

Geostatistical Modeling of Subsurface Uncertainty in Deep Sedimentary Geothermal Reservoirs.

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ABSTRACT

Geothermal energy serves as a sustainable and low-carbon alternative that supports the adoption of a diversified and sustainable energy mix. The deep sedimentary basins of North Dakota, particularly within the Mississippian and Devonian formations, possess substantial geothermal potential, making them promising targets for geothermal energy development. Efficient utilization of these geothermal resources requires a robust understanding of the inherent subsurface uncertainties and spatial heterogeneities that influence reservoir performance. This study integrates geostatistical modeling with geothermal reservoir engineering principles to evaluate uncertainty parameters within the geothermal system of the Antelope field in the Three Forks formation (Williston basin). Through probabilistic analysis and Monte-Carlo simulation, we quantify the variability and ambiguity of critical subsurface properties within the target formation to improve the reliability of resource assessment and project feasibility within the basin. Field data from the Mississippian and Devonian intervals were analyzed to characterize uncertainties in key parameters that control geothermal energy potential, thereby reducing exploration risks and promoting sustainable development. Uncertainty quantification and probabilistic resource assessment are crucial for informed decision-making and efficient reservoir management. In the case of the Three Forks formation, the arithmetic mean estimates for total geothermal resources, aquifer geothermal resources, and producible geothermal resources were found to be approximately 3.3×10^{18} J, 1.08×10^{17} J, and 1.02×10^7 J, respectively. These insights provide a quantitative basis for optimizing geothermal energy extraction from the Mississippian–Devonian formations in North Dakota.

1. INTRODUCTION

The global energy transition toward low-carbon and sustainable energy systems has intensified interest in geothermal energy as a reliable and environmentally friendly resource capable of providing continuous baseload power. Unlike renewable sources such as wind and solar, geothermal energy offers high-capacity factors, long operational lifetimes, and minimal greenhouse gas emissions, making it a critical component of future energy portfolios (Tester et al., 2006; DiPippo, 2012). Geothermal systems exploit internal heat of the Earth through the circulation of fluids within permeable geological formations, where heat extraction efficiency is governed by subsurface temperature distribution, reservoir permeability, porosity, thickness, and fluid properties (Grant & Bixley, 2011; Gyimah et al., 2024). Typical geothermal systems include volcanic or igneous Geysers, the Cooper, Fenton Hill, and Soultz-sous-Forets hot dry rocks, and the Paris, North German, and Pannonian sedimentary basins.

The sedimentary basin geothermal resources, in particular, have gained increasing attention in recent years due to their widespread availability, established subsurface data coverage, and compatibility with existing oil and gas infrastructure (Buscheck et al., 2013; McKenna et al., 2004). In North America, deep sedimentary basins such as the Williston Basin exhibit favorable geothermal gradients and extensive permeable formations that are suitable for geothermal development, particularly for direct-use applications and binary power generation systems (Blackwell et al., 2011). Within the Williston Basin, the Mississippian and Devonian carbonate formations represent promising geothermal targets due to their significant thickness, lateral continuity, and relatively high porosity and permeability inherited from their depositional and diagenetic histories (Smith et al., 2019). Despite the recognized geothermal potential of sedimentary basins, uncertainty associated with subsurface properties remains a major barrier to efficient resource development. Key geothermal reservoir parameters, including temperature, porosity, permeability, net thickness, and fluid saturation, are inherently heterogeneous and only sparsely sampled by well data (Caers, 2011; Gyimah et al., 2024). These uncertainties propagate into resource estimates, economic forecasts, and operational decisions, thereby increasing exploration and development risks (Williams et al., 2011). Deterministic approaches that rely on single “best-estimate” values often fail to capture the full range of plausible subsurface conditions, leading to optimistic or overly conservative resource assessments (Sanyal & Butler, 2005).

Uncertainty quantification (UQ) and probabilistic resource assessment have therefore become essential tools in modern geothermal reservoir engineering. Probabilistic methods allow for explicit characterization of uncertainty by representing key reservoir parameters as probability distributions rather than fixed values, enabling risk-informed decision-making (Caers & Zhang, 2004). Geostatistical modeling techniques, including variogram analysis, stochastic simulation, and conditional realization methods, are widely used to model spatial heterogeneity and quantify uncertainty in subsurface systems (Journel & Huijbregts, 1978; Deutsch & Journel, 1998). These techniques have been successfully applied in petroleum engineering and groundwater hydrology and are increasingly being adopted in geothermal resource assessment (Malinverno, 2002; Fox et al., 2016).

In geothermal systems, uncertainty directly influences estimates of heat in place, recoverable thermal energy, and producible power. The total geothermal resource represents the theoretical heat stored within a geological volume, while the recoverable or producible portion depends on reservoir transmissivity, fluid flow behavior, and technological constraints (Williams et al., 2008). Accurately distinguishing between these categories is crucial for realistic project evaluation and financial planning. Probabilistic geothermal resource assessments provide a framework for evaluating multiple development scenarios and identifying key parameters that exert the greatest control on project outcomes (Beardsmore et al., 2010).

This study integrates geostatistical modeling with geothermal reservoir engineering principles to quantify uncertainty in key subsurface parameters controlling geothermal energy potential. By employing probabilistic analysis and Monte Carlo simulation, the study evaluates the variability of total geothermal resources, aquifer geothermal resources, and producible geothermal resources within the Three Forks formation. In general, this work contributes to the advancement of sustainable geothermal energy development by promoting robust resource assessment methodologies that support informed decision-making and efficient reservoir management.

