KarboEx2

Project Meeting,
06.07.2026

AP4: Geologische und markscheiderische Neuinterpretation aller Daten im Hinblick auf eine geothermische Nutzung

Univ.-Prof. Florian Wellmann, Ph.D.
Dr. David Nathan, Ph.D.
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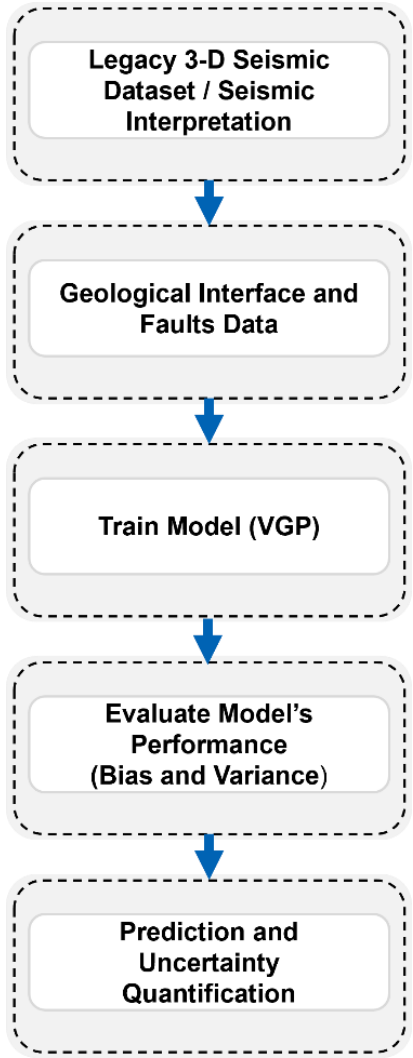
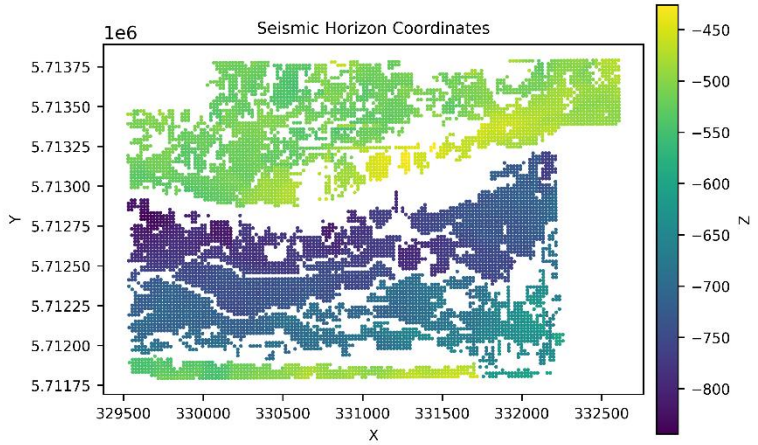
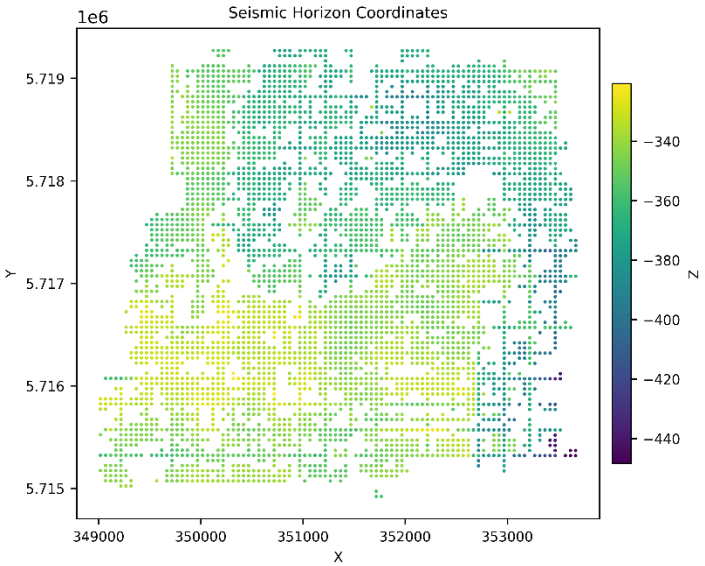
Chair of Computational Geoscience, Geothermics and Reservoir Geophysics (CG3)

