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Geothermal Potential of Alberta: Intermediate-Depth Temperature Mapping and Precambrian Basement Characterization

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Summary

Geothermal resource assessment in Alberta is increasingly supported by integrated, regional-scale geoscience datasets developed through multidisciplinary initiatives at the Alberta Geological Survey (AGS). This abstract presents new insights from (1) province-wide intermediate-depth (150–1000 m) temperature mapping using high-graded well-based temperature data, and (2) Precambrian basement characterization, focusing on petrography, radiogenic heat production (RHP), thermal conductivity, rock mechanics, and Curie point depth (CPD). Intermediate-depth temperature mapping supports low-enthalpy geothermal applications such as ground-source heat pumps, thermal energy storage, and district heating, by focusing on shallow subsurface thermal conditions across the province. Basement characterization addresses deeper geothermal potential relevant to advanced systems such as enhanced geothermal systems (EGS) and closed-loop technologies.

Initial results in southern Alberta from intermediate-depth temperature mapping show a predominantly linear increase of temperature with depth, consistent with regionally conductive geothermal gradients across Alberta. New petrographic and geochemical data reveal systematic variability in radiogenic heat production across basement tectonic domains, constraining crustal heat generation and its contribution to regional heat flow. Curie point depth estimates indicate marked spatial variability in lithospheric thermal structure, with relatively shallow Curie point depths in parts of southwestern, east-central, and northwestern Alberta. Laboratory measurements show that basement thermal conductivity is controlled by lithology and fabric and decreases with temperature, while rock mechanical testing confirms that basement rocks are generally strong and brittle, potentially favourable for sustaining fracture networks under stimulation. Together, these results provide an updated evaluation of Alberta's geothermal resource base across both intermediate-depth and Precambrian basement settings.

Background

Alberta's geothermal potential spans both the Western Canada Sedimentary Basin (WCSB) and the underlying Precambrian basement. Previous assessments have focused primarily on Devonian stratigraphic units and basin-scale heat-flow mapping (Grasby et al., 2011; Weides & Majorowicz, 2014; Banks and Harris, 2018). For example, Brinsky et al. (2022) developed a three-dimensional temperature model for the Alberta Basin from 1000 m depth to the top of the Precambrian basement, improving upon previous basin-scale thermal studies. Initiatives such as the *Geothermal Atlas of Alberta* by the AGS utilized temperature data from Brinsky et al. (2022) for formation-scale favourability mapping and resource estimation for key Devonian units, including the Leduc, Swan Hills / Slave Point, and Granite Wash. However, comprehensive geothermal characterization requires integration across all depth intervals, from near-surface direct-use

systems through the sedimentary column and into the Precambrian basement for advanced geothermal technologies.

Intermediate-depth geothermal resources are increasingly recognized as practical low-enthalpy energy sources for space heating, cooling, and seasonal thermal-energy storage. Various studies demonstrate that mapping of subsurface temperature and geothermal gradients is essential for deployment of such technologies (e.g., Arola et al., 2014). In Alberta, despite the availability of extensive downhole temperature data from legacy oil and gas wells, a standardized temperature model for this depth interval is still outstanding. AGS is therefore compiling and conducting quality control on well-based temperature data to develop province-wide temperature and geothermal-gradient maps for the intermediate depth interval.

The crystalline Precambrian basement beneath Alberta is a large, geologically complex, and underexplored geothermal target, especially for enhanced geothermal systems (EGS) and closed-loop technologies. It consists of Archean to Paleoproterozoic igneous and metamorphic rocks, subdivided into at least 17 lithotectonic domains, intersected by major crustal structures. Lithologies include granitoids, quartzofeldspathic gneisses, granulites, and metasedimentary and metavolcanic rocks, many exhibiting amphibolite to granulite facies metamorphism and strong foliation, imparting anisotropy to thermal and mechanical behaviour. Geothermal feasibility in the basement is governed by thermal state, crustal heat generation, heat transfer properties, and rock mechanics controlling borehole stability and fracture development (Wang et al., 2023). Previous studies indicate elevated thermal regimes in parts of Alberta relative to the exposed Canadian Shield, suggesting significant contributions from crustal heat generation and lithospheric thermal structure (Weides & Majorowicz, 2014; Majorowicz et al., 2014; Majorowicz, 2016). However, direct measurements of basement RHP, thermal conductivity, and mechanical properties have been sparse. This study integrates new petrographic analysis and laboratory measurements with regional geophysical constraints to link geothermal potential to basement geology and tectonic architecture.