2. BACKGROUND OF THE STUDY AREA

2.1 Regional Geological Setting

The study area is located within the Williston Basin, a large intracratonic sedimentary basin extending across North Dakota, South Dakota, eastern Montana, and southern Saskatchewan. The basin developed through long-term thermal subsidence from the Paleozoic through the Mesozoic, resulting in the accumulation of more than 4 km of sedimentary strata in its deepest regions (Gaswirth et al., 2013; LeFever et al., 2011). The structural simplicity and tectonic stability of the basin have led to relatively predictable burial histories and thermal gradients, which are favorable conditions for sedimentary basin geothermal systems.

Extensive hydrocarbon exploration over several decades has generated a dense network of wells, core data, and geophysical logs across the basin. This exceptional subsurface data coverage significantly reduces geological uncertainty relative to frontier geothermal regions and enables detailed stratigraphic, petrophysical, and thermal characterization. As a result, the Williston Basin has increasingly been recognized as a promising target for low- to moderate-enthalpy geothermal development, particularly where deep carbonate and mixed carbonate-siliciclastic formations are present (Blackwell et al., 2011; McKenna et al., 2004).

2.2 Stratigraphy of the Three Forks Formation

The Three Forks Formation is a Late Devonian stratigraphic unit that directly underlies the Bakken Formation and overlies the Birdbear (Nisku) formation (Figure 1). It is laterally extensive throughout much of the central Williston Basin and has been subdivided into multiple stratigraphic benches based on lithology and depositional character (LeFever et al., 2011; LeFever et al, 2005). These benches reflect deposition in shallow marine to restricted shelf environments and exhibit significant vertical and lateral heterogeneity. Lithologically, the Three Forks Formation consists of interbedded dolomite, limestone, siltstone, and shale. Dolomitization is widespread and has exerted a strong control on porosity evolution, while carbonate-rich intervals tend to be mechanically brittle. These characteristics influence fracture development and permeability distribution, which are critical factors governing geothermal fluid circulation and heat extraction. The thickness of the Three Forks Formation varies across the basin but generally ranges from tens to several hundreds of feet, contributing to substantial thermal storage capacity (Gaswirth et al., 2013).

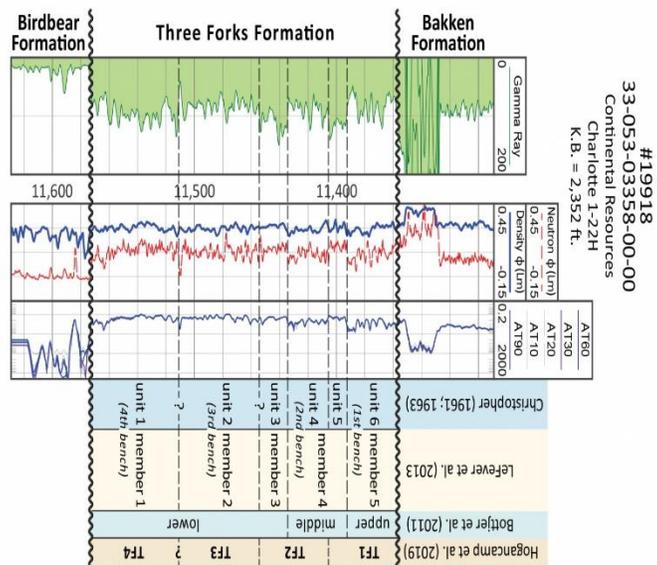


Figure 1. Wireline log response and stratigraphic subdivision of the Bakken-Three Forks interval in the Charlotte 1-22H well, Williston Basin, North Dakota (after LeFever et al, 2013;2014).

2.3 Thermal Regime and Geothermal Context.

The geothermal potential of the Three Forks Formation is closely linked to the regional thermal structure of the Williston Basin. Temperature-at-depth maps indicate that geothermal gradients increase toward the basin center, with Devonian formations reaching temperatures suitable for direct-use geothermal applications and binary-cycle power generation systems (Blackwell et al., 2011). The burial depth of the Three Forks Formation places it within a temperature range that is increasingly attractive given advances in low-temperature geothermal technology. However, subsurface temperature estimates in the basin are often derived from corrected bottom-hole temperature data or extrapolated geothermal gradients rather than direct formation temperature measurements. This introduces uncertainty into thermal models and geothermal resource estimates, particularly at the field scale. Consequently, probabilistic approaches are necessary to capture the range of plausible thermal conditions within the Three Forks Formation (Williams et al., 2008).

2.4 Reservoir Properties and Heterogeneity.

Reservoir performance in the Three Forks Formation is governed by porosity, permeability, fluid saturation, and reservoir connectivity, all of which exhibit pronounced spatial variability. This heterogeneity reflects changes in depositional facies, diagenetic alteration, and local structural features. While these characteristics have been extensively evaluated for unconventional hydrocarbon production, they are equally relevant for geothermal energy extraction, where fluid flow efficiency and heat transfer control system performance. Heterogeneity in sedimentary geothermal systems represents one of the dominant sources of uncertainty in geothermal resource assessment. Geostatistical approaches are therefore essential for quantifying spatial variability and propagating uncertainty into estimates of heat in place, recoverable energy, and producible geothermal resources (Caers, 2011). The Three Forks Formation provides a representative example of such heterogeneity within sedimentary basins.

