Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Application of the Monte Carlo Method for Geothermal Resource Assessment in Low-Exploration, High-Potential Areas: A Case Study of the Longchuan Basin, Yunnan

Jiang Xiaoxue[1,2], Zhu Chuanqing*[1,2],Cao Qian[3], Xie Fang[1,2], Sun Yuanjin[1,2] and Xue Yaodong[1,2]

1 State Key Laboratory of Deep Geothermal Resources, Beijing, China

2 China University of Petroleum (Beijing), Beijing, China

3 PetroChina Research Institute of Petroleum Exploration and Development, Beijing, China

Affiliation A[1]*, Affiliation B[2], Affiliation C[3] on one line <Address style>

*Corresponding author: zhucq@cup.edu.cn

Keywords: Longchuan Basin; Geothermal resources; Monte Carlo simulation; Resource uncertainty; Low-exploration basin

ABSTRACT

The Longchuan Basin, located in the high-temperature geothermal zone of the Mediterranean-Himalayan region, exhibits significant geothermal potential due to intense tectonic activity and a high heat flow background. However, limited exploration and insufficient data have hindered accurate resource assessment. In this study, reliable heat flow values were obtained through systematic drilling temperature measurements and core thermal property analysis, clarifying the spatial distribution of the basin's temperature field. Using the Monte Carlo volumetric method, key reservoir parameters such as temperature, thickness, and porosity were modeled to quantify the uncertainty of geothermal resource estimates. Results show an average geothermal gradient of 3.87°C/100 m and surface heat flow ranging from 70 to 90 mW/m^2. Hydrothermal resource potential is estimated at 9.62 × 10^{14} KJ, while hot dry rock resources range from 1.15 × 10^{16} KJ to 1.55 × 10^{16} KJ. Compared with conventional methods, the Monte Carlo approach effectively captures parameter uncertainty, improving assessment reliability. This study provides a methodological reference for geothermal exploration in under-explored basins with high geothermal potential.

1 INTRODUCTION

Under the dual pressures of the global energy crisis and environmental pollution, the development of clean and renewable energy sources has become increasingly urgent. Among them, geothermal energy stands out due to its abundance, stability, and renewability, and has therefore become a major research focus worldwide (Carlino et al., 2012; Bahadori et al., 2013; Zhang and Hu, 2018; Wang et al., 2020). The Yunnan–Xizang subtropical zone, located within the high-temperature geothermal belt of the Himalayas, lies along the principal collision zone between the Indian Plate and the Eurasian Plate. Strong tectonic deformation in this region has resulted in typical modern hydrothermal activities (Tong and Zhang, 1981). The Longchuan Basin in western Yunnan is situated in the central–southern segment of the Sanjiang Orogenic Belt of Dehong Prefecture. This region is characterized by well-developed fault systems, vigorous magmatic activities, and a pronounced high-temperature geothermal anomaly, all of which create favorable geological conditions for the formation and enrichment of geothermal resources (Huang et al., 2020). Previous studies have investigated the geothermal geological background and hydrothermal activity in parts of this area, and have preliminarily summarized the controlling factors of geothermal occurrence (Liu et al., 2015; Duan et al., 2019; Wu et al., 2021). Due to the low exploration level of the Longchuan Basin, drilling data are limited and unevenly distributed, resulting in significant uncertainty in reservoir characterization. This makes conventional deterministic volumetric methods inadequate for capturing subsurface heterogeneity. In contrast, the Monte Carlo volumetric approach accounts for the variability of key parameters—such as temperature, thickness, and porosity—through probabilistic sampling, making it more suitable for geothermal assessment in poorly explored regions. Therefore, this study integrates geological, temperature-logging, and thermal property data to characterize the geothermal field and reservoir–caprock system of the Longchuan Basin. On this basis, hydrothermal and hot dry rock (HDR) geothermal resource potentials are quantitatively evaluated using the Monte Carlo volumetric method, providing scientific support for geothermal exploration and development in this and other high heat-flow areas.

2 GEOLOGICAL SETTING

The Tengchong Block lies within the continental collision zone between the Indian (Gondwana) and Eurasian (Yangtze) plates, forming an important segment of the Eastern Tethys tectonic belt. It is bounded by the Gaoligong Mountain shear zone to the east and connects to the Myanmar Block through the Myitkyina–Sagaing

Fault and Mogu metamorphic belt to the west (Li et al., 2011). NE- and N-trending strike-slip faults and multiple tensile basins subsequently developed under NW-directed extensional stress and NE-directed compression (Gao et al., 2023; Chen et al., 2023).

The Longchuan Basin, located in the western Tengchong Block, is a typical NE–SW-trending Cenozoic fault-controlled basin with an area of 475 km^2. Stratigraphy includes the Cambrian basement and Cenozoic Nanlin and Mangbang formations overlain by Quaternary sediments. The Proterozoic Gaoligong Group and Cambrian rocks consist mainly of metamorphic units such as gneiss and marble. The Neogene Nanlin Formation comprises sandstone–siltstone with mudstone interlayers, while the Mangbang Formation contains conglomerate and mudstone with minor coal seams. The widely distributed Neogene–Quaternary sedimentary cover acts as an effective cap layer, providing favorable geological conditions for geothermal resource accumulation in the Longchuan Basin (Fig. 1).