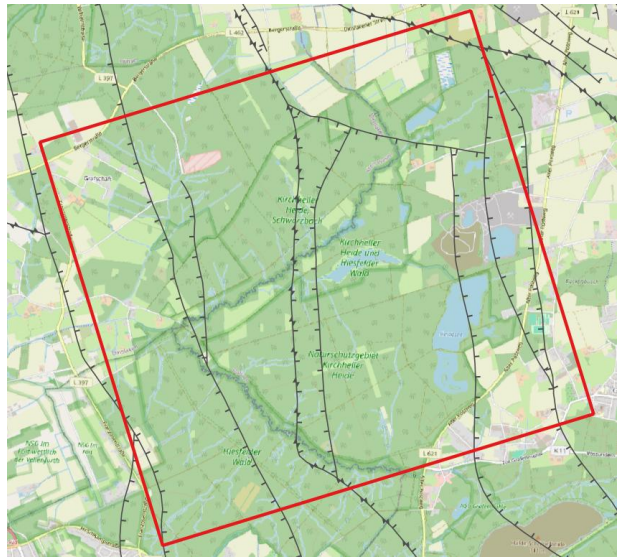
Chair of Computational Geoscience, Geothermics & Reservoir Geophysics
RWTH AACHEN UNIVERSITY
Kofinanziert von der Europäischen Union
Gefördert durch:
Ministerium für Wirtschaft, Industrie, Klimaschutz und Energie des Landes Nordrhein-Westfalen
KarboEx²

VGP Application on Rheinberg and Prosper Haniel









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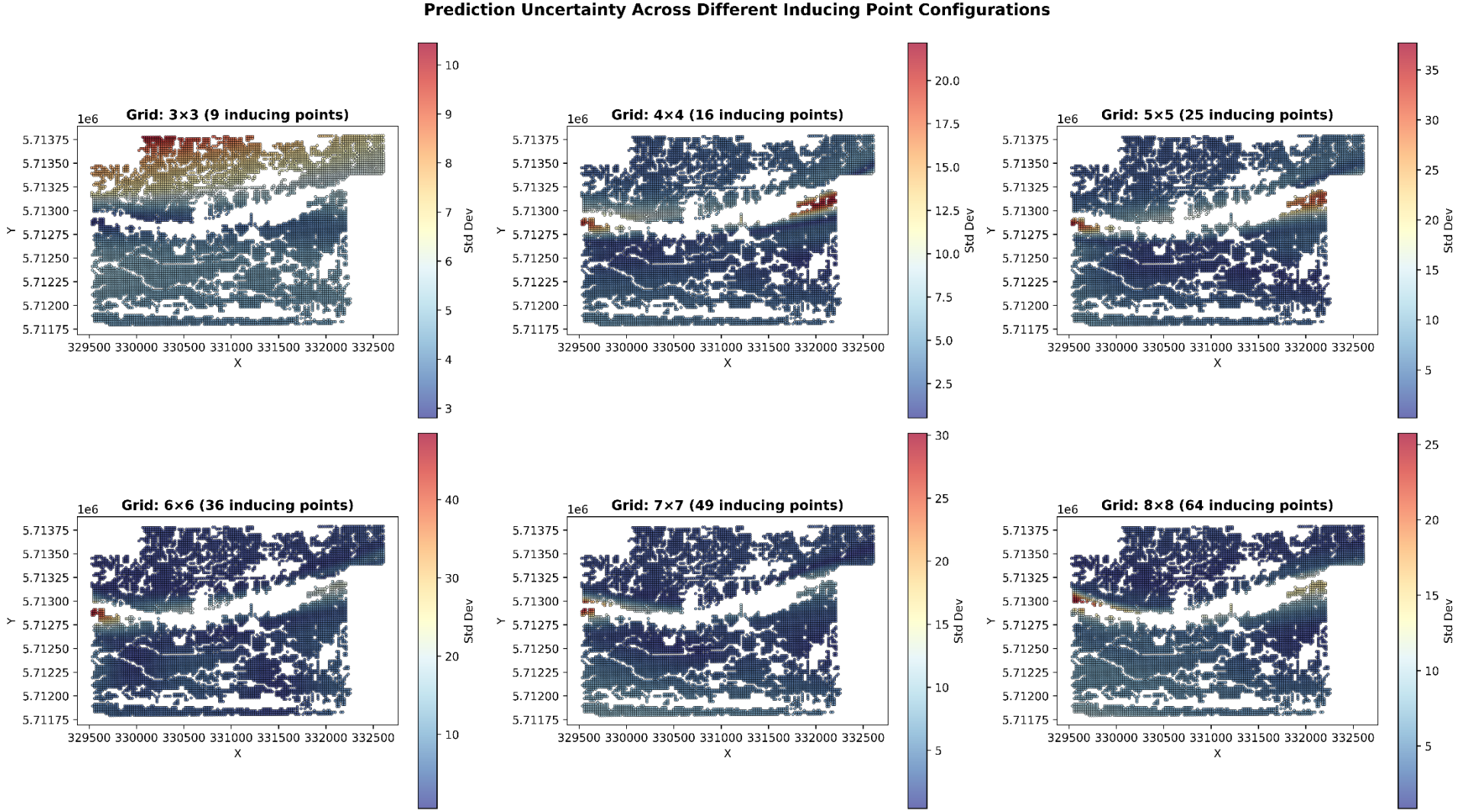