3. METHODOLOGY

3.1 Reservoir Parameters Determination

Reservoir core and petrophysical data for the study area were obtained from the North Dakota Industrial Commission (NDIC) database for wells penetrating the Three Forks Formation. Data compiled from multiple wells were statistically analyzed to derive representative reservoir properties for the formation. For each key parameter, the arithmetic mean and standard deviation were calculated and subsequently used as input variables for probabilistic assessment and uncertainty quantification. These representative reservoir properties are essential for characterizing the subsurface behavior of the Three Forks Formation and capturing the inherent variability associated with sedimentary heterogeneity. A parametric probabilistic approach, based on statistical distribution theory, was employed to generate expectation curves and quantify uncertainty in the reservoir parameters. This approach enables explicit representation of uncertainty arising from limited sampling and spatial variability, providing a more robust framework for subsurface evaluation than deterministic methods. Probabilistic assessment and uncertainty quantification techniques have been widely applied in oil and gas reservoir evaluation and resource estimation to support risk-informed decision-making (Ampomah et al., 2016; Asante et al., 2021; Li et al., 2011). In this study, the same methodological framework is adapted to evaluate the geothermal potential of the Three Forks Formation. The formation temperature was calculated using the Temperature Stratigraphy (TSTRAT) method. Figure 2 shows the well through the Three Forks Formation.

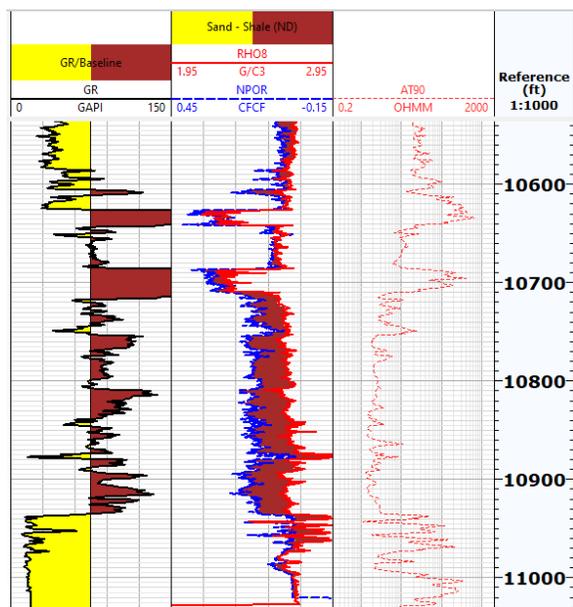


Figure 2. Wireline log response through the Three Forks Formation.

3.2 Probabilistic method for Geothermal Resource.

This study aims to quantify the geothermal resource potential and associated subsurface uncertainties of the Antelope field in the Three Forks Formation in North Dakota. The geothermal resource is classified into three hierarchical categories: total geothermal resource, aquifer geothermal resource, and producible geothermal resource, reflecting progressively constrained estimates of recoverable heat. This classification framework enables systematic evaluation of both theoretical and practically extractable geothermal energy. A probabilistic assessment approach is adopted to account for the inherent variability and uncertainty in subsurface reservoir properties. Probabilistic methods are particularly well-suited for handling large datasets and complex reservoir engineering problems, where deterministic approaches may fail to capture the full range of plausible outcomes. In this study, a parametric probabilistic method is employed, in which uncertainty is represented analytically using statistical descriptors. The parametric method utilizes the mean and standard deviation of key reservoir variables to generate probabilistic outcomes and quantify uncertainty. The methodological workflow is illustrated in Figure 3. Following statistical characterization of the reservoir parameters, the arithmetic mean and standard deviation are first transformed into their corresponding lognormal mean and lognormal standard deviation, reflecting the positively skewed nature of subsurface properties. The geothermal resource estimates expressed in lognormal space are then aggregated by summing the lognormal means and variances, allowing derivation of probabilistic geothermal resource distributions. This approach provides a framework for uncertainty quantification and supports risk-informed evaluation of geothermal potential within the Antelope field of the Three Forks Formation.

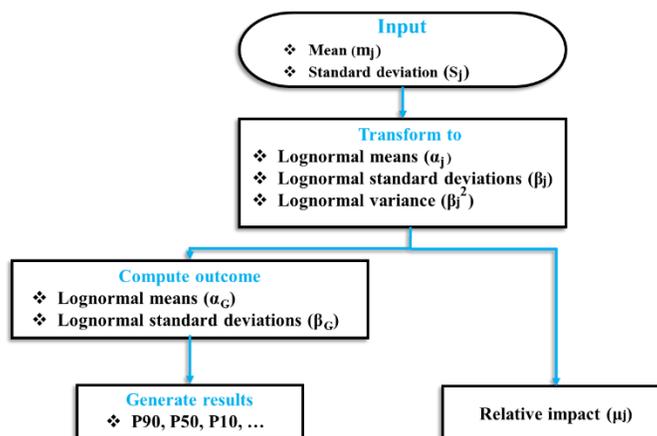


Figure 3. Flow chart for Probabilistic methods

Table 1: Reservoir Variables for Total Geothermal Resource

Reservoir Variable	Mean	Standard deviation
Area (m ²)	194524558.3	0
Gross thickness(m)	55.08	14.11
Density (kg/m ³)	2600	100
Temperature (°C)	106	5
Heat capacity (J/kg/K)	950	30

