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An uncertainty quantification modelling approach for assessing the resource and planning the development of low enthalpy geothermal fields

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ABSTRACT

Subsurface geological systems employed in low-enthalpy geothermal applications, such as conventional doublet systems, thermal energy storage, or unconventional approaches like Enhanced Geothermal Systems (EGS), are increasingly being explored as low-carbon, resilient solutions for industrial and urban heating, and are behind the power generation using ORC technology for power hungry industries such as data centres. Large sedimentary basins often offer favorable conditions for such developments, either by harnessing existing geothermal resources or by integrating external heat sources from industrial activities (e.g., thermal waste, data centers, hospitals).

While the general procedures for geothermal field development—such as surface investigations, drilling, and infrastructure deployment—are well established, project decisions at each stage rely heavily on the interpretation of available data. Consequently, the integration of modelling tools that incorporate uncertainty quantification is essential for informed decision-making and risk mitigation.

This study introduces a three-dimensional reservoir modelling framework that leverages uncertainty quantification to optimize resource utilization and guide the selection of development scenarios that are both technically viable and environmentally sustainable. The methodology is applied to a real-world case study, exploring variations in geological configurations, petrophysical properties, well designs, and fluid management strategies (e.g., flow rates, temperatures, and operational durations). The resulting spectrum of outcomes provides quantitative insights to support stakeholders in addressing economic, social, and technical challenges.

1 INTRODUCTION

1.1 Context

Low-temperature (below 100 °C) to medium-temperature (100–150 °C) geothermal systems can be developed for various applications, including direct use and small-scale power generation, through conventional or unconventional geothermal technology. These systems are usually conduction-dominated and occur in diverse geological settings such as sedimentary basins, intra-cratonic basins or orogenic basins (Moeck 2014). When associated with aquifers, these contexts represent approximately 35% of the continental surface underlain by aquifers, or 16% of the total continental surface area (Limberger et al., 2018).

Unlike high temperature geothermal fields, where resource estimation can be assessed through uncertainty quantification methods facilitated by surface manifestations and more recently by delineating the extent of the clay cap through geophysical surveys (O'Sullivan et al., 2024), low to medium enthalpy fields offer fewer obvious indicators for resource characterization. Approaches such as the one developed by Davalos-Elizondo et al. (2023), which assesses geothermal potential of low to medium enthalpy play types in the USA using relevant datasets and Play Fairway Analysis, help reduce development risks. Building on this approach, our study adopts a similar methodology and enhances it by incorporating uncertainty quantification based on geological, geophysical, and downhole data, along with their associated sensitivities. Ultimately, the resource assessment should primarily be based on subsurface temperature profiles, the thickness and permeability of the target production zone or aquifer, and the proposed development strategy.

To demonstrate the reservoir modelling framework designed to identify zones of geothermal potential and de-risk the exploration and production phases, this study presents a resource assessment case study of a sedimentary basin located in northwestern Australia. This study considers a large regional area in which key geological features are incorporated into a reservoir model. These features and associated parameters are evaluated through an uncertainty quantification process to assess their influence on the performance of the geothermal system. Historical data are used to validate the range of simulated outcomes.

1.2 Background Geology

Our case study considers the Phanerozoic Canning Basin, it is Western Australia's largest onshore basin, covering approximately 795,000 km^2, with an additional 55,000 km^2 extending offshore. The onshore stratigraphic succession, reaching thicknesses of up to 15 km, is predominantly Paleozoic in age. Despite over a century of petroleum exploration, much of the basin remains underexplored (DMIRS, 2024).

The basin comprises a series of west-northwest trending sub-basins, primarily affecting strata deposited prior to the middle Carboniferous compressional phase. In contrast, overlying units exhibit significantly less deformation. The principal tectonic subdivisions include:

- **Fitzroy Trough and Gregory Sub-basin**: A Devonian–Triassic northern depocentre with a Phanerozoic succession up to 15 km thick. Older strata may exist but have not been confirmed by drilling.
- **Kidson and Willara Sub-basins**: An Ordovician–Devonian southern depocentre, up to 5 km thick, overlain by a thin Permo-Carboniferous and Mesozoic cover.
- **Broome and Crossland Platforms**: A central basement high with an extensive Ordovician–Devonian succession overlain by thin Permo-Carboniferous layers.

Structural shelves flank the basin margins, where pre-Permian strata either abut, thin, or pinch out. Minor grabens and platforms adjacent to the Anketell Shelf fringe the southwestern margin and transition westward into similar features along the northern edge of the West Australian Craton. These structures are identified based on limited data. Further details on regional stratigraphy and structural configuration are available in Parra-Garcia et al. (2014).

