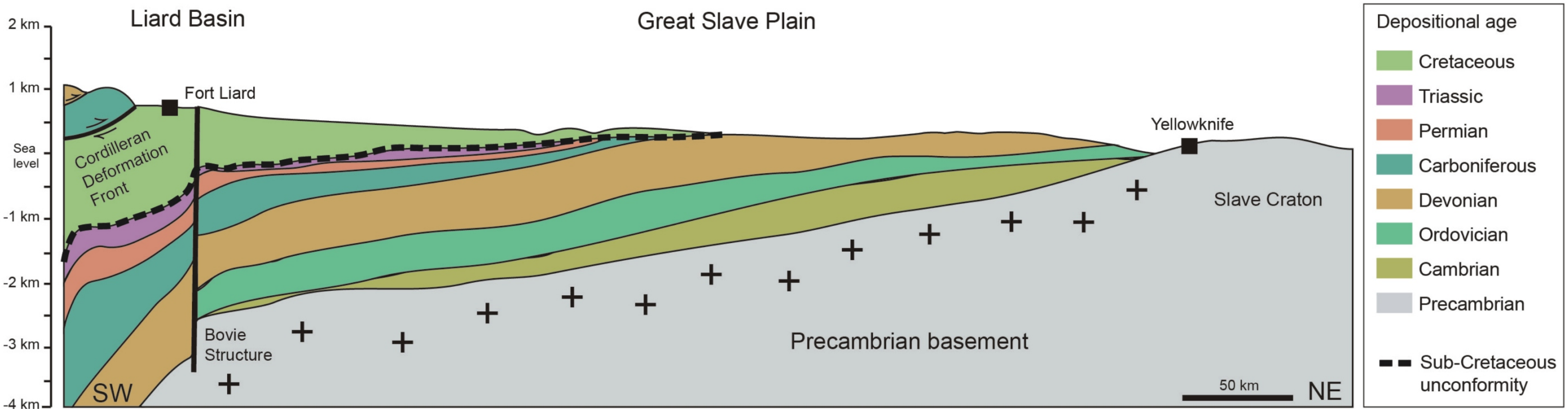

Figure 2. Schematic cross-section across the Cordilleran Fold-and-Thrust Belt, Western Canada Sedimentary Basin and exposed Canadian Shield (dashed grey line in the Figure 1 inset). Stratigraphic units after Mossop et al. (1994) and Rocheleau and Fiess (2014).

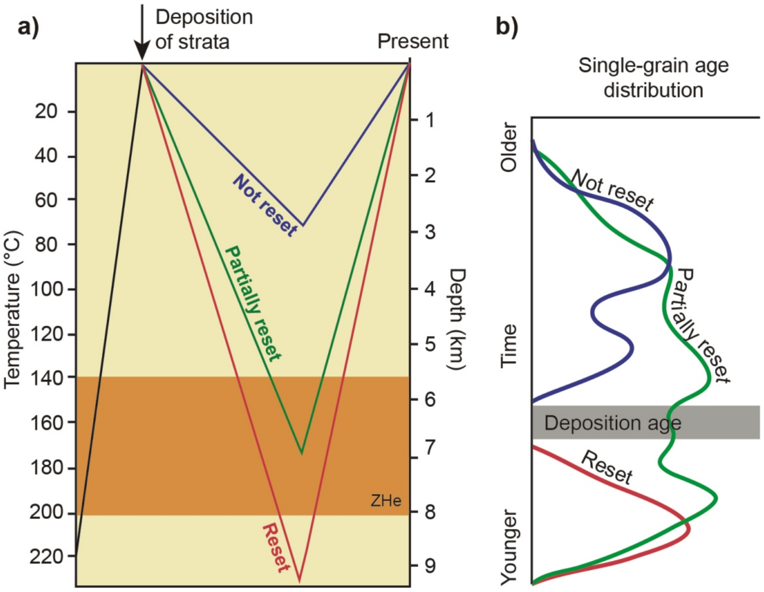

Figure 3. Theoretical thermal histories of rocks that experienced different amounts of heating due to burial in a basin: **a)** partial retention zone (PRZ) of the zircon (U-Th)/He system is in orange; **b)** schematic date distribution of zircon