VGP Inducing Points Evenly Spaced



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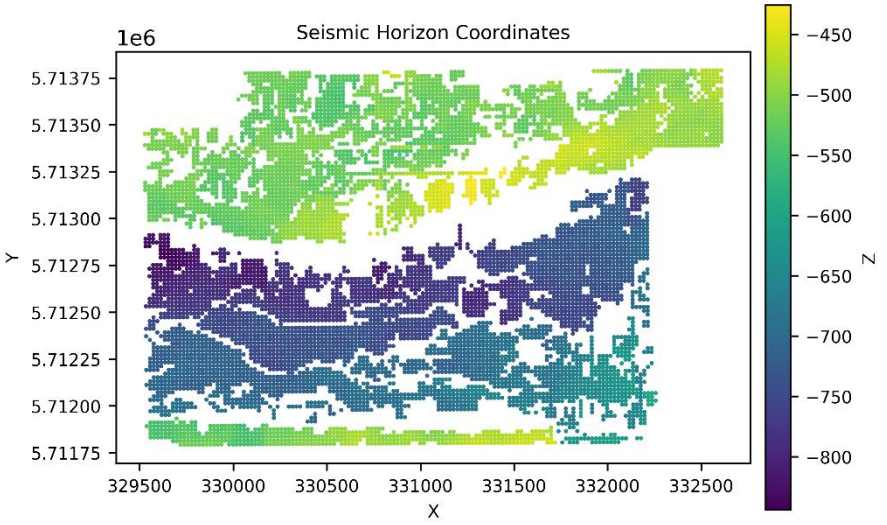
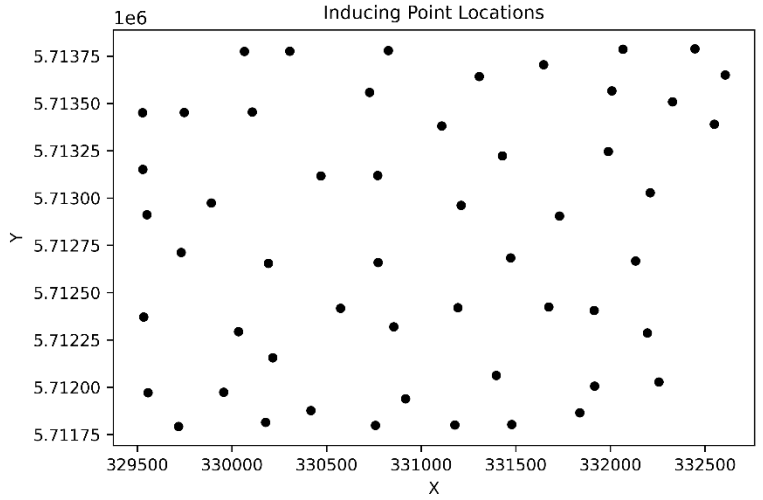
Placement of Inducing Points

- Inducing Points are placed using a local structural-importance score which is computed from the data using neighborhood-based estimates of slope, residual curvature, and local contrast.