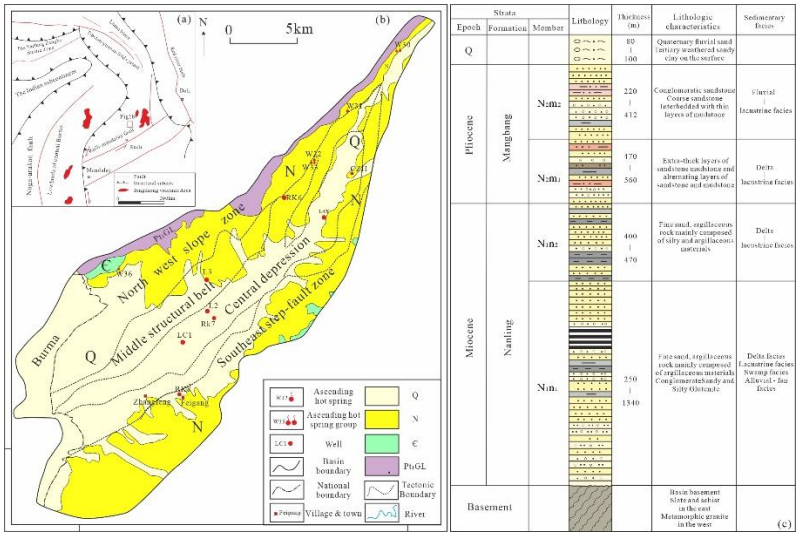


Figure 1. Tectonic division in the study area and integrated stratigraphic column (Zhang et al., 2021).

3 GEOTHERMAL FIELD CHARACTERISTICS

3.1 Geothermal Gradient

Based on the systematic temperature measurement data of Wells Long4X and Long4AX (Fig. 2), the temperatures of the 2 Wells increase linearly with depth as a whole, but there are local thermal disturbances. The geothermal gradient of Well Long4X drops significantly below approximately 1500 meters, presenting as a single deep disturbance. However, abnormalities were observed in Well Long 4AX at both 200-500 m and 1200-1800 m, and even negative geothermal gradients were shown in some shallow sections of the well. This phenomenon may be related to groundwater recharge: low-temperature water seeps into the surface, exerting a cooling effect on the deep high-temperature strata and causing the temperature curve to shift towards a lower temperature. In addition, the differences in geothermal gradients among different well sections are also related to the differences in thermal conductivity caused by lithological changes. The hydraulic action in the fault zone further enhances the complexity of geothermal distribution.

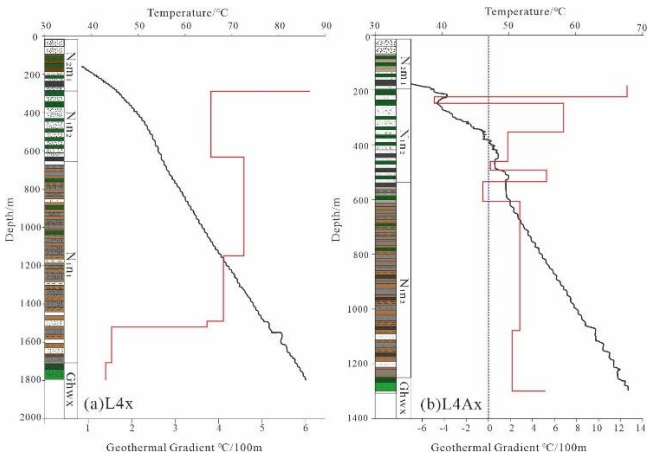


Figure 2. System temperature measurement wells. (a) L4x well. (b) L4Ax well. The black line represents temperature, and the red line represents the geothermal gradient.

3.2 Rock Thermal Properties

A total of 31 core samples were collected from Wells Long4 and Long4X, covering Paleogene and Neogene intervals dominated by coarse sandstone, siltstone, argillaceous sandstone, mudstone, and locally metamorphic rocks. Thermal conductivity measurements were conducted using the transient plane heat source method, yielding values ranging from 1.24 to 3.23 W/m·K with an average of 1.75 W/m·K, which provides a reliable basis for geothermal gradient and heat-flow calculations in the Longchuan Basin.

The radiogenic heat production rate is a crucial parameter for assessing deep thermal regimes, as it quantifies the heat generated per unit volume by the decay of radioactive elements. Natural gamma logs record γ-ray intensity associated with U, Th, and K abundances, which can be linearly correlated with radiogenic heat production. Following the empirical relationship established by Bücker and Rybach (1996), the heat production rate A can be calculated as:

$$A = 0.0158[GR(API) - 0.8] \quad (1)$$

Based on natural gamma logging data and the Bücker & Rybach empirical relationship, the radiogenic heat production of the Longchuan Basin exhibits notable stratigraphic variability. The Neogene clastic succession shows relatively high heat production values of 1.6–3.8 μW/m^3 (mean:2.82 μW/m^3), with the Mangbang Formation ranging 1.6–3.2 μW/m^3, the Nanlin Formation Member II ranging 2.0–3.5 μW/m^3, and Member I ranging 2.4–3.8 μW/m^3. Owing to their limited thickness, the contribution of these sedimentary units to the surface heat flow remains minor. In contrast, the deeper crystalline basement is dominated by metamorphic rocks with a more stable heat production range of 1.8–2.8 μW/m^3; however, because of its substantial thickness, its cumulative heat generation has a more pronounced effect on the regional geothermal field(Fig. 3).