southwestern BC; >200 MW/m^2) and the Liard Basin and Great Slave Plain (70 MW/m^2; Figure 1; Grasby et al., 2012). In the Liard Basin, thermal blanketing is key to the development of geothermal anomalies within lower conductivity rocks (i.e., coal, shale) that allow thermal trapping. The origin of the geothermal anomalies is not well understood. The subject has been studied extensively, considering parameters such as basin-wide fluid flow, basement heat production and the presence of younger magmatic rocks (e.g., Majorowicz and Jessop, 1981; Majorowicz, 1996). The most recent hypothesis is that basement heat production is higher than previously thought (Majorowicz, 2018). However, no evidence for this has been found.

Methods

Low-temperature thermochronology is used to constrain the thermal history of upper crustal rocks. These dating methods are temperature-sensitive and can therefore record processes that thermally affect rocks. Examples of heating-related processes are burial and hydrothermal activity, and cooling can be caused by rock exhumation and denudation. In this study, zircon (U-Th)/He (ZHe) analysis constrains heating and cooling between 140 and 200 °C (Reiners et al., 2004; Guenthner et al., 2013).

The ZHe is based on alpha decay of the parent nuclides uranium-238 (^{238}U), uranium-235 (^{235}U) and thorium-232 (^{232}Th) to their stable daughter isotope helium-4 (^{4}He, alpha particle; Farley et al., 2002). The dates determined by ZHe analysis will be a function of the thermal history of the rock. In the case of sedimentary rocks with complex thermal histories (postdepositional heating due to burial and cooling due to erosion), the dates are interpreted based on the extent to which the rock was exposed to temperatures in the Partial Retention Zone (PRZ; ZHe, 140-200 °C; Reiners et al., 2004; Guenthner et al., 2013). In sedimentary rocks, each grain already carries a cooling age that records its source-rock cooling history. If burial after deposition reaches temperatures >PRZ, the He is lost by diffusion (reset; Figure 3, red line), resulting in dates younger than deposition that record cooling after burial. If maximum burial is limited to temperatures <PRZ, most He is kept, resulting in dates older than deposition (not reset), and each grain records their source region (Figure 3, blue line). If temperatures were within the PRZ, single-grain dates will vary from younger to older than deposition age (partially reset; Figure 3, green line). Thermal history modelling should be performed to define possible time-temperature paths that statistically fit the data and further explore the rock's possible cooling/heating histories (Ketcham, 2005).

In order to obtain the zircon fraction and perform the ZHe dating, the study samples were first subjected to mineral-separation procedures. These include, in order, jaw crusher, disk mill, water table, magnetic separator and heavy-liquid separation (heteropolytungstate [LST] and methylene iodide [MI]; e.g., McKay et al., 2021). After mineral separation, the samples containing zircons were identified and dated. Individual zircons were picked under a stereomicroscope, aiming for euhedral, transparent and inclusion-free grains. However, this was not always possible due to the age and history of the rocks, which directly influence mineral yield and grain quality. After picking, width and length of the grains were measured for later use in alpha-ejection date correction (Ft correction). The Ft correction was necessary to account for He that was ejected from the grain during al-