The most prominent structural feature in the region is the Admiral Bay Fault Zone (ABFZ), which separates the Broome Platform to the north from the Willara Sub-basin to the south. The ABFZ hosts a significant Mississippi Valley-type lead-zinc deposit hosted in a structurally complex part of the ABFZ located adjacent to the project. The ABFZ was initiated as an extensional system in the Tremodocian and was compressionally reactivated in the Late Silurian-earliest Devonian. It was during the latter, compressional phase that the mineralisation occurred (Sangster, 1996).

Out of this geological setting, our study finally covers an area of 25,000 km^2. Figure 1 details the geological units and faults that have been incorporated in our geological model. This area overlays the Broome Platform while the southern part is in the Willara sub-basin. The Admiral Bay Fault Zone separates the two sub-basins. Stratigraphical layers and fault traces generated by the Geological Survey of Western Australia (GSWA) and basement composition derived from the most recent Canning Basin OzSeebase study are used to build a 3D geological model with Leapfrog Energy

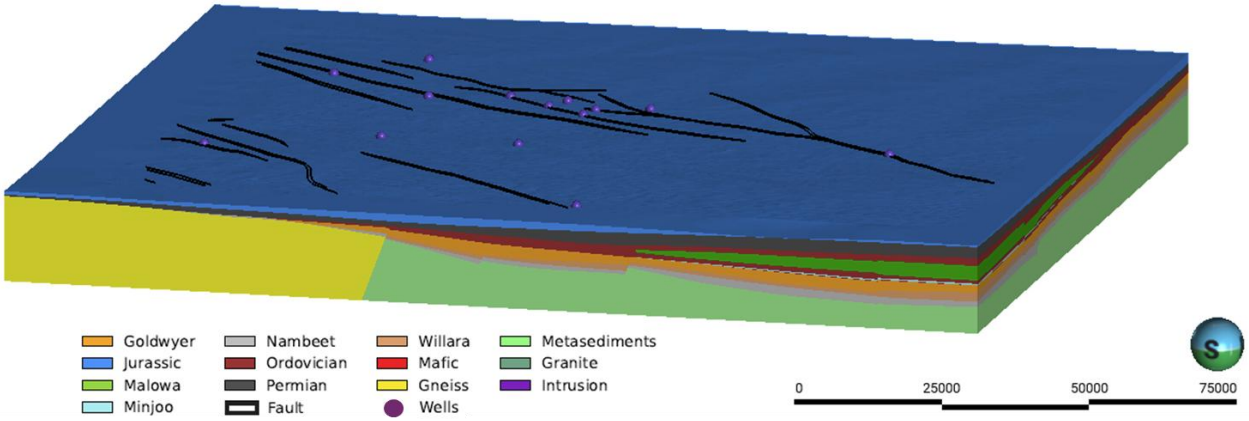


Figure 1: 3D view of the geological model with lithologies, fault zones and well location

2 GEOLOGICAL PARAMETER SETTINGS

2.1 Input Data

The objective of this resource assessment is to utilize all available data to inform and constrain the uncertainty quantification (UQ) process, following the workflow described by Dekkers et al. (2022). Most of the data employed in this study originates from publicly accessible databases. While the dataset is not exhaustive, incorporating a broader range of data enhances the robustness and reliability of the UQ analysis. Data acquisition, whether conducted prior to or during the project, provides valuable insights and can be integrated into the workflow at any stage to improve model constraints and reduce uncertainty.

The data selected for this uncertainty quantification analysis include detailed documentation regarding the techniques used for their measurement or derivation. They were chosen based on their relevance to conduction-dominated geothermal systems or their capacity to serve as reliable indicators of subsurface conditions.

2.1.1 Heat Fluxes

The Canning Basin has a median heat flow of 68 $mW.m^{-2}$. Whilst this is only marginally higher than the Australian median of 64.5 $mW.m^{-2}$, there are portions of the basin where the heat flow is considerably higher (Driscoll et al., 2009) including the area adjacent to the ABFZ.

Based on analytical measurements of radioactive elements in basement rock samples, representative of the study area, median heat generation values and associated ranges were obtained from Driscoll et al. (2009). Combined with thickness estimates for each basement rock type, these values were used to calculate heat flux distributions, which are summarized in Table 1.