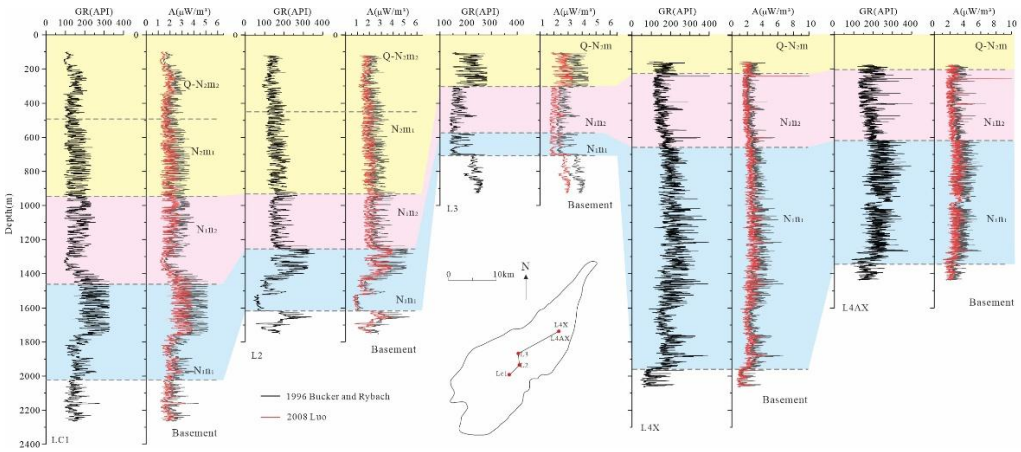


Figure 3. Gamma-Ray and Heat Generation Rate Curves for Different Logging Curves in the Longchuan Basin

3.3 Heat Flow

High-quality (Grade A) heat-flow data were obtained from Well L4X by combining downhole temperature logs with laboratory-measured thermal conductivity, while Grade B heat-flow values were derived from LC1 well temperature data constrained by thermal conductivity measurements from adjacent wells. Integrating these results with the fifth edition of the Compilation of Geothermal Heat Flow Data in the Chinese Mainland and previously published datasets, a regional heat-flow map of the Tengchong Block and Longchuan Basin was constructed (Fig. 4).

The Tengchong Block exhibits high heat-flow values predominantly ranging from 75 to 110 mW/m^2, substantially exceeding the Chinese continental average of 61.5 mW/m^2, reflecting strong lithospheric thinning and asthenospheric heat input associated with India–Eurasia collision. The Longchuan Basin, situated in the southeastern Tengchong Block, displays a spatial pattern of higher heat flow along basin margins and lower values in the basin interior, with a secondary gradient from north to south. This distribution is governed by the structural configuration and thermal conductivity contrast between high-conductivity metamorphic rocks along the basin margins (2.95 W/m·K) and low-conductivity Neogene sand–mudstone within the basin (1.57–2.03 W/m·K), which induces lateral heat-flow redistribution and ultimately defines the present geothermal structure (Wang et al., 2022).

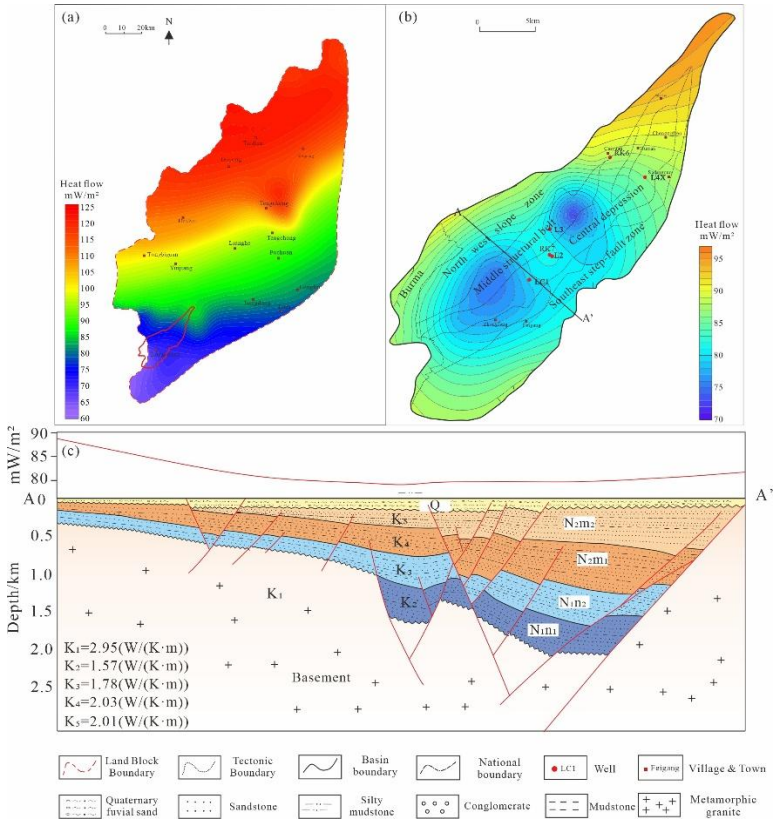


Figure 4.Heat flow distribution map of Tengchong block and Longchuan Basin

3.4 Temperature Distribution Characteristics

Due to the limited number and shallow depth of drillholes in the study area, direct constraints on the deep geothermal regime remain insufficient. Analysis of the available temperature logs and regional geological characteristics indicates that, although localized hydrothermal convection affects shallow intervals, the basin-scale heat transfer is dominated by thermal conduction. Combined with the nearly uniform spatial distribution of radiogenic heat production, the subsurface temperature profile can be reasonably assumed to vary approximately linearly with depth. Consequently, a one-dimensional steady-state conductive model is appropriate for predicting deep temperatures. Under these assumptions, the temperature–depth relationship can be described by the classical one-dimensional steady-state heat conduction equation:

$$T(Z) = T_0 + \frac{q_0 Z}{K} - A_0 Z^2/(2K) \quad (2)$$

In this formulation, $T(Z)$ denotes the temperature (°C) at depth Z(m), T_0 is the surface temperature, taken as 19 °C, q_0 represents the surface heat flow (mW/m^2), and K is the weighted average thermal conductivity of strata

from 0 to Z(W/m·K). The weighted conductivity was determined based on the sandstone–mudstone ratio, which is approximately 70% sandstone according to drilling data. A_0 represents the average radiogenic heat production in the interval 0–Z (μW/m^3), which was evaluated by a stratified weighting method.

Using this conductive model, temperatures at the top of major stratigraphic units were calculated and spatially interpolated using Kriging (Fig. 5). The results show that the shallow Neogene formations exhibit relatively low temperatures due to limited burial depth. The Mangbang Formation, buried at 300–600 m, generally has temperatures below 45 °C and is therefore unsuitable for developing low-temperature hydrothermal resources. In contrast, the Nanlin Formation Member II shows a southeastward increase in temperature driven by greater burial depth, reaching 60 °C-1,250 m, indicating moderate geothermal potential. Member I is more deeply buried (1400-1600 m), with temperatures around 70 °C. In structurally deeper zones where burial reaches 1700–2200 m, temperatures may rise to 80 °C, providing favorable conditions for low-temperature hydrothermal systems.

Although formation temperatures are moderate due to the shallow burial of reservoir units, the roof of the thermal reservoir typically lies at depths <1500 m. This shallow occurrence significantly reduces drilling and utilization costs, indicating that the hydrothermal system in the Longchuan Basin still possesses considerable development potential.

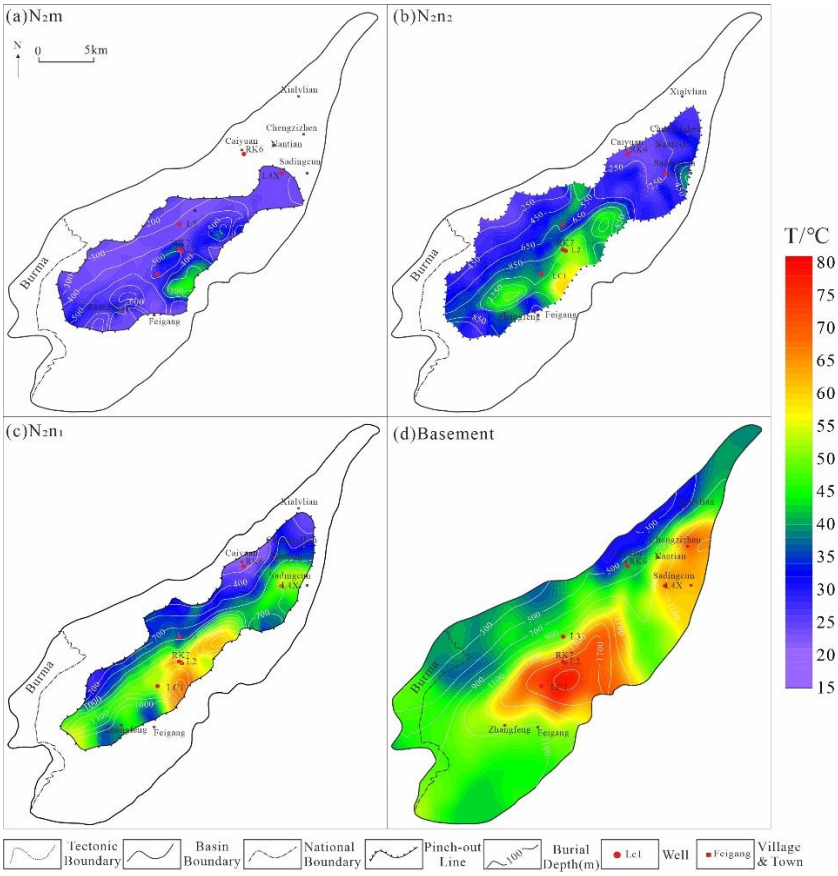


Figure 5. Temperature Distribution of Different Strata in the Longchuan Basin.

3.5 Reservoir-cap rock combination

Sandstones in the study area are mainly developed within the Mangbang Formation and the first and second members of the Nanlin Formation. The cross-well correlation profile (Fig. 6) reveals significant lateral variability in sandstone thickness within Member I of the Nanlin Formation: Wells Lc1 and L2 exhibit well-developed sand bodies, whereas Well L3 shows much thinner intervals, indicating pronounced lateral heterogeneity. Overall, the sandstone units occur in laterally extensive, stratified bodies with notable local thickness variations. At the basal part of Member I, sandstone connectivity is relatively strong. The alternation of sandstone and mudstone also provides effective vertical flow barriers, where locally thick and continuous mudstones can function as sealing layers that support geothermal fluid retention.