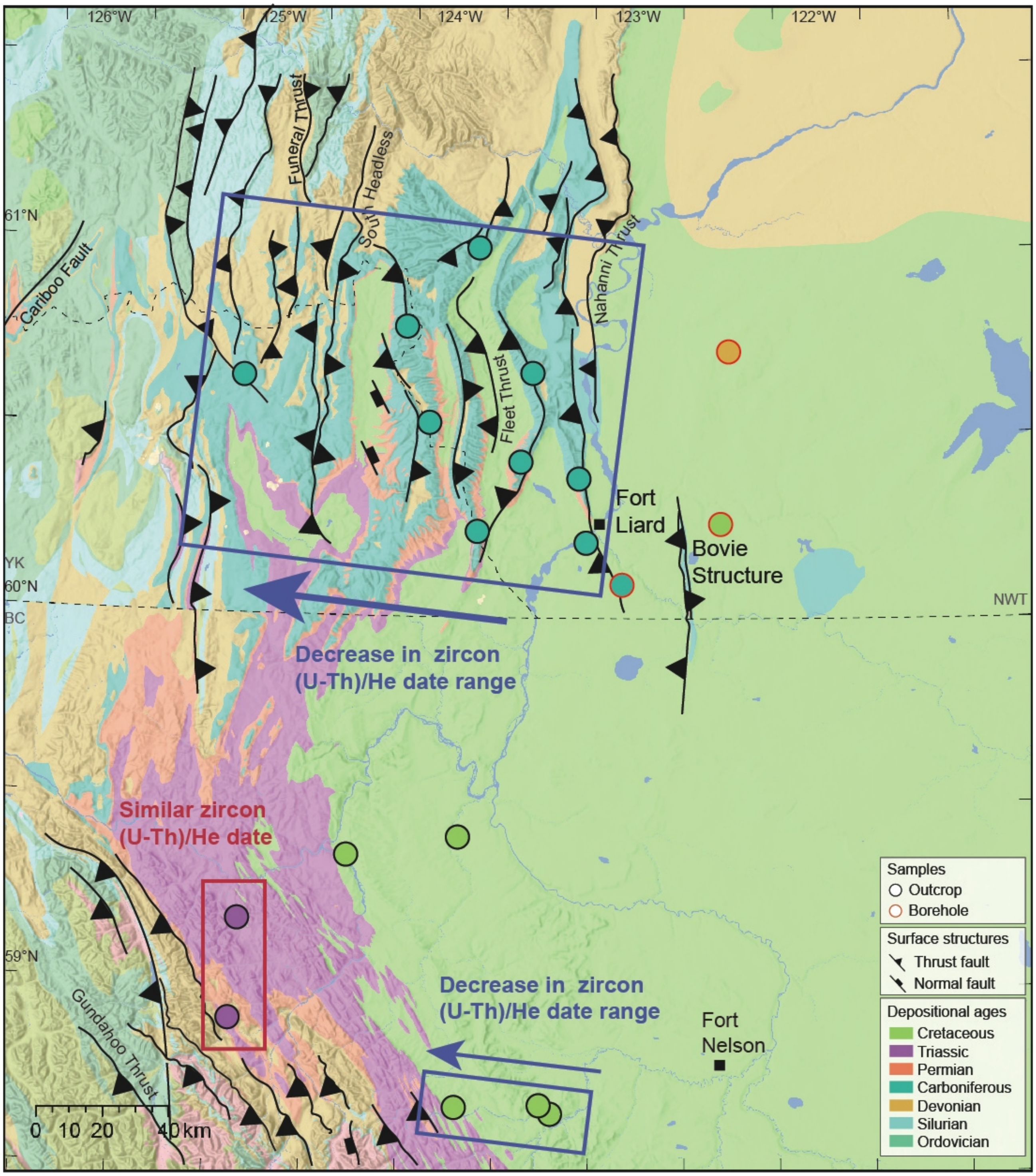

Figure 4. Geology of the Liard Basin, showing locations of zircon (U-Th)/He dated samples. Samples are colour-coded according to their stratigraphic age. Coloured boxes mark samples with similar date patterns, the arrows indicating trends toward samples with younger dates. Geological units and structures from digital databases (Alberta Geological Survey, 2013; Lipovsky and Bond, 2014; Cui et al., 2017; Okulitch and Irwin, 2017).

pha decay. The grains were packed in Nb tubes and analyzed to quantify their daughter He content (using a He-extraction line) and parent U and Th content (using solution ICP-MS). Due to the expected complexity of the thermal history in the area, five grains were dated per sample. All analyses were conducted at the University of Calgary Geo- and Thermochronology Laboratory.

Results

The 16 outcrop and 4 borehole samples taken across the Liard Basin (Figure 4) are from units that vary with respect to the depositional age. The majority are Carboniferous, with fewer Cretaceous, Triassic and Devonian ages. The results are presented for British Columbia and the Northwest Territories (Figure 4).

