Progressive Generative Geomodeling with Ensemble Filtering for Synthesizing Deep-RL and Algorithmic Geosteering Policies

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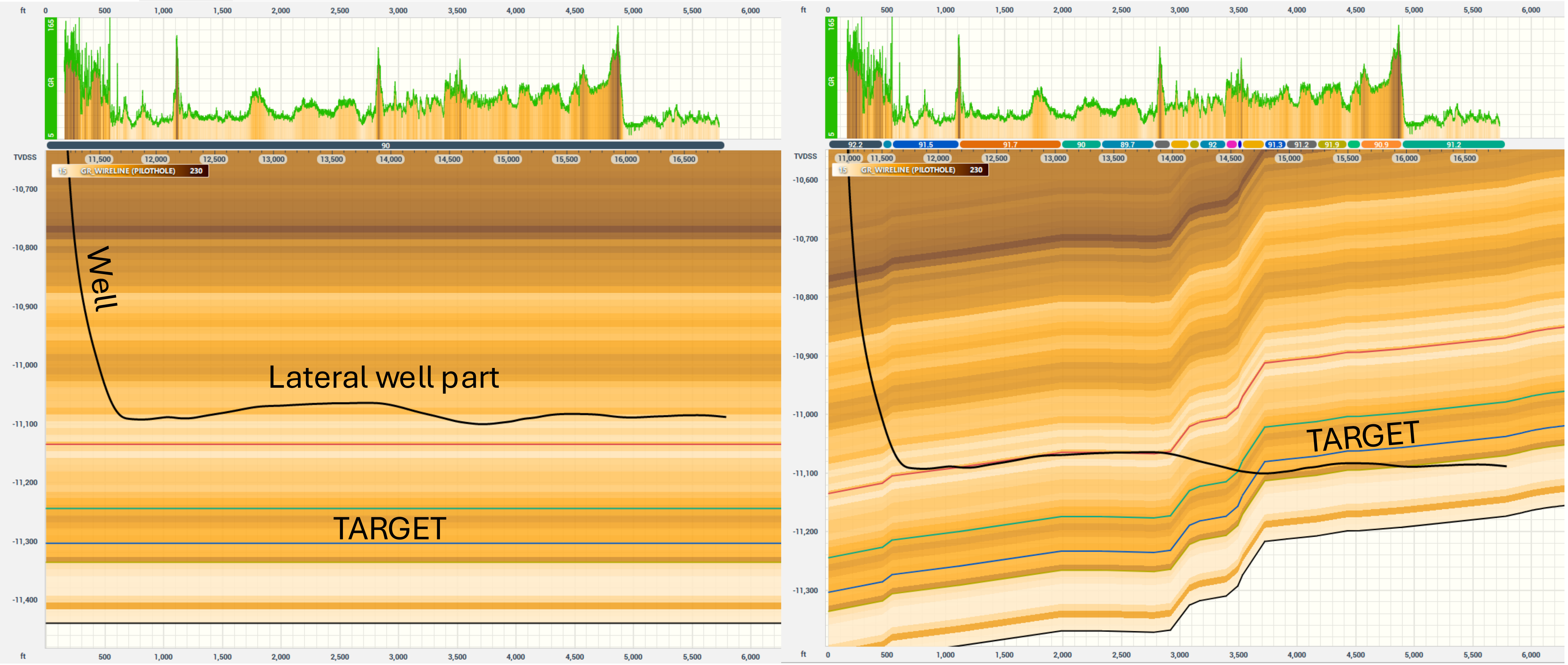
Contents

Low-data geosteering: 1D geology

fixed thickness

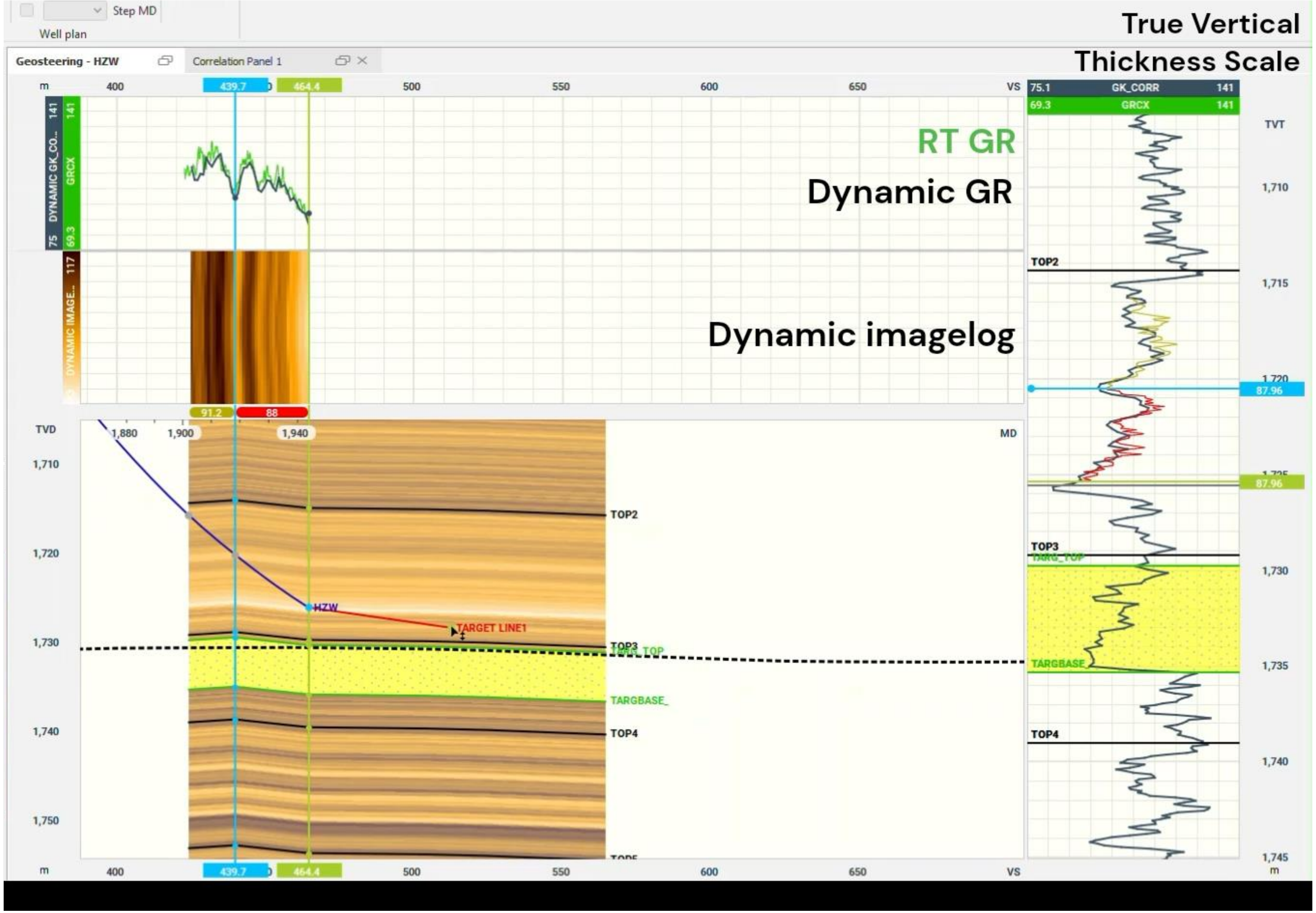


Low-data geosteering pre-requisite:

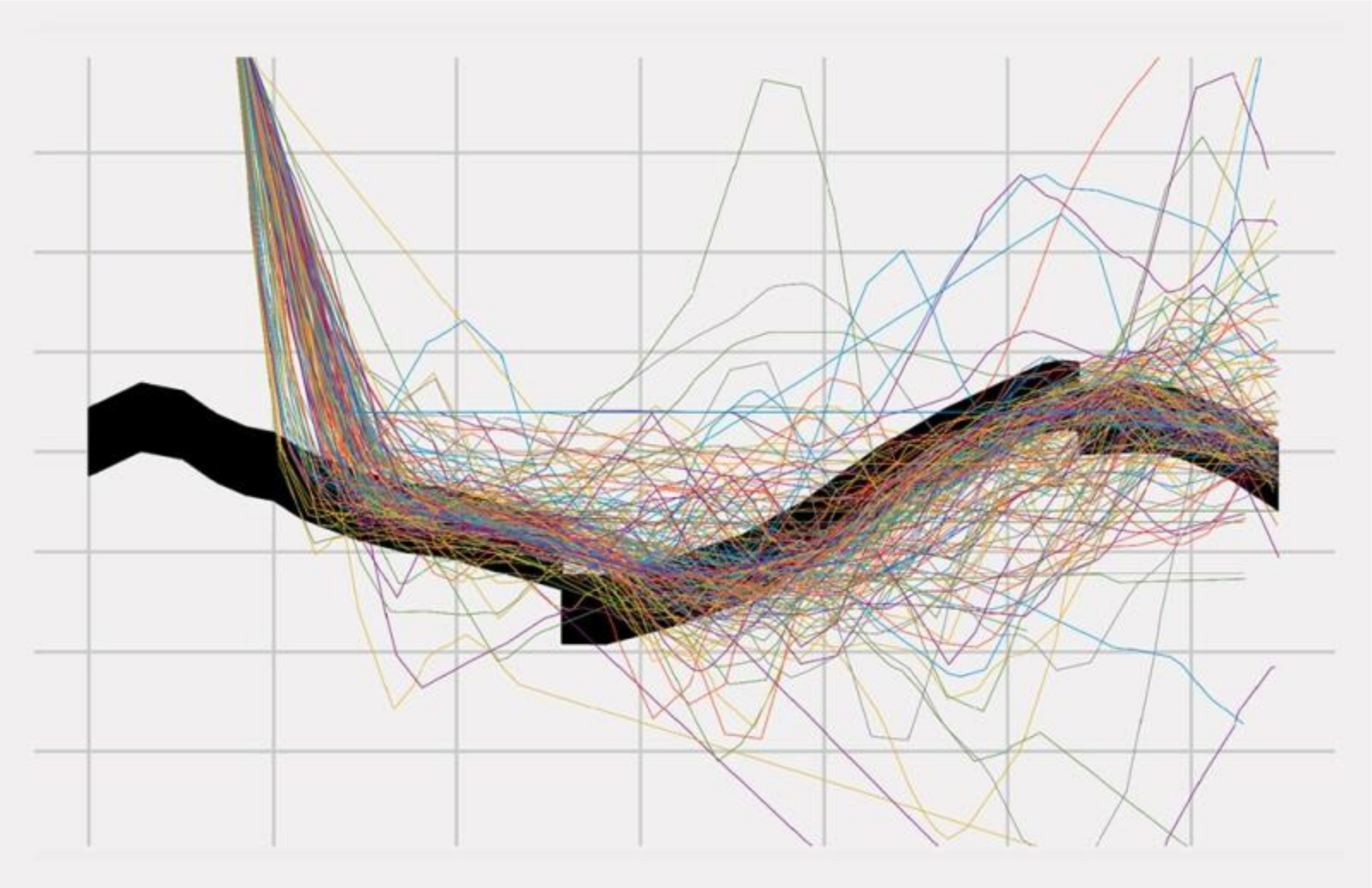
Identify your location in geological layers from corelating 1D measurements

