Petro-physical Characterization of Lodgepole Formation as a Geothermal Reservoir

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ABSTRACT

Geothermal energy is a sustainable and reliable source of energy as an alternative to conventional energy sources. Well logging is an essential tool in geothermal energy exploration as it provides information on subsurface lithology, fluid content, temperature and other variables that are interpreted as reservoir parameters. The combination of different logs and their interpretation provide a comprehensive understanding of a geothermal system. The Lodgepole formation located on top of the Bakken is a geological unit with great potential for geothermal exploration and development. Previous studies on the formation had been for hydrocarbon production and its geothermal potential is yet to be fully explored. A detailed reservoir characterization of the Lodgepole formation is essential for identification of potential geothermal reservoirs. Our studies involve acquiring, processing, and interpreting open hole logs and core data to estimate subsurface properties such as porosity and permeability, identify flow zones, and create petro-physical models to characterize geothermal reservoirs. Extensive analysis of temperature gradients, heat flow, thermal conductivities, hydraulic flow units and reservoir properties in the Lodgepole formation are performed to access the reservoir geothermal energy potential. The results of this study show Lodgepole formation has significant geothermal potential in these areas and our studies serve as a guide for future geothermal exploration and development. Furthermore, our results can be used for resource assessment, reservoir modelling, drilling optimization and understand the geothermal system and its potential for energy production.

1. Introduction

1.1 Geothermal Energy: An Overview

Geothermal energy, derived from heat stored within the Earth, has emerged as a promising renewable energy source with vast untapped potential. Unlike other forms of renewable energy, such as solar or wind, geothermal power is not reliant on external factors like weather conditions. Instead, it harnesses the heat from the Earth's subsurface to generate electricity or provide direct heating for various applications. Geothermal energy is a clean, sustainable, and reliable resource that offers numerous environmental and economic benefits(U.S. Department of Energy, 2023; Microsoft Sustainability, 2023). The utilization of geothermal energy dates back centuries, with ancient civilizations recognizing the power of naturally occurring hot springs and geysers. However, it was not until the early 20th century that geothermal energy began to be harnessed on a larger scale for electricity generation (Britannica, 2021). Today, geothermal power plants are operational in numerous countries worldwide, making significant contributions to their energy portfolios (Malcolm A. Grant et al., 2011). Geothermal systems typically rely on the presence of a geothermal reservoir, which is a subsurface geological formation capable of storing and transmitting heat. These reservoirs can vary in their characteristics, ranging from high-temperature volcanic systems to low-temperature sedimentary formations. The successful development and utilization of geothermal reservoirs require a thorough understanding of their petrophysical properties and behavior.

In this article, we focus on the petrophysical characterization of the Lodgepole Formation as a geothermal reservoir. The Lodgepole Formation, known for its diverse lithology and sedimentary deposition, has shown promising potential as a geothermal resource. By examining the petrophysical properties of this formation, we aim to gain insights into its suitability for geothermal energy extraction and understand the challenges and opportunities associated with its utilization. In the realm of sustainable energy exploration and development, it is of utmost importance to effectively tackle the urgent issues posed by climate change. The 'International Collaborative Cluster-Based Carbon Sequestration Plan' highlights the necessity of substantial endeavors in order to address the issue of carbon emissions stemming from the utilization of fossil fuels for electricity production. This matter is closely linked to our ongoing research on the geothermal capabilities of the Lodgepole Formation (Solomon et al., 2023), The study of petro-physical properties involves the analysis of various parameters, such as porosity, permeability, thermal conductivity, and rock-fluid interactions. These properties are crucial in determining the reservoir's capacity to store and transmit heat, the fluid flow characteristics, and the efficiency of energy extraction processes (Malcolm A. Grant et al., 2011). By characterizing the Lodgepole Formation's petrophysical properties, we can assess its geothermal potential and contribute to the broader understanding of geothermal reservoirs. Great energy storage systems and geothermal potential can be harnessed from the lower formations of Williston basin (W. Gosnold et al., 2017); (Gyimah et al, 2023a). In the following sections, we will delve into the methodologies employed for petrophysical characterization, examine the existing literature on geothermal reservoir characterization, and present our findings on the Lodgepole Formation. Through this research, we aim to contribute to the knowledge base surrounding geothermal energy and provide insights into the feasibility of utilizing the Lodgepole Formation as a geothermal reservoir.

