# Science-informed machine learning for reservoir characterization

Velimir ("monty") Vesselinov
Tracy Kliphuis

monty@envirace.com
trais@envitrace.com

EnviTrace, Santa Fe, New Mexico

info@envitrace.com
http://envitrace.com

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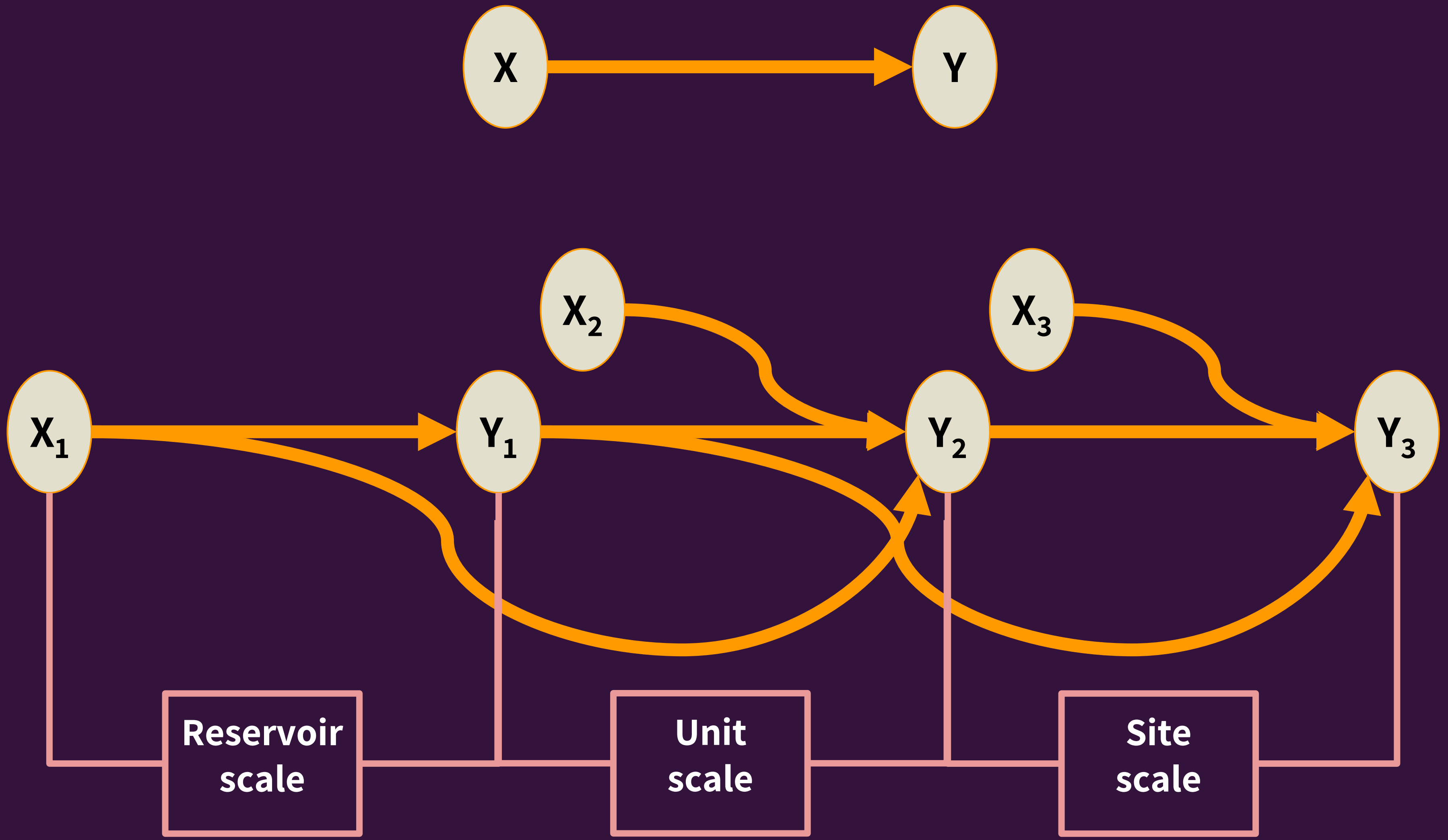
# Geologic Reservoir Data Issues

- Gaps, Uncertainties, Errors & Inaccuracies
- Representativeness & Information Content
- Differences in spatiotemporal support scales of data & features/processes
- Heterogeneity (faults, facies, layers, synclinals, vents, volcanos, …)
- “Hidden” (latent) features/signatures

# GeoML: Cloud software suite for geospatial ML analyses

- Physics- and geology-aware ML algorithms
- Automated cross-validations and fine tuning
- Identifying the best multi-scale(step) approach for a given dataset/problem
- Geospatial test problems & benchmarks
- ML multi-scale(step) techniques (with standardized APIs):
    - Nonnegative matrix/tensor factorization (NMFk/NTFk)
    - Support Vectors (SVM/SVR)
    - XGBoost/EvoTrees
    - Inverse Distance Weighted (IDW)
    - Spatial splines/Minimum curvature (Biggs FD and classical)
    - Kriging/Vecchia/Gaussian Process/Nearest Neighbour Gaussian Process
    - Kriging Convolutional Neural Networks (KCN)
    - Gaussian Markov Random Field (GMRF)
    - GNNs, MLPs, CNNs, LSTMs, Diffusion Models (DMs)
    - Stochastic PDEs (SPDE)
    - Transformers
    - Differentiable physics models (analytical/numerical)

# Multi-scale(step) ML approach for geospatial analyses

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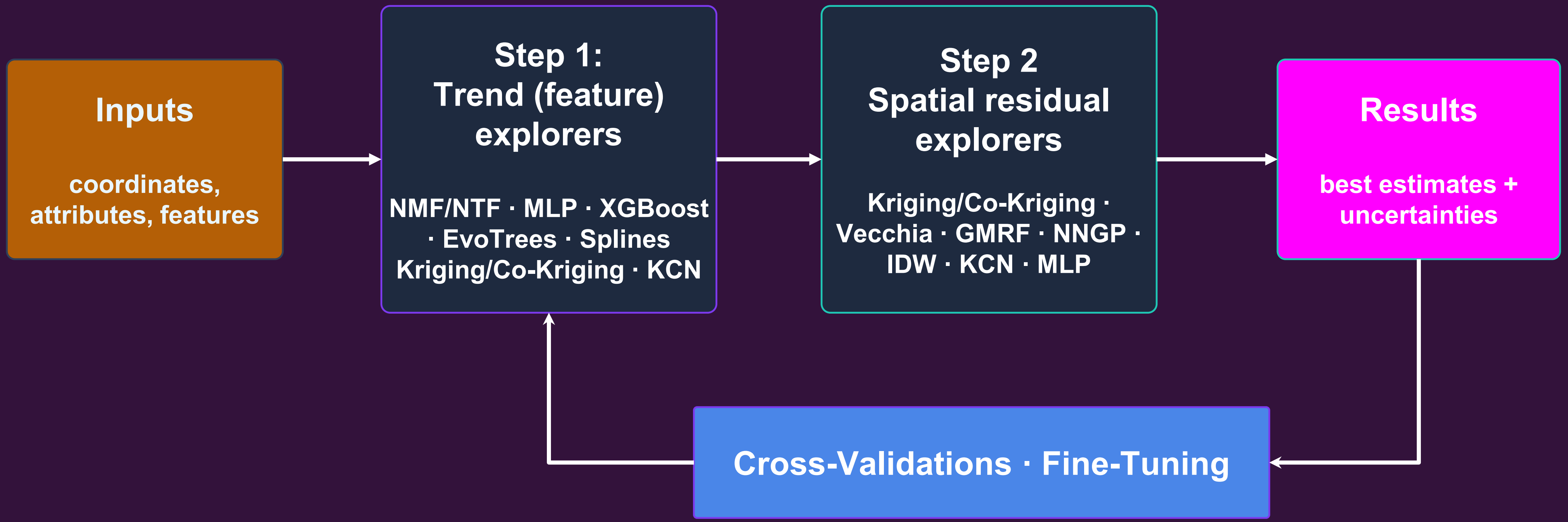
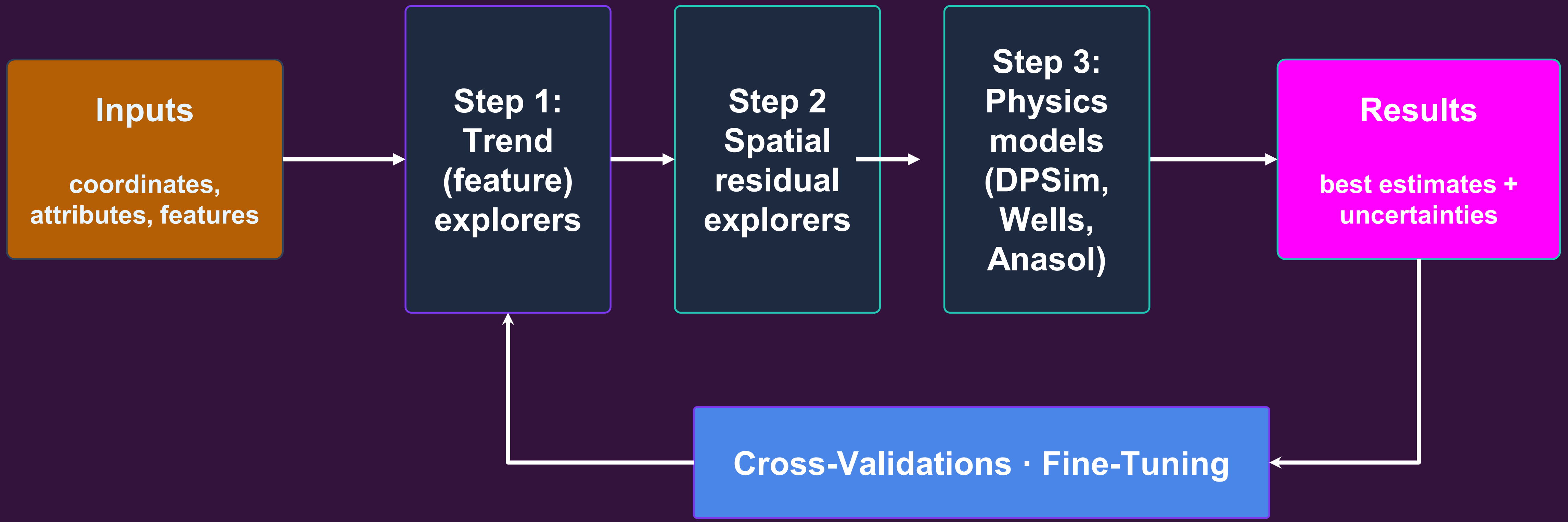
# GeoML: Multi-scale(step) approach for geospatial analyses



# GeoML: Multi-scale(step) approach for geospatial analyses

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# GeoML: Multi-scale(step) approach for geospatial analyses

## Physics integration

- Analytical flow expressions (well equations: Theis, Hantush, etc.)
- Analytical transport expressions (Fickian and non-Fickian dispersion models)
- Numerical simulators (DPSIm)

- Differentiable programming (Julia)

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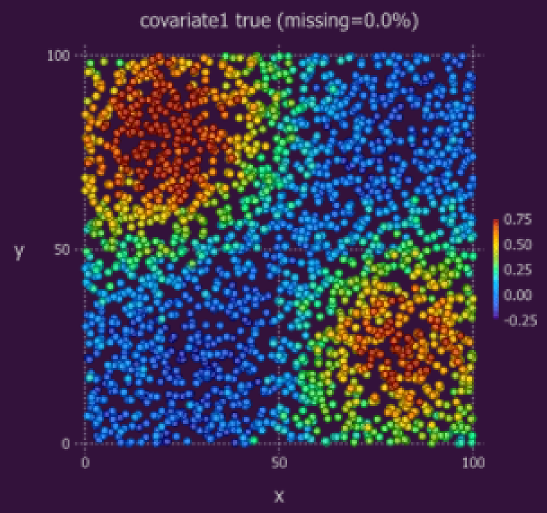
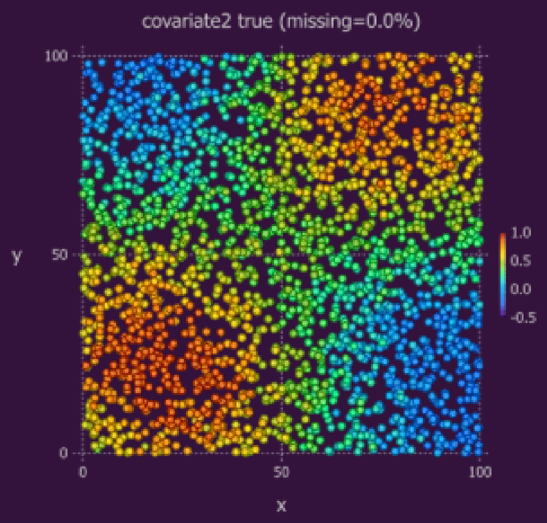
# Data, Models, Machine Learning …

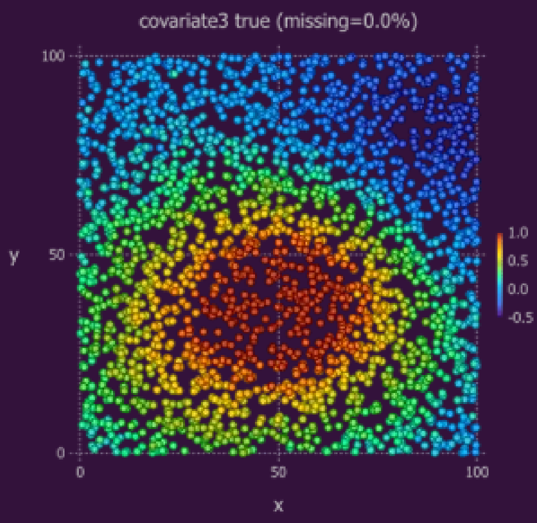
- Data assimilation
- Data imputation
- Model inversion (calibration)