Table 1: Median and Range of Heat Flux Values for Basement Rock Types in the Study Area

Basement lithologies	Median heat flux ($mW.m^{-2}$)	Minimum heat flux ($mW.m^{-2}$)	Maximum heat flux ($mW.m^{-2}$)
Granite and Felsic Intrusions*	88.4	5.0	190
Gneiss	79.9	60	90
Mafic	62.0	45	90
Metasediment	81.8	60	122

**The large uncertainty in heat flux estimates for granite and felsic intrusions is primarily driven by radiogenic heat production associated with uranium, potassium, and thorium concentrations measured in core samples. Median heat generation values for these lithologies are consistently higher than those of other basement types. Although heat flux will vary with the specific mineralogical composition of individual granites, it is highly improbable that an entire basement column composed of these rocks would exhibit uniformly low heat flux*

2.1.2 Rock thermal Conductivities

Thermal conductivity measurements of the rocks were conducted and are detailed in Driscoll et al. (2009). Interpretation of the measured data was necessary to ensure accurate representation of the typical lithologies present in the basin. Thermal conductivity values and associated uncertainty ranges from Antriasan (2009) are summarized in Table 2.

Table 2: Thermal Conductivity and Uncertainty for Rock Types in the Study Area

Rock Type	Thermal Conductivity (W/m·K)	Uncertainty (± W/m·K)
Gneiss	3.29	0.11
Granite	3.36	0.26
Intrusion	3.36	0.42
Mafic	1.8	0.18
Metasediment	4.01	1.0
Goldwyer	2.03	0.35
Permian	3.07	0.28
Jurassic	2.7	0.11
Nambeet	2.03	0.35
Ordovician	2.03	0.35
Willara	3.24	0.2
Malowa	4.89	0.32
Minjoo	4.89	0.32

2.1.3 Downhole Temperature Data

Numerous wells are present from previous oil, gas, and mining exploration campaigns, with associated data available in public databases such as OzTemp, GSWA, and Source Geoscience. To assess the representativeness of the regional reservoir model, downhole temperatures across the area were compared with model results. Some well locations and their corrected downhole temperatures are shown in Figure 5.

For some wells, minor temperature corrections were applied to account for the cooling effect of drilling fluids, using the Horner method, when sufficient data were available. For others, an empirical correction method previously applied by Ghori and HDR Pty Ltd (2009) was used and averaged to estimate corrected temperatures. This adjustment typically increases the original downhole temperature values by approximately 10–15%.

The corrected data indicate the potential to achieve commercial temperatures in the range of 130–150 °C at depths of less than 4 km, which are accessible with current drilling technology.

3 RESERVOIR MODELLING WORKFLOW

3.1.1 Numerical Modelling

To represent this regionally conductive-dominated setting, we employed the Waiwera geothermal reservoir simulator (developed at the University of Auckland by Croucher et al., 2020) in conjunction with parallel cloud computing to enable rapid execution and processing of multiple model runs. When required, Waiwera also provides functionality for simulating convective systems involving two-phase geothermal flow.

We transferred the 3D regional geological model to a 3D numerical reservoir model. To provide an initial assessment of regional temperature distribution, the reservoir model encompasses an area of 120 km × 140 km and extends vertically from the surface topography to a depth of 5 km. The domain is discretized into grid blocks measuring 2,000 meters horizontally and 50 meters vertically, resulting in approximately 420,000 cells. This resolution offers a balance between capturing vertical heterogeneity in thermal conductivity and maintaining computational efficiency.

Several simplifying assumptions were adopted for this preliminary modeling attempt:

- Lateral boundaries are treated as closed, assuming negligible regional horizontal flow.
- The upper boundary is assigned a fixed temperature of 25 °C and a hydrostatic pressure of 1 bar, consistent with a stable water table and near-flat surface topography.
- Bottom boundaries are defined by heat flux values representative of basement lithologies.

3.1.2 Uncertainty Quantification Framework

The study employs an ensemble modeling approach in which multiple reservoir models are generated by varying key parameters around their median values. Each model is simulated, and those that reproduce observed downhole temperatures within predefined tolerance limits are retained to construct a probabilistic representation of the geothermal resource. The primary parameters varied in this analysis were thermal conductivities and heat fluxes associated with the deepest geological units.

Thermal conductivities for each lithology (or reservoir rock type) were varied using a Gaussian distribution derived from the values presented in Table 2. An example of the resulting distribution is provided in the Figure 2. For consistency, a uniform thermal conductivity was assigned to each individual rock type across the entire model domain.