1.2 The Untapped Geothermal Potential of the Lodgepole Formation

Geothermal energy has gained recognition as a reliable and sustainable source of renewable energy. While volcanic regions are commonly associated with geothermal power generation, there is a vast untapped potential in sedimentary formations as well (Ruth Shortall et al., 2015). One such promising sedimentary formation is the Lodgepole Formation, located in North Dakota, which has shown indications of significant geothermal potential. Traditionally, the Lodgepole Formation has been predominantly studied for its hydrocarbon reservoir potential. However, recent investigations have revealed the presence of favorable geothermal characteristics within this formation (Nordsven, M.J. et al., 2016). The Lodgepole Formation exhibits several geologic attributes that make it an attractive target for geothermal exploration and development (Lorraine A. Manz 2009). One of the key factors contributing to the geothermal potential of the Lodgepole Formation is its favorable thermal conductivity. Studies have shown that the formation exhibits decreasing thermal conductivity with depth, indicating a potential increase in the content of bentonite clay, a known thermal insulator (Lorraine A. Manz, 2008). Furthermore, the Lodgepole Formation's extensive sedimentary nature provides ample opportunities for fluid accumulation and circulation. The formation consists of alternating layers of sandstone, shale, and limestone, which can act as potential reservoirs and conduits for geothermal fluids (Mackie, J.et al., 2013). These fluid-filled intervals within the formation allow for the transfer of heat and enable the extraction of thermal energy for power generation or direct use applications.

The geothermal potential of the Lodgepole Formation extends beyond its thermal attributes. North Dakota's geological setting, characterized by deep sedimentary basins and complex fault systems, creates an environment conducive to enhanced geothermal systems (EGS) development (Gosnold et al., 2013). EGS involves stimulating the subsurface to enhance permeability and create artificial reservoirs, allowing for increased heat extraction and energy generation. The presence of fault zones within the Lodgepole Formation offers the potential for creating such enhanced reservoirs and expanding the geothermal energy capacity of the region (Murphy, E. C. 2023). Despite these promising indications, the geothermal potential of the Lodgepole Formation in North Dakota remains largely untapped (North Dakota Geological Survey, 2012). The majority of research and development efforts have focused on conventional energy resources within the formation, with limited attention given to its geothermal attributes. Unlocking this untapped geothermal potential requires further investigation, including comprehensive geological and geophysical studies, drilling of dedicated geothermal wells, and extensive reservoir characterization. In this article, we aim to shed light on the untapped geothermal potential of the Lodgepole Formation in North Dakota.

1.3 Geological Background: The Lodgepole Formation

The Williston Basin is an intracratonic sag basin that developed on the North American craton during the Ordovician. It has undergone episodic subsidence through the Phanerozoic. The basin is roughly circular; the United States portion of the basin covers eastern Montana, North Dakota, and northwestern South Dakota. The basin extends into the adjacent Canadian provinces of Saskatchewan and Manitoba (Gerhard et al., 1991). The basin is underlain by three Archean structural provinces: The Superior province in the east, the Wyoming and Churchill provinces in the west, and the Trans-Hudson orogenic belt, which represents a continent-to-continent suture zone. The interaction of the two Archean shear systems, the Brockton–Froid fault zone and the

Transcontinental arch, created a structural depression that formed the basin during the Late Ordovician (Gerhard and Anderson, 1988). The Williston Basin consists of approximately 16,000 ft (4900 m) of sedimentary rocks of Cambrian through Eocene age. Paleozoic-aged strata are primarily carbonates with some clastic units, whereas Mesozoic and Cenozoic strata are mainly clastic rocks (Heck, 1978). (Figur.1)

Figure 1. The Williston Basin: A Structural Depression on the North American Craton.

The Lodgepole Formation is a significant geological unit found in various regions, including parts of North Dakota, Montana, and Saskatchewan, Canada. It holds valuable insights into the geological history and processes that shaped the area. The formation is part of the Upper Cretaceous period, specifically the Campanian stage, and is known for its diverse lithology and depositional environments. The Lodgepole Formation is recognized as the lowermost unit within the Madison Formation, which is mostly composed of carbonates and evaporates and dates back to the Mississippian period. It is particularly noteworthy for hosting the development of "Waulsortian Reefs," which have the potential to serve as reservoirs (Will Gosnold et al., 2015). It consists of alternating layers of sandstone, shale, and limestone, reflecting changes in sediment sources, sea levels, and environmental conditions over millions of years (Wooster Geologists, 2023). Sandstone is a prominent lithology within the Lodgepole Formation. It typically exhibits fine- to medium-grained texture and displays sedimentary structures such as cross-bedding, ripple marks, and mud drapes. Sandstone layers within the formation are often reservoir-quality rocks, capable of storing and transmitting fluids. Shale is another important component of the Lodgepole Formation (LeFever, J. A., 1991). It consists of fine-grained, allowing the rock to split into thin layers. Shale layers provide important sealing properties within the formation, preventing fluid migration and compartmentalization. Bentonite contributes to the formation's low thermal conductivity and can serve as thermal insulators or markers for geothermal anomalies. Limestone units occur less frequently within the Lodgepole Formation but are still present in some areas