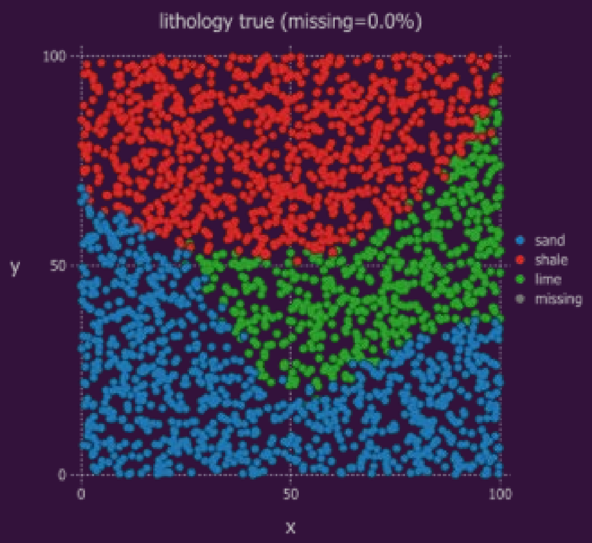
- All infer missing or hidden information from uncertain observations
- In Bayesian view, they can be viewed as conditional inference

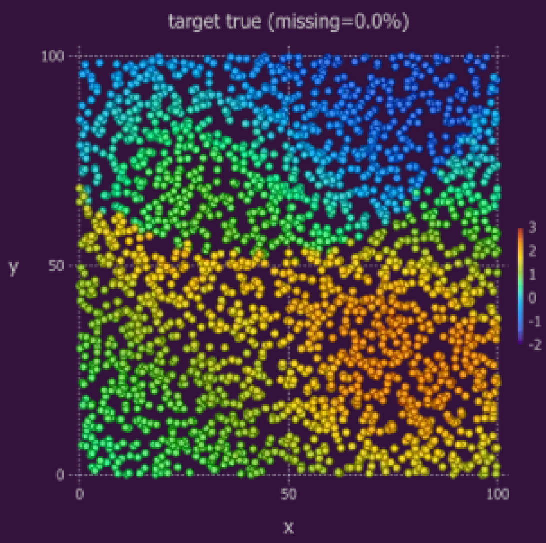
# Geospatial problem

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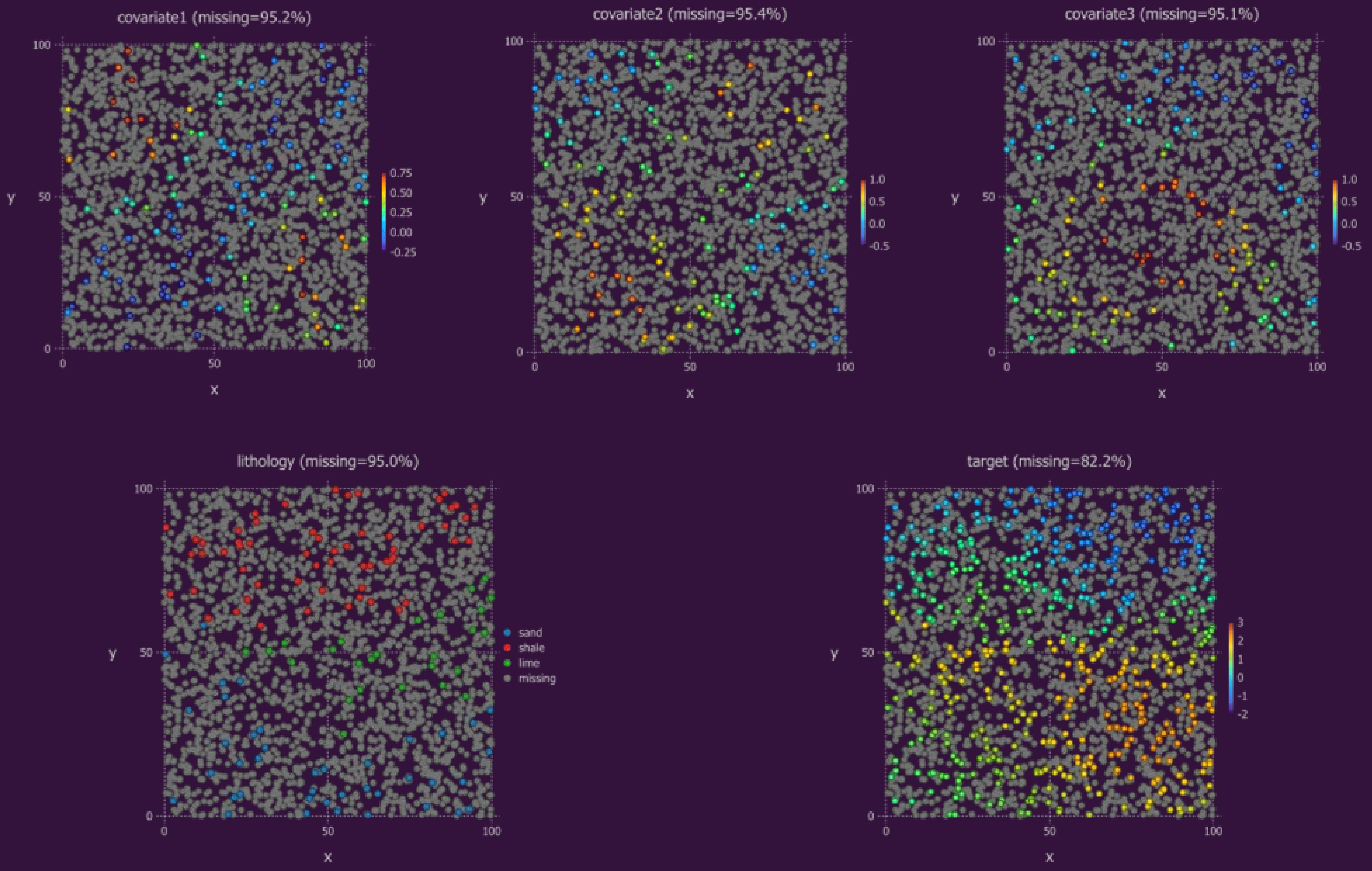
# Geospatial problem (~95%)

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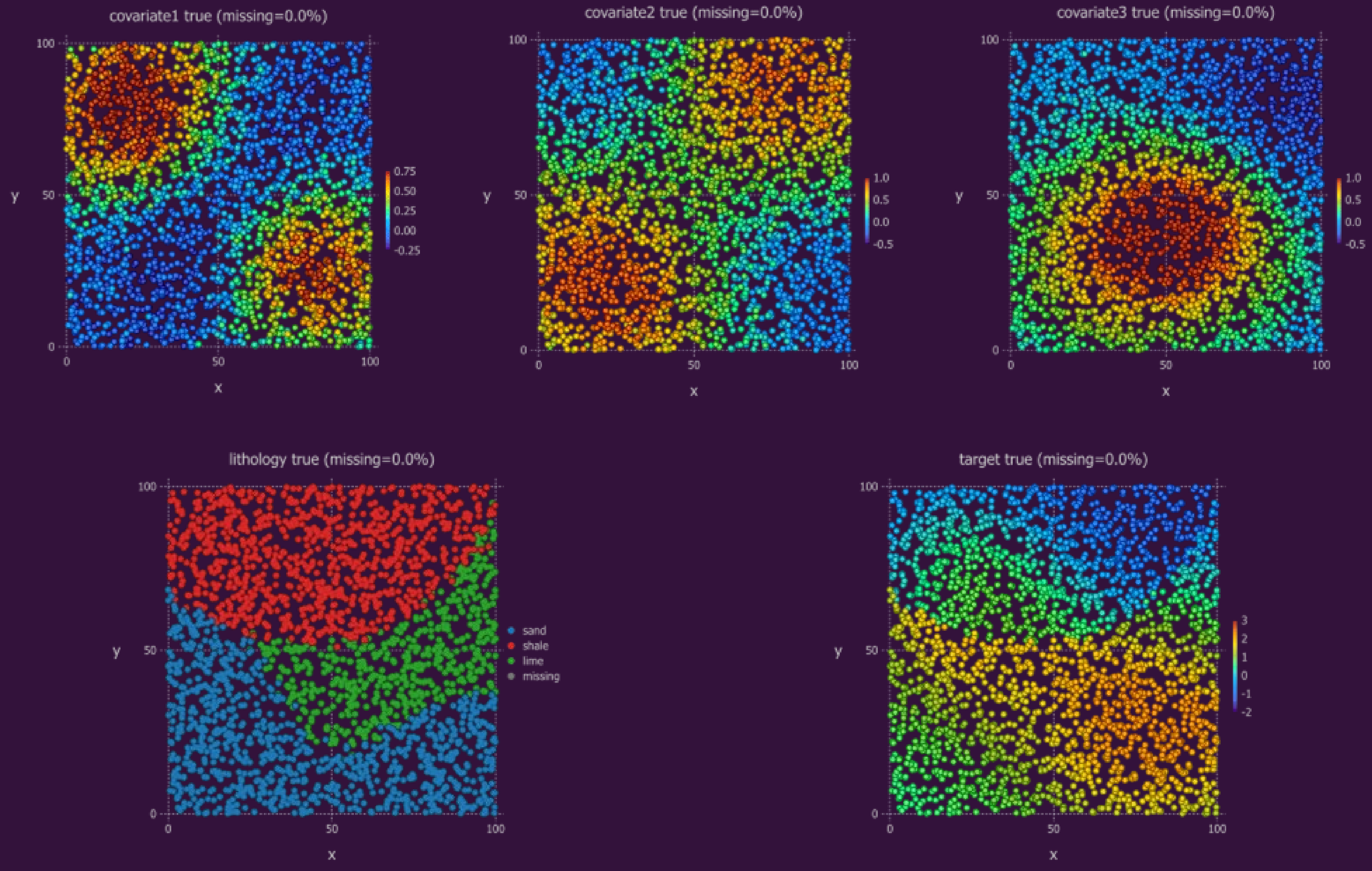
# Geospatial problem (truth)

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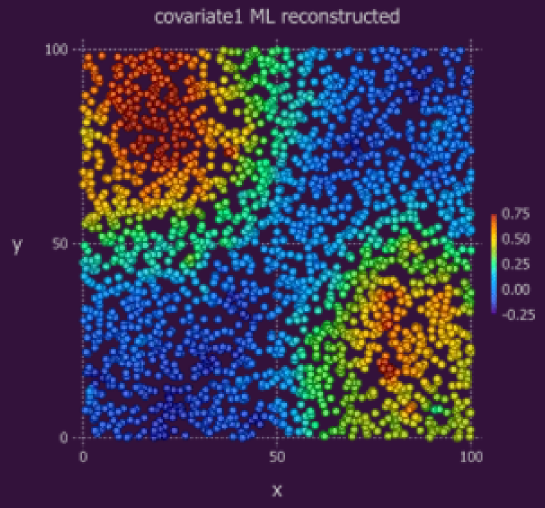
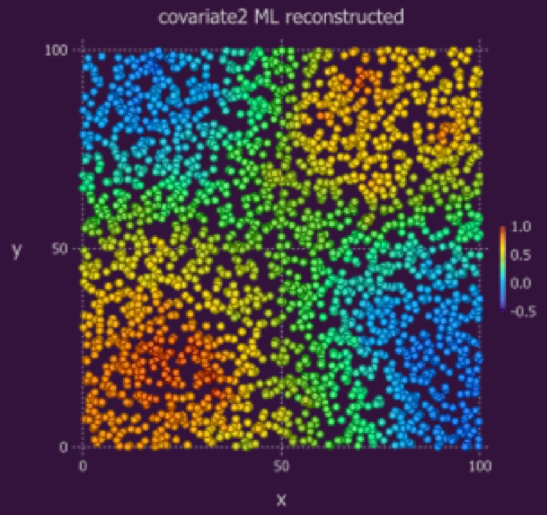
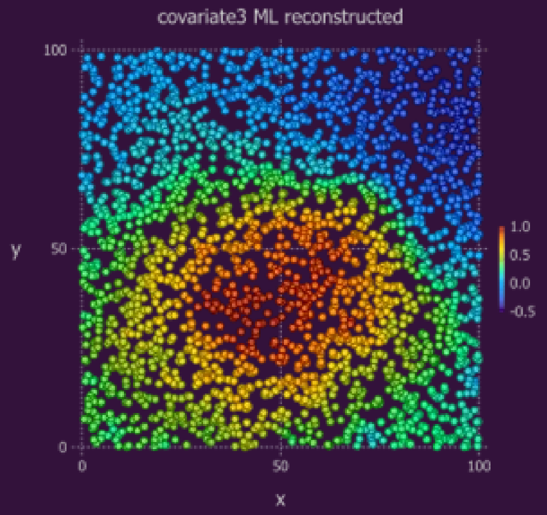
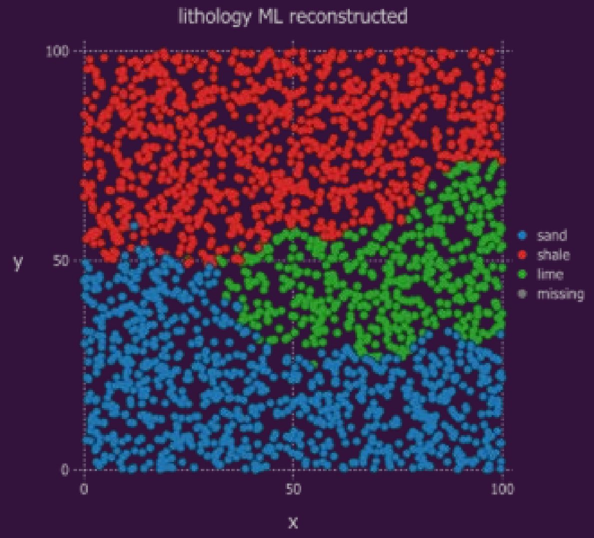
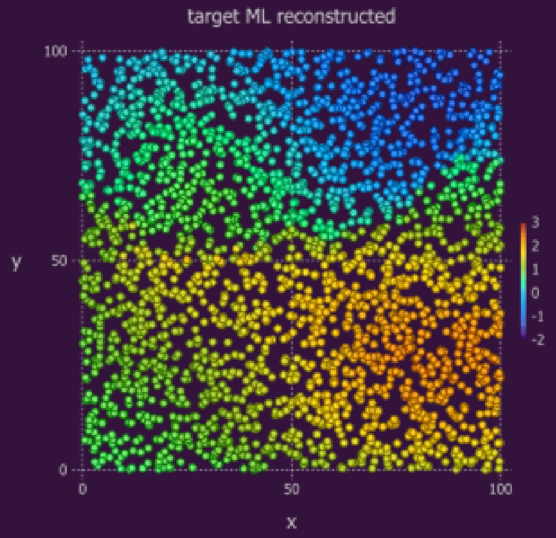
# Geospatial problem