Table 2: Reservoir Variables for Aquifer Geothermal Resource

Reservoir Variable	Mean	Standard deviation
Area (m ²)	194524558.3	0
Gross thickness(m)	55.08	14.11
Density (kg/m ³)	2600	100
Temperature (°C)	106	5
Heat capacity (J/kg/K)	950	30
Water saturation (stb/rb)	0.4795	0.1311
Porosity	0.0633	0.00612

Table 3: Reservoir Variables for Producing Geothermal Resource

Reservoir Variable	Mean	Standard deviation
Area (m ²)	194524558.3	0
Gross thickness(m)	55.08	14.11
Density (kg/m ³)	2600	100
Temperature (°C)	106	5
Heat capacity (J/kg/K)	950	30
Water saturation (stb/rb)	0.4795	0.1311
Porosity	0.0633	0.00612
Flow rate (m ³ /h)	1.196812281	0.317236794

Table 4. Useful equations.

No.	Equation	Variable definitions
(1)	$V_j = \frac{S_j}{m_j}$	<ul style="list-style-type: none"> • V_j – coefficient of variation • S_j – standard deviation • m_j – mean
(2)	$\beta^2 = \ln(1 + V_j^2)$	<ul style="list-style-type: none"> • β^2 – lognormal variance
(3)	$u_j = \frac{\beta_j^2}{\sum \beta_j^2}$	<ul style="list-style-type: none"> • u_j – Relative impact • α_j – lognormal mean
(4)	$\alpha_j = \ln(m_j) - 0.5 * \beta^2$	<ul style="list-style-type: none"> • E_A – Aquifer geothermal resources
(5)	$P90 = \exp(\alpha - 1.281\beta)$	<ul style="list-style-type: none"> • S_w – water saturation • \emptyset – porosity (frac)
(6)	$P50 = \exp(\alpha)$	<ul style="list-style-type: none"> • E_p – producible geothermal resource
(7)	$P10 = \exp(\alpha + 1.281\beta)$	<ul style="list-style-type: none"> • ρ – density (kg/m³) • c_p – heat capacity (J/kg/K)
(8)	$T_z = T_o + \sum_{i=1}^n \frac{Qz_i}{\lambda_i}$	<ul style="list-style-type: none"> • v - volume (m³) • q - flowrate (m³/h)
(9)	$E_p = \rho c_p v q \Delta T (T_f - 20^\circ\text{C})$	<ul style="list-style-type: none"> • T_f – reservoir temperature (°C)
(10)	$E_A = \emptyset \rho S_w c_p v \Delta T (T_f - T_a)$	<ul style="list-style-type: none"> • T_a – annual mean temperature (°C)
(11)	$E_T = \rho c_p v \Delta T (T_f - T_a)$	<ul style="list-style-type: none"> • λ - thermal conductivity (W/m/K) • T_z – depth temperature • T_o – surface temperature • z_i – formation thickness • Q - heat flow (mW/mm2) • P10 - Probability at least 10% • P50 - Probability at least 50% • P90 - Probability at least 90% • E_T – Total geothermal resources

3.3 Monte Carlo-Based Relative Impact Assessment

In this study, the Monte Carlo simulation framework was employed specifically to evaluate the relative impact of formation parameters on geothermal resource uncertainty, rather than as a general risk-analysis tool. The Monte Carlo analysis begins with the formulation of a deterministic geothermal resource model representing the most likely subsurface conditions. Key formation parameters governing geothermal energy storage and production, such as gross thickness, temperature, density, heat capacity, porosity, water saturation, and flow rate, are identified. For each parameter, a physically realistic range is defined around its base (most likely) value, reflecting geological variability and measurement uncertainty. Appropriate probability distributions (e.g., uniform, triangular, or Gaussian) are assigned to each parameter to characterize its stochastic behavior. This step establishes the probabilistic domain over which relative impact is evaluated. Once the parameter distributions are defined, random samples are generated for each parameter at the start of every Monte Carlo realization. During each iteration, all parameters are simultaneously perturbed according to their prescribed probability distributions. Sampling is constrained within the predefined parameter bounds to ensure physical realism and numerical stability of the geothermal resource calculations. This process enables exploration of a wide range of plausible subsurface scenarios while preserving consistency with known formation characteristics. The deterministic geothermal resource model is transformed into a stochastic model by replacing fixed input values with randomly sampled parameters. Because uncertainty originates from the inherent variability of formation properties, the probability distributions assigned to each parameter serve as the basis for propagating uncertainty through the resource calculations. Where data availability permits, distributions are selected or calibrated using statistical fitting techniques, such as the method of moments or maximum likelihood estimation, to ensure representative sampling behavior.

For each Monte Carlo iteration, geothermal resources are computed using the governing analytical expressions for total, aquifer, or producible geothermal energy, depending on the assessment level. All calculations are performed deterministically for the sampled input set, and the resulting resource estimate is stored. This process is repeated for a large number of realizations to generate statistically stable output distributions. After completion of all Monte Carlo iterations, the ensemble of output results is analyzed to quantify the contribution of each input parameter to the total variability of the geothermal resource estimate. The relative impact of a parameter is determined by evaluating how variations in that parameter influence the spread of the output distribution relative to other parameters. These contributions are normalized so that the sum of relative impacts equals unity, allowing direct comparison of parameter influence. Final results are expressed in terms of relative impact fractions (or percentages) and are supported by probabilistic outputs such as cumulative distribution functions and frequency histograms.

