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Impact of Geological Heterogeneity and Uncertainty on the Performance of Hydrothermal Doublets in the Midyan Basin (Saudi Arabia)

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INTRODUCTION

- Hydrothermal doublets are sensitive to reservoir heterogeneity, connectivity, and uncertainty in porosity–permeability distributions.
- Saudi Arabia's Al Wajh Formation (NW Red Sea) shows strong depositional and diagenetic variability affecting reservoir quality .
  - Syn-rift siliciclastics with strong grain-size variability, clay matrix content, and early diagenetic modification.
  - Braided fluvial facies show porosity up to 23% and permeability reaching 3000 mD; nearshore facies drop to <10% porosity and ~400 mD permeability
- Previous hydrothermal studies demonstrate that well spacing and fracture connectivity strongly impact heat extraction .
- Recent UQ studies highlight the large spread in NPV, temperature, and energy output driven by facies uncertainty and poro-thermal parameters .
- Objective: Quantify how spatial heterogeneity + correlation lengths + porosity/permeability uncertainty influence heat extraction, pressure behavior, and techno-economic metrics

NUMERICAL MODEL

- 1800 m × 900 m × 200 m reservoir section.
- 3D COMSOL Multiphysics model (Heat Transfer in Porous Media + Darcy Flow).
- Heterogeneity Generation, Variability in:
  - Porosity (φ)
  - Permeability (k)
  - Correlation lengths Lx, Ly, Lz (anisotropy)

Uncertainty & Techno-Economics

- Latin hypercube sampling (500 realizations)
- Outputs: production temperature, LCOH, NPV
- Economic assumptions: CAPEX/OPEX

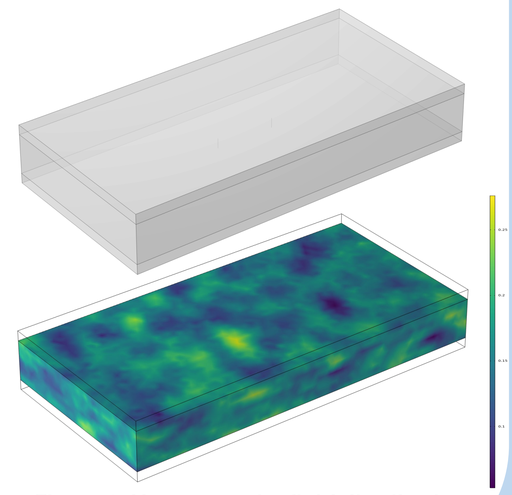


Figure 1. Heterogeneity field distribution

RESULT

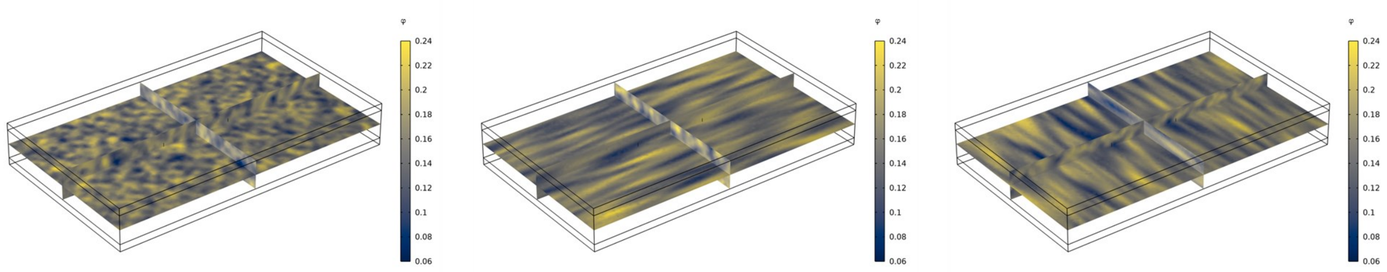
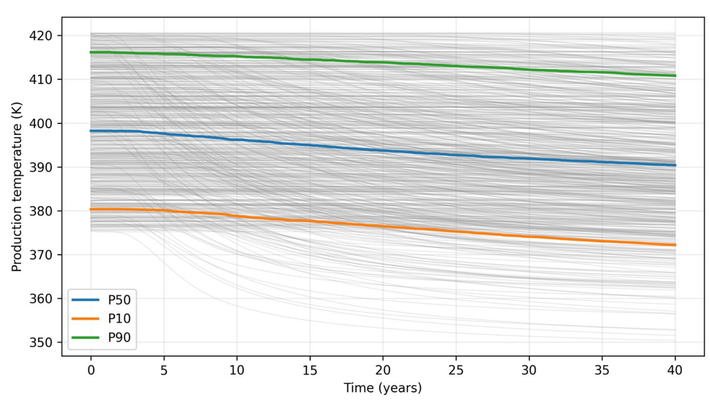


Figure 2. Porosity realizations for different correlation lengths



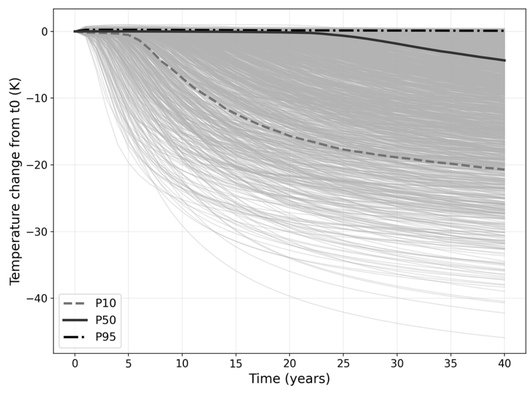


Figure 4. Temperature distribution over 40 years between injector and producer wells

- Temperature decline rate strongly controlled by longitudinal k-connectivity.
- NPV shows larger variance than thermal energy due to market uncertainty.
- Minimum injection–production spacing: 300–500 m depending on heterogeneity.
- Optimum permeability anisotropy ratio increases lifetime.
- Realizations following empirical φ–k relationships (Costa, 2006) produce smoother connectivity and slightly higher long-term temperature.