Petrophysical analysis of 219 core samples from Well Lc1 shows porosities ranging from 1.42% to 34.10% (average 16.2%). High-quality reservoir intervals with porosity >25% account for 10% of samples, and 85% fall

within 5%–25%. Permeability measurements from 149 samples show a maximum of 1000×10^{-3} μm^2 and an average of 52.67×10^{-3} μm^2, displaying a clear bimodal distribution, with samples in the $0.001–0.01\times10^{-3}$ μm^2 and $0.1–1\times10^{-3}$ μm^2 ranges both exceeding 20%. The temperature at the top of Nanlin Member I is 40–80 °C, meeting the requirements for hydrothermal geothermal exploitation.In deeper sections, the crystalline basement is composed of dense metamorphic granites with elevated temperatures and well-developed fracture and joint systems. These mechanical discontinuities provide favorable conditions for permeability enhancement through hydraulic stimulation, supporting the formation of an efficient Enhanced Geothermal System (EGS).

Overall, the Nanlin Formation sandstones exhibit moderate reservoir quality, favorable sealing conditions, and suitable temperature levels, representing a promising hydrothermal geothermal target. Meanwhile, the high-temperature fractured basement provides significant potential for EGS development.

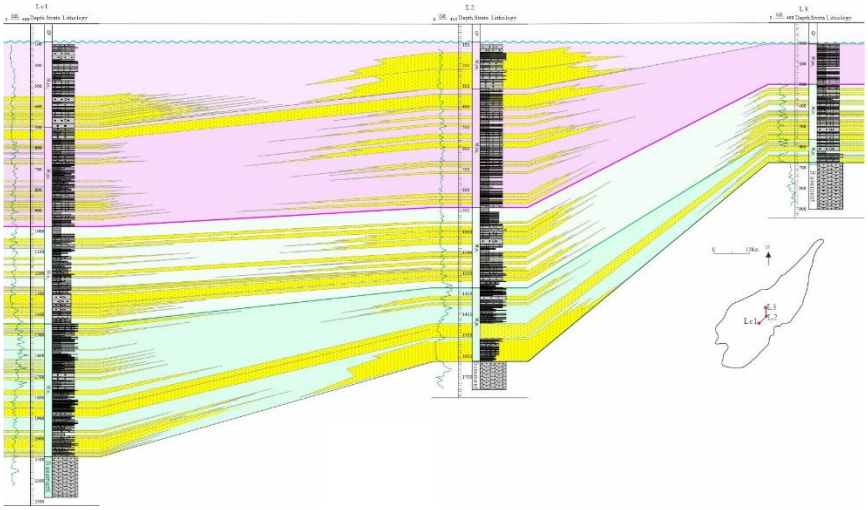


Figure 6. Longchuan Basin Connecting Well Section

4 ESTIMATION OF GEOTHERMAL RESOURCES USING THE MONTE CARLO VOLUMETRIC METHOD

Currently, several methods are commonly used for geothermal resource evaluation, including the plane fracture method, surface heat flux method, magma heat balance method, heat storage volume method, and statistical analysis method. Among these, the volumetric method, as proposed by Muffler and Cataldi (1978), is the most widely used. This method estimates the total geothermal energy (relative to a reference temperature) in a given rock volume, which includes both the rock skeleton and the fluid in its pores. When the reservoir porosity and the thermal properties of water and rock are known, the total geothermal resources in the study area can be calculated using the following equations (3) - (5).

$$QTotal = QR + QW \tag{3}$$

$$QR = AD(1-\varphi)\rho RCR\ \ (T-T0) \tag{4}$$

$$QW = AD\varphi\rho WCW(T-T0) \tag{5}$$

Where QTotal, QR, and QW respectively represent the total geothermal energy, as well as the thermal energy stored in rocks and pore water, J; A (m ^{2}) and D (m) represent the area and thickness of the heat storage, respectively. ρR and ρW represent the densities of geothermal reservoirs and geothermal water, kg/m ^{3}, while CR and CW are the specific heat of the geothermal reservoir rock and the hot water, J/ (kg·°C). ϕ represents the porosity of thermal storage rocks, %; T represents the average temperature of the rock and water within the specified volume, in °C. T0 is the reference temperature, °C, and the local constant temperature layer temperature is generally adopted.

Due to limited drilling data, complex geological conditions, and significant uncertainty in reservoir parameters, the volumetric method often yields substantial errors when estimating resources in low-exploration areas. The calculation of the volumetric method requires assigning values to key parameters such as reservoir thickness, porosity, and permeability based on regional geological predictions and empirical data. These parameters can vary significantly across regions, directly impacting the accuracy of the estimates. Additionally, thermal reservoirs in low-exploration areas are frequently influenced by tectonic activity, which can cause significant lateral and vertical variations. However, the volumetric method assumes a uniform distribution of reservoirs,

making it difficult to accurately capture these complexities. Moreover, traditional volumetric methods typically use a single deterministic value for calculations, disregarding the variability of geological parameters and failing to provide a reasonable error range, leading to large uncertainties in resource quantity estimates (Li et al.,2023). To address these challenges, this study combines the Monte Carlo simulation with the volumetric method, establishes probability distributions for key parameters, and performs large-scale random simulations to quantify the impact of parameter uncertainty on resource assessment, thereby improving the accuracy of the results (Sutopo et al., 2019; Wang et al., 2021; Palmer-Wilson et al., 2018).