- A Gaussian kernel matrix is built on a subset of candidate points.
- A weighted pivoted-Cholesky or greedy Nyström-type procedure selects candidate locations that explain the largest structurally weighted fraction of the kernel variance.
- Selected locations are passed as inducing points to a GeoML VGP network that uses a Gaussian likelihood and stochastic variational inference.
- The number of inducing points controls the effective complexity of VGP.
- The purpose is not only to accelerate training, but to allocate the model's representational capacity where it is geologically most valuable.
- This is particularly important for seismic horizon modeling, where broad smooth regions may require few inducing points, while faulted, folded, steep, or high-curvature zones may require a denser inducing-point representation.





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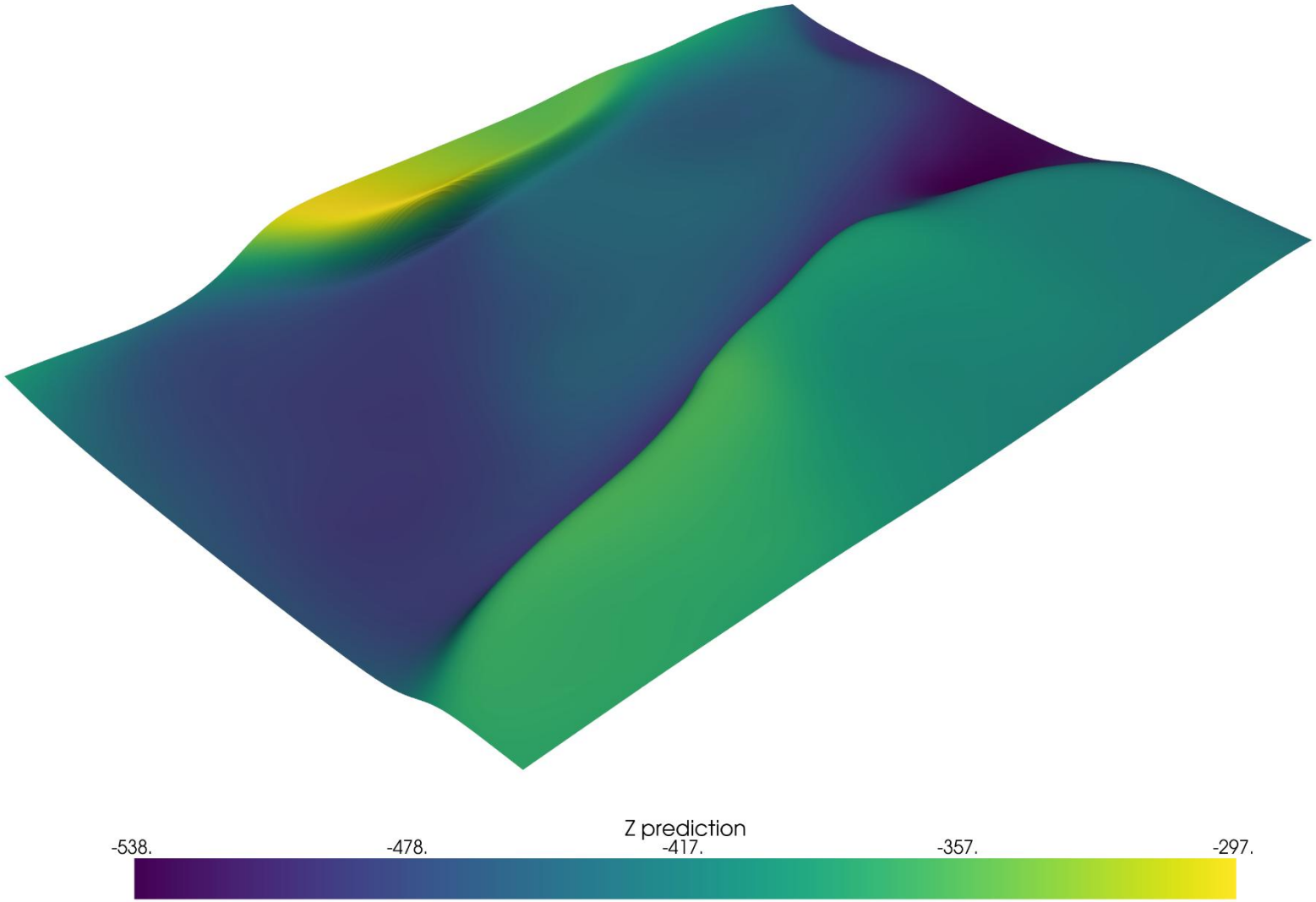