(Wooster Geologists). Limestone represents periods of carbonate deposition and can contain fossil assemblages that provide insights into the paleoenvironment and the ancient marine ecosystem. These limestone layers contribute to the overall stratigraphic complexity of the formation. Understanding the geology of the Lodgepole Formation is crucial for assessing its potential as a geothermal reservoir. The alternating sandstone, shale, and limestone layers create opportunities for fluid storage, permeability, and heat transfer (Waldner, K., and Gosnold, W. 2015). The presence of bentonite-rich shale intervals indicates the potential for thermal anomalies and favorable conditions for geothermal energy extraction (Alshammari, M. A et al., 2021).

2. METHODOLOGY

2.1 Petro-physical Characterization of the Lodgepole Formation

Petro-physical characterization is a critical step in assessing the potential of the Lodgepole Formation as a geothermal reservoir (Fred Aminzadeh, et al., 2013). This involves analyzing the petrophysical properties, identifying flow zones, and developing petrophysical models to understand the reservoir behavior and optimize energy extraction. Petro-physical models are developed to characterize the geothermal reservoir within the Lodgepole Formation. These models integrate petrophysical parameters such as porosity, permeability, fluid saturations, and rock properties to estimate the reservoir's capacity for fluid storage, flow, and heat transfer. Petrophysical models aid in understanding the spatial distribution of reservoir properties, identifying sweet spots for geothermal energy extraction, and optimizing reservoir performance. These models integrate data from well logs, core samples, production data, and geological information to create a comprehensive representation of the reservoir's petro-physical properties. Overall, the methodology for reservoir characterization of the Lodgepole Formation involves petrophysical analysis, permeability modeling, flow zone identification, and the development of petrophysical models. These steps provide a comprehensive understanding of the reservoir's properties, flow behavior, and geothermal potential. By applying these methodologies, geoscientists can optimize reservoir management strategies, improve well placement, and maximize the efficient and sustainable extraction of geothermal energy from the Lodgepole Formation. Figure 2 shows the variable lithology of the Red River formation from Well 18631.