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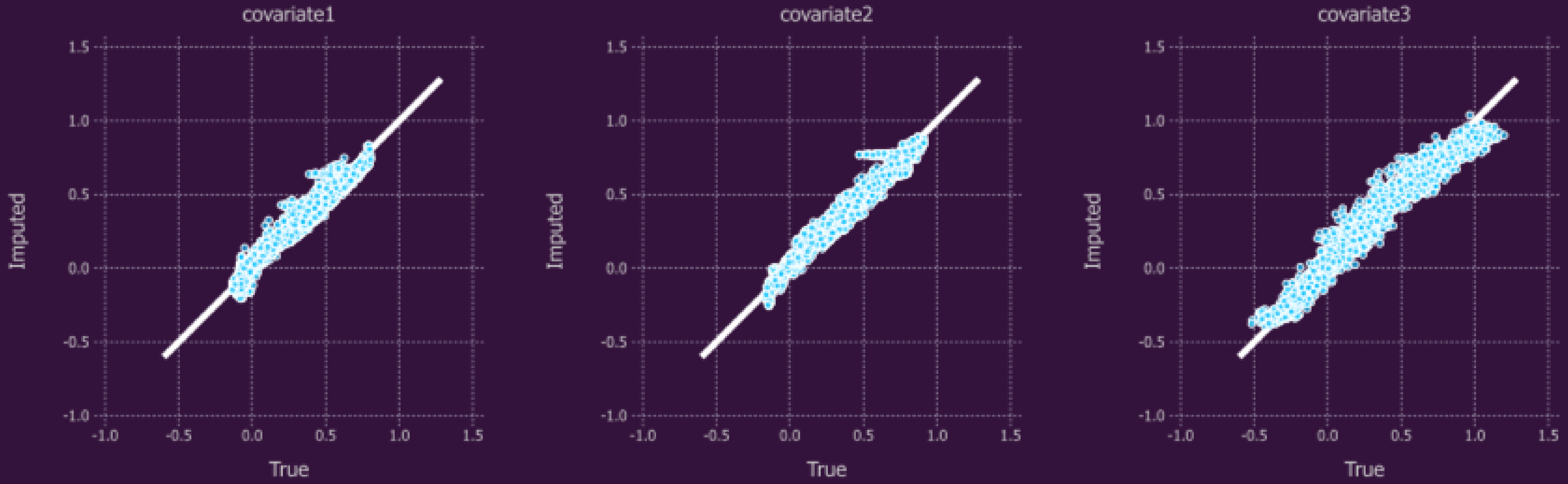
# Geospatial problem

# Geospatial problem

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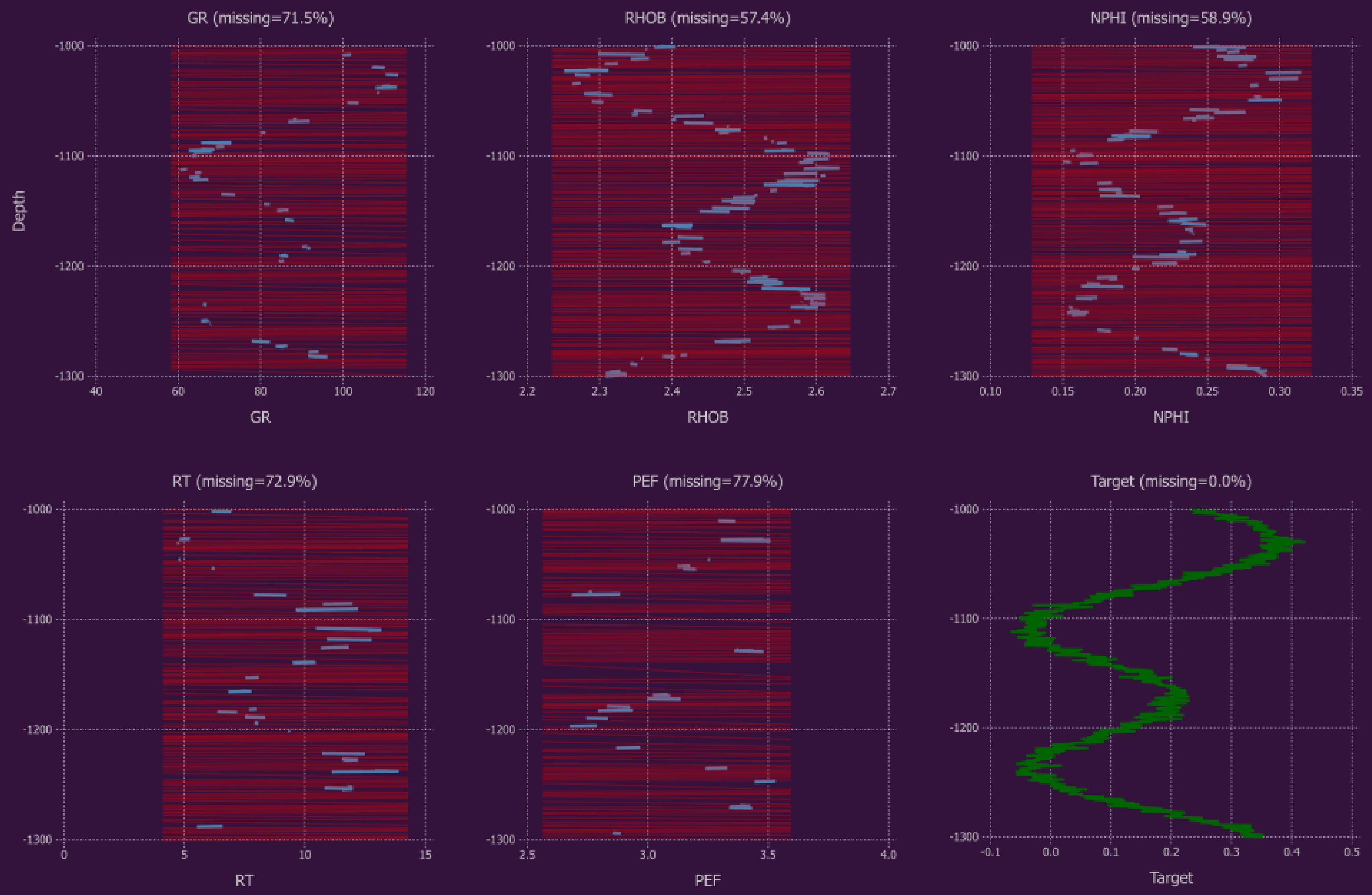
# Well-log demo problem

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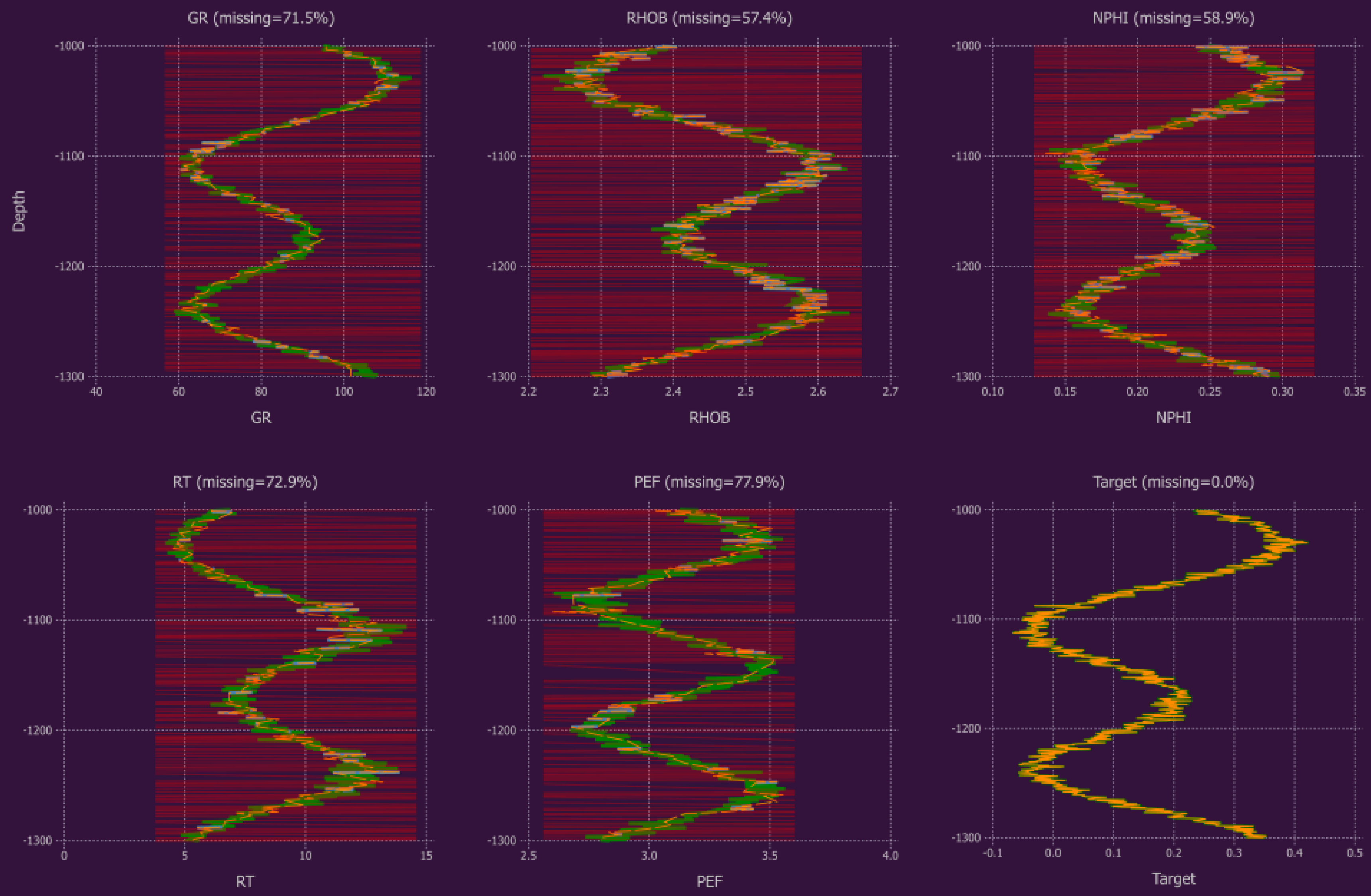
# Well-log demo problem

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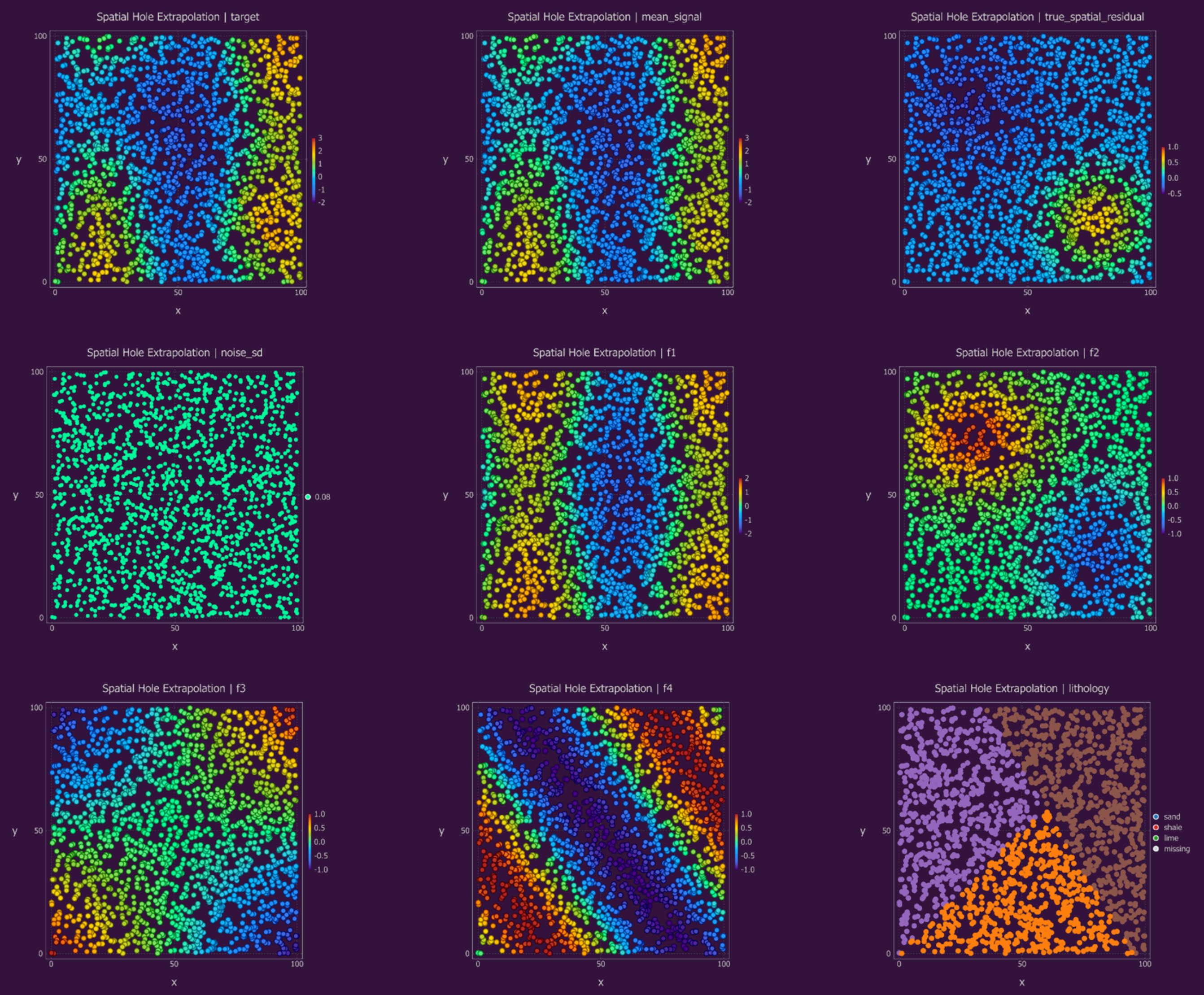
# Big data gap imputation