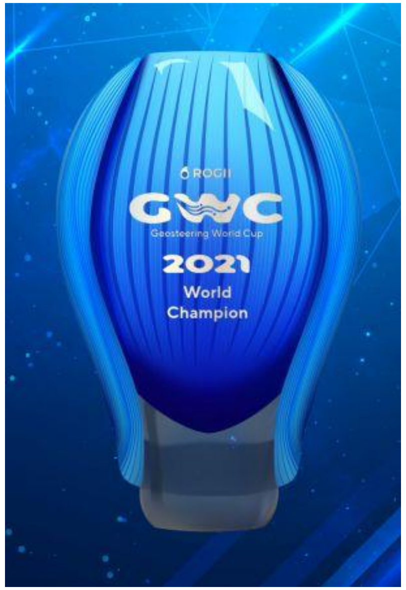
Human geosteering

Video courtesy of ROGII



Human results: Geosteering World Cup 2021





Interpretation + decision
Dataset available!

[Cheraghi et al. 2025 Analyzing expert decision-making in geosteering…]

How to beat humans?

- Decisions are dominated by uncertainty
- Geosteering requires real-time steps
  - Geomodel modification to fit new data (reduce uncertainty)
  - Decision selection (commit irreversibly)
- In practice:
  - Humans use **one or few** geomodels to fit data
  - Decisions are based on **extrapolation of that geomodel**

This is a filtering problem!

- Decisions are dominated by **uncertainty captured in an ensemble**
- Geosteering requires real-time steps:
  - Extend geomodel realizations 🡐 Forecast
  - Geomodel **filtering** to fit new data 🡐 Analysis
  - Decision selection **under uncertainty** 🡐Markov Decision Process (partially observable)

This is a filtering problem!

- Decisions are dominated by **uncertainty captured in an ensemble**
- Geosteering requires real-time steps:
  - Extend geomodel realizations ← Forecast ✓ assume
  - Geomodel **filtering** to fit new data ← Analysis ✓
  - Decision selection **under uncertainty** ← Markov Decision Process (partially observable) ?

Sequencial Decision Making
Markov Decision Process (MDP)

Sequencial process has decision history leading to **the current state**

Markov property:

- **Next state**
  only depends
  on the **current state**
  and the **decision**

- Next state **does not depend on history**

Solving Markov Decision Process

Action value function Q

$$Q_\pi(s, a) = r(s, a) + \gamma V_\pi(s'),$$

Value
for taking action *a*
from state ***s***
Given policy $\boldsymbol{\pi}$

Immidiate
reward

Expected
future
value

Discount multiplier

$$V_\pi(s) = E_{a \sim \pi(\cdot|s)}\left[Q_\pi(s, a)\right],$$

Solving Markov Decision Process

Greedy

Ignore

$$Q_\pi(s,a) = r(s,a) + \cancel{\gamma V_\pi(s')},$$

Value
for taking action *a*
from state ***s***
Given policy $\boldsymbol{\pi}$

Immidiate
reward

Expected
future
value

Discount multiplier

$$\cancel{V_\pi(s) = E_{a\sim\pi(\cdot|s)}\left[Q_\pi(s,a)\right]},$$

Solving Markov Decision Process
Dynamic programming

Unfold

$$Q_\pi(s,a) = r(s,a) + \gamma V_\pi(s'),$$

Value
for taking action *a*
from state ***s***
Given policy $\boldsymbol{\pi}$

Immidiate
reward

Expected
future
value

Discount multiplier

Modelling
On descrte space

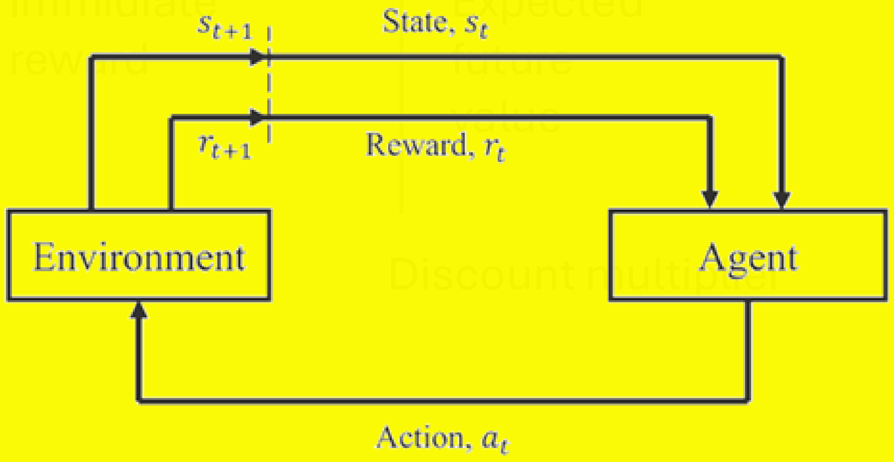
$$V_\pi(s) = E_{a\sim\pi(\cdot|s)}\left[Q_\pi(s,a)\right],$$

Solving Markov Decision Process
Reinforcement Learning (RL)

$$Q_\pi(s, a) =$$

Value
for taking action *a*
from state ***s***
Given policy $\boldsymbol{\pi}$

Deep Q Network
learns from environment



Create sandbox

[Figure from [Muhammad et al. (2025) High-precision Geosteering...]]

Partial Observability for Markov Decision Process (POMDP)

Available:

- Indirect observations
- Approximated uncertain state

$$Q_\pi(s, a) = r(s, a) + \gamma V_\pi(s'),$$

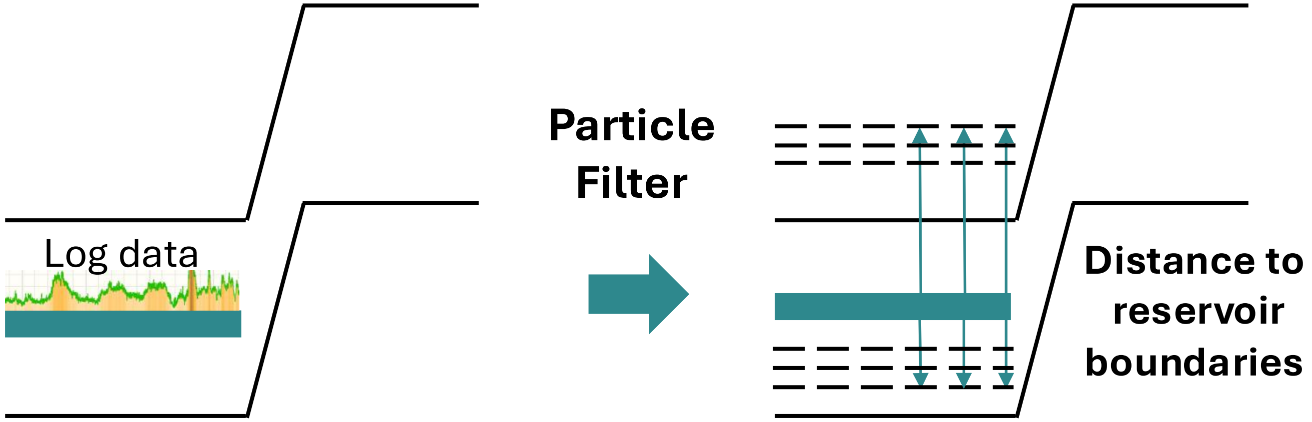
State ***S*** **not available**!

Pluralistic Reinforcement-Learning for Geosteering MDP

Particle-Filter-informed RL method: represent subsurface as realizations

✓ *

1. A forward model **extends every realization** ahead of drilling
2. **PF** performs **Bayesian re-weighting** of realizations **to fit new data**
3. **RL** learns using **updated "plurality" of realizations** to inform actions



[Muhammad et al. (2025) High-precision Geosteering...]

Pluralistic Reinforcement-Learning for Geosteering MDP

Particle-Filter-informed RL method: represent subsurface as realizations

1. A forward model **extends every realization** ahead of drilling
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Practical considerations

1. Assumes **closed-form** forward stochastic model for geology
2. For **RL training** use less particles (N) and collapse checks in PF
3. Use **top-probability particles** and weights to avoid dependence on N

[Muhammad et al. (2025) High-precision Geosteering...]

Pluralistic RL beats
PF + Greedy method
Full AI solution

Methods	Input	Rewards	Reservoir contact (%)	MAE of Input
Rule-based[13]	1 Look-ahead	-101.36	54.75	4.27
Rule-based[13]	5 Look-ahead	-105.95	52.70	4.27
RL-Log	Gamma-ray	-74.27	66.84	-
RL-Estimation	1 PF	-25.36	88.67	1.29
RL-Estimation	5 PF	-24.99	88.91	1.31

[Muhammad et al. (2025) High-precision Geosteering...]