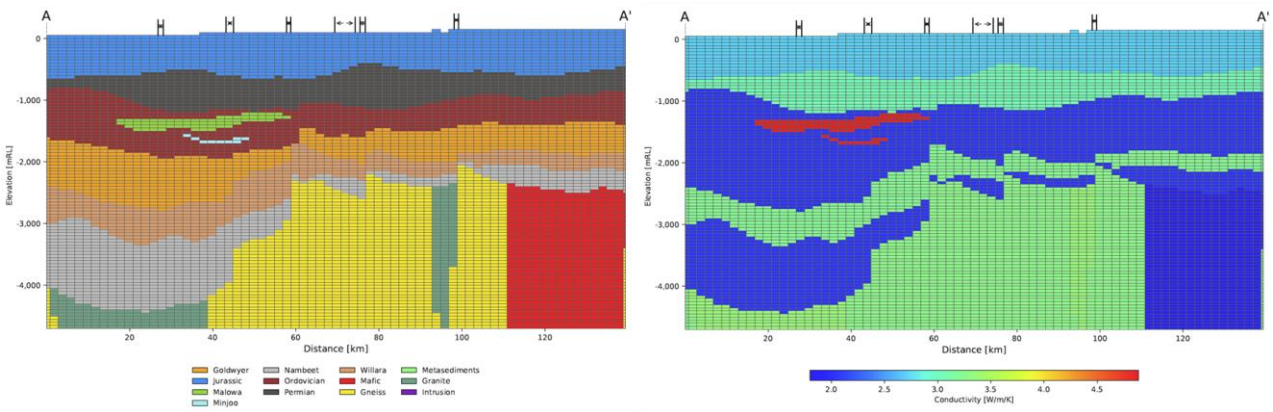


Figure 2: Cross-sectional views of the numerical model, showing rock types (left) and corresponding thermal conductivity distributions (right)

Heat flux sources are determined by the lithology present at the base boundary of the model. These values were sampled from a Gaussian distribution parameterized by the ranges reported in Table 1. Spatial heterogeneity was incorporated to account for variability among similar lithologies occurring in different geological settings. For example, two granite intrusions may exhibit distinct heat flux values within their respective ranges due to differences in magma composition. Figure 3 illustrates the lithological units represented in the deepest stratigraphic layer, along with their median heat flux values derived from Table 1.

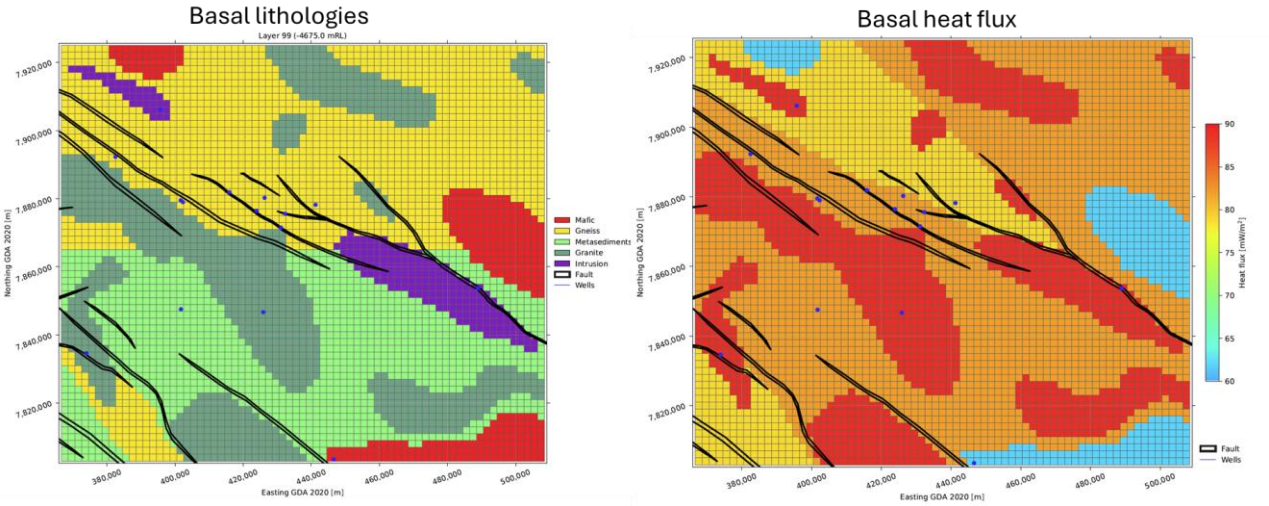


Figure 3: Plan views of the bottom of the numerical model with the rock types on the left and corresponding heat fluxes on the right

3.1.3 Sensitivity Overview

An ensemble of models was generated from the Gaussian distributions applied to thermal conductivities and basal heat-flow sources to quantify uncertainty in geothermal resource estimates. Figure 4 illustrates the parameter space used for all model realizations: the blue columns represent the overall distribution of input parameters. The upper two plots show the distribution of basal heat flux for two distinct granite units, while the lower two plots depict the thermal conductivity distributions for the Goldwyer and Jurassic lithologies.