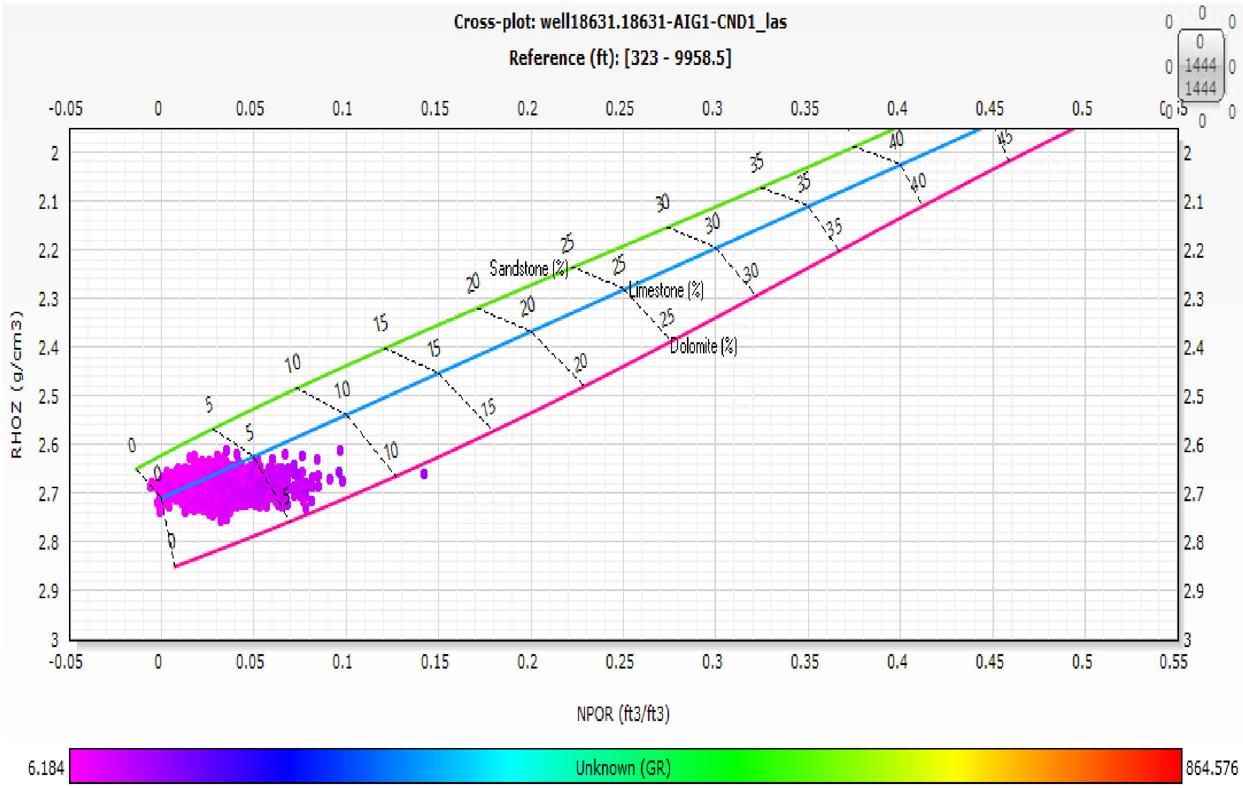

Figure 2: Cross-Plot of bulk density and neutron porosity to highlight formation lithology.

2.2 Permeability modeling techniques

Permeability modeling techniques are employed to estimate the reservoir's ability to transmit fluid and assess the flow potential within the geothermal system. These may include conventional correlations and most recently machine learning techniques (Khan, H., Srivastav, A., Kumar Mishra, A. et al., 2022). The application of machine learning in reservoir characterization and production optimization is rapidly growing. (Koray et. al, 2023c; Koray et al, 2023a) defines a comprehensive workflow in applying machine learning techniques in improving reservoir characterization. Petro-physical analysis is conducted to determine the key petro-physical properties of the Lodgepole Formation, with a focus on permeability. This involves integrating log data, core samples, and rock property measurements well to build permeability models that capture the spatial variability of permeability across the reservoir. Flow zones within the Lodgepole Formation are identified to better understand fluid flow behavior and optimize reservoir management. This involves analyzing various well logs, including resistivity, porosity, and saturation logs, to identify intervals with similar petro-physical characteristics. These intervals are grouped into hydraulic flow units (HFUs), which represent distinct flow behavior and provide insights into permeability distribution and connectivity. Flow zone identification and HFU analysis assist in predicting fluid flow patterns and optimizing well placement and production strategies. Figure 3 shows the poor correlation between permeability and porosity. This poor correlation highlights the need for improved methods of rock typing. The discrete rock typing method and

Lorenz method both had seven number of rock types, and very high correlation for permeability and porosity. Figure 4 shows the high correlation between permeability and porosity using discrete rock tying (DRT) method. Figure 5 shows consistency in number of rock types with DRT method and high correlation co-efficient for each rock type. Optimization algorithm was performed on the DRT method to generate the optimal solution. The optimization algorithm was best to reduce errors sum of absolute errors (SAE) and mean absolute error (MAE) in permeability modelling techniques. The Table 1 summarizes the results of permeability modelling techniques. In this case study there is no major fault in the formation. However, there would be some natural fractures.

2.2.1Flow zone Indicator

The flow zone indicator (FZI) is permeability modelling technique based on the quality of reservoir. Each hydraulic flow unit obtained using this technique is associated with the identification of geophysical properties which include the mineralogy and pore geometry of the rock. The properties are fundamental in controlling the flow of fluids within the reservoir (Koray et al., 2023b). It identifies spatial distribution within the reservoir and classifies flow units within the reservoir (Amaefule et al, 1993).

$$RQI = 0.0314 \times \sqrt{\frac{k}{\emptyset}} \qquad (1)$$

$$\emptyset_z = \frac{\emptyset}{1-\emptyset} \qquad (2)$$

$$FZI = \frac{RQI}{\emptyset_z} \qquad (3)$$

where $\emptyset_z$ is the normalized porosity, ø is the reservoir porosity, k is reservoir permeability, DRT is discrete rock typing and FZI is flow zone indicator

2.2.2 Lorenz Plot

Lorenz Plot is from concept of transmissivity and Storativity for rock type classification. A change in the plot direction highlights more than one rock unit for every depth (Gunter at al, 1997).

$$\text{Transmissivity} = \frac{\sum(k \times h)}{cum(k \times h)} \qquad (4)$$

$$\text{Storativity} = \frac{\sum(\emptyset \times h)}{cum(\emptyset \times h)} \qquad (5)$$

Where k is the permeability, h is the thickness and $\emptyset$ is the porosity.