Generalization of Pluralistic-AI concept

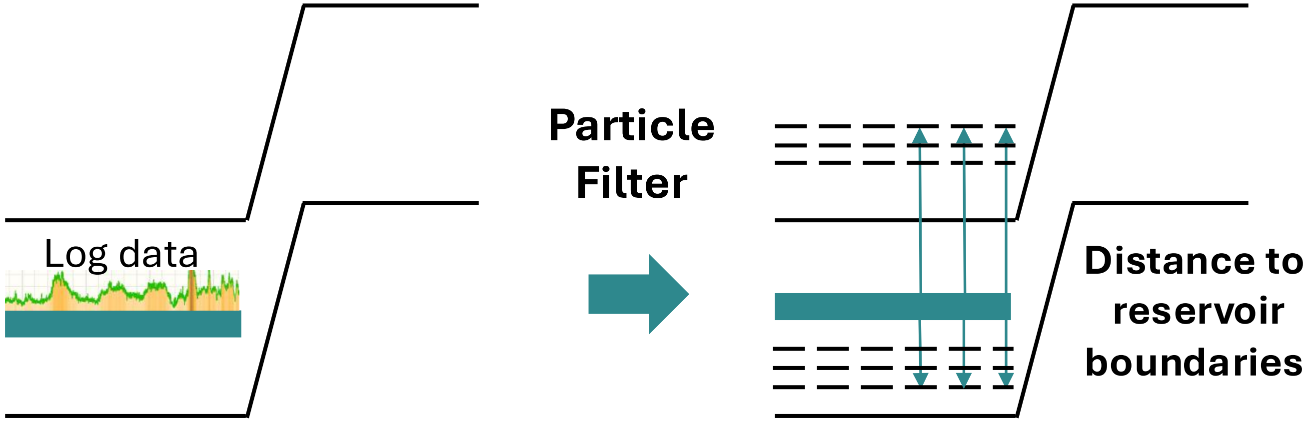
Particle-Filter-informed RL method: represent subsurface as realizations

? 1. A forward model **extends every realization** ahead of drilling

✓ 2. **PF** performs **Bayesian re-weighting** of realizations **to fit new data**

✓ 3. **RL** learns using **updated "plurality" of realizations** to inform actions

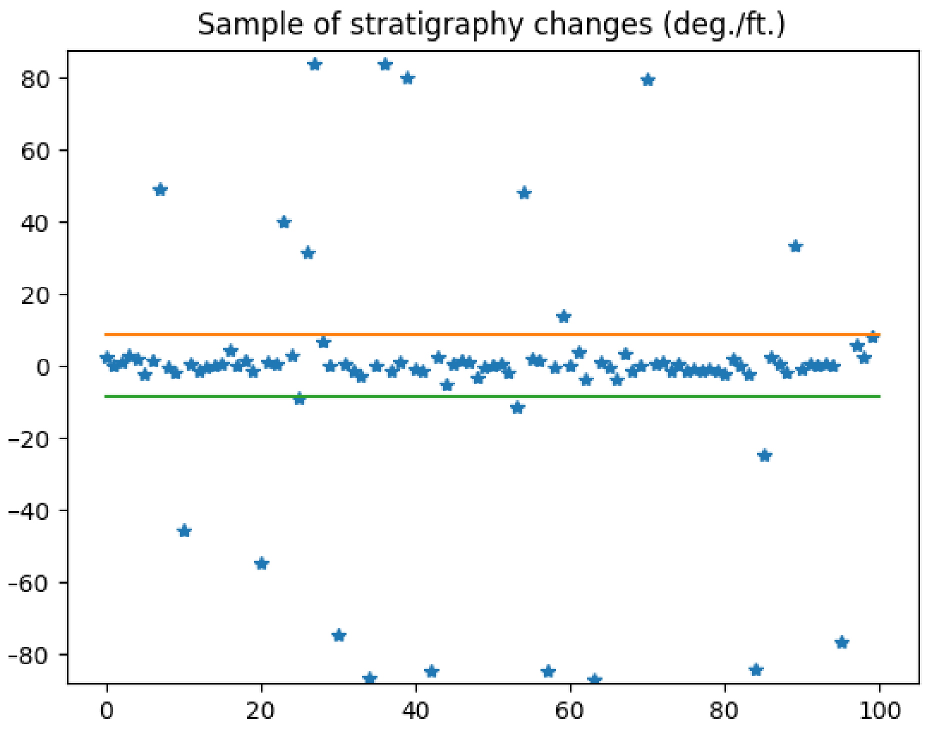
- **How to forecast geology using data?**

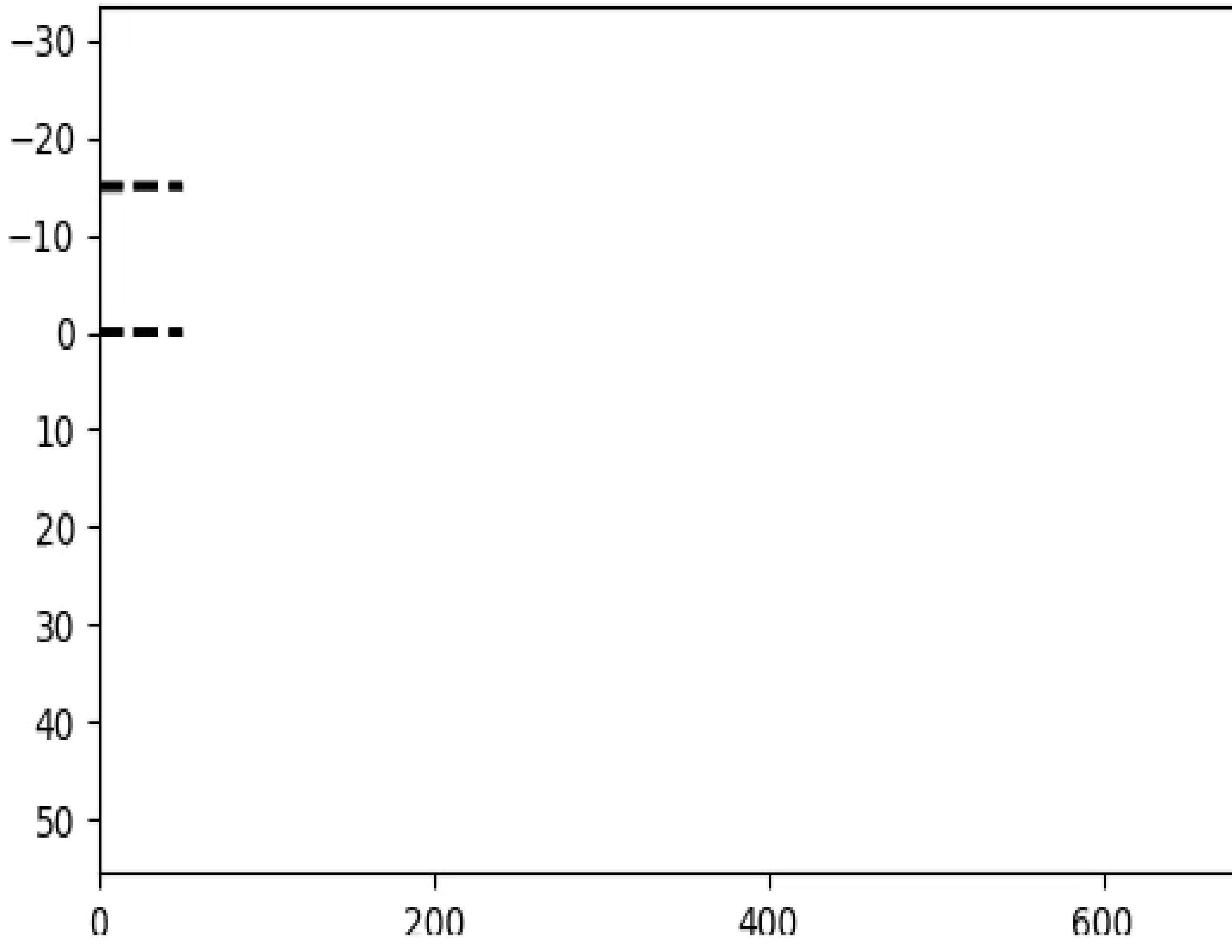


[Muhammad et al. (2025) High-precision Geosteering...]

Naïve data-driven approach of geology forecasting

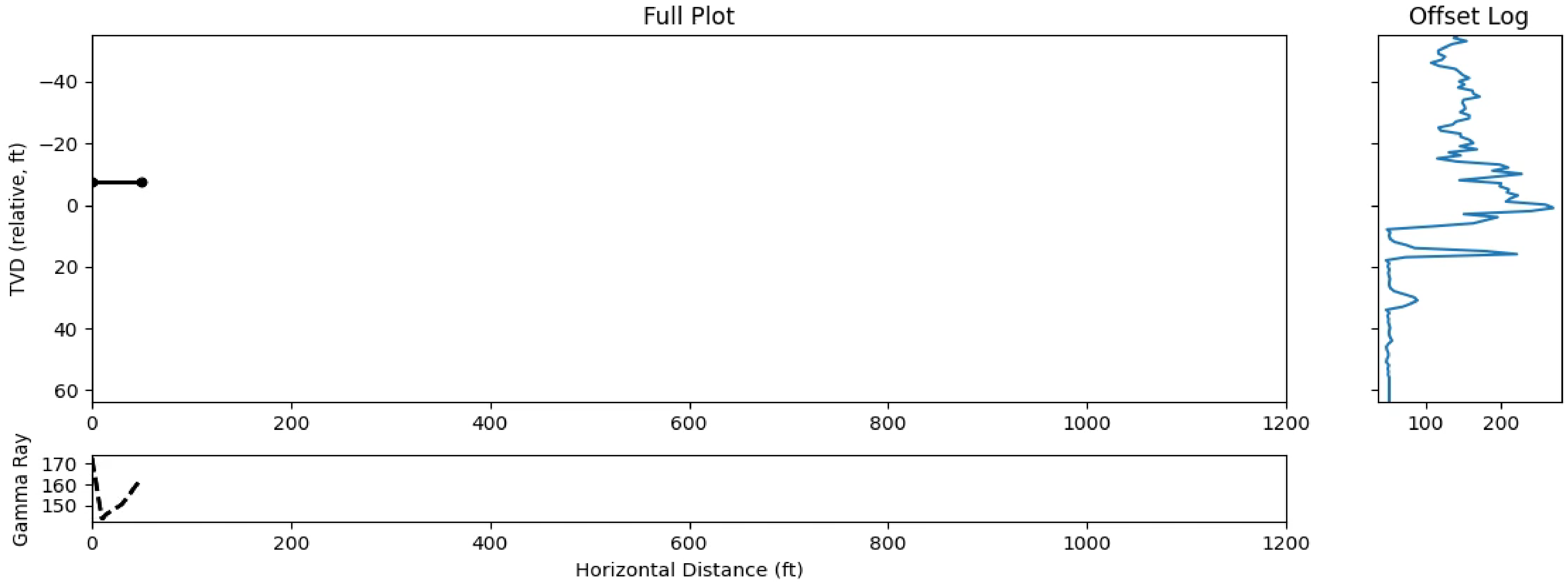
- Fit Kernel Density Estimation (KDE) to geological interpretations
- Allows sampling geological changes
  - Inclination changes
  - Faults (jumps)