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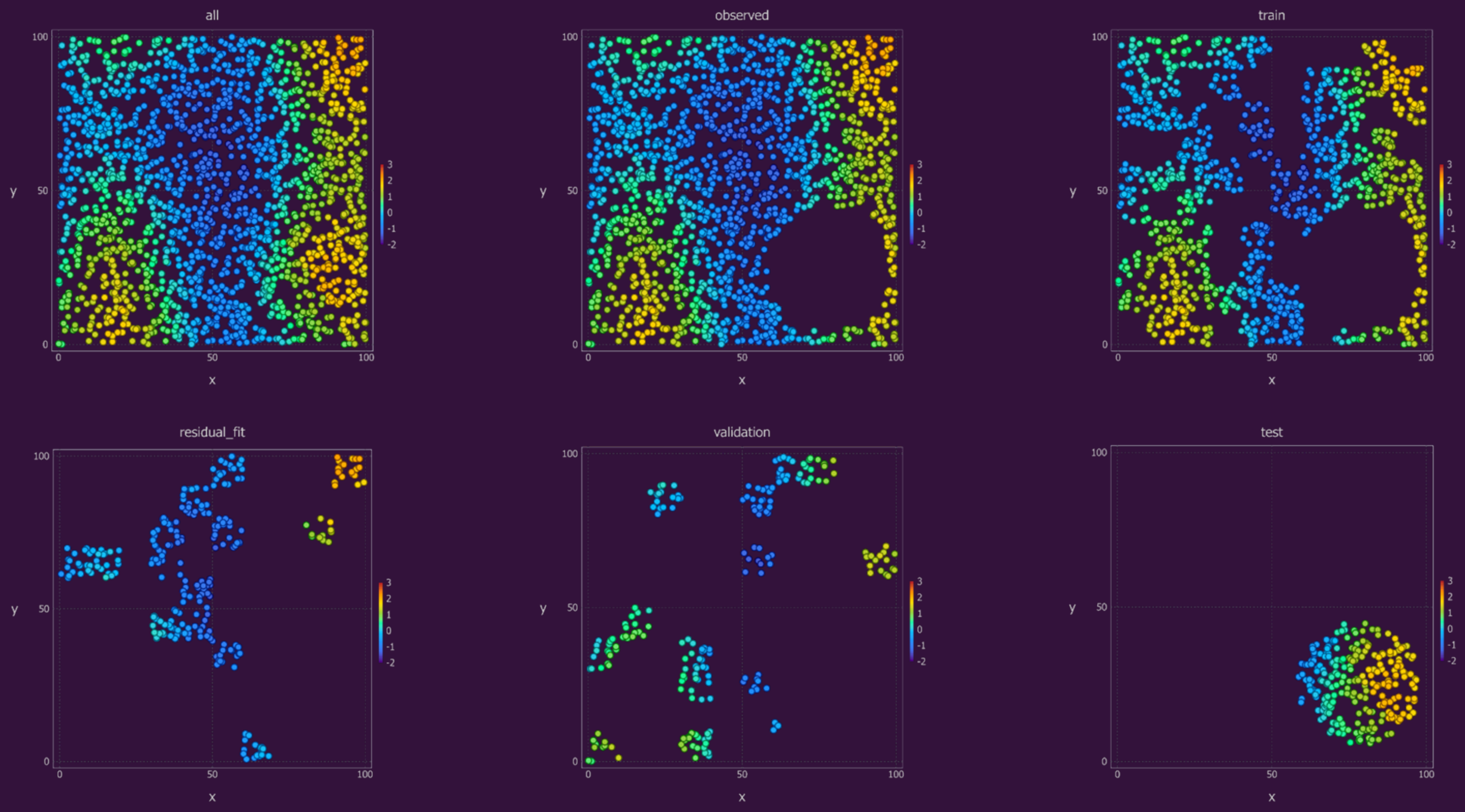


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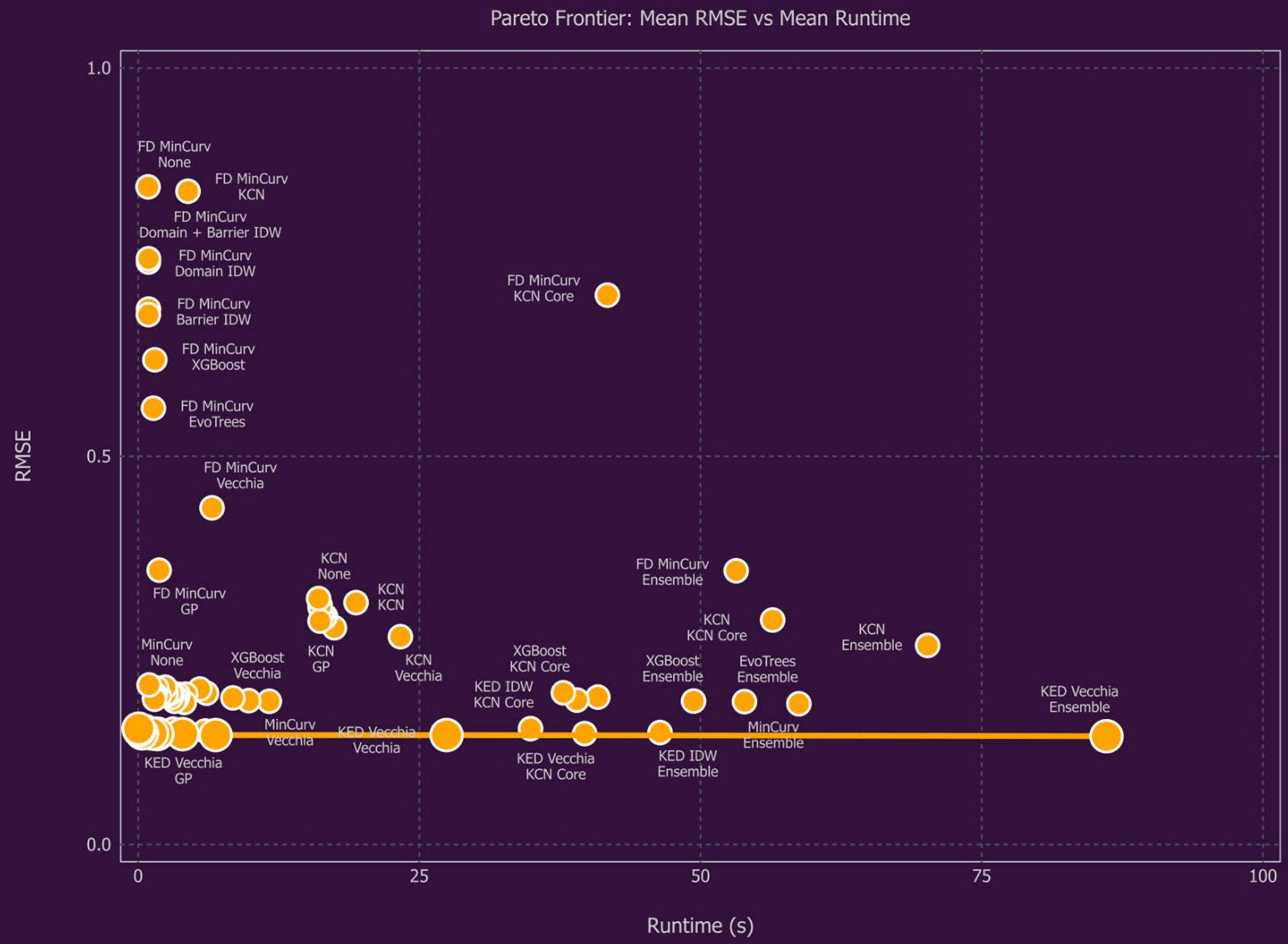
# Performance

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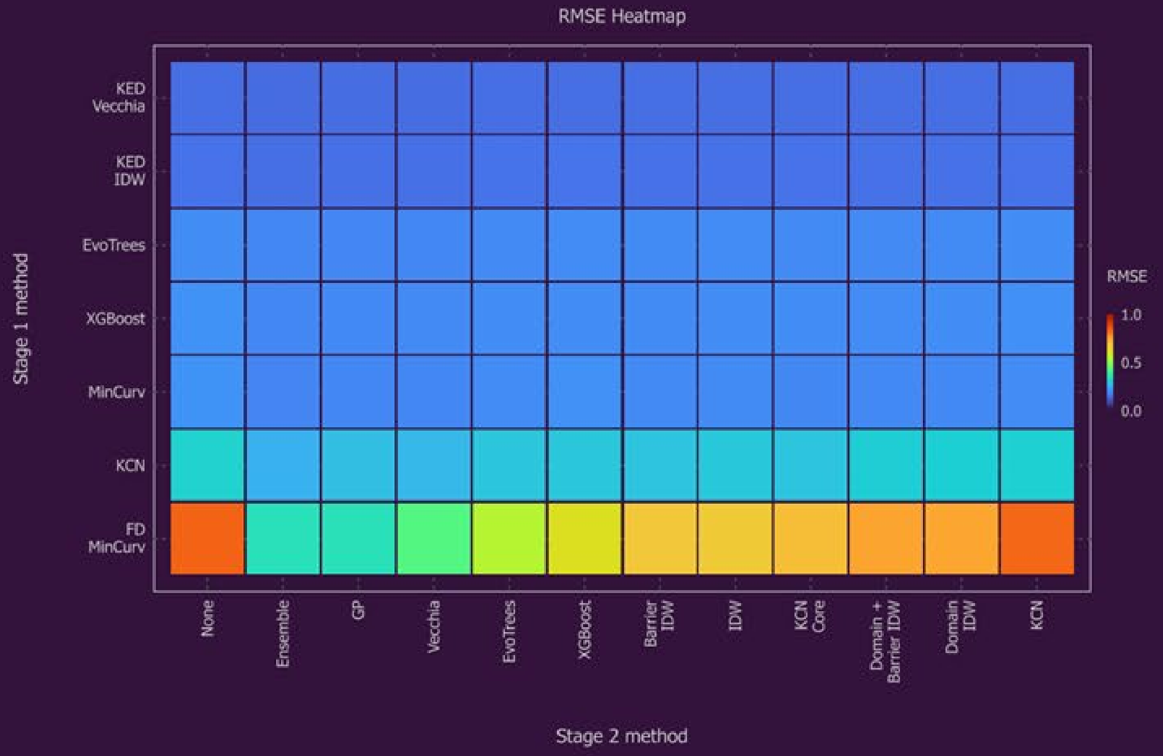
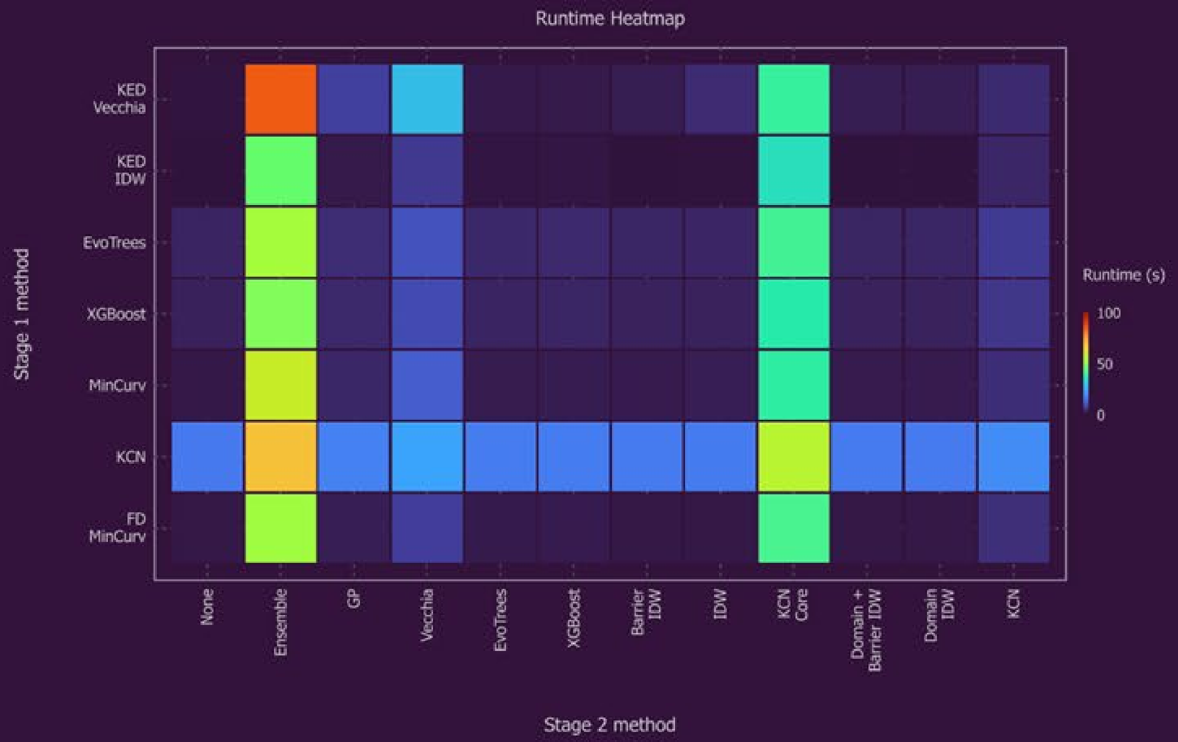
# Performance