The depositional ages of the samples in BC are Triassic (Ludington Formation) and Cretaceous (Dunvegan, Sikanni, Scatter and Garbutt formations). The Triassic samples present ZHe dates that range from Jurassic to Cretaceous. Due to their ZHe dates being younger than deposition, postdepositional burial temperatures reached >140 °C. These samples are the only ones in the entire study area that show a very similar range of dates (Figure 4). Conversely, all of the Cretaceous samples present ZHe dates that are Cretaceous and older. This suggests that postdepositional burial was limited to temperatures of 140-200 °C. The Cretaceous strata in the eastern part of BC yield ZHe dates ranging from middle Carboniferous to early Cretaceous. In the western part of the area, Triassic samples yield ZHe dates ranging from early to late Cretaceous. These dates portray a trend that becomes younger and less dispersed toward the west (Figure 4). This preliminary assessment of the ZHe dates in the area could indicate that the Triassic strata experienced higher postdepositional temperatures than the Cretaceous strata.

The depositional ages of samples in the Northwest Territories are primarily Carboniferous (Mattson and Prophet formations), and fewer samples are Devonian (basal clastics) and Cretaceous (unspecified). The Carboniferous outcrop samples yielded ZHe dates that generally range from Cambrian to Cretaceous. However, the range of ZHe dates varies from sample to sample, depending on their geographic location. For example, the easternmost sample has a Cambrian–Triassic ZHe date range, suggesting they are partially reset, while the westernmost sample has a Triassic–Cretaceous ZHe range, indicating that it has been reset. Overall, the ZHe dates and date range decrease toward the west (Figure 4). Based on this, it can be stated that the postdepositional burial temperatures were higher toward the west but are still limited to maximum temperatures of 140-200 °C. The westernmost sample likely experienced >200 °C. The Carboniferous borehole samples are located at depths of 1.2 km and 1.6 km. Their ZHe dates are older than those of their outcrop counterparts, ranging from Neoproterozoic to Carboniferous, which suggests partial resetting. The Devonian borehole sample (from a depth of 2.4 km) is also partially reset but with a Cambrian–Cretaceous ZHe range. Finally, the Cretaceous borehole sample from 0.5 km presents a Neoproterozoic–Ordovician ZHe range and is therefore interpreted as not reset, having experienced post-depositional burial temperatures of <140 °C. This ZHe dataset from across the Liard Basin thus enables a better understanding of the maximum burial experienced across the basin. The upcoming thermal history modelling will link their histories with the distribution of the geothermal gradients in the basin (Figure 1).

Summary

This paper summarizes current progress in constraining the thermal history of the Liard Basin and its possible link to the development of the high geothermal gradients in the area. The southern Liard Basin presents Triassic strata that experienced postdepositional maximum temperatures >200 °C, while Cretaceous strata experienced 140-200 °C. In the northern Liard Basin, Carboniferous strata all experienced temperatures between 140 and 200 °C. However, the range of ZHe dates is gradually less dispersed and younger toward the west, suggesting that rocks in the west experienced higher temperatures than those in the east. The link between the maximum burial temperatures and the current geothermal gradient cannot be stated at the moment, given the need to quantify erosional/exhumation rates of the analyzed samples. Thermal-history modelling is currently underway to quantify the timing and rates of cooling of these rocks. Only through modelling it will be possible to constrain whether erosion was fast enough to result in isotherms not having time to equilibrate, hence generating the observed high geothermal gradients.

Understanding how geothermal anomalies develop is critical in guiding future exploration efforts. Geothermal energy is one of the most promising energy alternatives due to its potential for long-term use and low-carbon footprint. For diesel-dependent remote communities in northern BC and NWT especially, the use of geothermal heat would be beneficial in providing energy autonomy and reliability. Geothermal heat could be used by communities not only for district heating, but also for greenhouse food production and wood-pellet drying, creating many economic opportunities. Heating alone currently accounts for 80% of the energy demand (Majorowicz and Grasby, 2021), so making use of the geothermal resources would have a significant impact on the health, environment and economic and social well-being of all northern communities.