4 UNCERTAINTY ANALYSIS: RESULTS AND DISCUSSION

4.1.1 Sensitivity Analysis Results

From a large ensemble of Natural State realizations, a subset of models was selected to provide a representative characterization of the probabilistic distribution of the resource. The parameter distributions after selection can guide further analysis to identify the most appropriate model configurations for accurately representing the geothermal field. The following figure illustrates examples of parameter selection based on observational data, where the red columns indicate the parameter values retained in the selected models that satisfy the downhole temperature constraints.

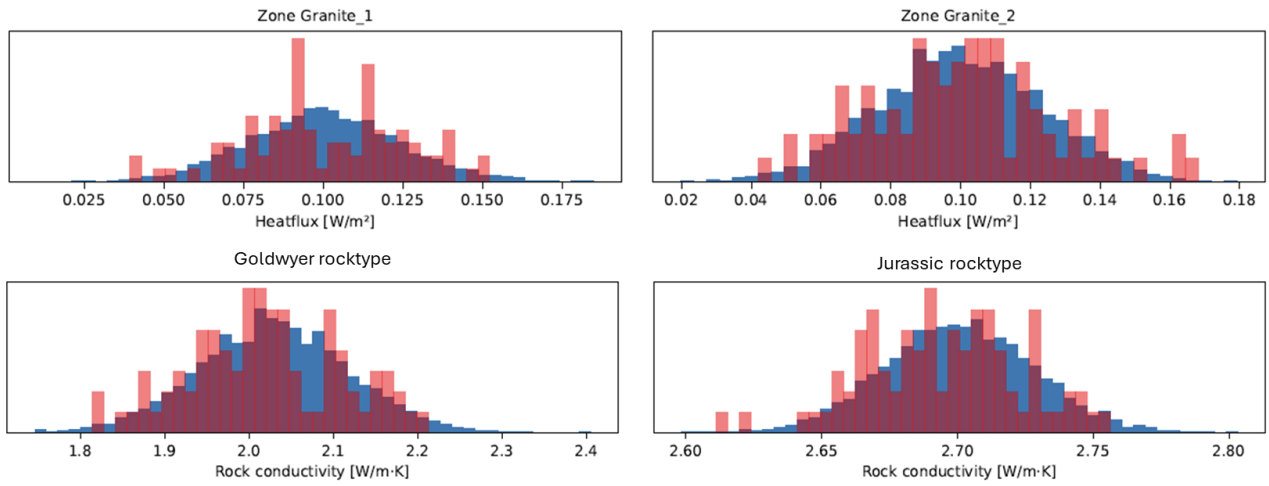


Figure 4: Parameter distributions for the uncertainty quantification study, showing heat flux examples (top) and thermal conductivity examples (bottom). Blue columns indicate the initial parameter ranges, while red columns represent the ranges after data-based filtering

Downhole temperature measurements mentioned in Section 2.1.3 were employed to constrain the uncertainty quantification results using Approximate Bayesian Computation (ABC) techniques. This filtering process retained only those realizations that satisfactorily reproduce key field observations (Gravatt et al., 2023). A subset of the model outputs, compared against observed field temperature data, is presented in Figure 5.