4.1 Hydrothermal Geothermal Resources

The shallow hydrothermal resources in the study area are primarily hosted within the sandstone reservoirs of Nanlin Formation Member I. In contrast, the Mangbang Formation and Nanlin Member II are considered unsuitable for utilization due to their shallow burial depth and top-formation temperatures lower than 40 °C. The top of Nanlin Member I exhibits temperatures of approximately 45–65 °C, meeting the criteria for low-enthalpy geothermal development. The effective reservoir area is estimated to be 17.2 km^2, indicating a promising development potential.

In the Monte Carlo simulation, several thermal physical parameters were treated as constants to maintain computational stability: specific heat capacities of sandstone, mudstone, and water were set as 826 J/(kg·°C), 702 J/(kg·°C), and 4200 J/(kg·°C), respectively; densities of sandstone and mudstone were assigned as 2600 kg/m^3 and 2350 kg/m^3. The weighted thermal properties were constrained using a sandstone proportion of ~70%, while mudstone porosity was fixed at 15%.

Conversely, the reservoir thickness (H), mid-reservoir temperature (T), and sandstone porosity (ϕ) exhibit considerable spatial variability and therefore require probabilistic characterization. Statistical analysis based on drilling data, temperature estimates, and porosity measurements indicates that these parameters are statistically independent. Goodness-of-fit assessments using the Kolmogorov–Smirnov (K–S) test and Q–Q analysis show that H follows a normal distribution, whereas T and ϕ conform to triangular distributions. Accordingly, these distributions were applied for random sampling throughout the Monte Carlo procedure to more accurately represent parameter uncertainty and enhance the scientific robustness of the resource evaluation (Fig. 7).

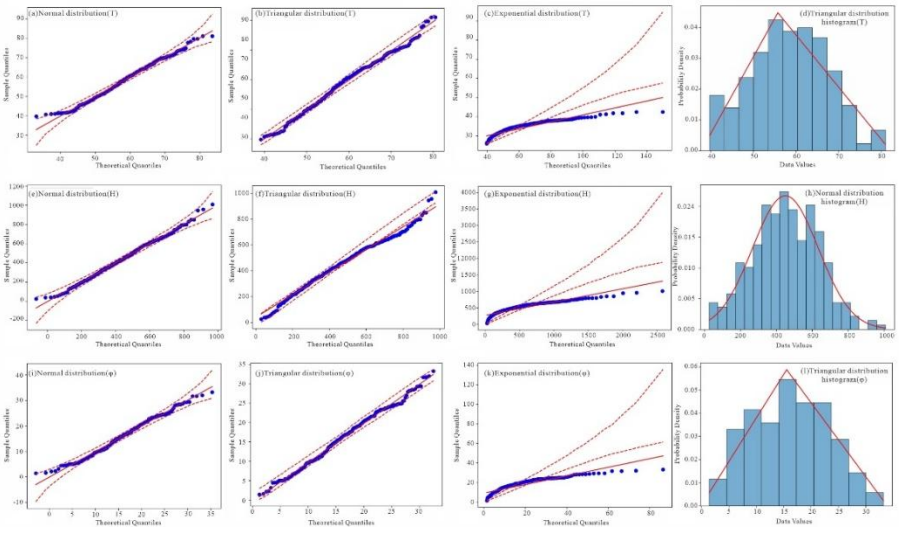


Figure 7. The distribution of temperature(T) in the middle part of Nanlin Formation, thickness(h) and sandstone porosity parameters(ϕ) in Nanlin Formation.

Random sampling was performed using Python and NumPy to conduct 10,000 Monte Carlo iterations for hydrothermal resource estimation of Nanlin Formation Member I. The simulation outcomes were statistically analyzed using Matplotlib (Fig. 8). The results indicate a mean recoverable heat content of 9.62×10^{14} KJ, with a median of 8.89×10^{14} KJ and a standard deviation of 4.76×10^{14} KJ. The estimated range spans from 3.80×10^{13} KJ (pessimistic scenario) to 3.44×10^{15} KJ (optimistic scenario). The 95% confidence interval, [2.10×10^{14}, 2.08×10^{15} KJ], reveals a noticeable but quantifiable uncertainty in the resource assessment.

To assess the robustness of the simulation, a 5-fold cross-validation approach was applied (Fig. 9). The mean relative error was 0.78%, and the relative error of standard deviation was 1.79%, demonstrating high stability of

the statistical outputs. Outlier identification based on interquartile range (IQR) and Z-score methods detected 197 (1.97%) and 87 anomalous samples, respectively, suggesting a limited influence of outliers on the final estimation results.