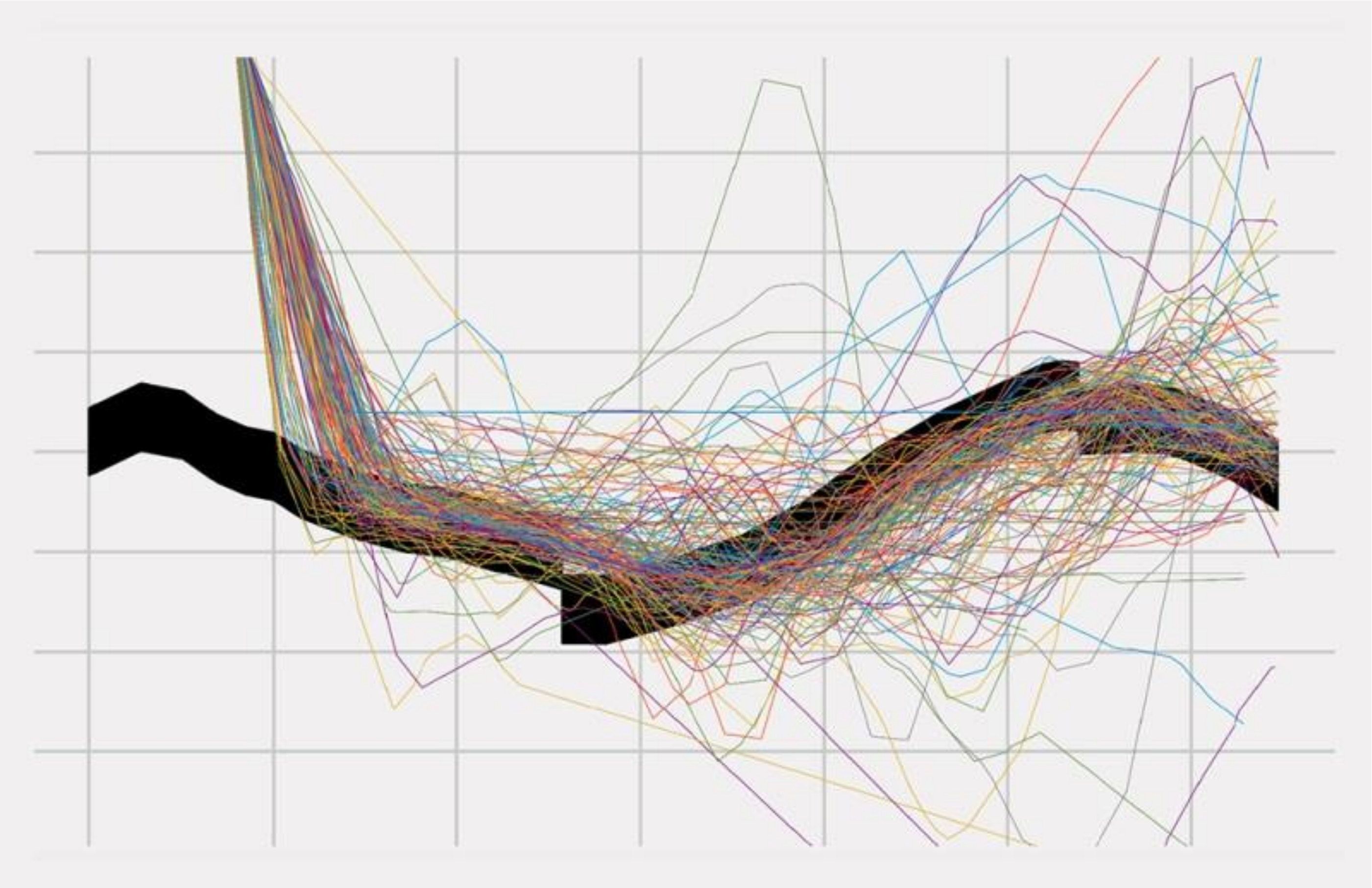
[Muhammad et al. (2025): Geosteering Robot…]

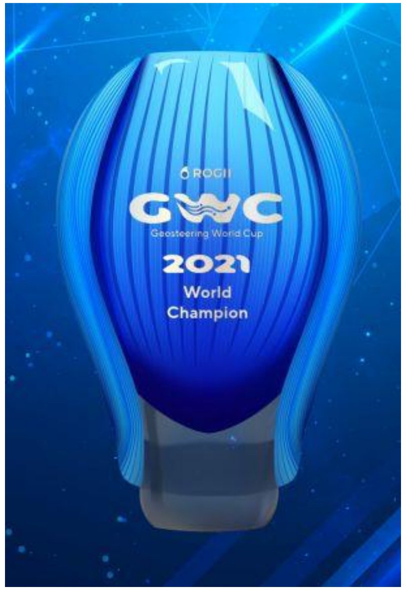
Usage example of Pluralistic approach
with Progressive Geology Generation



[Muhammad et al. (2025): Geosteering Robot…]

Did we beat humans?
Geosteering World Cup 2021





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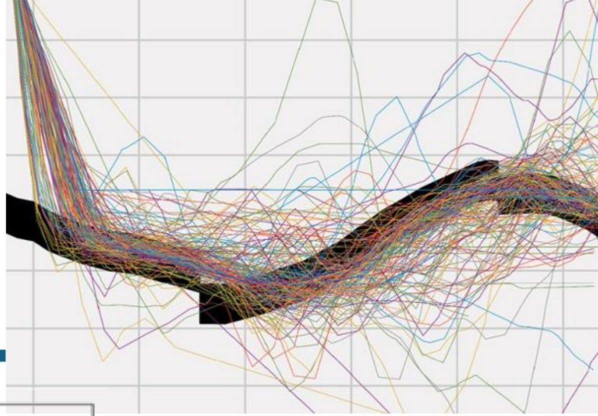
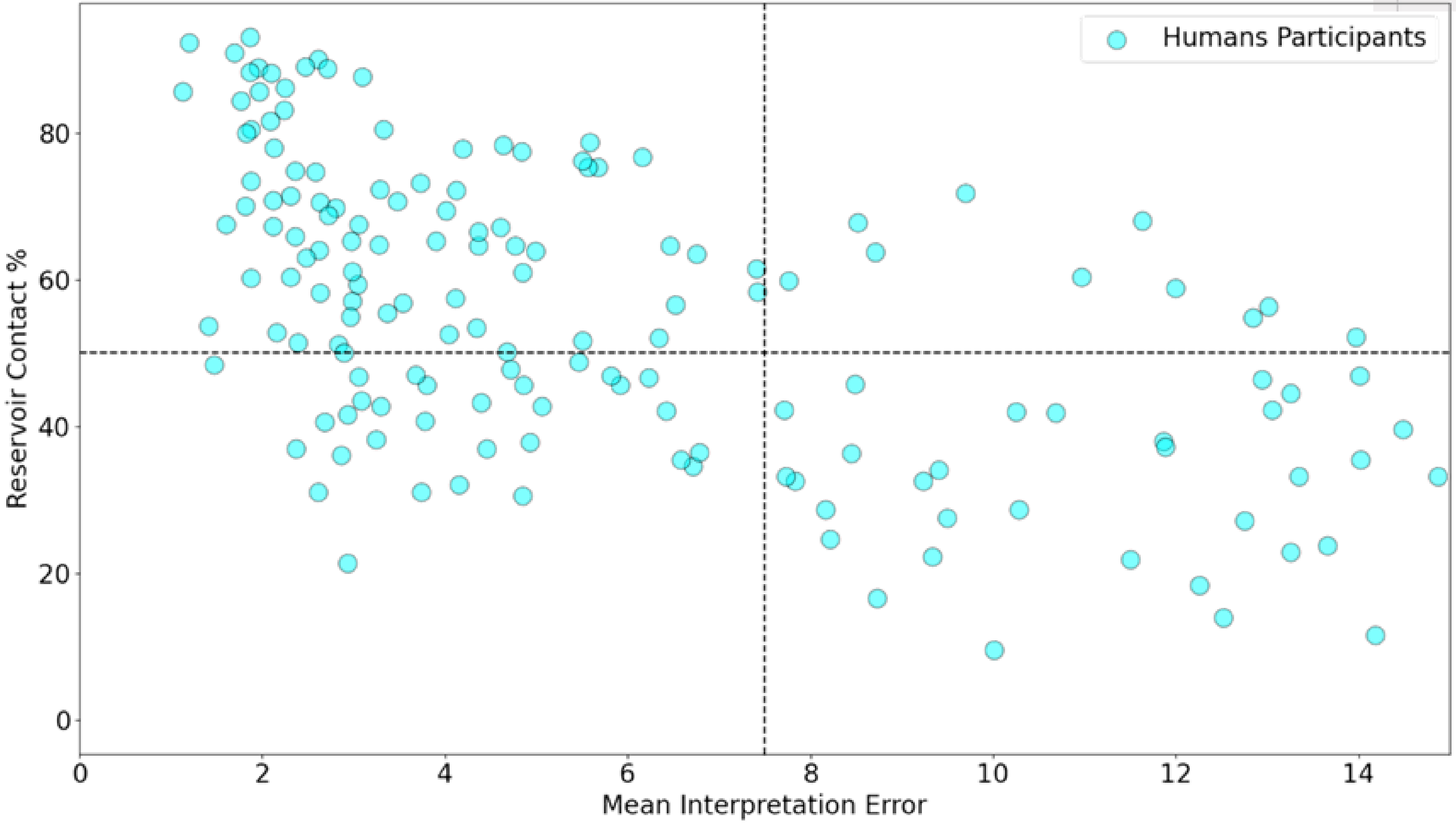
Comparison against Human Experts