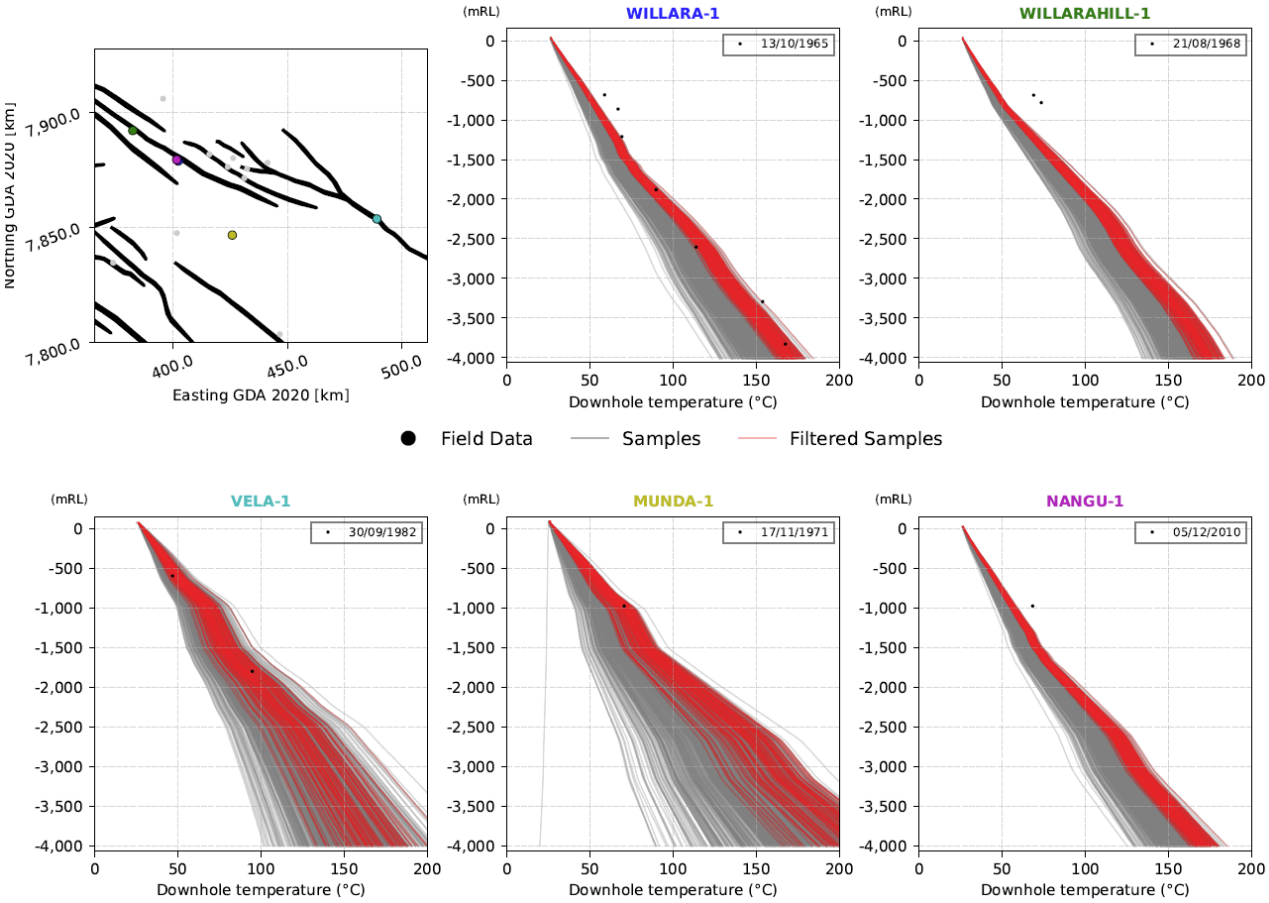


Figure 5: Downhole temperature results from all probabilistic model realizations (grey lines) and selected realizations (red lines), compared with field measurements (black dots).

Based on data from 15 downhole surveys, the majority of observed field temperatures fall within the probabilistic range predicted by the model realizations. However, discrepancies persist for certain data points, indicating that the current model configuration, defined by its boundary conditions and rock property assumptions with associated uncertainties, does not fully capture the actual behavior of the system. Further analysis and discussion of these limitations are provided in the following section.

4.1.2 Discussion of Results

The selected set of model realizations adequately reproduces most of the observed temperature data, indicating that the dominant physical processes, primarily conductive heat transfer across the various geological units, are effectively captured and delineated. The range of expected temperatures presented in the following section will provide valuable insights for characterizing potential resource utilization in areas where observational data are well represented.

Nonetheless, several temperature surveys are not adequately represented by the parameter uncertainty analysis. The figure below illustrates three wells that exhibit higher temperature values between –1,000 and –1,500 mRL. Near these wells, the range of thermal conductivity regimes explored in the uncertainty study is insufficient to reproduce the observed temperatures. Additional analysis and refined modeling is likely to be required to capture the governing physical processes in this area.