4. RESULTS AND DISCUSSION

4.1 Thermal Characteristics of the Three Forks Formation.

Figures 4a and 4b present the temperature–depth and geothermal gradient profiles for the Three Forks Formation derived from Well 31944 and Well 26990. Formation temperatures estimated using the Temperature Stratigraphy (TSTRAT) method, assuming a regional heat flow of 70 mW/m^2 and an annual mean surface temperature of $6.8 \text{ }^\circ\text{C}$, show a systematic increase in temperature with depth in both wells (Figure 4a). The temperature profiles from the two wells are closely aligned, indicating a laterally consistent thermal regime across the field, with only minor deviations that are likely to reflect local stratigraphic heterogeneity. The calculated geothermal gradients (Figure 4b) exhibit pronounced depth-dependent variability within the Three Forks Formation. Both wells display elevated gradients at intermediate depths, followed by a reduction and stabilization toward greater depths. This pattern suggests stratigraphic control on heat transfer, with variations in thermal conductivity influencing the vertical distribution of heat flow. The similarity in gradient trends between the wells further supports the presence of a coherent and regionally consistent thermal formation. The observed temperature and geothermal gradient trends indicate that heat transfer within the Three Forks Formation is dominated by conductive processes, with no clear evidence of strong convective heat transport. These results define the subsurface thermal framework of the formation and provide a robust basis for subsequent geothermal interpretation.

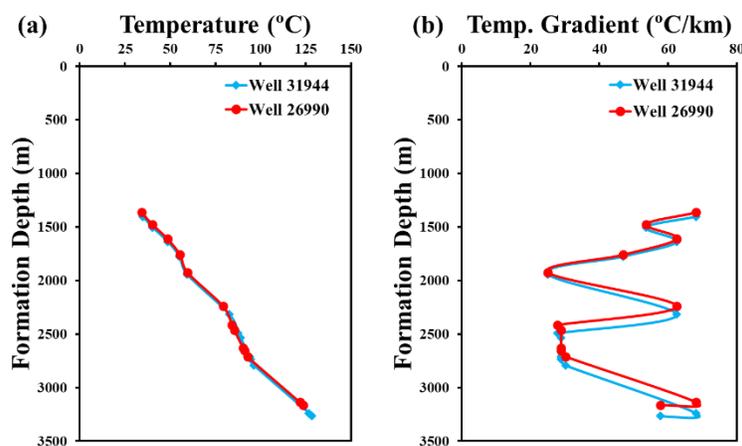


Figure 4. (a) Temperature profile and (b) Temperature gradient profile in the Three Forks formation, Williston basin derived from the TSTRAT method.

4.2 Probabilistic Assessment of Geothermal Reservoir Energy

Figures 5–7 present the cumulative probability distributions of total, aquifer, and producible geothermal energy for the Three Forks Formation in the Bonnie View Field. The expectation curves quantify the uncertainty associated with subsurface thermal energy estimates and illustrate the progressive reduction in accessible energy across the three cases. The total geothermal energy distribution (Figure 5) spans the widest energy range, indicating substantial uncertainty associated with formation-scale heat content. From the curve, the P90, P50, and P10 energy estimates are approximately 2.8×10^{12} MMJ, 3.4×10^{12} MMJ, and 4.6×10^{12} MMJ, respectively. The gradual slope of the curve reflects sensitivity to thermal and volumetric parameters governing the total heat stored within the formation. The aquifer geothermal energy distribution (Figure 6) is shifted toward lower energy values relative to the total geothermal energy, with a noticeably steeper decline in probability. The estimated P90, P50, and P10 values are approximately 7.5×10^{10} MMJ, 1.0×10^{11} MMJ, and 1.6×10^{11} MMJ, respectively. This narrower spread indicates reduced uncertainty when energy estimates are constrained to the fluid-bearing portion of the formation. The producible geothermal energy curve (Figure 7) exhibits the lowest energy values and the steepest probability gradient, indicating a tightly constrained distribution. The P90, P50, and P10 estimates are approximately 8 MMJ, 10 MMJ, and 15 MMJ, respectively. The sharp curvature reflects the cumulative effect of practical recovery limitations, resulting in lower high-confidence energy outcomes. The probabilistic results show a clear hierarchical reduction in energy magnitude and uncertainty from total geothermal energy to aquifer-based and finally producible energy. The consistent leftward shift and increasing steepness of the curves demonstrate how successive constraints progressively limit the range of achievable geothermal energy within the Three Forks Formation.