Better result for a human

Better result for a human



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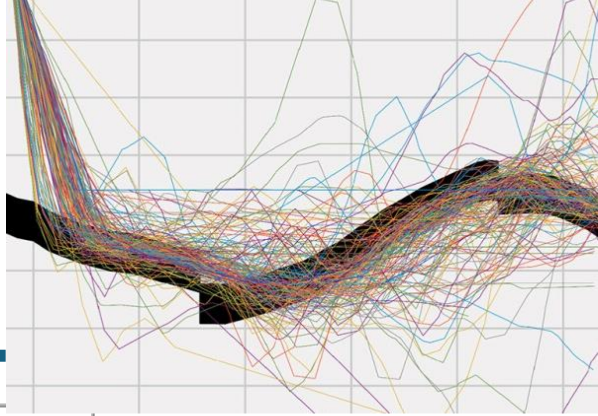

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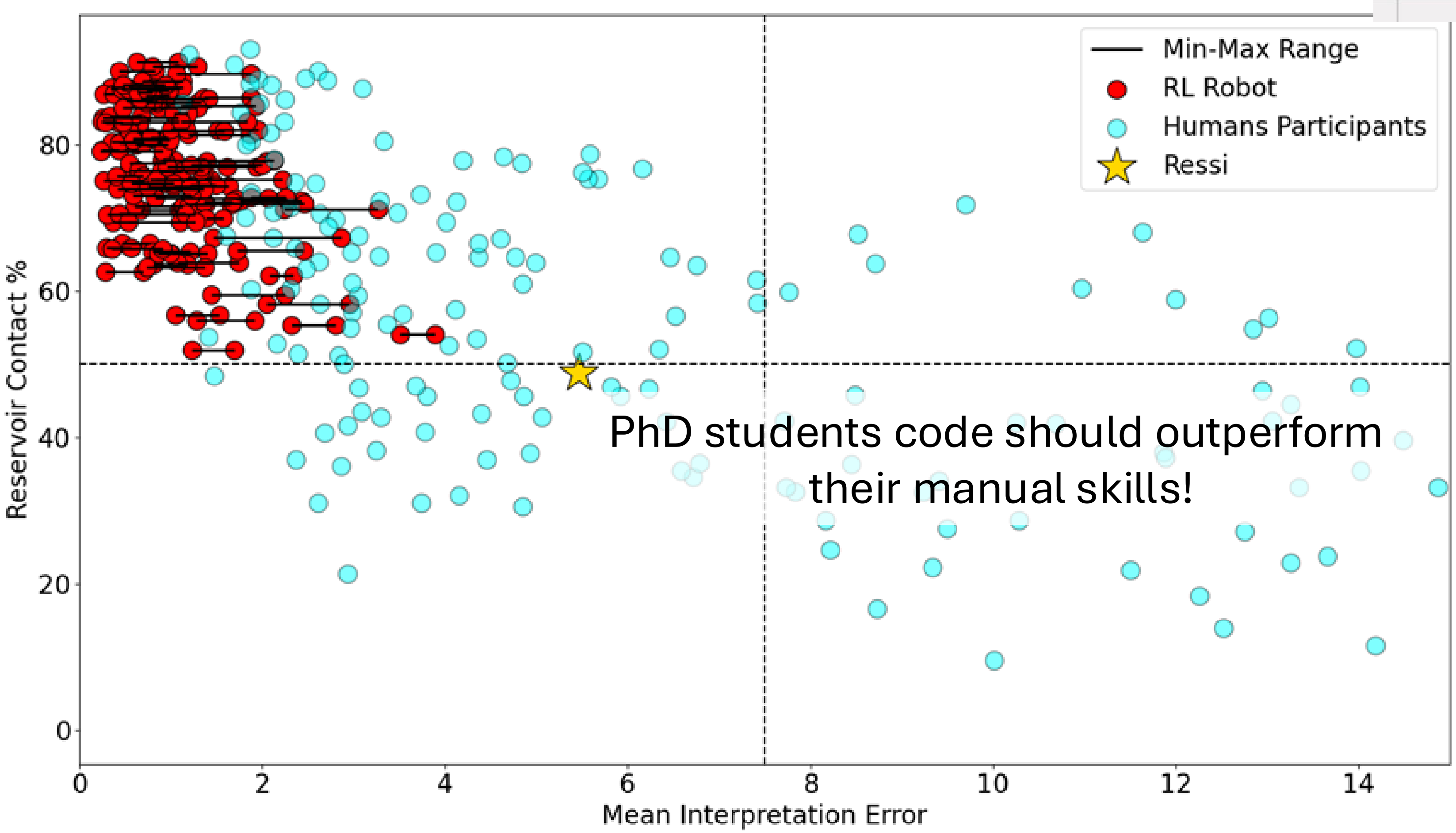

PhD students code should outperform their manual skills!

[Muhammad et al. (2025): Geosteering Robot...]

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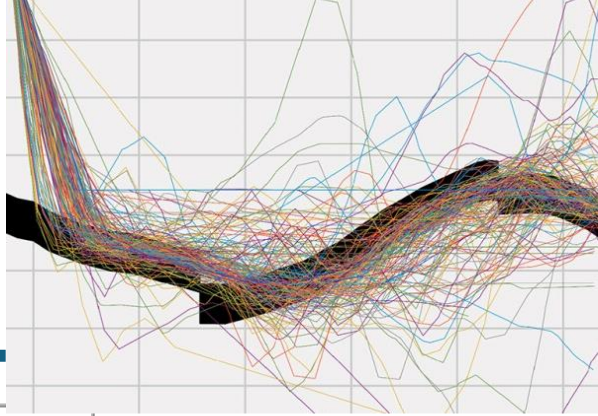

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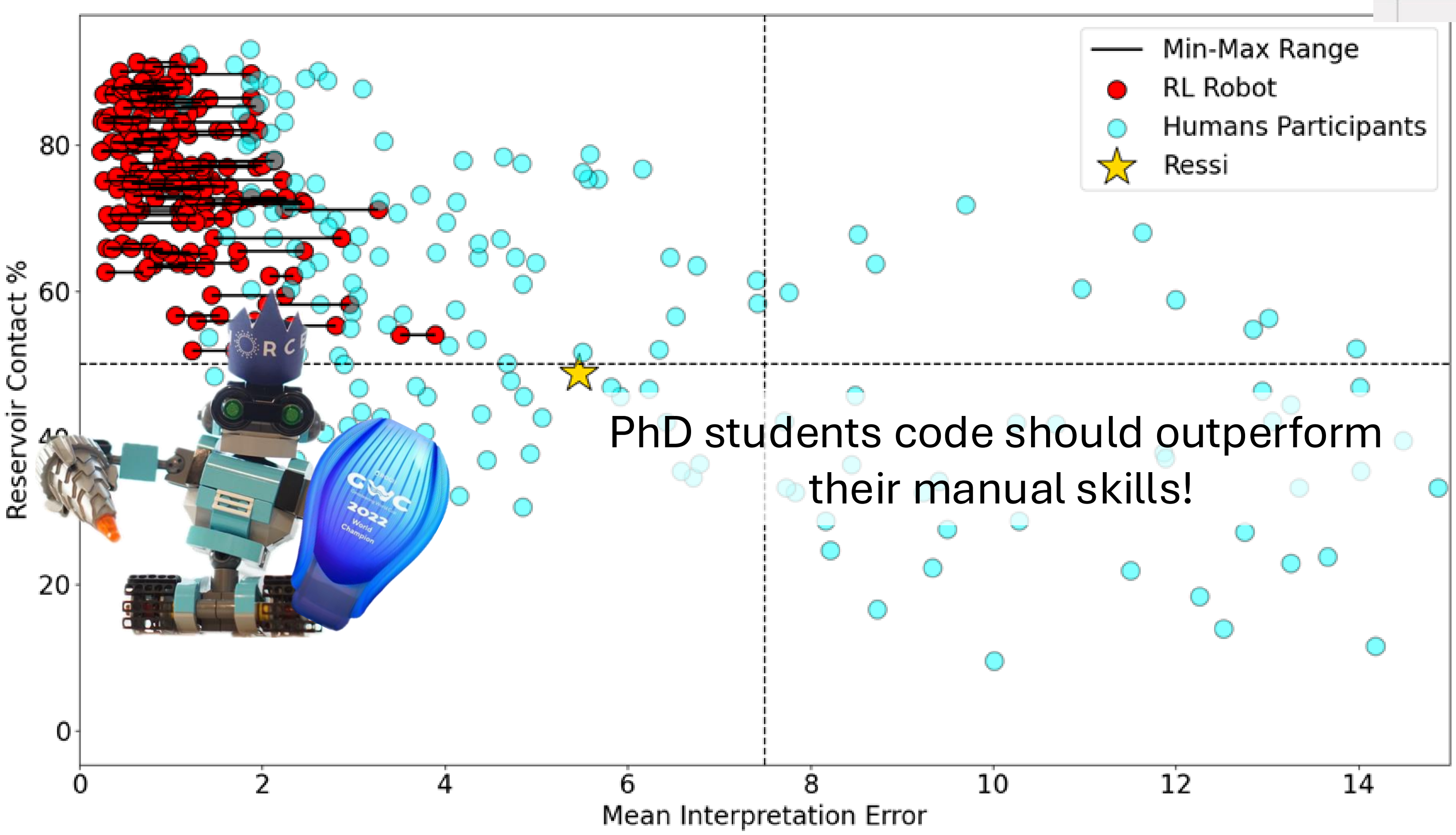
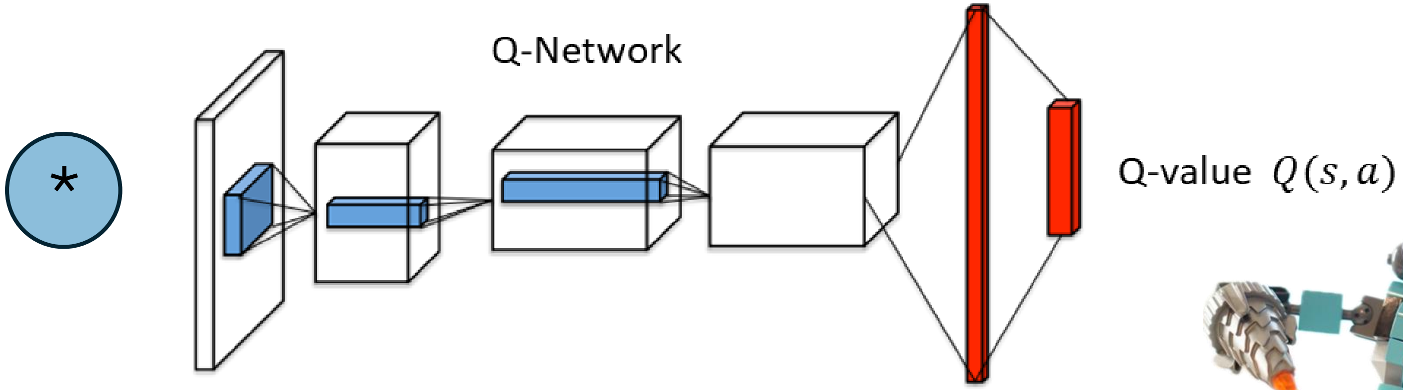