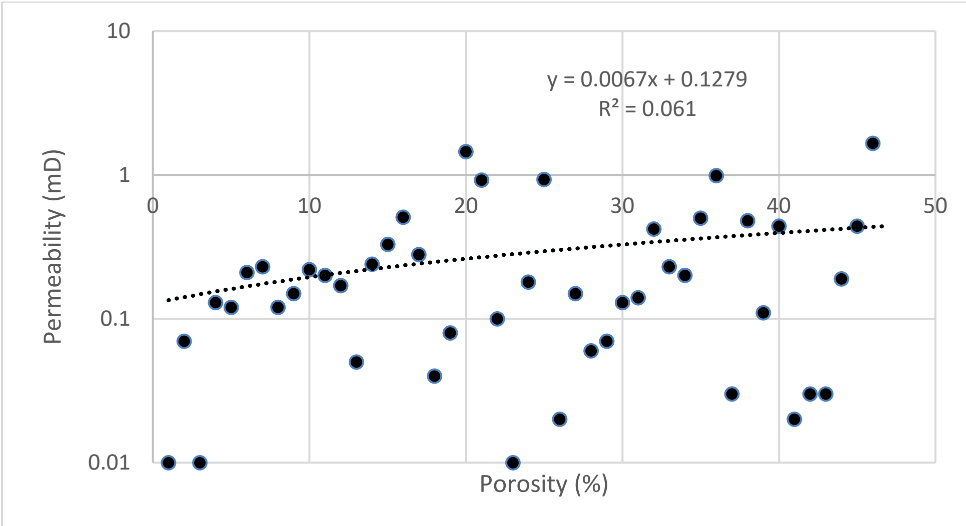

Figure 3: Cross-plot of permeability and porosity

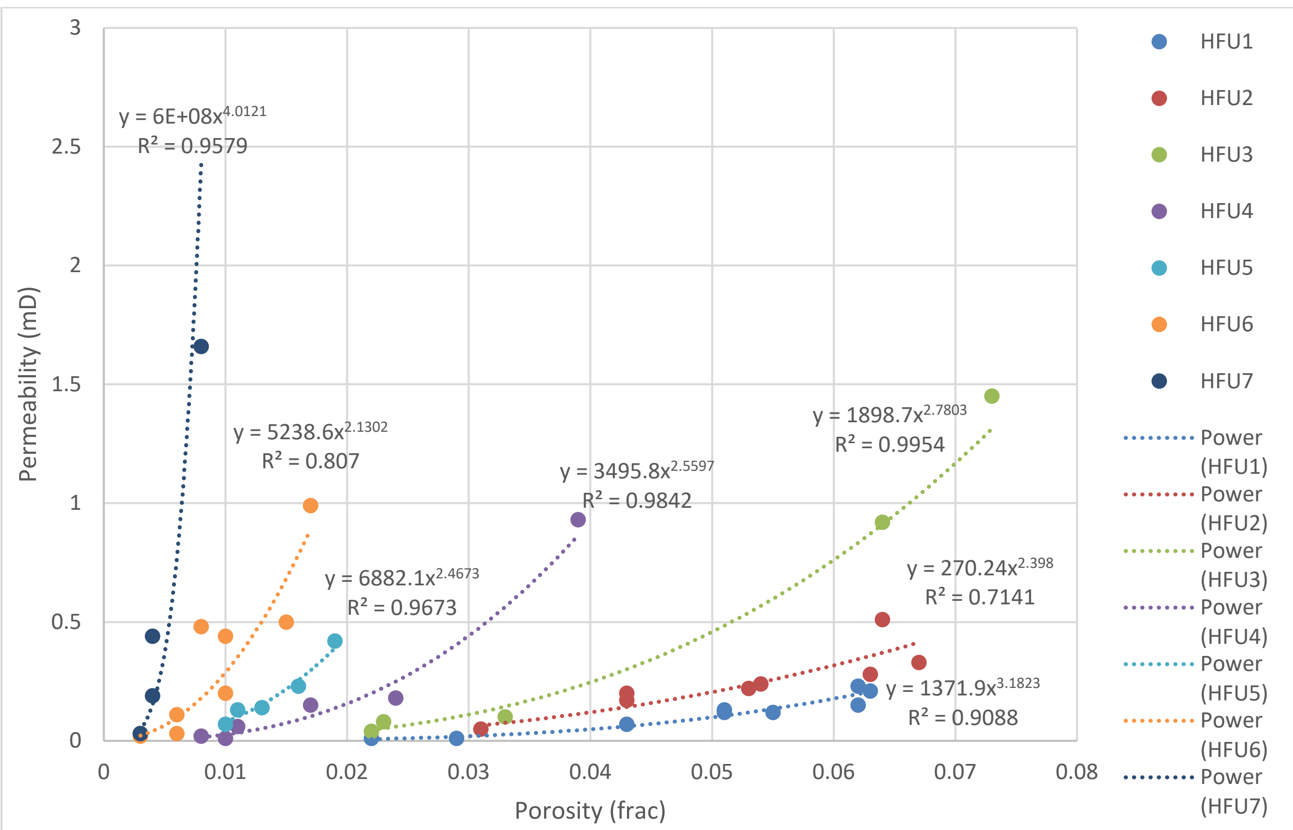

Figure 4: Cross-Plot of Permeability and Porosity for Flow Zone Indicator

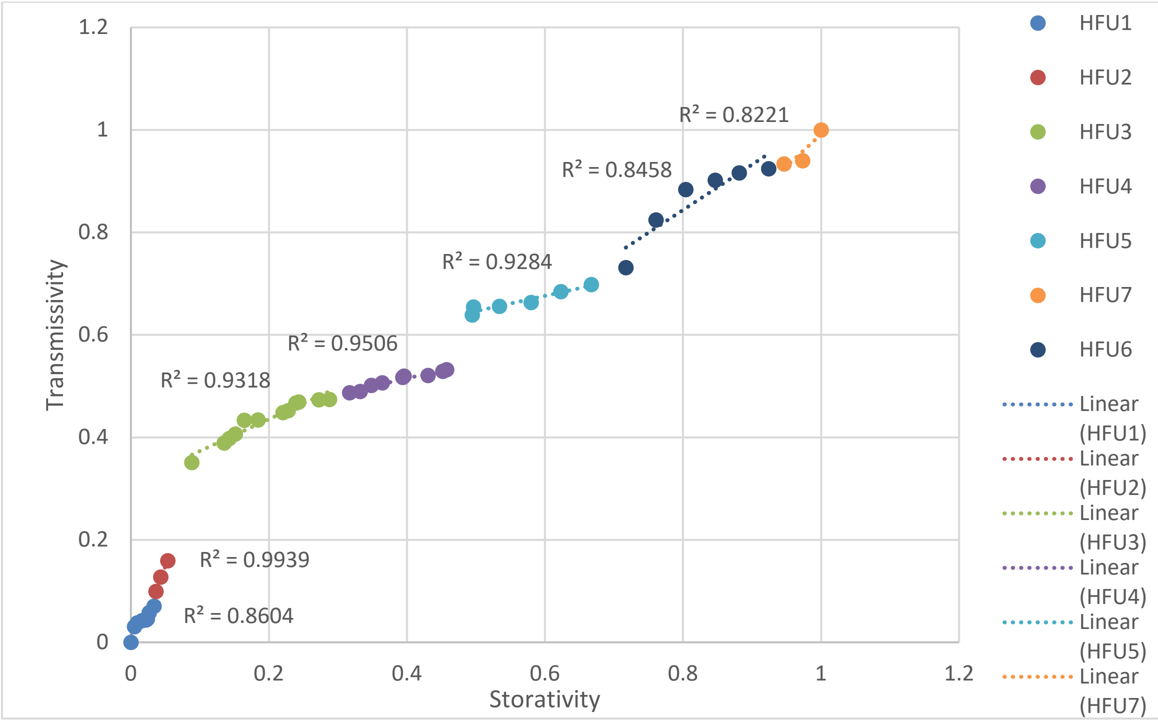

Figure 5: Lorenz Cross-plot of transmissivity and Storativity

Table 1: Summary of permeability modelling techniques

Method	R2	SAE	MAE
DRT	0.904	3.074	0.067
Optimized DRT	0.939	2.316	0.05

2.3 Assessing Geothermal Energy Potential

Assessing the geothermal energy potential of the Lodgepole Formation requires a systematic approach that incorporates temperature gradients analysis and thermal conductivity evaluation. These methods are essential in quantifying the heat available within the reservoir and determining the feasibility of geothermal energy extraction (Anthony E. Ciriaco et al., 2019). By evaluating the temperature gradients, geoscientists can estimate the geothermal heat flow, which indicates the amount of heat transfer occurring within the reservoir. This analysis provides valuable insights into the subsurface heat distribution and helps identify regions with higher geothermal energy potential. Thermal conductivity evaluation focuses on quantifying the ability of the rocks within the Lodgepole Formation to conduct heat(Wooster geologists). By integrating the thermal conductivity data with the temperature gradients, geoscientists can assess the heat transfer capabilities of the formation and identify areas with higher thermal conductivity, indicating better geothermal energy extraction potential. The Temperature Stratigraphy was used to measure the temperature of the red river formation. The Beaver lodge field was assumed a heat flow value and annual surface mean temperature of 65 mW/$\boldsymbol{m^2}$ and 6.8 C, and TSTRAT was applied to determine the geothermal resource in Fig. 6 and Fig. 7