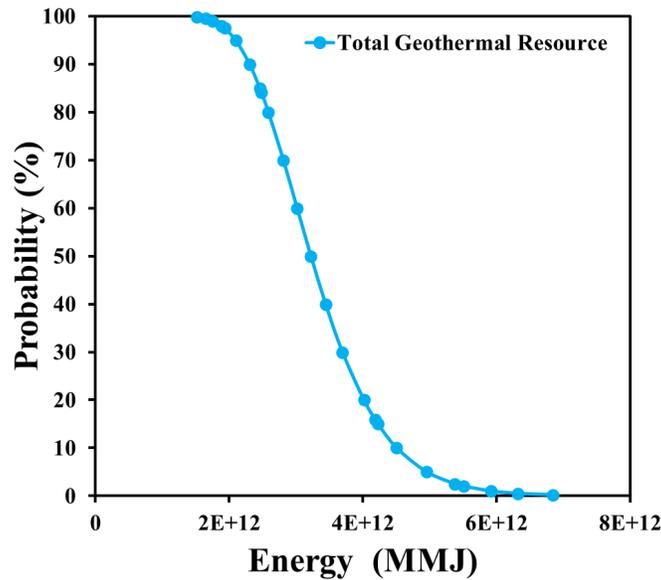


Figure 5. Probabilistic Expectation Curve for Total Geothermal Resource, Three Forks Formation.

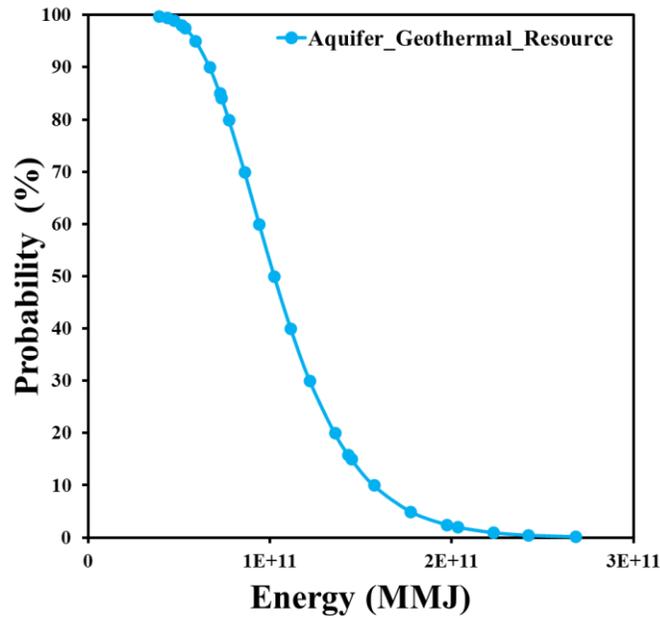


Figure 6. Probabilistic Expectation Curve for Aquifer Geothermal Resource, Three Forks Formation.

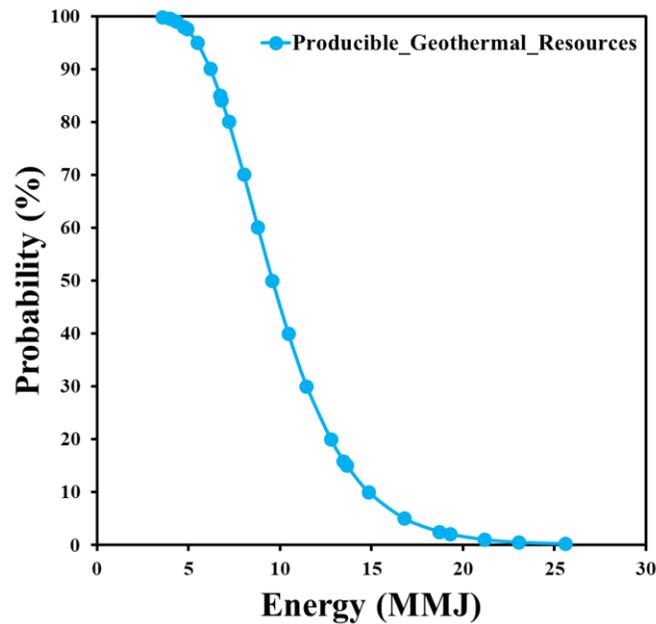


Figure 7. Probabilistic Expectation Curve for Producing Geothermal Resource, Three Forks Formation.

4.3 Uncertainty and Relative Impact of Geothermal Reservoir Parameters

Figures 8–10 present a comparative relative-impact assessment of key reservoir parameters controlling uncertainty in the total, aquifer, and producible geothermal resource estimates for the Three Forks Formation. Relative impacts were normalized such that the summed contribution of all parameters equals unity, allowing direct comparison of the percentage contribution of each parameter to overall uncertainty. Results are shown for both the deterministic parametric sensitivity analysis and the stochastic Monte Carlo simulation, which captures nonlinear parameter interactions. For the total geothermal resource (Figure 8), uncertainty is overwhelmingly controlled by gross reservoir thickness, contributing approximately 93.1% in the parametric analysis and 93.6% in the Monte Carlo simulation. Secondary contributors are minor and broadly consistent between methods, with temperature accounting for ~3.3–3.6%, density for ~1.7–2.2%, and rock heat capacity for ~1.1–1.5% of the total uncertainty. The close agreement between the two approaches indicates that total geothermal