Methods

Intermediate-depth temperature data: Intermediate-depth temperature data were compiled from downhole pressure surveys, including build-up and static gradient tests acquired under shut-in conditions. Static gradient tests provide temperature measurements at multiple depth stations along the wellbore, enabling estimation of geothermal gradients within the 150–1000 m interval. The dataset was thoroughly quality-controlled to remove duplicate records and non-equilibrated measurements before spatial interpolation to generate provincial temperature and gradient maps. Data was collected, starting with southern Alberta, using S&P Global's Accumap Software in both spreadsheet format and PDF documents. Data contained within PDF documents were extracted using an in-house, purpose-built, AI model to collect information of interest and transfer to a digital format for further processing. These data were subsequently categorized and cleaned by applying corrections for depth (horizontal or deviated wells only), removal of duplicate or erroneous data, and identification of outliers for further analysis and validation.

Basement thermal conductivity: Thermal conductivity was measured on basement core samples spanning felsic granitoids and gneisses to mafic metavolcanic rocks. Measurements were conducted through steady state divided bar, optical scanning, and transient plane source methods—under dry and water-saturated conditions—with a subset tested at elevated

temperatures up to ~250–275°C to capture temperature-dependent behaviour. Directional measurements were used where fabric was present to assess anisotropy.

Radiogenic heat production: Radiogenic heat production (A) was calculated from whole-rock uranium, thorium, and potassium concentrations using standard empirical formulations (e.g., Rybach, 1988; Majorowicz et al., 2014):

$$A = 10^{-5}\rho(cU + 2.56\,cTh + 3.48\,cK), in\ \mu W m^{-3}$$

where ρ is rock density (e.g., 2700 kg/m^3).

Rock mechanics: The mechanical behaviour of Alberta basement rocks was investigated using multi-stage triaxial compression tests on plugs taken from drillcores. Samples were subjected to confining pressures representative of depths of a few kilometres (on the order of 5–20 MPa) and then loaded axially to failure. From these tests, we obtained elastic moduli, compressive strength, and frictional parameters (failure envelopes) for typical basement rocks. Some samples were also tested for thermal expansion and ultrasonic wave velocity changes over a range of temperatures to gauge thermoelastic effects relevant to reservoir stimulation.

Curie point depth: We estimated the Curie point depth (CPD) across Alberta from regional aeromagnetic data (Alberta Geological Survey, 2024). Using spectral analysis of magnetic anomaly power spectra (centroid method), the depth to the 580°C isotherm (the temperature at which magnetite loses ferromagnetism) was estimated. The CPD provides a broad-scale indicator of the lithospheric thermal regime: relatively shallow CPD suggests higher deep heat flow or thinner thermal lithosphere, whereas deeper CPD implies cooler crust and mantle.

Observations

Initial analysis of intermediate-depth temperature data from southern Alberta wells reveal consistent conductive thermal behaviour across the intermediate-depth interval.

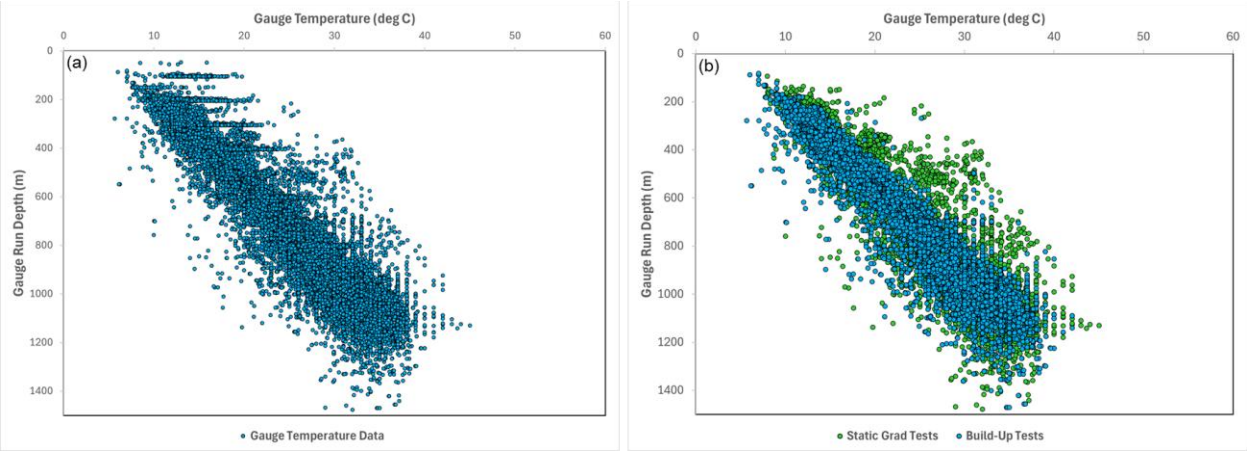


Figure 1: Example of intermediate-depth subsurface temperature data from southern Alberta, showing temperature vs. depth profiles for select wells. Linear temperature increase with depth reflects regional conductive geothermal gradients.