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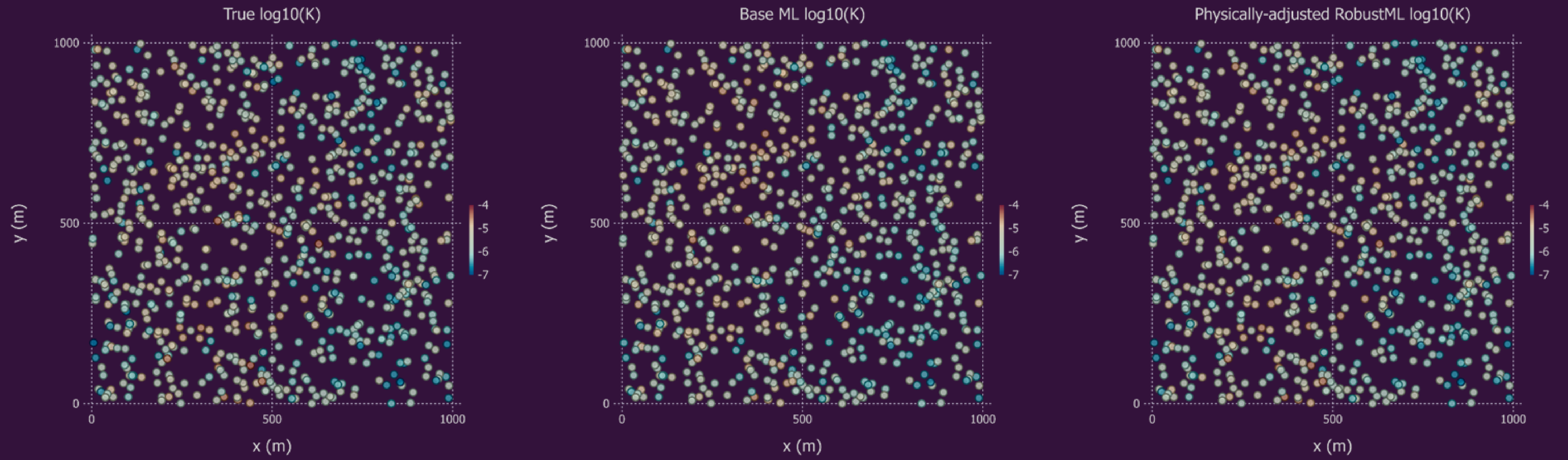
# Physics layer (pumping tests)



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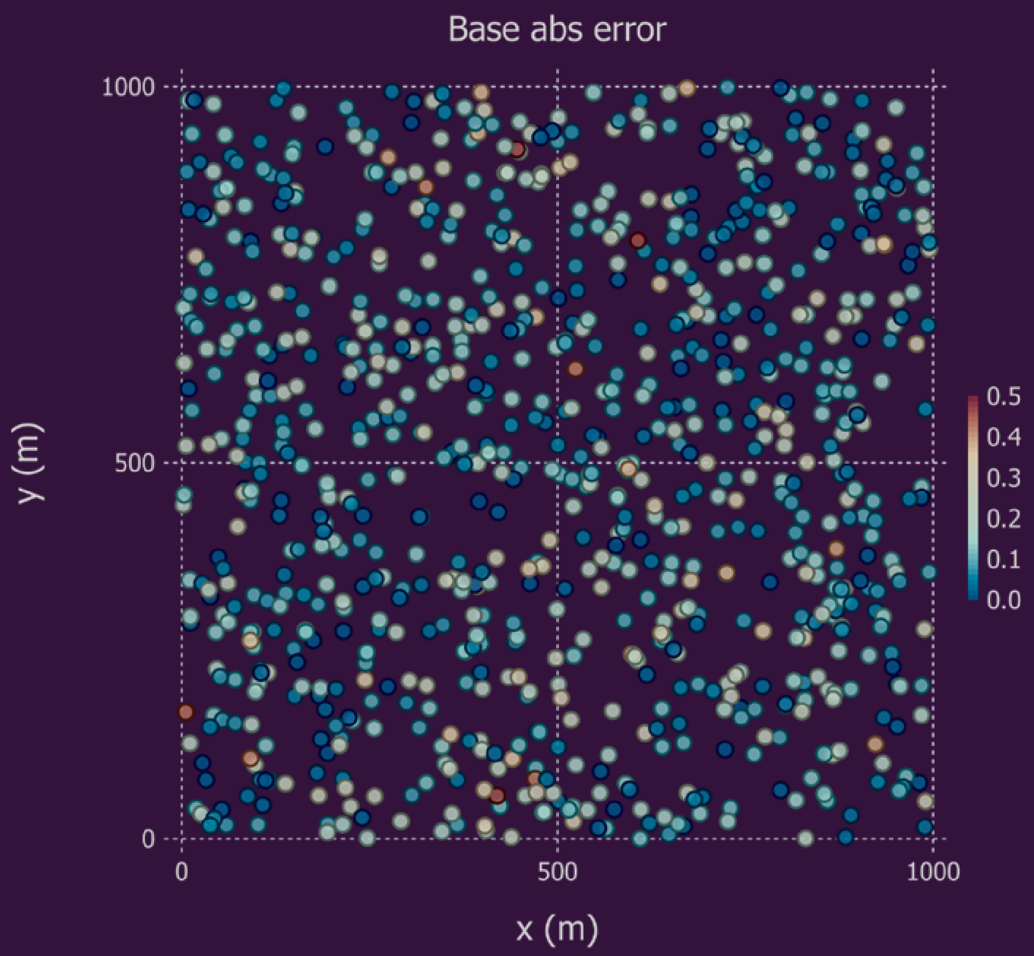


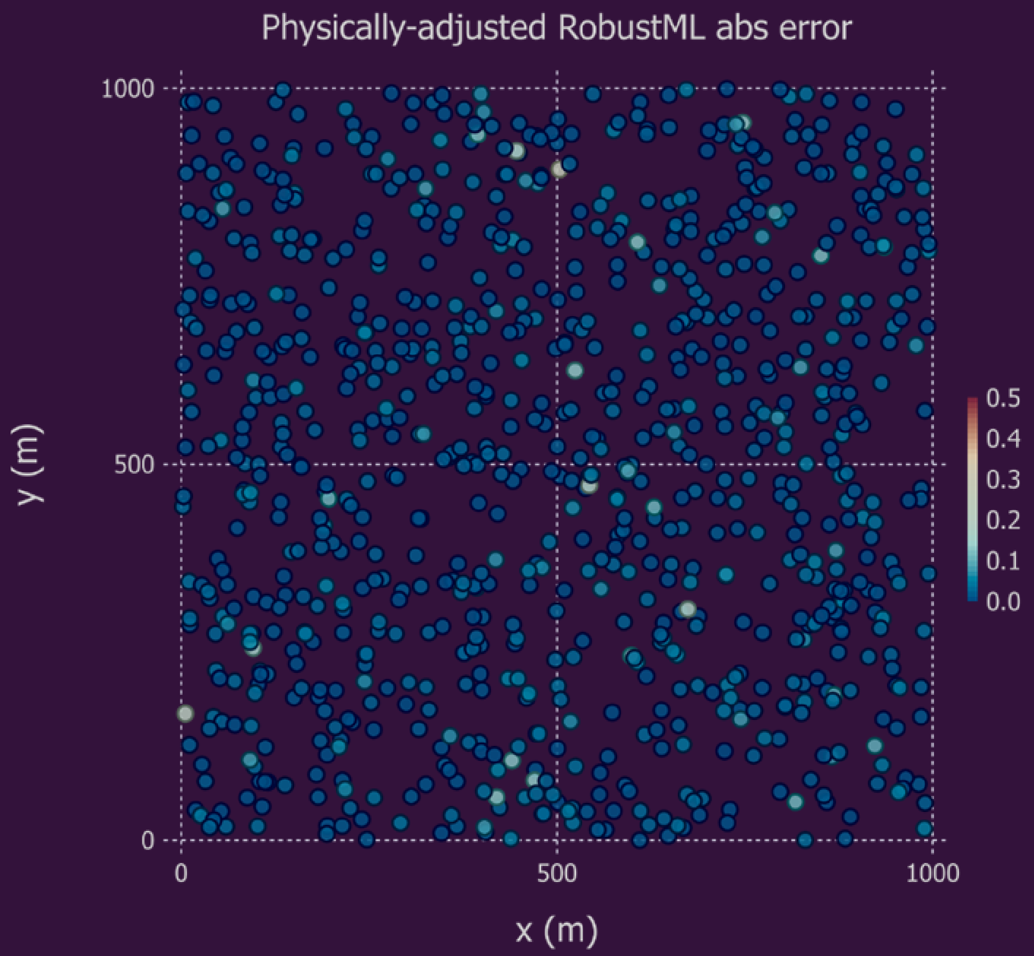


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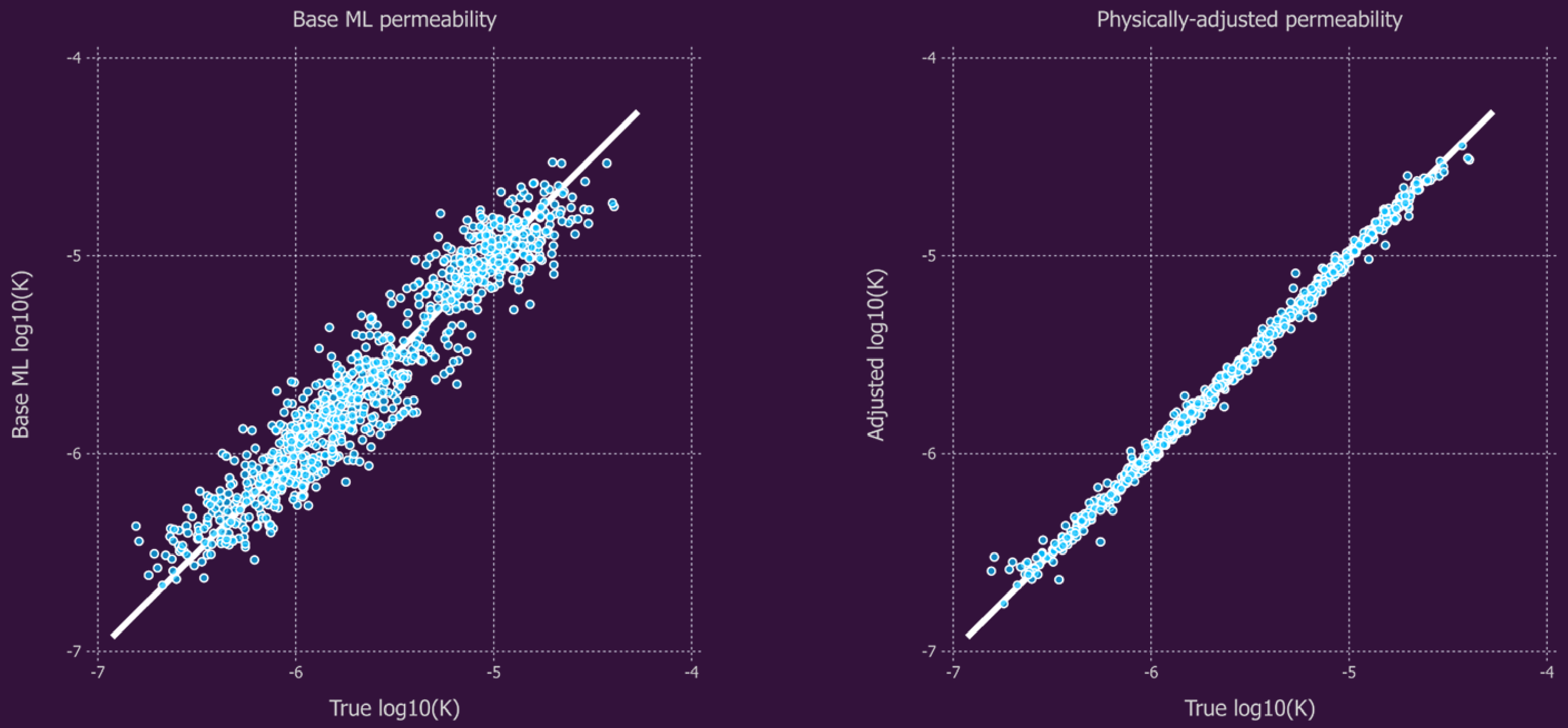


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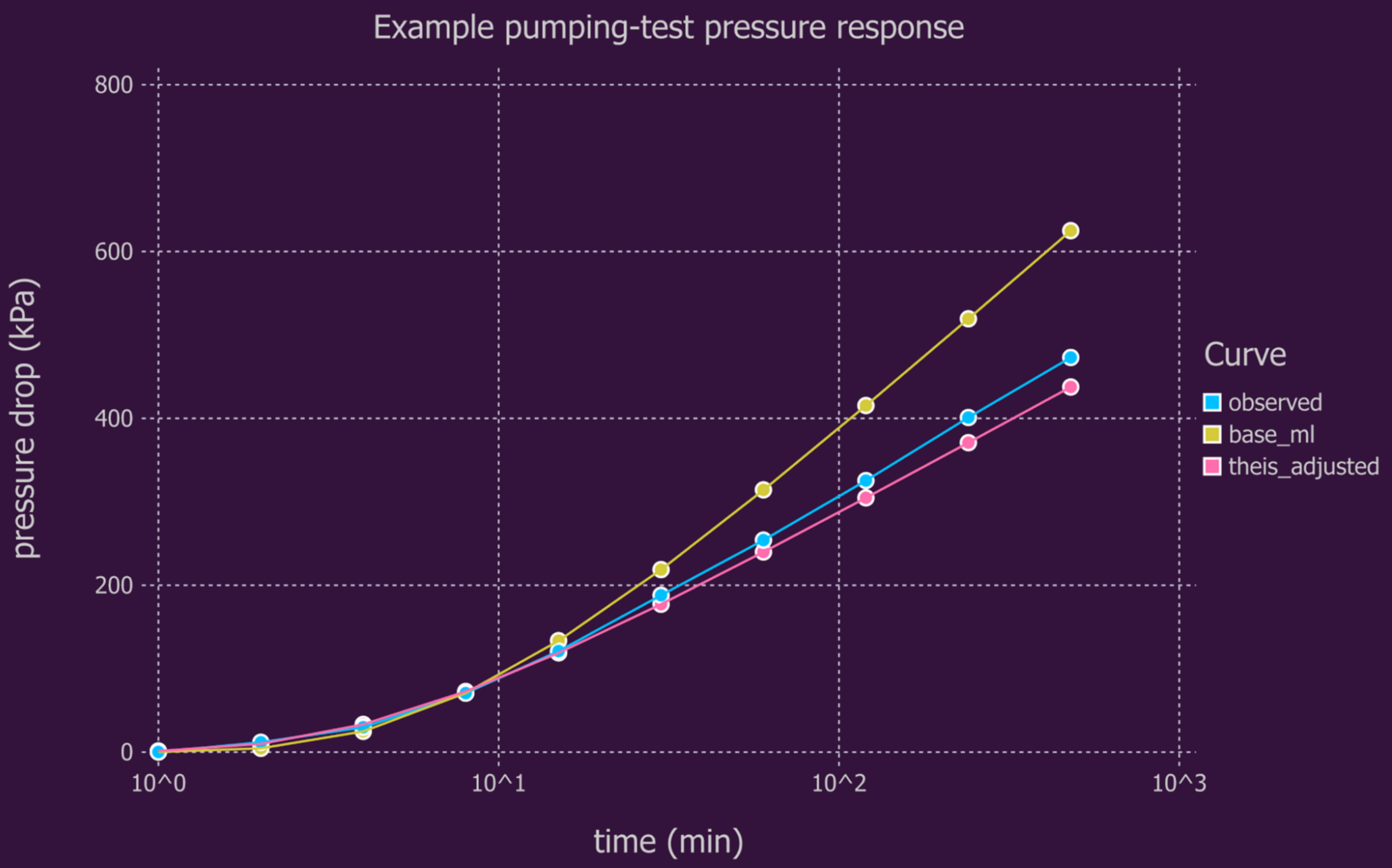