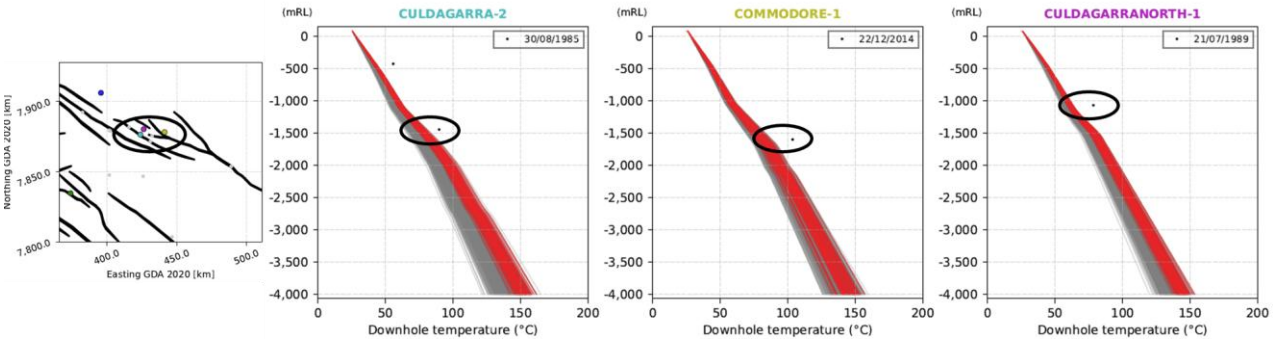


Figure 6: Subset of downhole temperature profiles highlighting discrepancies between uncertainty quantification results and field measurements

As an initial interpretation, the presence of structural discontinuities due to the extensional regime of the area, combined with deep elevated heat flow may favor some convective behavior, with hot fluids ascending along fault zones into shallower formations. Deep-seated granitic or magmatic intrusions could provide the heat source driving such upflow, although these features are challenging to characterize at depth. Consequently, the current resource assessment probably underestimates temperatures in this area by approximately 20–25 °C at shallow depths.

Acquisition of complementary geophysical data such as gravity, magneto-telluric, or seismic surveys would improve the delineation of these geological structures and support their integration into the reservoir modelling and uncertainty quantification.

4.1.3 Resource Assessment and Future Developpement

Our findings highlight both the complexity and the opportunities associated with modeling geothermal fields at an early stage using the available data. The probabilistic modeling approach provides potential resource zones along with their associated uncertainties. The selection of target zones will depend on the type of geothermal project to be developed, which in turn is influenced by economic and technical constraints. Resource recoverability, determined by reservoir characteristics such as permeability, fluid properties, well configurations, and surface facilities, was not addressed in this study but should be considered in future work.

Figure 7 illustrates the estimated resource size and associated uncertainty ranges (P10, P50, P90) for target temperatures of 140 °C and 165 °C at –3500 mRL, as well as along cross-sectional profiles. These conditions are consistent with an Enhanced Geothermal System (EGS) concept analogous to Fervo's approach (Norbeck et al., 2023), given similar depths and thermal gradients. Notably, these temperature intervals occur within the crystalline basement rather than in overlying sedimentary formations with primary porosity and permeability (e.g., Jurassic and Willara formations). Such tools provide high-level insights for de-risking geothermal projects and support informed decision-making.