$$\boldsymbol{T_Z = T_0 + \sum_{i=1}^{n} \frac{qz_i}{\lambda_i}}$$

Where: $\boldsymbol{\lambda}$ is the thermal conductivity (W/m/K), $\boldsymbol{T_Z}$ is the depth temperature, $\boldsymbol{T_0}$ is the surface temperature, $\boldsymbol{z_i}$ is the formation thickness and q is heat flow (mW/$\boldsymbol{m^2}$).

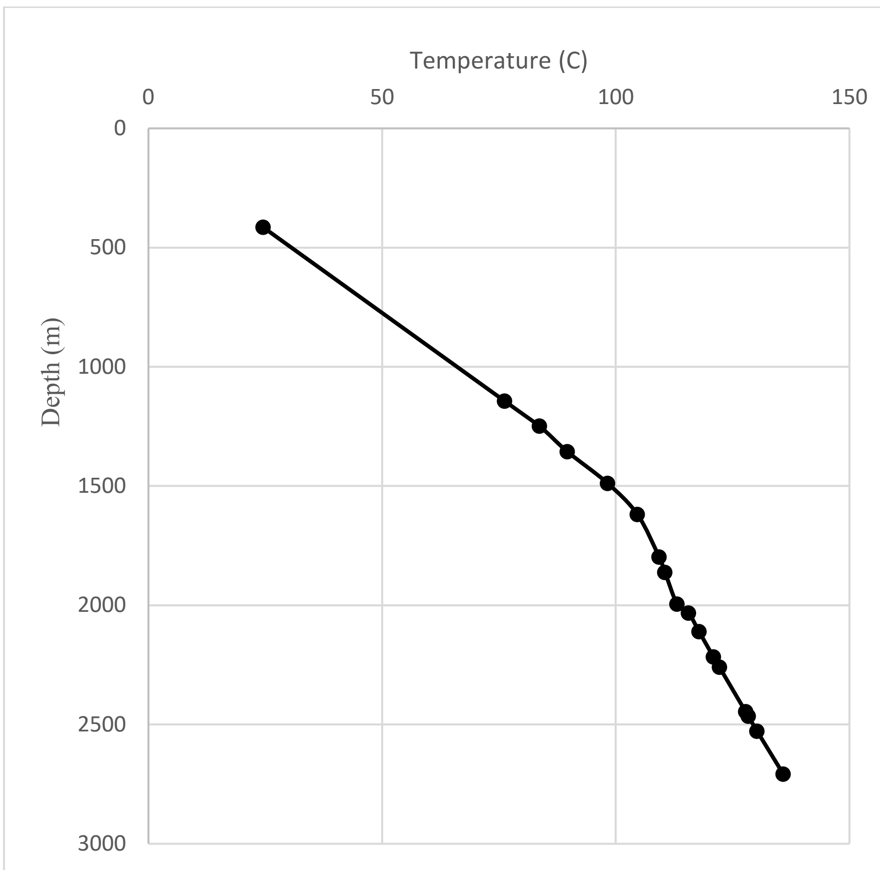

Figure 6: Cross-plot of Depth and Temperature

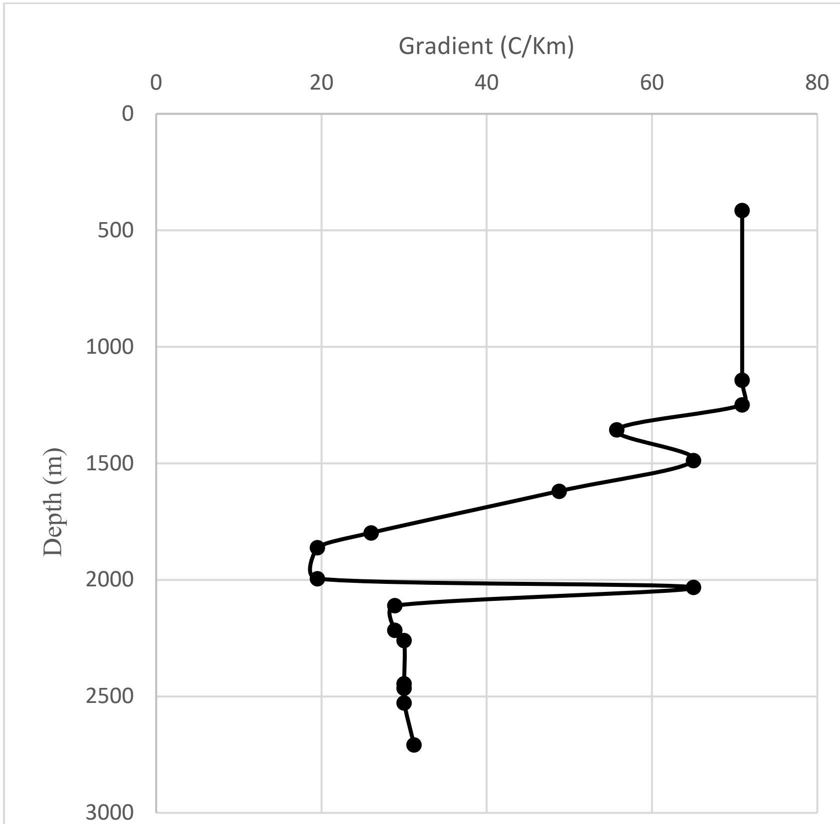

Figure 7: Cross-plot of Depth and Gradient

Given the thickness, thermal conductivity, heat flow and surface temperature for a well in the field, the temperature has been calculated and it shows a consistent trend from Depth vs Temperature and Depth vs Gradient for Lodgepole Formation depth at 2700 meter.

3. Geothermal Potential Estimation of the Lodgepole Formation

Based on the temperature gradients, heat flow analysis, and thermal conductivity evaluation, geoscientists can estimate the geothermal resource potential within the Lodgepole Formation. This involves calculating the available heat and assessing the potential for sustainable energy extraction. Estimation techniques, such as volumetric analysis or numerical reservoir simulations, may be employed to quantify the geothermal resource volume, energy content, and potential production rates. These estimates provide valuable information for evaluating the economic viability of geothermal projects and optimizing energy production strategies. The methodology outlined above, incorporating temperature gradients analysis and thermal conductivity evaluation, forms a fundamental approach for assessing the geothermal energy potential of the Lodgepole Formation. By employing these methods, geoscientists can make informed decisions regarding reservoir development, well placement, and the design of geothermal energy systems, leading to sustainable and efficient utilization of the geothermal resource. Aquifer resource was estimated with an average porosity of 8 % of the total resource. The producible resource was estimated with the average flow rate of 0.08 $\boldsymbol{m^3/h}$ and assuming as heat loss of 20 C to the surface.