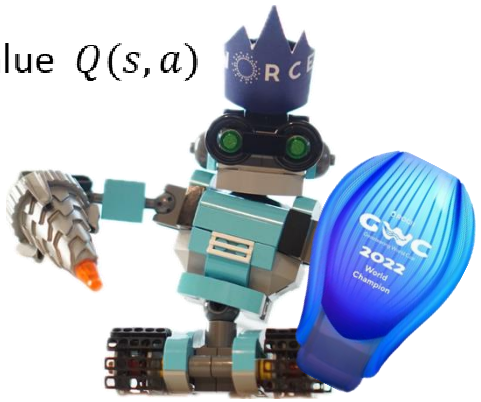
PhD students code should outperform their manual skills!

[Muhammad et al. (2025): Geosteering Robot...]

Can we do better than the robot?

Improving decision optimization





Can we do better than the robot?

Dynamic Programming

vs

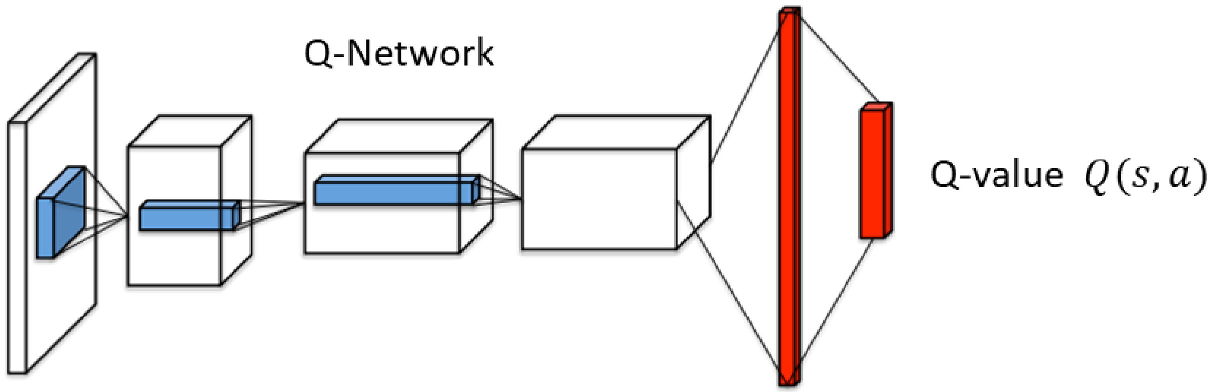
Q-Network

vs

Dual Q-Network

1 **Aproximate Dynamic Programming (Algorithmic)**

2



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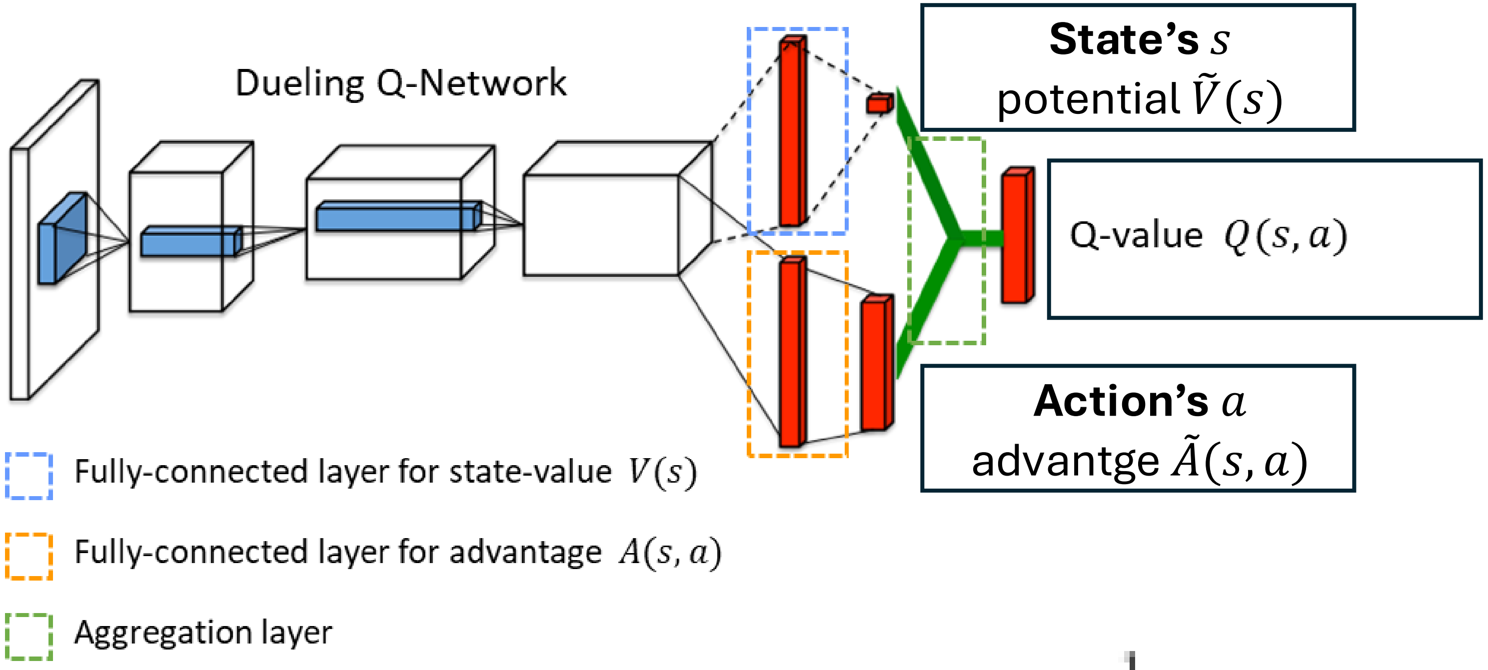


$$Q(s,a) = V(s) + A(s,a) - \frac{1}{|\mathcal{A}|} \sum_{a' \in \mathcal{A}} A(s,a')$$