Static gradient and build-up tests, particularly those completed after 2000, provide reliable subsurface temperature profiles due to extended shut-in durations that allow thermal equilibration. After rigorous filtering and correction, more than 22,000 post-2000 tests (9,597 build-up and 12,585 gradient) show clear and largely linear temperature-depth relationships that reflect conductive thermal behaviour. These data form a robust foundation for geothermal gradient mapping. Figure 1 illustrates these trends and underscores the value of legacy well data for province-scale geothermal assessment.

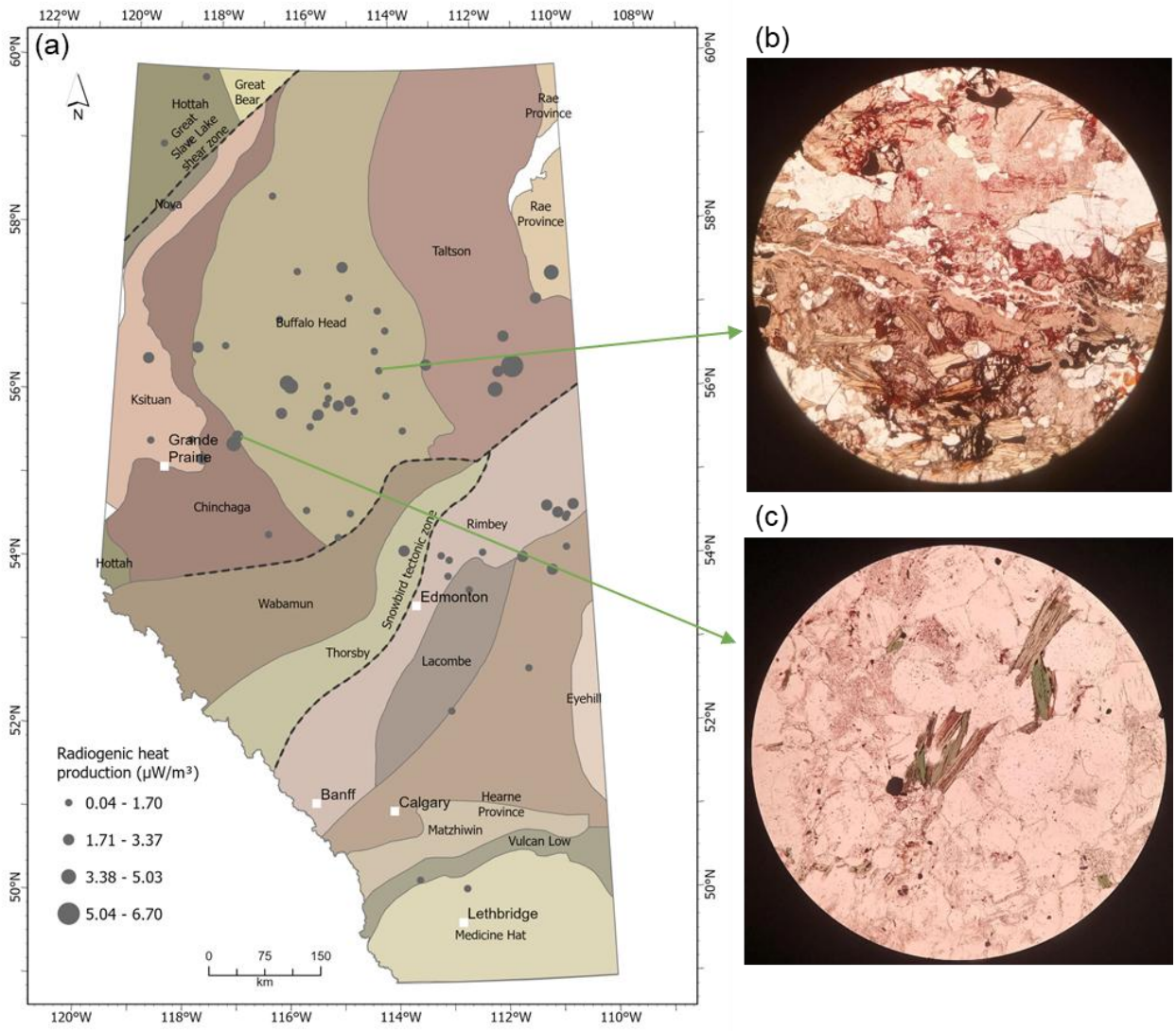


Figure 2: (a) Radiogenic heat production of Precambrian basement samples calculated from whole-rock U–Th–K concentrations, highlighting lithological and tectonic-domain variability; (b) Altered biotite gneiss #24BA027: Leucosome composed of quartz, plagioclase, and alkali feldspar; (c) Petrographic image of granite #24BA012: Cluster of chlorite and muscovite crystals, surrounded by anhedral quartz and feldspar. Thermal conductivities for #24BA027 and #24BA012 are 3.92 and 2.82 W m^{-1} K^{-1}, respectively; RHP values are 2.20 and 1.15 μW m^{-3}, respectively.