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References

Alberta Geological Survey (2013): Geology of Alberta, Digital Data 2013-0018, URL <https://ags.aer.ca/publication/dig-2013-0018> [November 2024].

Beranek, L.P. and Mortensen, J.K. (2011): The timing and provenance record of the Late Permian Klondike orogeny in northwestern Canada and arc-continent collision along western North America; Tectonics, v. 30, no. 5, TC5017, URL <https://doi.org/10.1029/2010TC002849> [November 2024].

Cecile, M.P., Morrow, D.W. and Williams, G.K. (1997): Early Paleozoic (Cambrian to Early Devonian) tectonic framework, Canadian Cordillera; Bulletin of Canadian Petroleum Geology, v. 45, no. 1, p. 54–74.

Cui, Y., Miller, D., Schiarizza, P. and Diakow, L.J. (2017): British Columbia digital geology; British Columbia Ministry of Energy, Mines and Low Carbon Innovation, British Columbia Geological Survey Open File 2017-8, 9 p., data version 2019-12-19, URL <https://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/british-columbia-geological-survey/geology/bcdigitalgeology> [November 2024].

Farley, K.A. and Stockli, D.F. (2002): (U-Th)/He dating of phosphates: apatite, monazite, and xenotime; Reviews in Mineralogy and Geochemistry, v. 48, p. 559–577, URL <https://doi.org/10.2138/rmg.2002.48.15> [November 2024].

Grasby, S.E., Allen, D.M., Bell, S., Chen, Z., Ferguson, G., Jessop, A.M., Kelman, M.C., Ko, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R. (2012): Geothermal energy resource potential of Canada (revised); Geological Survey of Canada, Open File 6914, 322 p., URL <https://doi.org/10.4095/291488> [November 2024].

Guenthner, W.R., Reiners, P.W., Ketcham, R.A., Nasdala, L. and Giester, G. (2013): Helium diffusion in natural zircon: radiation damage, anisotropy, and the interpretation of zircon (U-Th)/He thermochronology; American Journal of Science, v. 313, no. 3, p. 145–198, URL <https://doi.org/10.2475/03.2013.01> [November 2024].

Jessop, A.M., editor (1990): Thermal geophysics; Developments in Solid Earth Geophysics, v. 17, Elsevier Publishing Co., 305 p., URL <https://webapps.unitn.it/Biblioteca/it/Web/EngibankFile/Thermal%20geophysics.pdf> [November 2024].

Jiang, C., Bennett, B., Ferri, F., Chen, Z., Ardakani, O.H. and McMechan, M. (2021): Geochemistry of the Cretaceous Chinkeh oil from Maxhamish field and Garbutt black shale in the Liard Basin, Canada: implications for a liquid-rich shale hydrocarbon resource; International Journal of Coal Geology, v. 238, URL <https://doi.org/10.1016/j.coal.2021.103716> [November 2024].

Ketcham, R.A.(2005): Forward and inverse modeling of low-temperature thermochronometry data; Reviews in Mineralogy and Geochemistry, v. 58, no. 1, p. 275–314, URL <https://doi.org/10.2138/rmg.2005.58.11> [November 2024].

Leckie, D.A., Potocki, D.J. and Visser, K. (1991): The Lower Cretaceous Chinkeh Formation: A frontier-type play in the Liard Basin of western Canada; AAPG Bulletin, v. 75, p. 1324–1352, URL <https://doi.org/10.1306/0C9B2943-1710-11D7-8645000102C1865D> [November 2024].

Leslie-Panek, J. and McMechan, M. (2021): A seismic structural overview of Liard Basin, northeast British Columbia, Canada; Interpretation, v. 9(2), T523-T532, URL <https://doi.org/10.1190/INT-2020-0078.1> [October 2024].

MacLean, B.C. and Morrow, D.W (2004): Bovie Structure: its evolution and regional context; Bulletin of Canadian Petroleum Geology, v. 52, no. 4, p. 302–324, URL <https://doi.org/10.2113/52.4.302> [November 2024].