Top Permian Rheinberg



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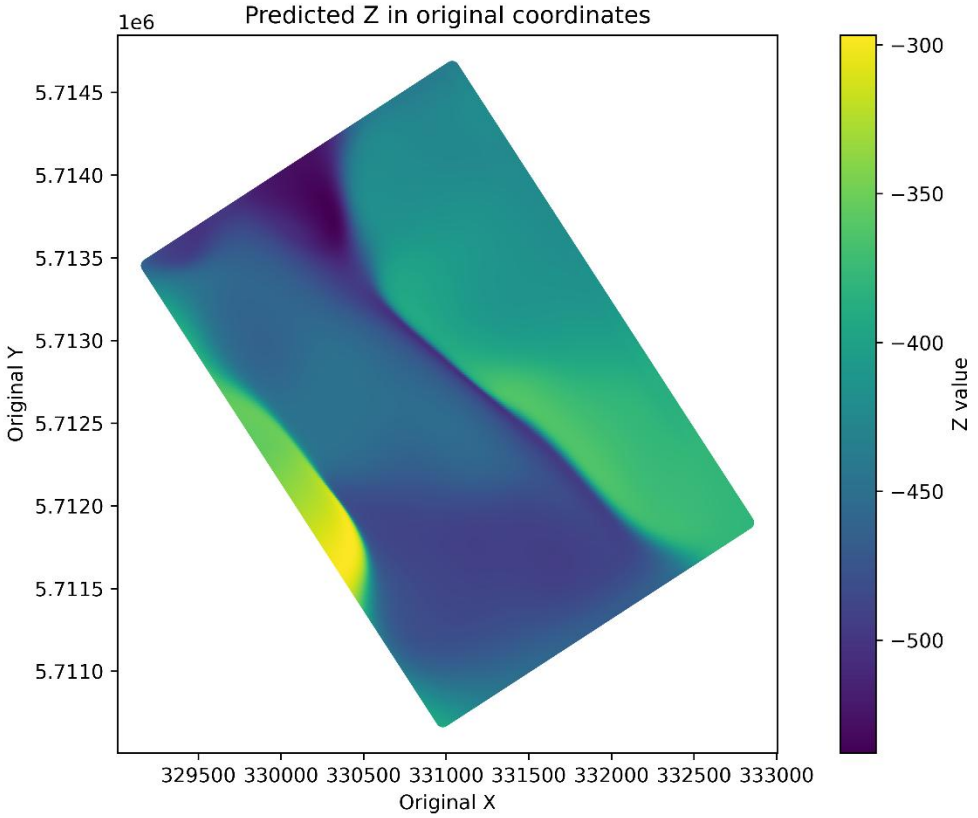
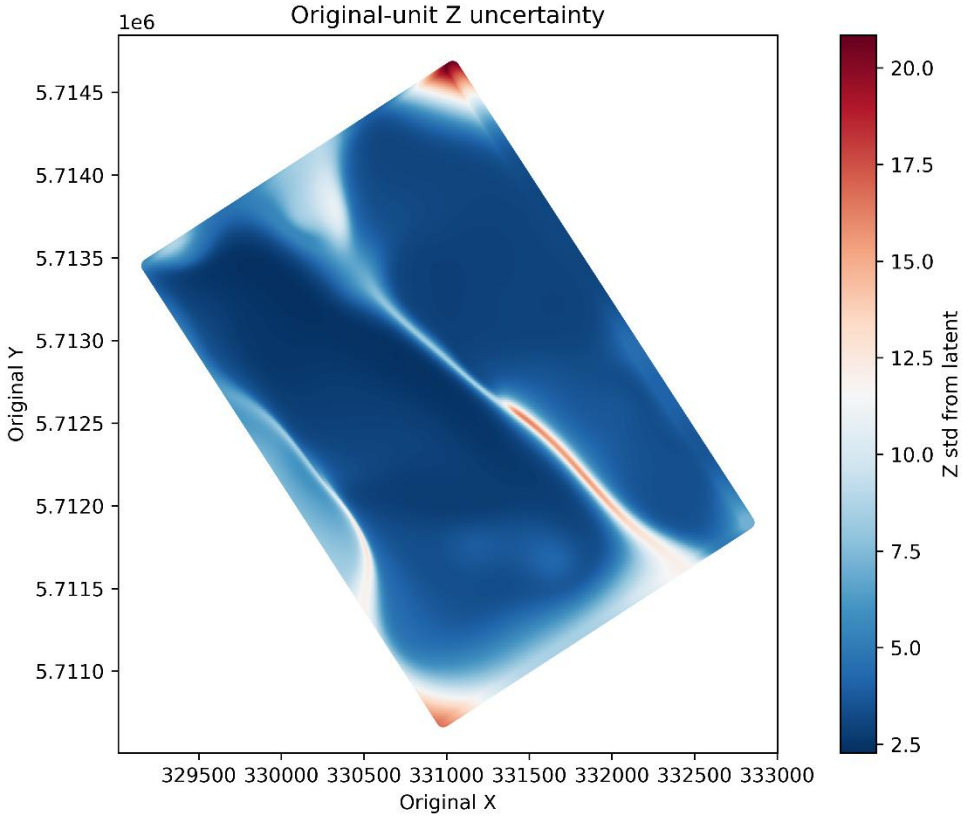
Uncertainty Map Top Permian Rheinberg





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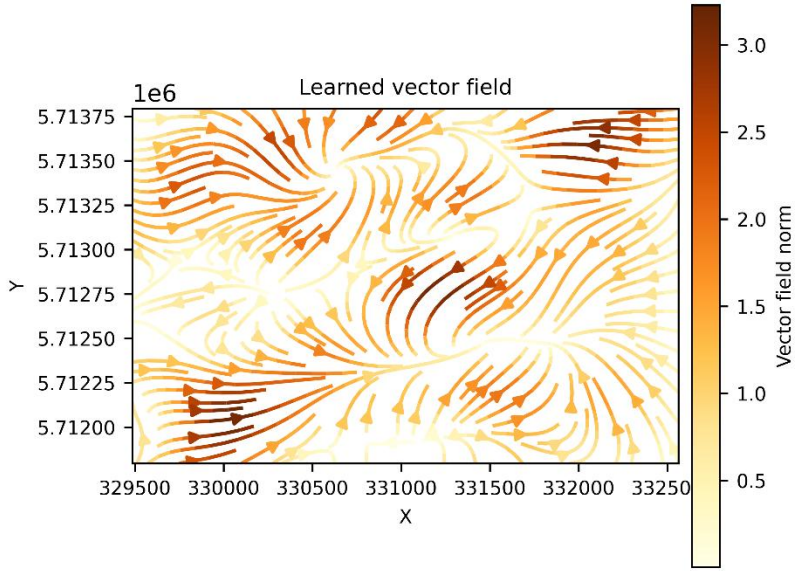
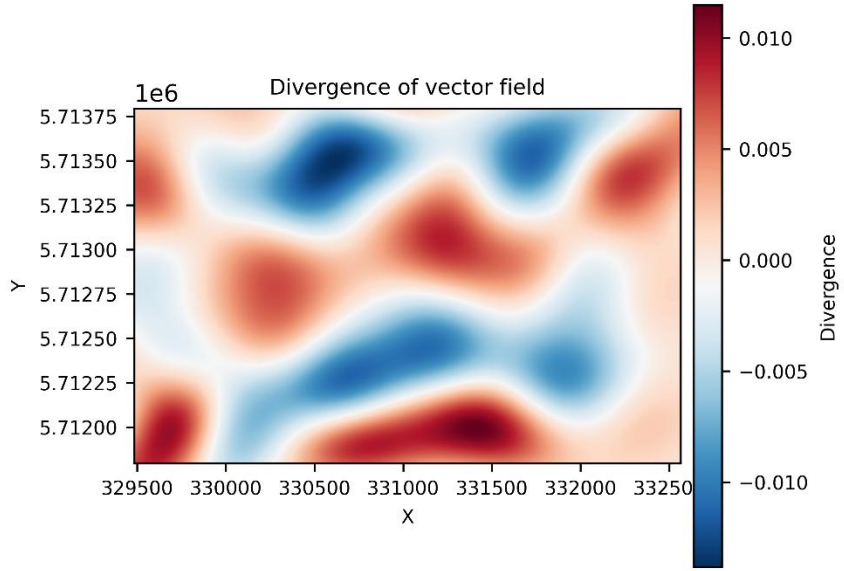