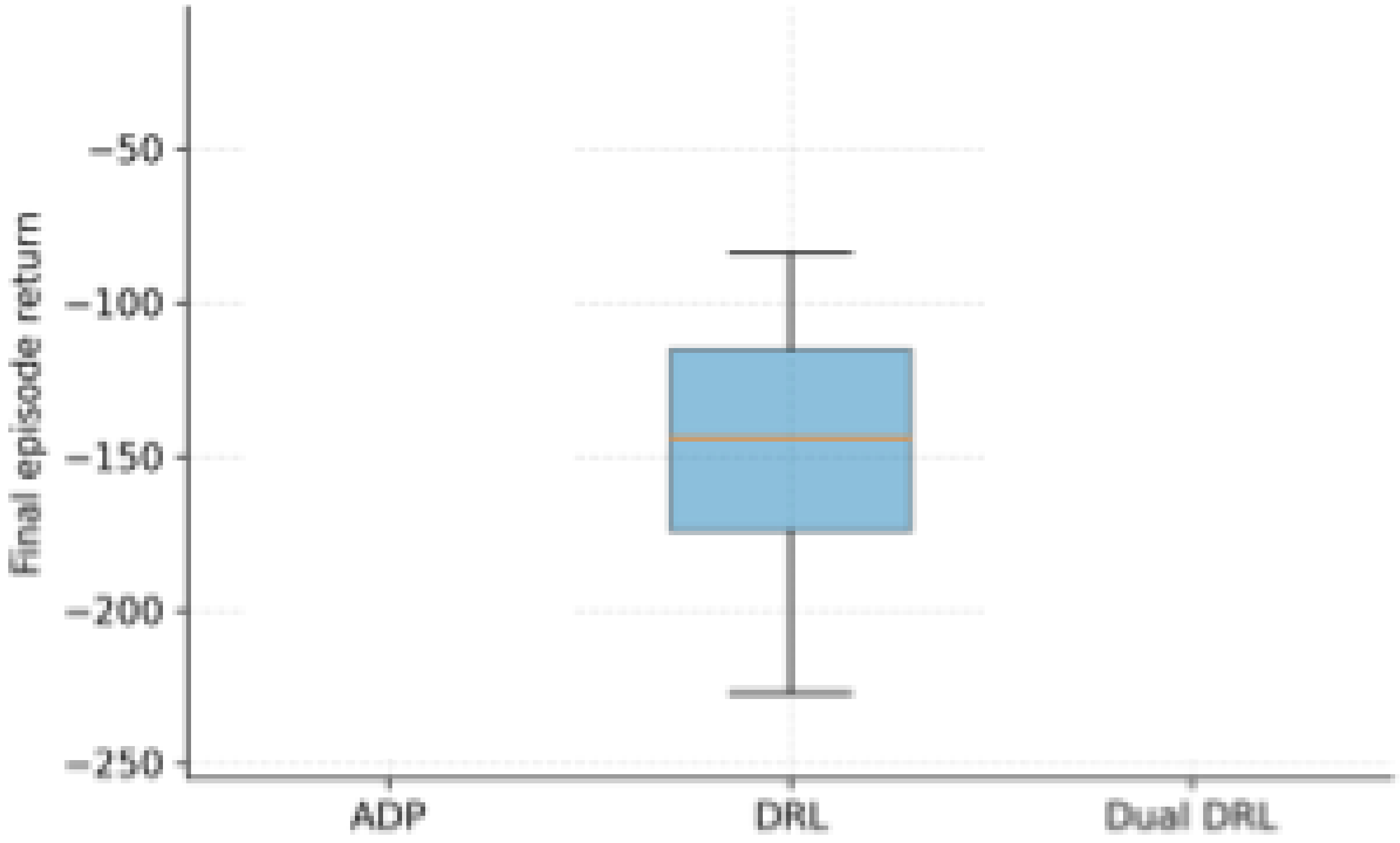
[Djecta et al. (2025): Uncertainty-aware geosteering … https://doi.org/10.1007/978-3-031-97554-7_14]

Comparison of robot policies

1 Algortihmic explainable

2 Baseline RL

3 Improved methos



[Djecta et al. (2026): Decision-Driven Geosteering... arXiv:2606.17331]

Comparison of robot policies

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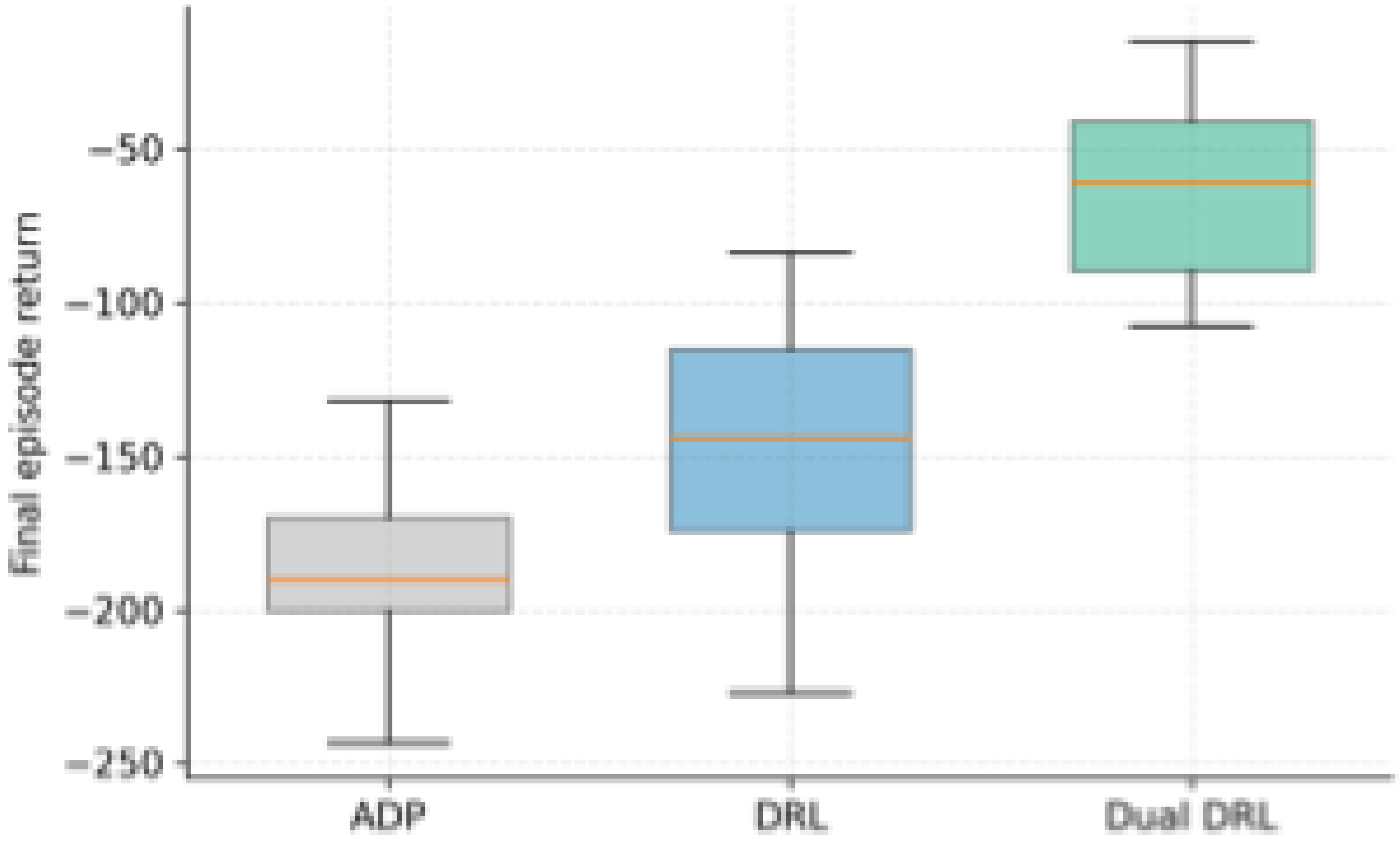

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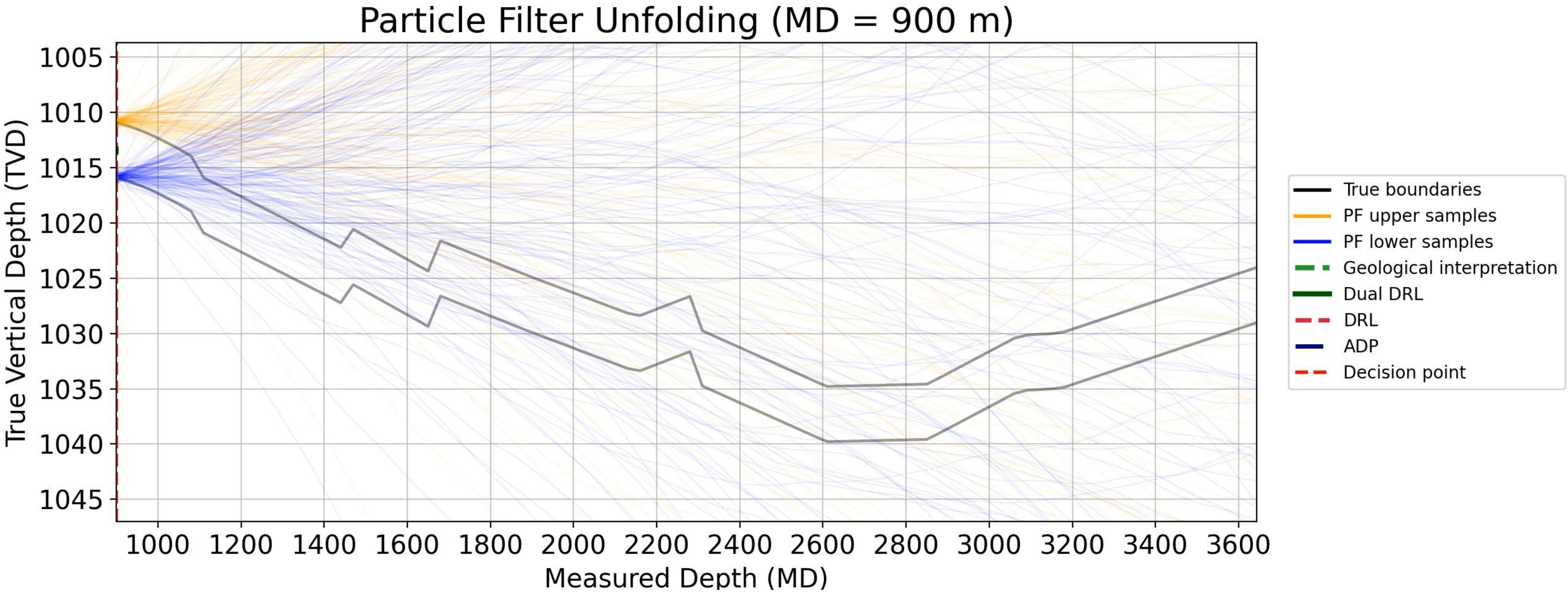
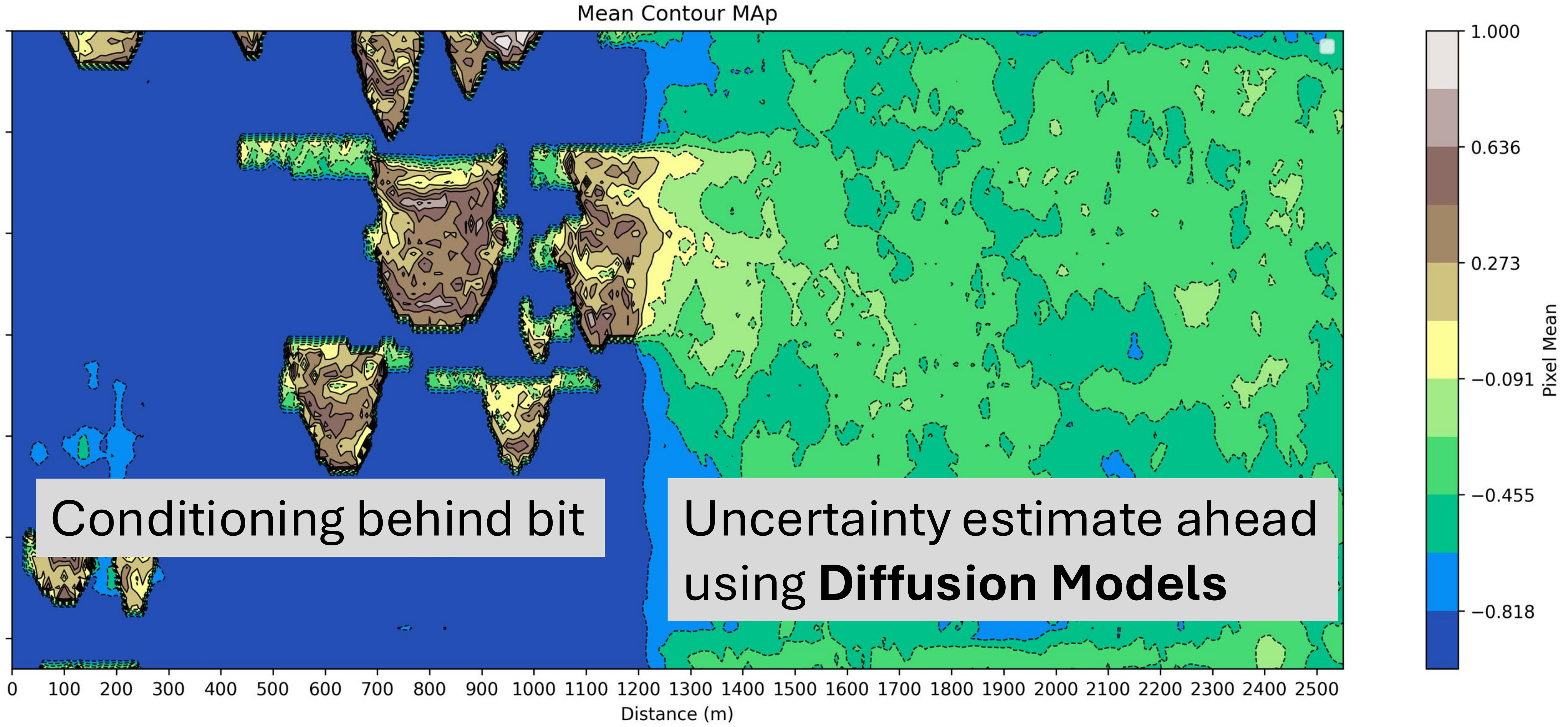
Dual DRL steering and explainable predictions
with Progressive Geology Generation