Economics

$$CAPEX = C_{drill} + C_{surface} + C_{pump} + C_{misc}$$
$$OPEX_{annual} = C_{elec} + C_{maint} + C_{labor}$$

Levelized Cost of Heat (LCOH)

$$LCOH = \frac{\sum_{n=0}^{N} \frac{CAPEX_n + OPEX_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_{th,n}}{(1+r)^n}}$$

Table 1. Parameter space

Parameter	Symbol / Units	Uncertainty Range
Mean porosity	ϕ (–)	0.08 – 0.25
Porosity variance	$\sigma^2(\phi)$	0.002 – 0.02
Mean permeability	k (m^2)	1e-15 – 3e-12 m^2 (≈1–3000 mD)
Correlation length (x)	Lx (m)	30 – 200
Anisotropy ratio	kH/kV (–)	2 – 10
Rock thermal conductivity	λr (W/m·K)	1.5 – 3.0
Rock heat capacity	Cp,r (kJ/m^3·K)	2300 – 2450
Injection fluid temperature	Tin (°C)	25 – 80
Injection rate	Kg/s	20 – 80
Well spacing	m	200 – 700
CAPEX & OPEX uncertainty	%	±20
Discount rate	%	±15
Heat price	%	±15

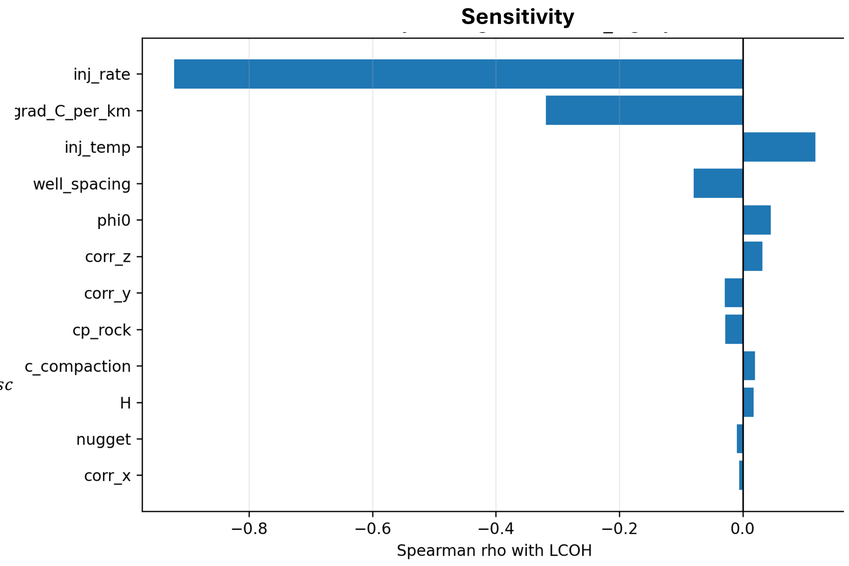


Figure 5. Sensitivity of LCOH over time for all different realizations

DISCUSSION

- The simulations demonstrate that geological heterogeneity is a first-order control on thermal performance
- The reservoir quality variability observed in Al Wajh Formation (porosity 10–25%, k = 50–3000 mD) directly explains the wide spread in simulated flow paths.
- The effect of correlation length is comparable in magnitude to the effect of mean permeability, consistent with hydrothermal studies .
- UQ clearly required: deterministic models severely misrepresent performance.
- Combining geological analogs, empirical φ–k trends, and optimized UQ reduces uncertainty in investment decisions.
- The combined influence of heterogeneity, anisotropy, and correlation length suggests that well spacing should not be fixed but instead treated as an optimization variable

CONCLUSION

- Heterogeneity and correlation lengths strongly control thermal lifetime.
- UQ reveals broad ranges for ΔT, Δp, and lifetime; heterogeneity cannot be ignored.
- Porosity–permeability uncertainty, driven by depositional and early diagenetic variability of the Al Wajh Formation, produces large uncertainty
- Economic performance is highly sensitive to geological variability: NPV varies by **>70%**, and only about one-third of realizations remain commercially viable under conservative pricing.
- The integrated workflow—combining heterogeneity generation, reservoir simulation, and techno-economic uncertainty—provides a robust decision-making framework

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REFERENCES < HEADING STYLE>

Bello, A.M. et al. (2023). Impact of depositional and diagenetic controls on reservoir quality of syn-rift sedimentary systems: Al Wajh Formation, NW Saudi Arabia. *Sedimentary Geology.*

Costa, A. (2006). Permeability–porosity relationship: A re-examination of Kozeny–Carman. *Geophysical Research Letters*

Chen, J., Kuang, X., Zheng, C. (2020). An empirical porosity–depth model for Earth's crust. *Hydrogeology Journal.*

Wang et al. (2023). Uncertainty quantification in heterogeneous reservoirs via Monte Carlo simulation. *Journal of Hydrology.*

Zhang et al. (2022). Heat extraction performance of multi-well EGS systems. *Renewable Energy.*