Majorowicz, J.A. (1996): Anomalous heat flow regime in the western margin of the North American craton; Canada; Journal of Geodynamics, v. 21, no. 2, p. 123–140, URL <https://doi.org/10.1016/0264-3707(95)00020-2> [November 2024].

Majorowicz, J.A. (2018): Heat flow–heat production relationship not found: what drives heat flow variability of the Western Canadian foreland basin? International Journal of Earth Sciences, v. 107, p. 5–18, URL <https://doi.org/10.1007/s00531-016-1352-x> [November 2024].

Majorowicz, J.A. and Grasby, S.E. (2021): Deep geothermal heating potential for the communities of the Western Canada Sedimentary Basin; Energies, v. 14, no. 3, p. 706, URL <https://doi.org/10.3390/en14030706> [November 2024].

Majorowicz, J.A. and Jessop, A.M., (1981): Regional heat flow patterns in the Western Canadian Sedimentary Basin; Tectonophysics, v. 74, no. 3–4, p. 209–238, URL <https://doi.org/10.1016/0040-1951(81)90191-8> [November 2024].

McKay, R., Enkelmann, E., Hadlari, T., Matthews, W. and Mouthereau, F. (2021): Cenozoic exhumation history of the eastern margin of the Northern Canadian Cordillera; Tectonics, v. 40, URL <https://doi.org/10.1029/2020TC006582> [November 2024].

Monger, J.W.H. and Gibson, H.D. (2019): Mesozoic–Cenozoic deformation in the Canadian Cordillera: the record of a "Continental Bulldozer"? Tectonophysics, v. 757, p. 153–169, URL <https://doi.org/10.1016/j.tecto.2018.12.023> [November 2024].

Morrow, D.W., Potter, J., Richards, B. and Goodarzi, F. (1993): Paleozoic burial and organic maturation in the Liard Basin Region, northern Canada; Bulletin of Canadian Petroleum Geology, v. 41, no. 1, p. 17–31, URL <https://pubs.geoscienceworld.org/cspg/bcpg/article-abstract/41/1/17/57579/Paleozoic-burial-and-organic-maturation-in-the?redirectedFrom=fulltext> [November 2024].

Mossop, G.D. and Shetsen, I., compilers (1994): Geological atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council, URL <https://ags.aer.ca/reports/atlas-western-canada-sedimentary-basin> [November 2024].

Mossop, D.D., Wallace-Dudley, K.E., Smith, G.G. and Harrison, J.C., compilers (2004): Sedimentary Basins of Canada; Geological Survey of Canada, Open File 4673, scale 1:5 000 000, URL <https://doi.org/10.4095/215559> [November 2024].

Okulitch, A.V. and Irwin, D. (2017): Geological compilation of the western mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09, ESRI® digital files and PDF files, URL <https://ntgs-open-data-ntgs.hub.arcgis.com/datasets/369a2fe1a6604ce7b270965fbea1a7e0/about> [November 2024].

Reiners, P.W., Spell, T.L, Nicolescu, S. and Zanetti, K.A. (2004): Zircon (U-Th)/He thermochronometry: He diffusion and comparisons with ^{40}Ar/^{39}Ar dating; Geochimica et Cosmochimica Acta, v. 68, no. 8, p. 1857–1887, URL <https://doi.org/10.1016/j.gca.2003.10.021> [November 2024].

Rocheleau, J. and Fiess, K.M., (2014): Northwest Territories Oil and Gas Poster Series: Basins and Petroleum Resources, Table of Formations, Schematic Cross Sections; Northwest Territories Geoscience Office, NWT Open File 2014-03, 3 posters (supersedes NWT Open File 2007-03), URL <https://doi.org/10.46887/2014-03> [November 2024].

Wright, G.N., McMechan, M.E. and Potter, D.E.G., (1994): Structure and architecture of Western Canada Sedimentary Basin; Chapter 3 *in* Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, URL <https://ags.aer.ca/atlas-the-western-canada-sedimentary-basin/chapter-3-structure-and-architecture> [November 2024].

Yukon Geological Survey (2023): Surficial geology dataset; Yukon Geological Survey, https://data.geology.gov.yk.ca/Compilation/33 [November 2024].