[Djecta et al. (2026): Decision-Driven Geosteering... arXiv:2606.17331]

Can we use robots with complex geology?

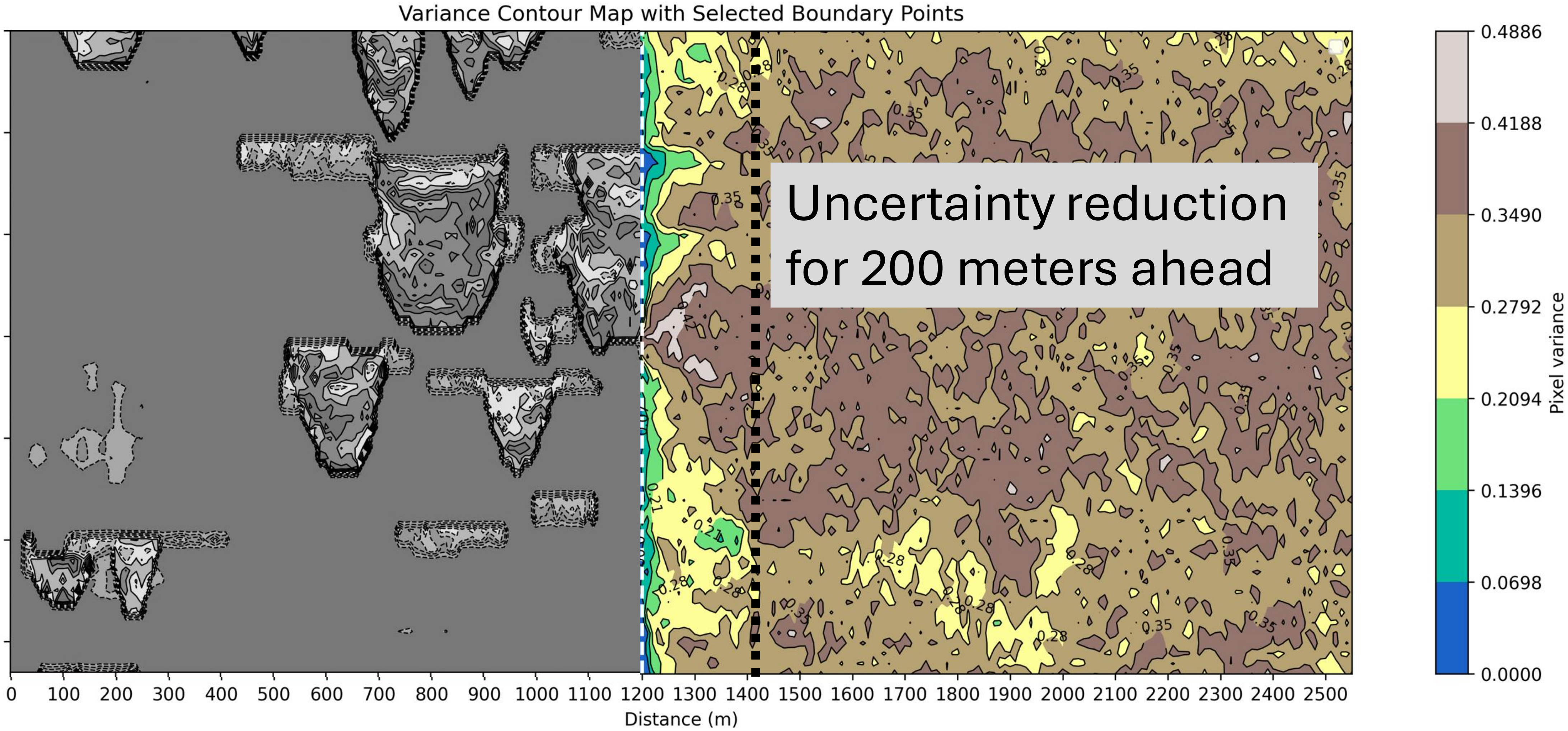


Conditioning behind bit

Uncertainty estimate ahead using **Diffusion Models**

[Saleem et al. 2026: Diffusion Models for Generating... (Accepted for EAGE ECMOR)]

A prediction ahead in complex geology



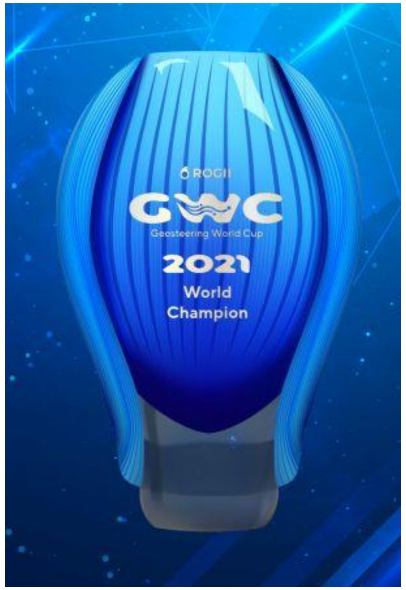
[Saleem et al. 2026: Diffusion Models for Generating... (Accepted for EAGE ECMOR)]

Conclusion

- Progressive Geology Generation + particle filtering
  = **pluralistic** state estimation
- **Pluralistic DQN Robot** outperforms most human experts
- **Pluralistic geosteering framework** extends to
  - Explainable decisions with dynamic programming
  - Improved decisions with Dual DQN
- Gen-AI geomodelling brings Pluralistic to complex geology (future work)

For those who like robots: Geosteering Data Competions

- **Geology Forecast Challenge**
  - NORCE
  - Prize period: passed, data available
  - https://www.kaggle.com/competitions/geology-forecast-challenge-open
- **ROGII - Wellbore Geology Prediction**
  - ROGII
  - Prize period until August 6, 2026
  - https://www.kaggle.com/competitions/rogii-wellbore-geology-prediction



All references (in order of appearance)

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- Djecta HE, Alyaev S, Fossum K, Bratvold RB, Muhammad RB, Srivastava A. **Uncertainty-aware well placement: Simulator-verified dual-network reinforcement learning approach meets particle filters.** In ICCS **(2025)**
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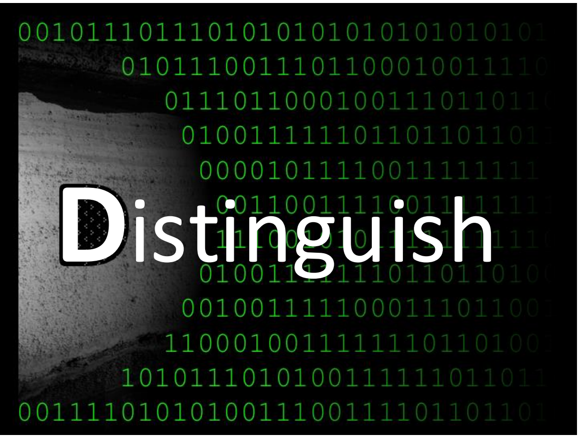
- Saleem H, Alyaev S, Fossum K, Blaser N, ElSheikh AH. **Diffusion Models for Generating Multiple Plausible Subsurface Realizations Ahead of Drilling**. Accepted in EAGE ECMOR **(2026)**

Acknowledgements



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Project GitHub page:

https://github.com/geosteering-no