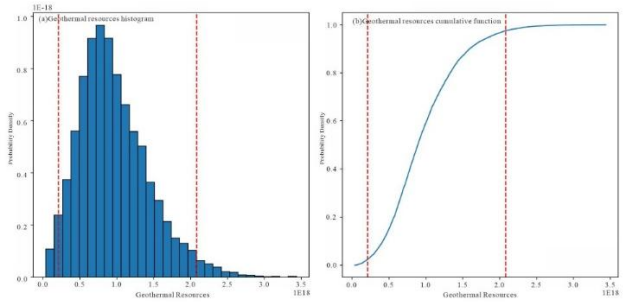


Figure 8.Evaluation of Geothermal Resources in the First Member of the Nanlin Formation, Longchuan Basin, Using the Monte Carlo Method

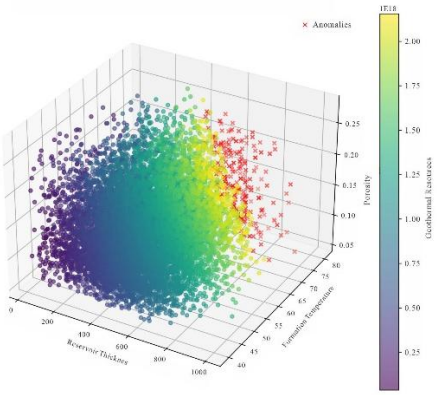


Figure 9. Scatter map of heat reservoir thickness, formation temperature, porosity and geothermal resources

4.2 Hot Dry Rock Geothermal Resources

The hot dry rock (HDR) geothermal resources in the study area are primarily hosted in dense metamorphic granites buried deeper than 5000 m, where heat transfer is dominated by thermal conduction. Based on the temperature distribution at 5000 m depth, the effective HDR reservoir zone (T > 150 °C) is delineated to be approximately 125.0 km^2. Goodness-of-fit tests (K–S and chi-square tests) performed on the temperature dataset confirm that the data follow a triangular distribution (Fig. 10), from which a temperature probability model was constructed.

For parameterization, reservoir thickness was set to 300 m, and thermophysical properties were designated considering typical Enhanced Geothermal System (EGS) conditions: rock density 2750 kg/m^3 and specific heat capacity 850 J/(kg·°C). A total of 5000 Monte Carlo iterations were performed. The simulations yield HDR resource estimates ranging from 1.15×10^{16} to 1.55×10^{16} KJ, with a mean of 1.32×10^{16} KJ, a standard deviation of 8.02×10^{14} KJ, and a 95% confidence interval of [1.19×10^{16}, 1.47×10^{16}] KJ (Fig. 11), indicating a high level of confidence in the assessment. In addition, 5-fold cross-validation was conducted to evaluate model stability. The relative errors of the mean and standard deviation are 0.0015 and 0.0106, respectively, confirming that the adopted stochastic volumetric approach demonstrates excellent stability and reliability for HDR resource estimation in the study area.

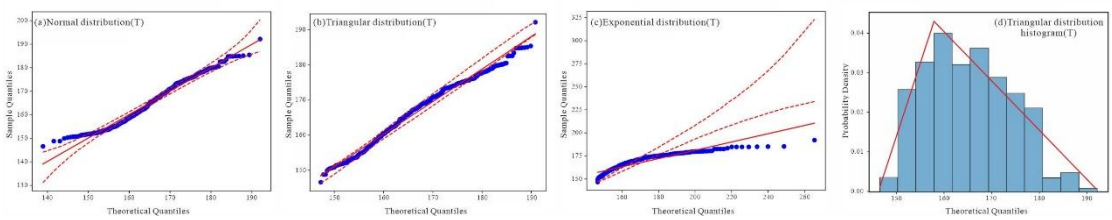


Figure 10. Test of effective reservoir temperature distribution in hot dry rock buried at 5000m

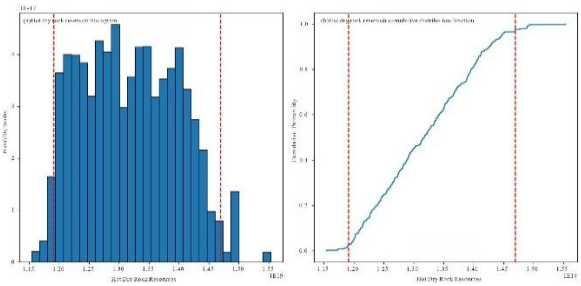


Figure 11. Evaluation of Hot Dry Rock Resources in buried at 5000m, Longchuan Basin, Using the Monte Carlo Method

5 DISCUSSION

Using the traditional deterministic volumetric method, the estimated hydrothermal resource volume of Nanlin Formation Member I is 1.13×10^{19} KJ, and the deep HDR resource volume is 1.32×10^{20} KJ. In contrast, the Monte Carlo-based probability model yields 95% confidence intervals of [2.10×10^{14}, 2.08×10^{15}] KJ and [1.15×10^{16}, 1.55×10^{16}] KJ, respectively. The estimates differ by approximately three orders of magnitude for hydrothermal resources and two to three orders for HDR resources, highlighting the tendency of deterministic approaches to substantially overestimate geothermal potential in data-limited regions.

This discrepancy arises from the traditional method's assumption of uniform reservoir parameters (porosity, temperature, and thickness), which neglects spatial heterogeneity and parameter uncertainty. In contrast, the Monte Carlo method incorporates probabilistic distributions and cross-validation (mean error <1%), effectively constraining uncertainty and providing reliable risk boundaries for resource assessment.

Therefore, probabilistic volumetric evaluation offers a more realistic and scientifically robust basis for geothermal resource assessment, especially in low-exploration settings, and can better guide future exploration and development planning.