energy estimates are primarily governed by uncertainty in bulk rock volume, while thermophysical property variability exerts only a marginal influence. The aquifer geothermal resource uncertainty distribution (Figure 9) exhibits a more distributed sensitivity pattern reflecting fluid-dependent storage mechanisms. Gross thickness remains the dominant source of uncertainty, contributing 56.9% in the parametric case and increasing to 60.7% in the Monte Carlo results. Water saturation represents the second most influential parameter, contributing 30.5% (parametric) and 28.2% (Monte Carlo), followed by porosity, which contributes 8.3% and 7.0%, respectively. Temperature contributes modestly (~2.0–2.4%), while density and heat capacity together account for less than ~2% of total uncertainty. The elevated sensitivity to porosity and water saturation relative to the total resource highlights the importance of pore-fluid volume and distribution in controlling aquifer-scale geothermal heat content. For the producible geothermal resource (Figure 10), the dominant uncertainty drivers shift decisively toward parameters governing fluid mobility and production capacity. The fluid flow rate emerges as the primary controlling factor, contributing 58.6% of the uncertainty in the parametric analysis and increasing slightly to 61.7% in the Monte Carlo simulation. Gross thickness remains significant but secondary, contributing 54.8% in the parametric case and decreasing to 23.3% under Monte Carlo sampling, indicating strong nonlinear interactions between thickness and flow-controlled productivity. Water saturation contributes 29.4% (parametric) and 10.8% (Monte Carlo), while porosity contributes 8.0% and 2.7%, respectively. Temperature, density, and heat capacity collectively contribute less than ~3% of the overall uncertainty. The relative-impact analysis reveals a systematic transition in uncertainty control across resource classifications. Total geothermal resource uncertainty is dominated by volumetric parameters, particularly formation thickness. Aquifer geothermal uncertainty reflects a balance between volumetric and fluid-storage parameters, while producible geothermal uncertainty is governed primarily by dynamic flow properties. The divergence between parametric and Monte Carlo results for producible resources underscores the importance of stochastic methods in capturing nonlinear dependencies and parameter coupling, particularly when moving from theoretical heat-in-place estimates toward realizable geothermal energy production.

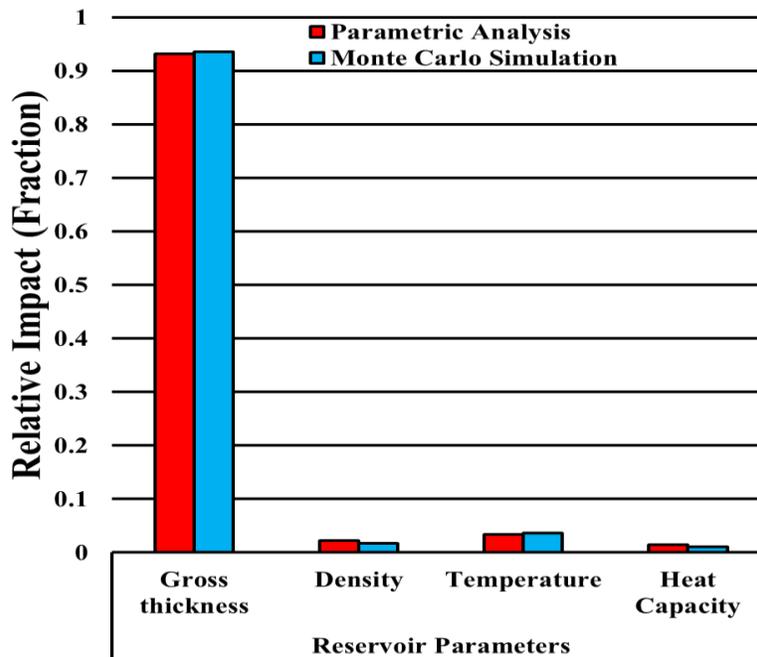


Figure 8: Relative Impact assessment of reservoir parameters comparison between Parametric and Monte Carlo Approach for Total Geothermal Resource, Three Forks Formation

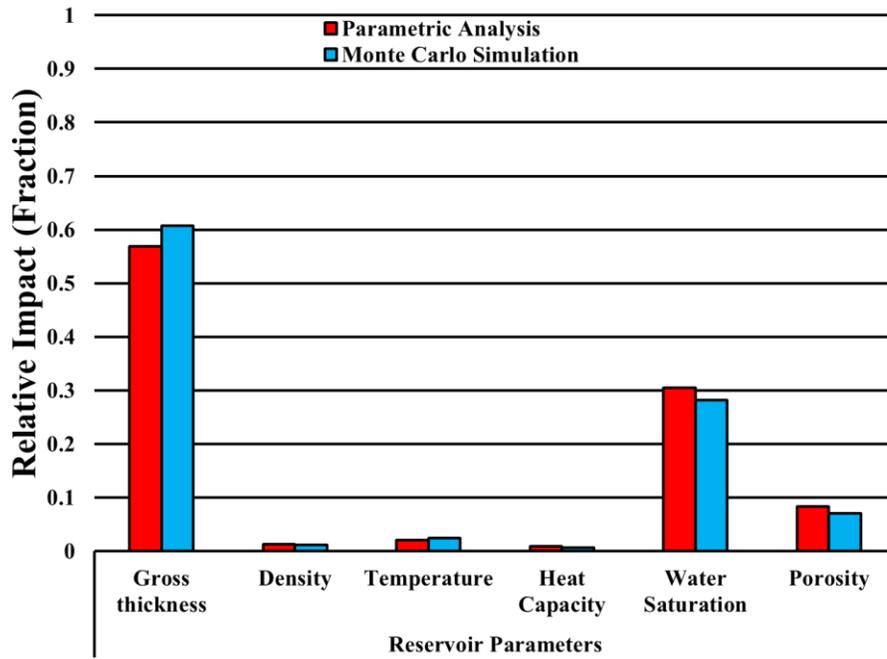


Figure 9: Relative Impact assessment of reservoir parameters comparison between Parametric and Monte Carlo Approach for Aquifer Geothermal Resource, Three Forks Formation.