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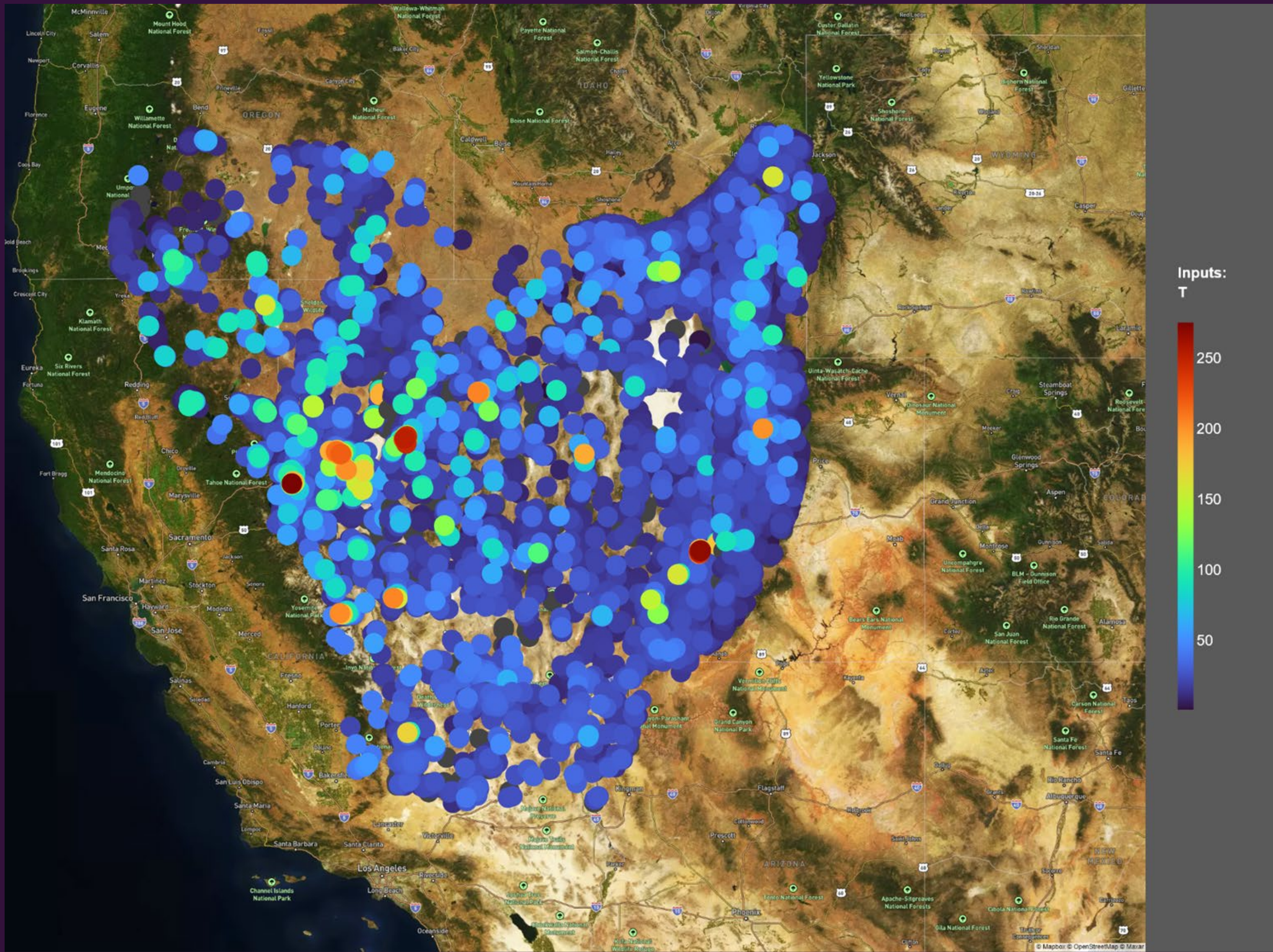
# Great Basin Datasets (126 attributes in total)

- Magnetics
- Radiometry
- Gravity
- Li, Mg, Na, Fe, HCO3, SiO2, Ba, F, SO4, K, B, Ca, Cl, As, …
- Heat flow
- Favorable Geothermal Structural Settings (INGENIOUS project)
- Quaternary Faults
- Well & Spring Chemistry
- Principal Aquifers

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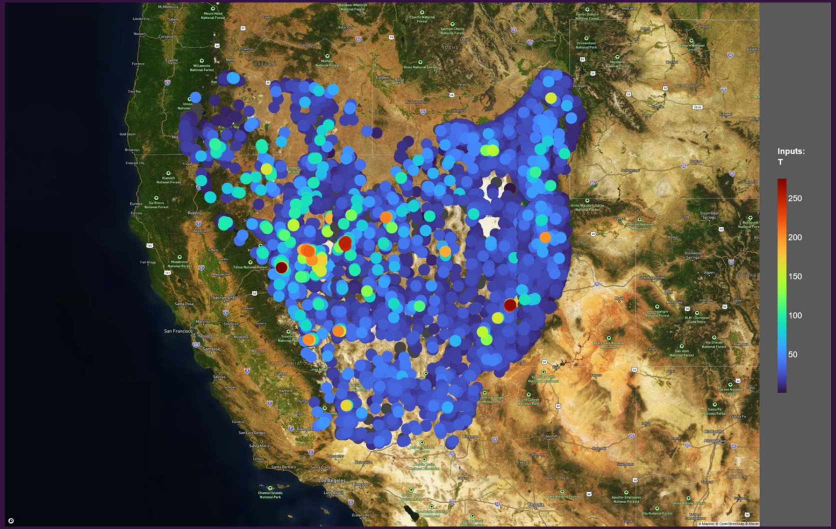
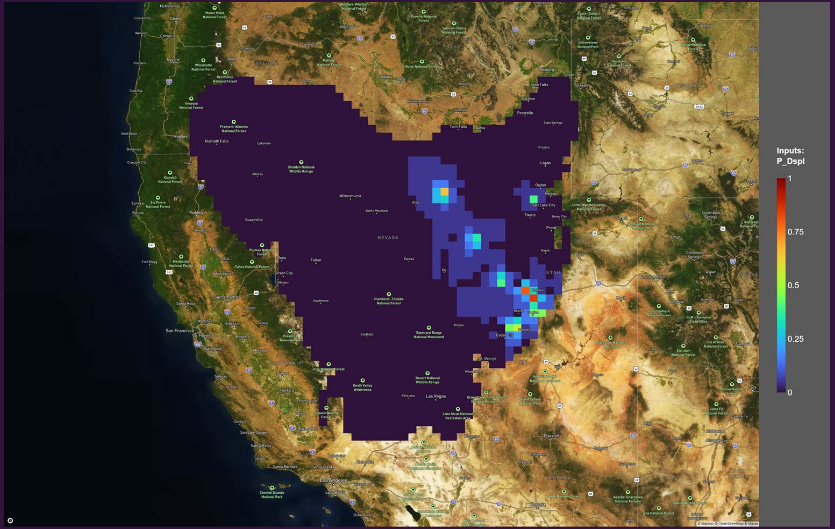
# Finding a Needle in a Haystack

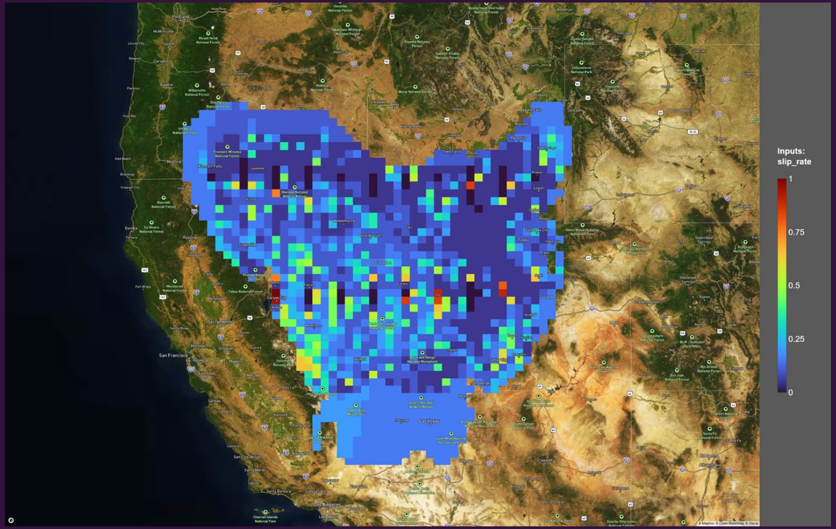
Temperature [°C]



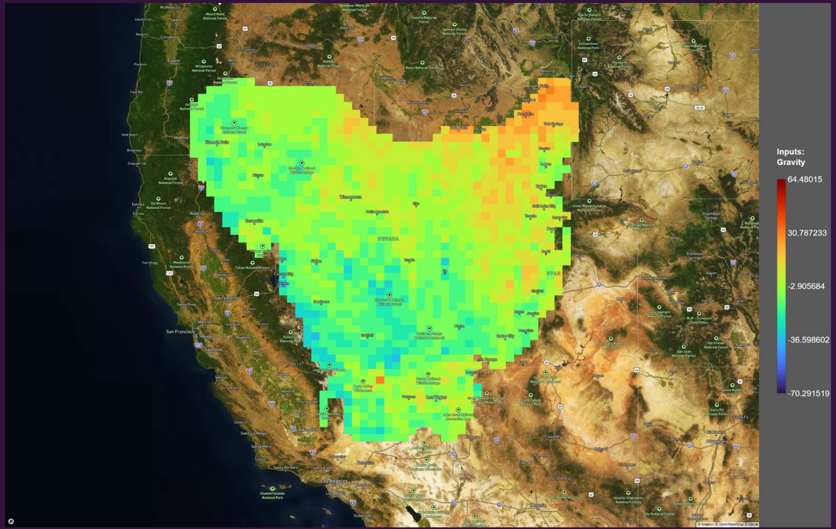

Displacement [normalized]




Slep Rate [normalized]

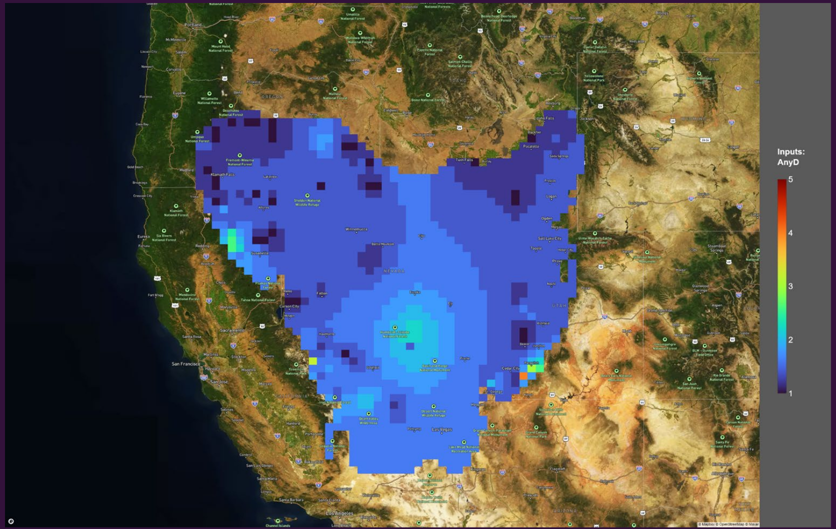



Gravity [m/s²]




Magnetics [nT]


Vent Density [-]