The radiogenic heat production (RHP) values for basement samples reveal strong variability tied to rock composition and regional geology, with an average of approximately 1.5 μW m^{-3} across all tested samples (Figure 2a). Low-radiation mafic rocks yield less than 1 μW/m³, while U- and Th-rich granitic rocks reach 5–6+ μW/m³. Many samples from Proterozoic felsic terranes have RHP in the 2–4 μW/m³ range, significantly above the ~0.5–1 μW/m³ typical of Archean cratonic rocks. This indicates that Alberta's buried basement is, on average, more heat-generative than the exposed Canadian Shield to the east. The highest heat-production samples correspond to domains known for felsic plutonic rocks (e.g., the Taltson magmatic zone in northeastern Alberta), supporting the link between basement geology and regional heat flow. Petrographic analysis confirms that high-RHP samples are enriched in K-bearing phases and U–Th–hosting accessory minerals, providing a mineralogical basis for the observed trend (figures 2b–c).

Basement thermal conductivity ranges from approximately 1.5 to 5.6 W m^{-1} K^{-1} (Figure 3). Felsic rocks generally exhibit higher values than mafic or altered units, while water saturation increases conductivity by ~10–25%. Conductivity decreases by ~20–30% between ambient conditions and ~250°C, indicating that room-temperature values alone would overestimate heat transfer at depth. Directional anisotropy ratios range from 1.0 to 1.3. Higher values occur in foliated gneisses and banded granites, where conductivity parallel to foliation exceeds conductivity perpendicular to foliation by up to 25 %.