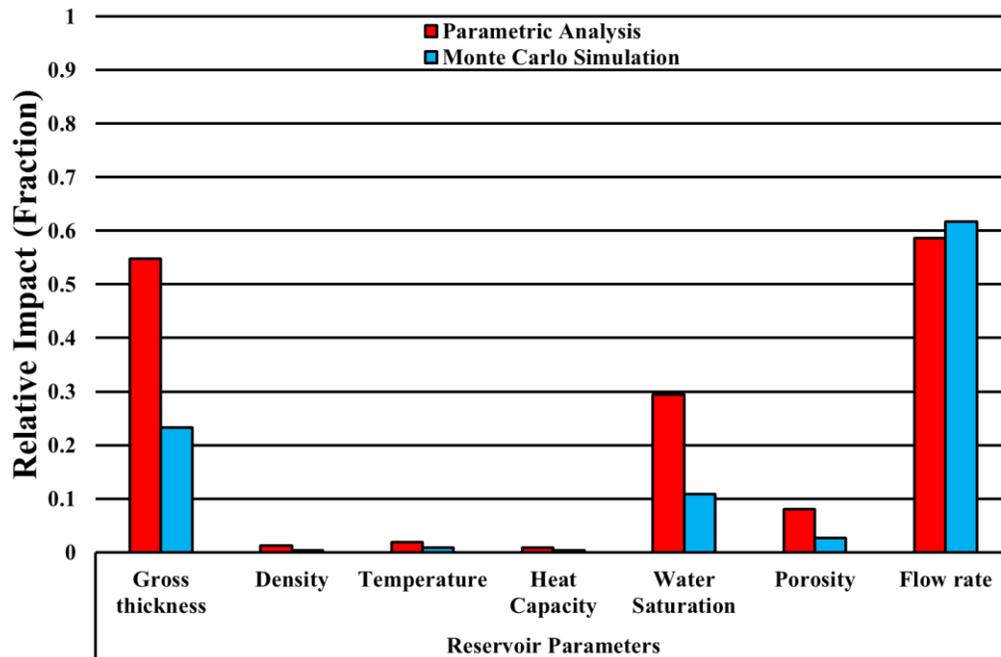


Figure 10: Relative Impact assessment of reservoir parameters comparison between Parametric and Monte Carlo Approach for Producing Geothermal Resource, Three Forks Formation

CONCLUSION

This study presents an integrated geothermal assessment of the Three Forks Formation that integrates temperature stratigraphy, geothermal gradient analysis, probabilistic energy estimation, and a dual-method relative impact assessment using both deterministic parametric

sensitivity analysis and Monte Carlo simulation. Temperature-depth and geothermal gradient profiles derived from multiple wells indicate a laterally consistent and predominantly conductive thermal regime, with variations controlled primarily by stratigraphic architecture and thermal property contrasts. The consistency observed across wells supports the robustness of the thermal framework used for subsequent resource estimation. Probabilistic energy analysis demonstrates a systematic reduction in accessible geothermal energy from total formation heat to aquifer-based and ultimately producible geothermal resources. Cumulative probability distributions show progressively narrower uncertainty envelopes as additional physical and operational constraints are introduced, with producible geothermal energy exhibiting the most constrained distributions and lowest high-confidence estimates. This progression highlights the importance of probabilistic methods in distinguishing theoretical heat-in-place from realistically recoverable geothermal energy. The combined parametric and Monte Carlo relative-impact analyses provided critical insight into the dominant sources of uncertainty at each assessment level. For the total geothermal resource, both methods consistently identify gross formation thickness as the overwhelming control on uncertainty, accounting for more than 93% of the total variability. This strong agreement confirms that uncertainty in bulk rock volume dominates theoretical heat storage estimates, while thermophysical properties such as temperature, density, and heat capacity exert only a secondary influence. At the aquifer geothermal resource level, uncertainty becomes more distributed as fluid-dependent storage mechanisms are introduced. Gross thickness remains the primary contributor; however, water saturation and porosity emerge as significant secondary controls in both analyses. The close correspondence between parametric and Monte Carlo results indicates that aquifer geothermal uncertainty is governed by a combined influence of volumetric and pore-fluid parameters, reflecting the importance of fluid occupancy and distribution within the reservoir. For the producible geothermal resource, the dominant uncertainty drivers shift decisively toward parameters controlling fluid mobility. Both methods identify fluid flow rate as the principal contributor to uncertainty, with Monte Carlo results indicating an even stronger influence due to nonlinear interactions with reservoir thickness and saturation. The divergence observed between parametric and Monte Carlo outcomes at this stage highlights the necessity of stochastic approaches for capturing parameter coupling and nonlinearity when evaluating practical geothermal recoverability. The integrated relative-impact assessment revealed a systematic transition in uncertainty control from volumetric parameters in total geothermal energy, to fluid storage parameters in aquifer energy, and finally to dynamic flow properties in producible geothermal resources. While the Three Forks Formation exhibits a well-defined and thermally consistent subsurface regime, the feasibility of geothermal development is ultimately constrained by uncertainties in formation thickness, fluid distribution, and, most critically, flow capacity. These findings emphasize that future geothermal appraisal efforts should prioritize improved characterization of reservoir geometry and hydraulic properties to reduce uncertainty and enhance confidence in producible geothermal energy estimates.

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