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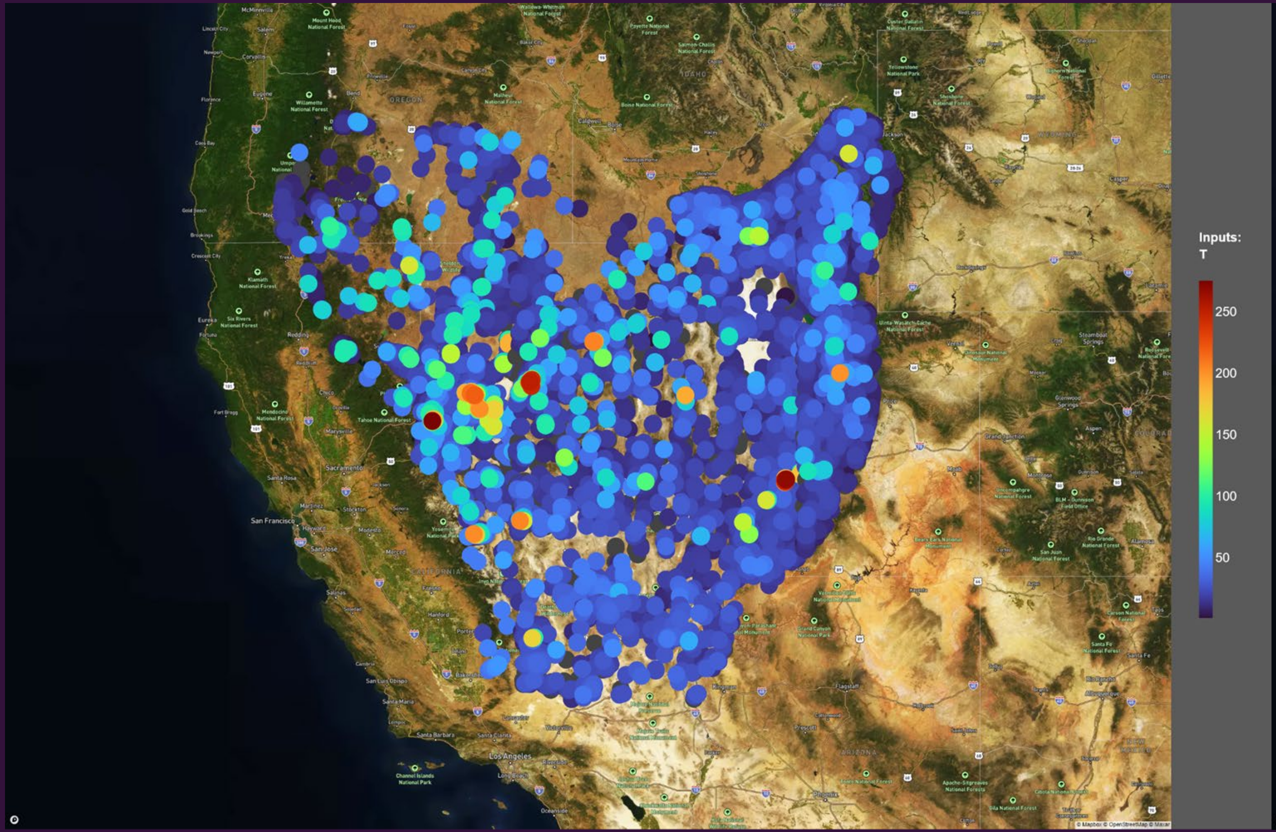
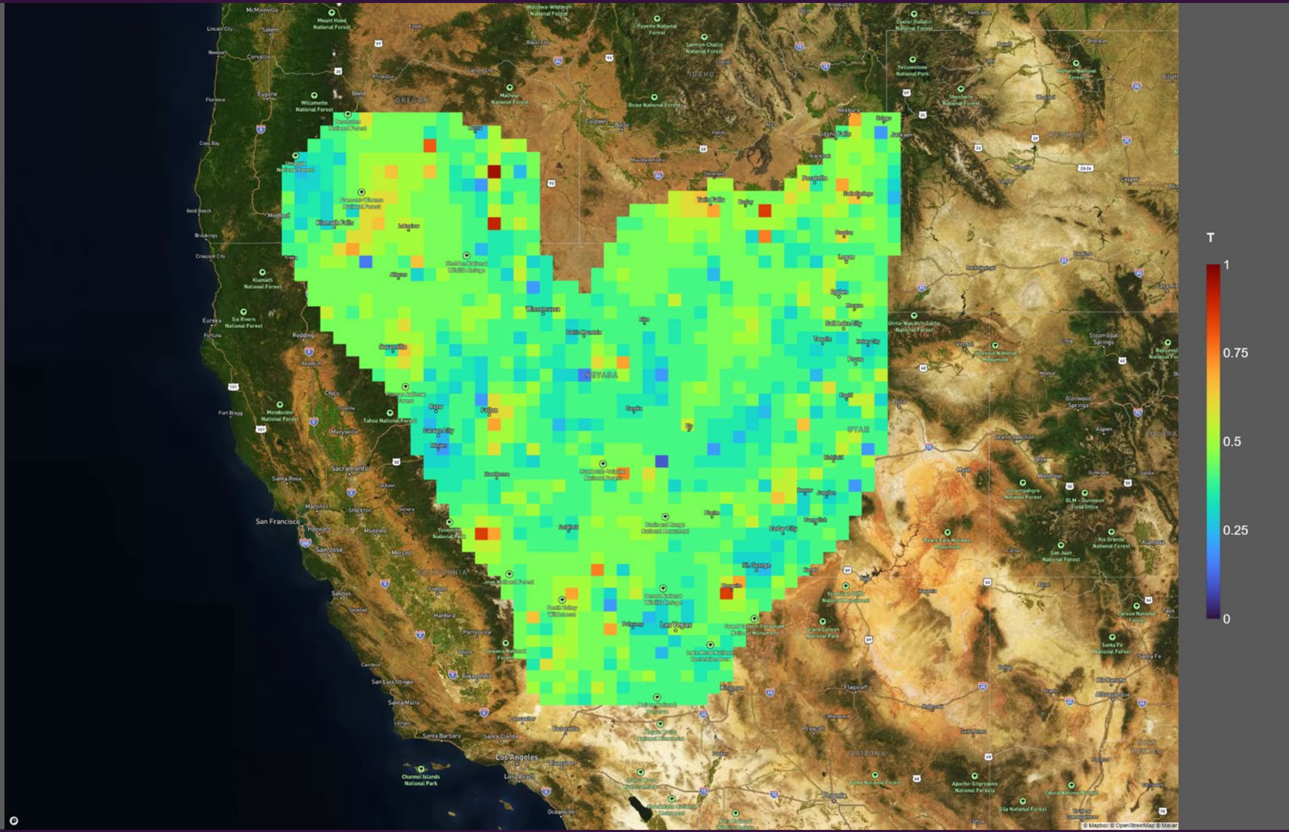
# Geothermal Temperature: Data vs Prospectivity

Temperature [°C]

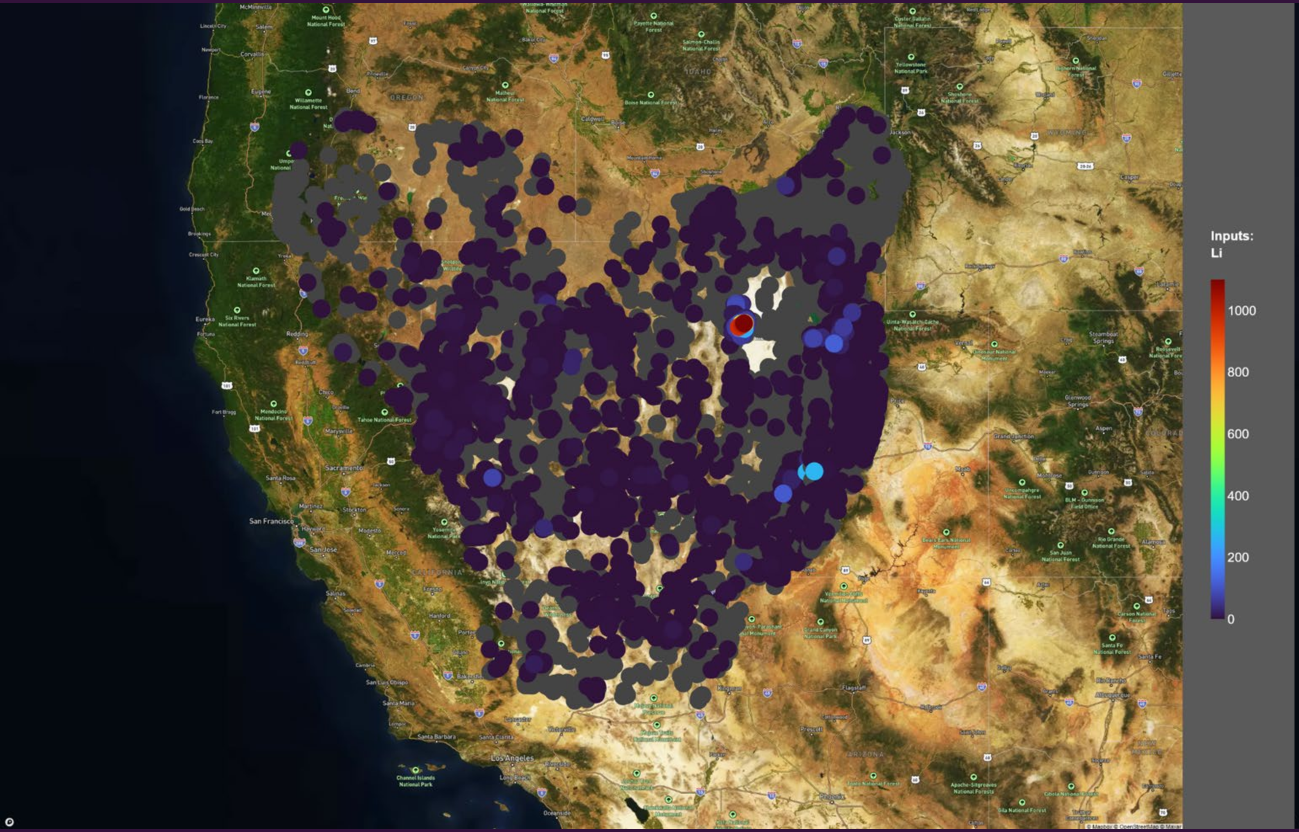



Geothermal Prospectivity [normalized]