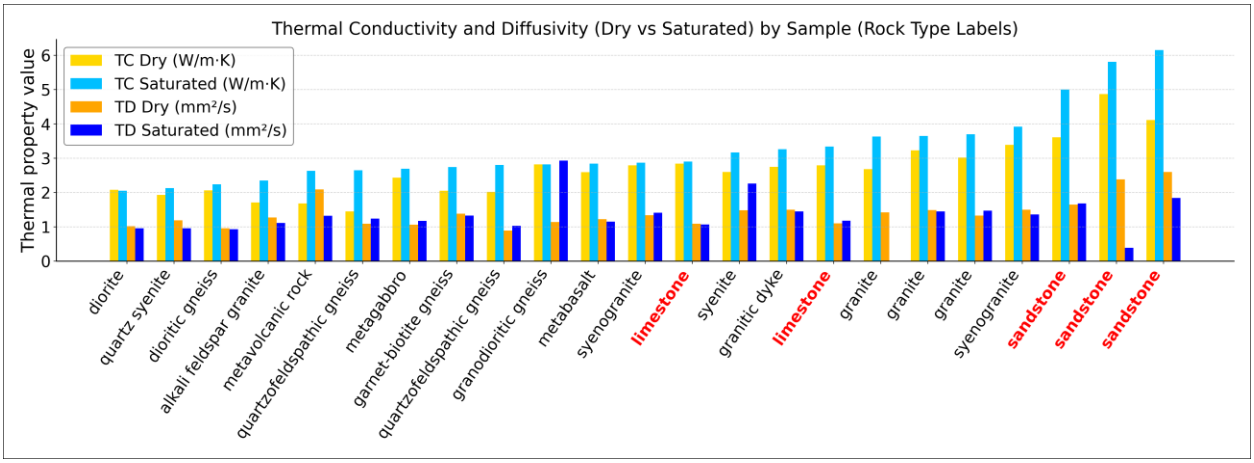
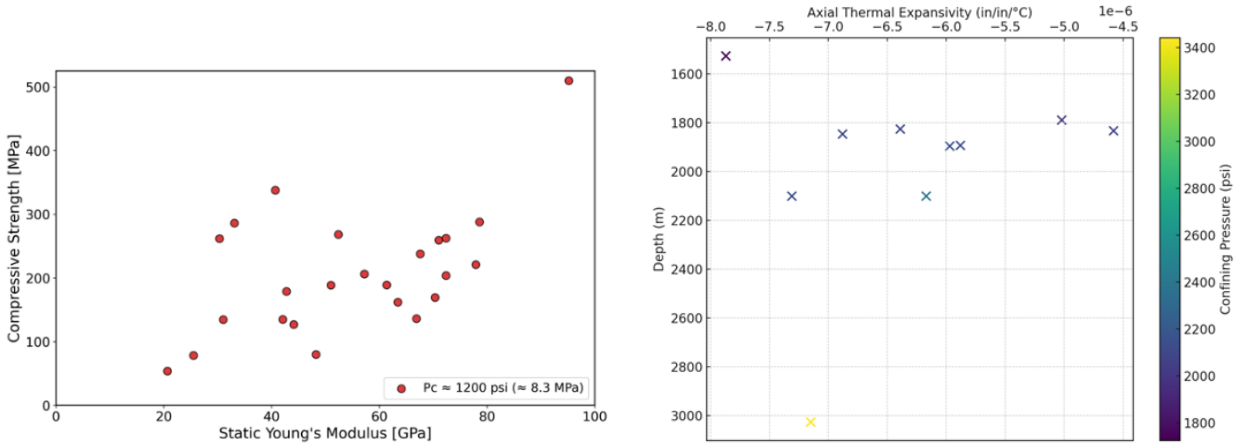


Figure 3: Dry and saturated thermal conductivity (TC) and diffusivity (TD) of selected basement samples compared to limestone and sandstone samples (colored red) from Devonian strata.

Mechanical parameters from compression tests include Young's modulus, Poisson's ratio, unconfined compressive strength (UCS), and Mohr–Coulomb failure parameters (Figure 4a). UCS reaches up to 439 MPa, with most specimens (19 of 23) between ~93 and ~230 MPa. Basement rocks exhibit high strength and brittle behaviour under upper-crustal conditions, with elastic moduli of ~30–95 GPa and frictional properties consistent with crystalline analogues. These results indicate negligible intact permeability but suggest favourable conditions for maintaining induced fracture networks in EGS scenarios. Thermal expansion coefficients range from 4.58E-6 to 7.87E-6 °C^{-1} (Figure 4b). Ultrasonic velocities at reservoir temperatures are high: P-wave 4,681–6,804 m/s, S-wave 2,974–4,051 m/s.

Curie point depth (CPD) estimates across Alberta range from approximately 8 to 30 km, with an average near 23–24 km. The fractal method suggests geothermal gradients between 19 and

59°C/km and heat flow values from ~48 to 149 mW/m². Shallow CPD zones in southwestern and northwestern Alberta correspond to elevated gradients and heat flow, reflecting radiogenic enrichment, while deeper CPD beneath the Rae and Hearne provinces indicate cooler, cratonic conditions with lower gradients.



(a) (b)

Figure 4: (a) Cross-plot of compressive strength versus static Young's modulus measured at confining pressure of 1200 psi. (b) Thermal expansion coefficient values ranged from 4.58E-6°C^{-1} to 7.87E-6°C^{-1}.

Conclusions

New developments in intermediate-depth temperature mapping and basement characterization provide complementary refinement on Alberta's geothermal potential. Intermediate-depth datasets directly support low-enthalpy geothermal applications, while basement measurements reduce uncertainty in temperature-at-depth predictions and feasibility assessments for advanced geothermal systems. Radiogenic heat production and petrography demonstrate strong lithological and tectonic-domain control on crustal heat generation, and CPD-derived thermal structure provides essential regional context. Together, these datasets form a coherent, multiscale geothermal framework that strengthens geothermal screening and modelling across Alberta and complements existing basin- and formation-scale assessments.

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