6 CONCLUSION

This study evaluates the geothermal potential of the low-exploration and high heat-flow Longchuan Basin through geological interpretation, geothermal field analysis, and a Monte Carlo–based volumetric assessment. The main conclusions are as follows:

The heat-flow distribution exhibits a pattern of higher values at the basin margins and lower values in the interior, controlled by basement structural relief and thermal conductivity contrasts.

Nanlin Formation Member I serves as the primary hydrothermal reservoir, with burial depths of 1400–1600 m and temperatures of 70–80 °C, yielding an average resource estimate of 9.62×10^{14} KJ. The shallow depth of the reservoir contributes to favorable development economics. Deep metamorphic basement rocks (135–185 °C) provide substantial potential for hot dry rock (HDR) utilization, with a mean estimate of 1.32×10^{16} KJ.

The Monte Carlo methodology effectively quantifies uncertainty in key reservoir parameters. Cross-validation verifies the stability and accuracy of the results, offering a more reliable geothermal assessment approach than traditional deterministic volumetric methods in data-scarce regions.

Acknowledgements

This study is supported by the National Key Research and Development Program of China (2021YFA0716003).

REFERENCES

Bahadori, A., Zendehboudi, S., and Zahedi, G.: RETRACTED: A review of geothermal energy resources in Australia: Current status and prospects, Renewable and Sustainable Energy Reviews, 21, (2013), 29–34.

Bücker, C., and Rybach, L.: A simple method to determine heat production from gamma-ray logs, Marine and Petroleum Geology, 13, (1996), 373–375.

Carlino, S., Somma, R., and Troise, C.: The geothermal exploration of Campanian volcanoes: Historical review and future development, Renewable and Sustainable Energy Reviews, 16(1), (2012), 1004–1030.

Chen, K.F., Lin, Y., and Shen, W.H., et al.: Advances in geophysical and geochemical studies on the origin of Tengchong volcano, Reviews in Earth and Planetary Physics (Chinese and English), 54(2), (2023), 216–230.

Duan, X.Z., Fan, H.R., and Zhang, H.F., et al.: Melt inclusions in phenocrysts track enriched upper mantle source for Cenozoic Tengchong volcanic field, Yunnan Province, SW China, Lithos, 324–325, (2019), 180–201.

Gao, Y., Li, G., and Liu, Z.H., et al.: Lower Paleozoic detrital zircon U–Pb geochronological characteristics of the Baoshan Block in western Yunnan and its constraints on the Proto-Tethys tectonic evolution, Acta Petrologica Sinica, 39(3), (2023), 921–937.

Huang, Q.H., Zhang, H., and Kang, X.B., et al.: Hydrochemical characteristics and circulation process of geothermal water in the Longchuan faulted basin, western Yunnan, Carsologica Sinica, 39(6), (2020), 793–801.

Li, H.Q., Xu, Z.Q., and Cai, Z.H., et al.: Discovery of Indosinian magmatic thermal events in the Tengchong block, western Sanjiang tectonic belt, and its geological significance, Acta Petrologica Sinica, 27(7), (2011), 2165–2172.

Liu, Y., Zhou, X., and Deng, Z., et al.: Hydrochemical characteristics and genesis analysis of the Jifei hot spring in Yunnan, southwestern China, Geothermics, 53, (2015), 38–45.

Luo, X., Zhu, C.Q., and Zhang, B.S., et al.: Estimation of heat production rate in the Tarim Basin sedimentary strata using natural gamma-ray logs, Acta Geologica Sinica, 94(7), (2020), 2078–2088.

Muffler, P., and Cataldi, R.: Methods for regional assessment of geothermal resources, Geothermics, 7(2), (1978), 53–89.

Palmer-Wilson, K., Banks, J., Walsh, W., et al.: Sedimentary basin geothermal favourability mapping and power generation assessments, Renewable Energy, 127, (2018), 1087–1100.

Sutopo, P., and Prabata, W., and Pratama, H.B.: The development study of Karaha–Talaga Bodas geothermal field using numerical simulation, Geothermal Energy, 7(1), (2019), 21.

Tong, W., and Zhang, J.: Characteristics of geothermal activities in Xizang Plateau and their controlling influence on Plateau's tectonic model, Science Publishers Inc., (1981), 841–846.

Wang, G.L., Liu, Y.G., and Zhu, X., et al.: Current status and development trend of geothermal resources in China, Earth Science Frontiers, 27(1), (2020), 1–9.

Wang, T.H., Wang, X.W., and Mao, X., et al.: Geothermal resource characteristics and development potential in the northern region of the Cangxian Uplift, Geology of China, (2022), 1–21.

Wang, Y., Wang, L., Bai, Y., et al.: Assessment of geothermal resources in the North Jiangsu Basin, East China, using Monte Carlo simulation, Energies, 14(2), (2021), 259.

Wu, Y., Zhou, X., and Wang, M., et al.: Comparison of hydrogeological characteristics and genesis of the Xiaguan Hot Spring and the Butterfly Spring in Yunnan of China, Journal of Hydrology, 593, (2021), 125922.

Zhang, Q.D., Liu, Z.N., and Yin, L.H.: Geochemical characteristics and genesis of geothermal fluids in high-grade metamorphic rock areas: A case study of hot springs in the Longchuan Basin, western Yunnan, Journal of Jilin University (Earth Science Edition), 51(6), (2021), 1838–1852.

Zhang, X., and Hu, Q.: Development of geothermal resources in China: A review, Journal of Earth Science, 29(2), (2018), 452–467.