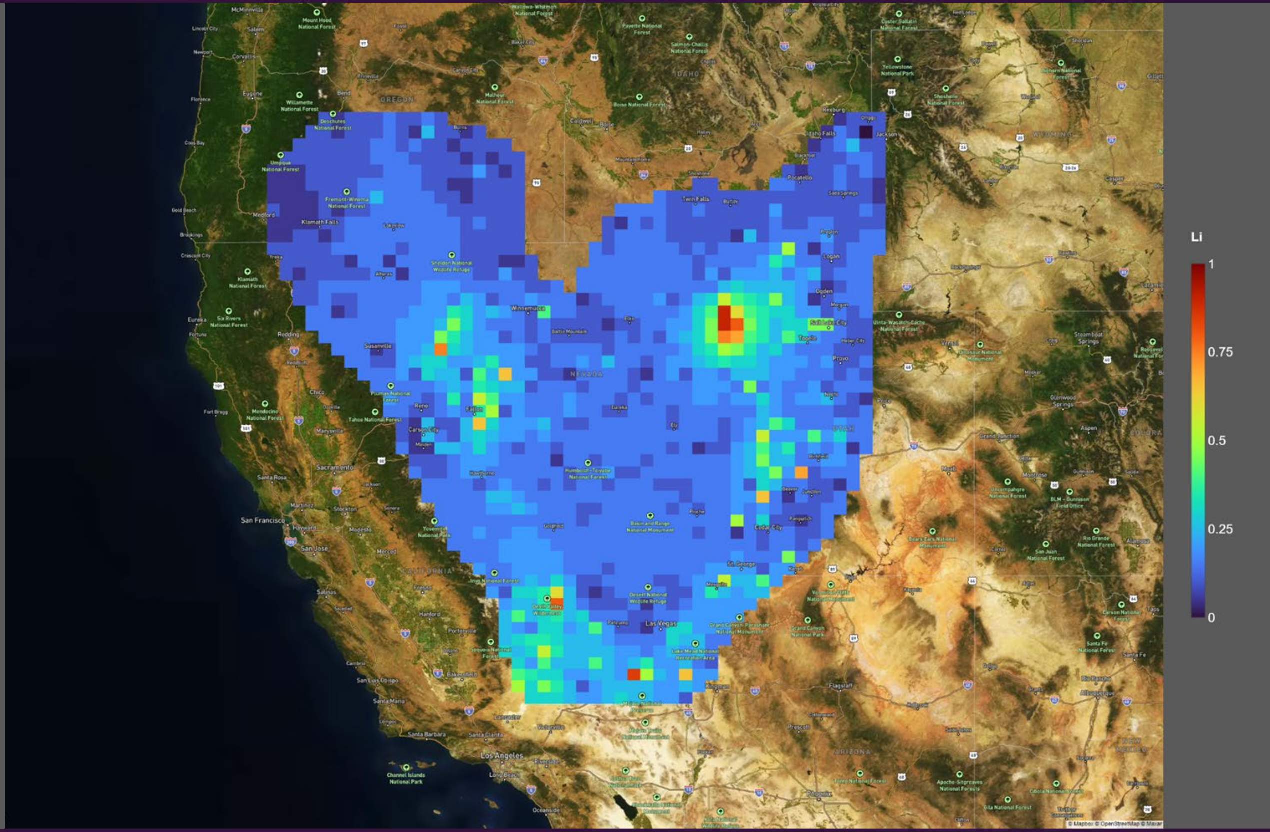


# Lithium: Data vs Prospectivity

**Lithium Groundwater Concentrations [ppb]**

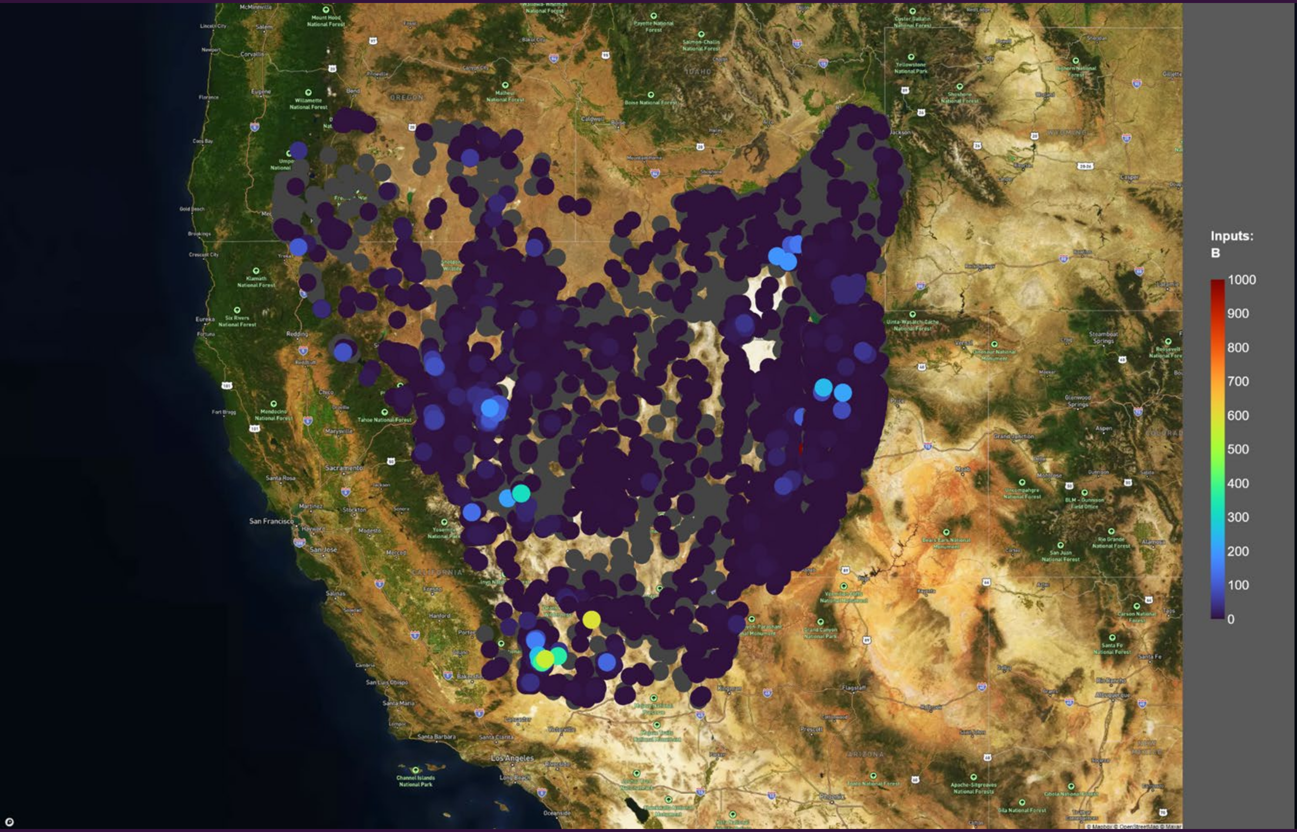



**Lithium Prospectivity [normalized]**

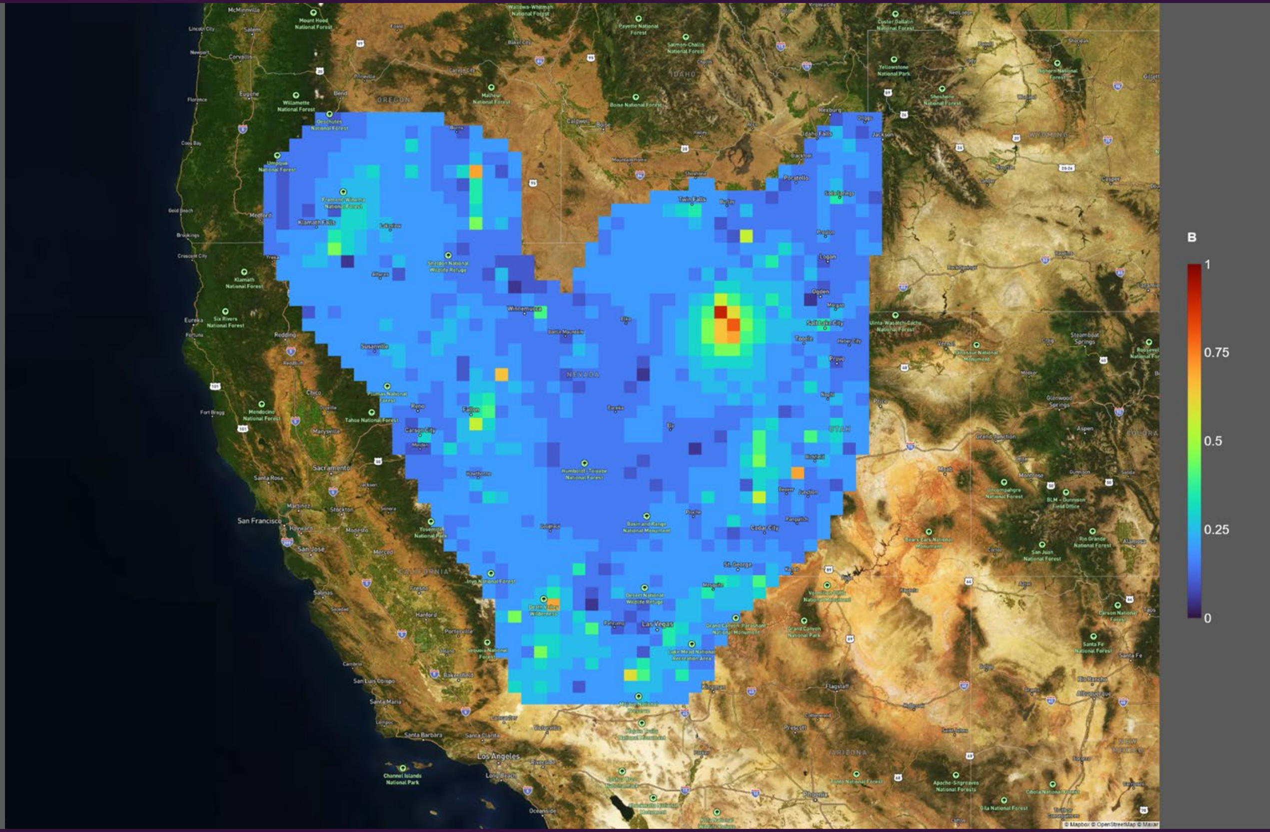


# Boron: Data vs Prospectivity

Boron Groundwater Concentrations [ppb]




Boron Prospectivity [normalized]

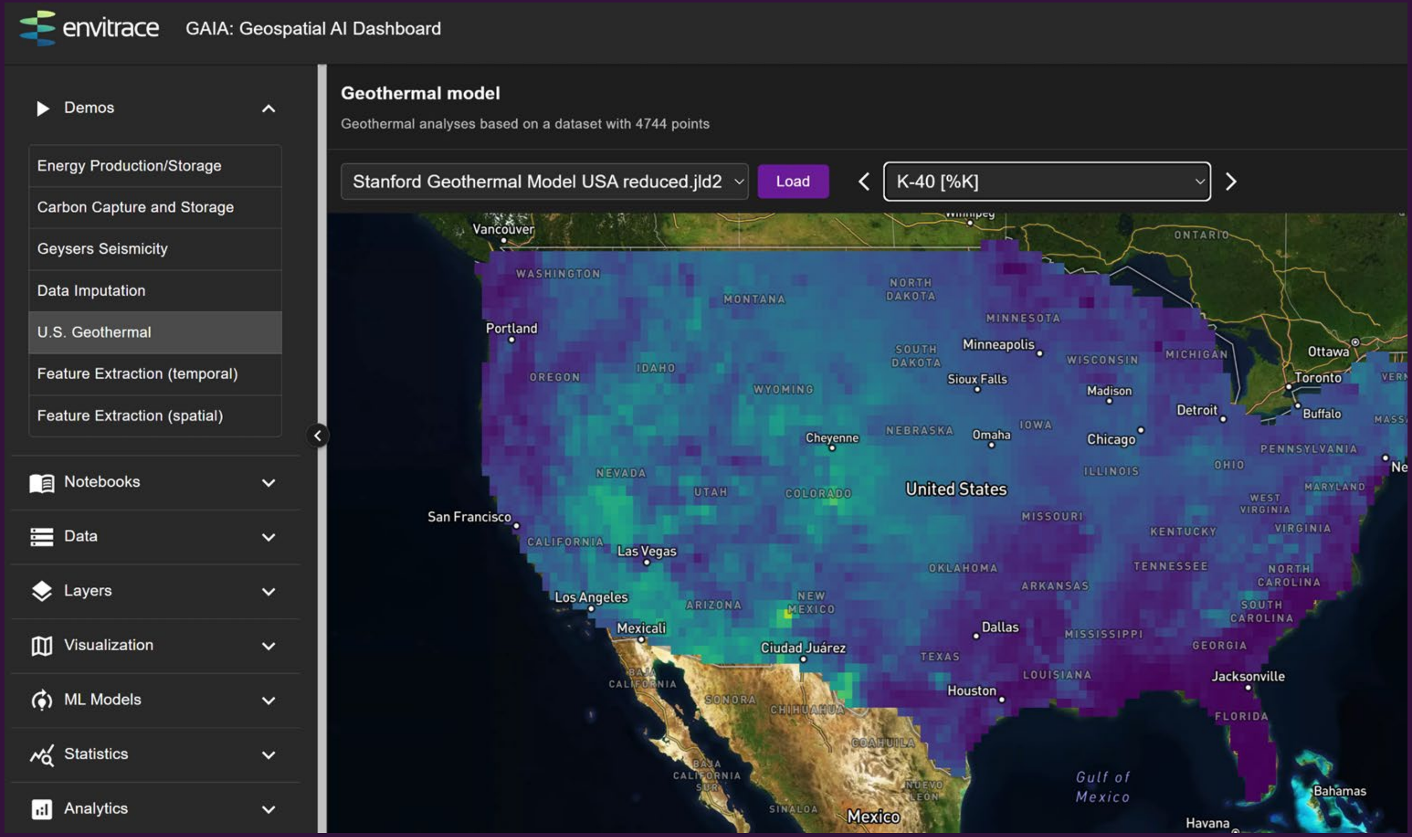


# Our SaaS

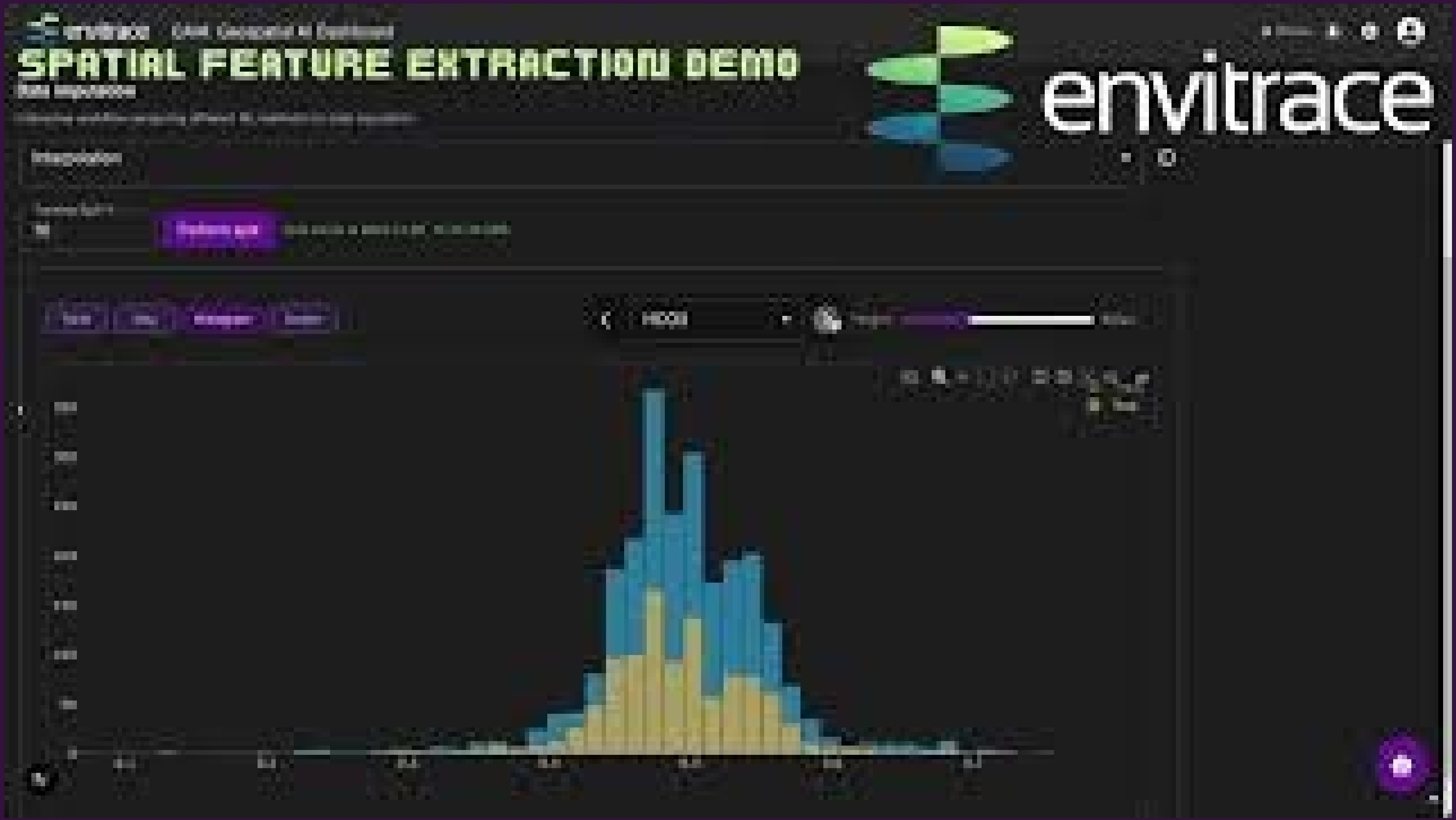
AI/ML cloud product for geo spatio-temporal analyses

- Public and proprietary data
- Various supervised, unsupervised, and physics-informed ML methods
- Accounting for physics and geology
- Accounting for data gaps and measurement errors
- Extraction of hidden geologic features
- Estimation of prospectivity and productivity

[http://envitrace.com/saas](http://envitrace.com/saas)



# Spatial Feature Extraction



# Conclusions

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- Our AI workflows allow for efficient, fast and robust data assimilation
- Exploration of ML alternatives
- Testing & Benchmarking
- Extracts features
- Imputes data
- Evaluates prospectivities
- SaaS dashboard: http://envitrace.com/saas

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# Acknowledgement

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