Table 2. Summary of Geothermal Resource in the Beaver Lodge field of the Lodgepole formation. ρ is density (kg/m^3), cp is heat capacity (J/kg/K), v is volume (m^3), q is flowrate (m^3/h), ϕ is porosity (frac), Tf is the reservoir fluid temperature (℃) and Ta is annual mean temperature (℃).

	Lodgepole Geothermal Resource	Methodology
Producible Resource	1.263 ExaJoules / Hour	E=ρ cp v q ΔT (Tf - 20)
Aquifer Resource	1.406 ExaJoules	E= ϕ ρ cp v ΔT (Tf - Ta)
Total Resource	17.58 ExaJoules	E= ρ cp v ΔT (Tf - Ta)

4. CONCLUSION

In conclusion, the geothermal assessment of the Lodgepole Formation provides valuable insights into its resource potential, drilling optimization strategies, reservoir characterization and improved reservoir simulation. The permeability modeling techniques employed indicated favorable permeability values, suggesting the reservoir's ability to transmit geothermal fluids efficiently. Flow zone identification and hydraulic flow units analysis provided a better understanding of fluid flow behavior within the formation. The findings contribute to the understanding of this geothermal resource and aid reservoir management decisions and risk assessments. Expanding geothermal utilization in the Lodgepole Formation and similar geological settings holds the promise of sustainable energy generation, reduced carbon emissions, and economic benefits for the region and beyond. The petro-physical analysis revealed promising characteristics of the Lodgepole Formation as a geothermal reservoir. The improved permeability modeling techniques indicates reservoir's ability to transmit geothermal fluids efficiently. Flow zone identification and hydraulic flow unit’s analysis provided a better understanding of fluid flow behavior within the formation. The results indicate that the Lodgepole Formation exhibits significant geothermal energy potential. The high temperature gradients observed within the formation, coupled with favorable thermal conductivity values, suggest the presence of substantial thermal energy resources. This geothermal potential makes the Lodgepole Formation a promising candidate for geothermal energy production.

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