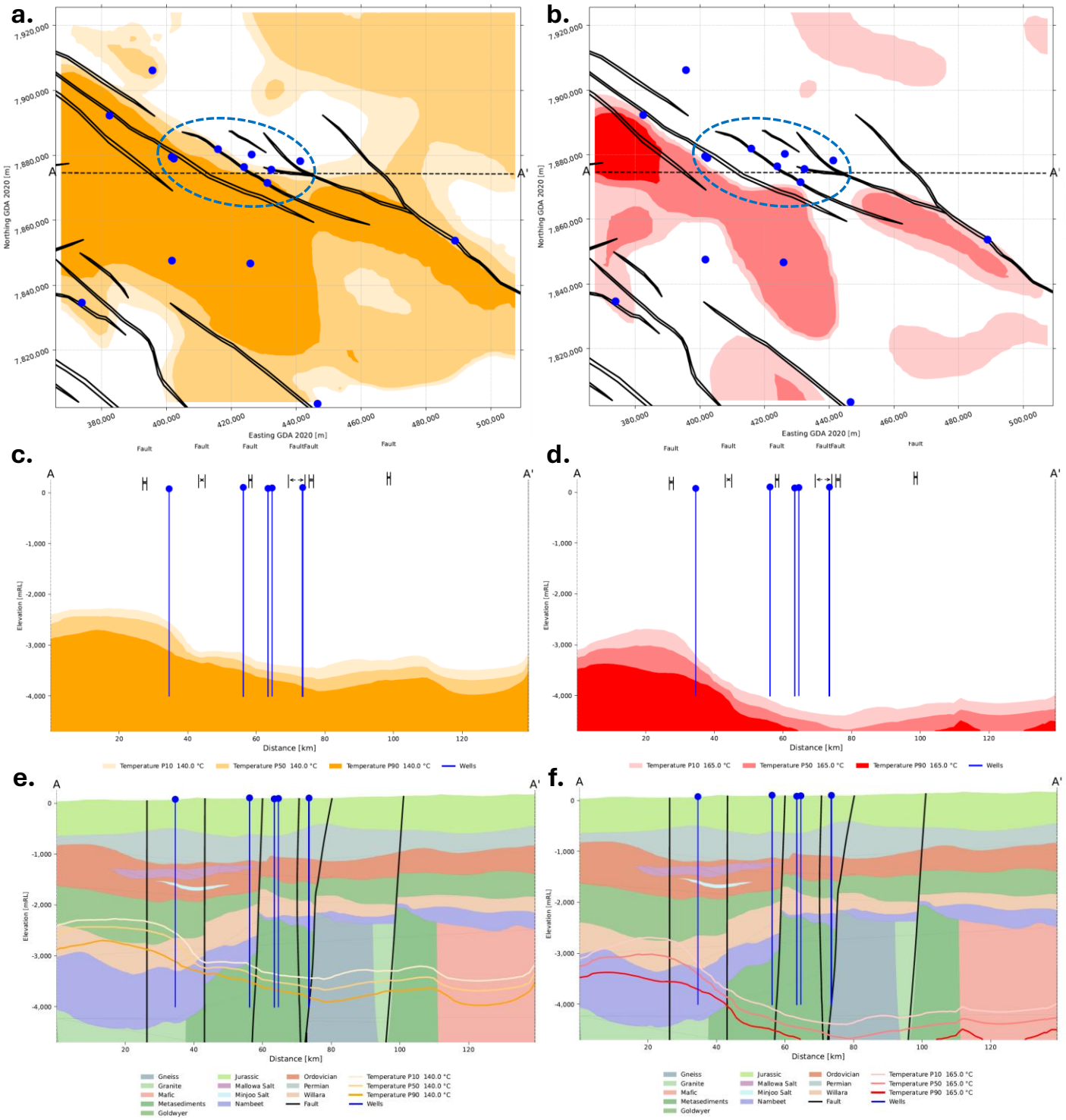


Figure 7: Plan views and cross-sectional slices of geothermal resource estimates for target temperatures of 140 °C (orange) and 165 °C (red), based on uncertainty quantification analysis. With maps of the probabilistic temperature distributions at -3,500 mRL (a. and b.), cross-sections of the probabilistic temperature distributions (c. and d.) on top of lithologies (e. and f.).

The delineated area (blue dashed line in the map in Figure 7) corresponds to a zone where the resource assessment probably underestimates temperatures, as convective circulation may occur within this structurally complex, fault-controlled system. In the preliminary JRG modeling study, manual adjustments to heat flow were required to account for this effect. This area could represent a promising target for a small-scale, fault-controlled hydrothermal system.

5 CONCLUSION

This study demonstrates the value of integrating uncertainty quantification into geothermal resource assessment for low- to medium-enthalpy systems. By applying a probabilistic reservoir modeling framework to the Canning Basin case study, we have shown that early-stage resource characterization can be significantly improved through systematic variation of key geological and thermal parameters. The ensemble modeling approach, constrained by downhole temperature observations, provides a robust basis for identifying zones of geothermal potential and quantifying associated uncertainties.

Our results indicate that conductive heat transfer dominates the regional thermal regime. However, localized discrepancies between modelled and observed temperatures suggest that convective processes may occur along structural discontinuities. This zone could represent a potential target for a small-scale, fault-controlled hydrothermal system. The primary resource potential, however, resides within the crystalline basement and may be developed using next generation Enhanced Geothermal System (EGS) methodologies.

These findings underscore the importance of integrating additional geophysical datasets and refining model assumptions to better capture complex subsurface behavior. Future work should extend this framework to incorporate permeability and fluid-flow properties, enabling a more comprehensive evaluation of resource recoverability and project economics. A more convective-focused model for the fault-controlled area could provide further insights into resource assessment.

Ultimately, the methodology presented here offers a practical pathway for de-risking geothermal development in sedimentary basins. By combining geological modeling, numerical simulation, and uncertainty quantification, stakeholders can make informed decisions that balance technical feasibility, environmental sustainability, and economic viability.

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