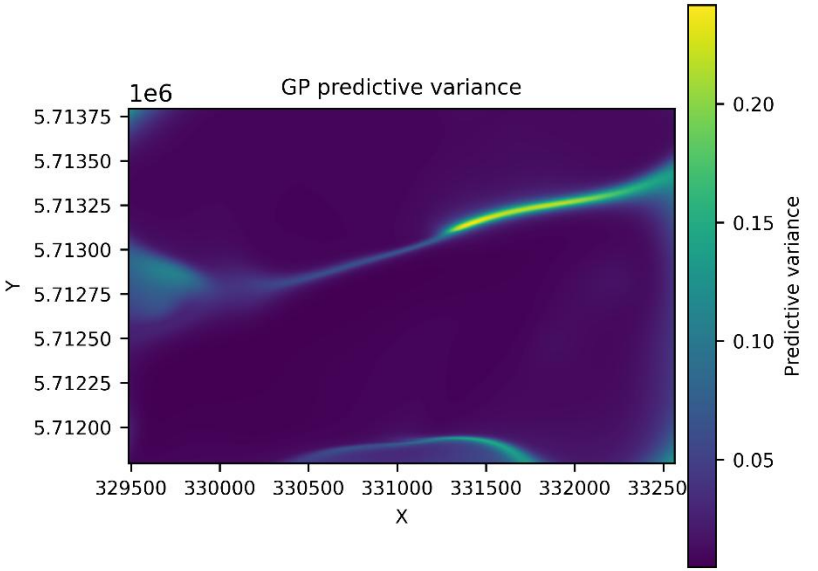
Vector Field | Divergence | Variance | Top Permian Rheinberg







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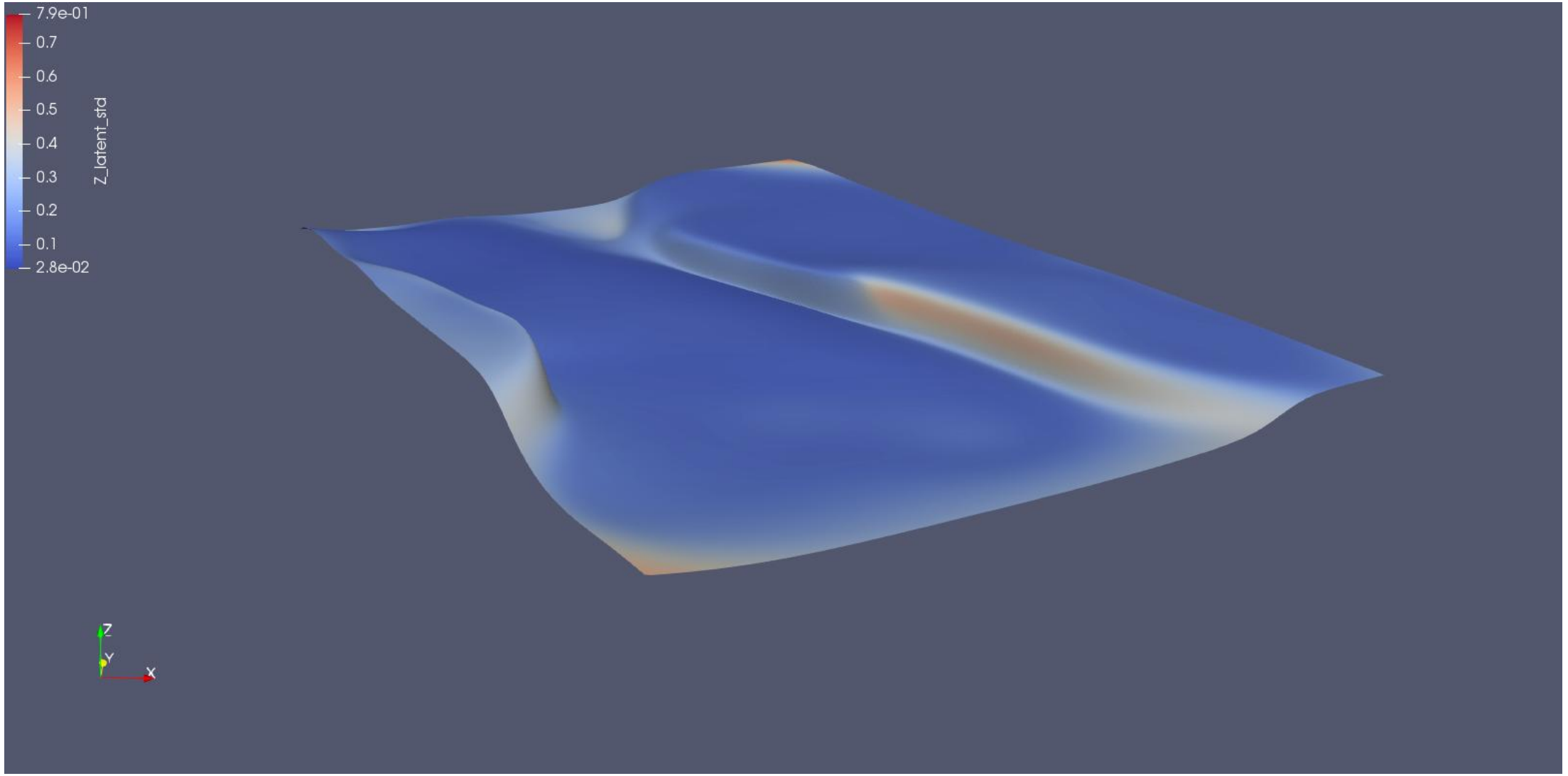
Uncertainty Top Permian Rheinberg



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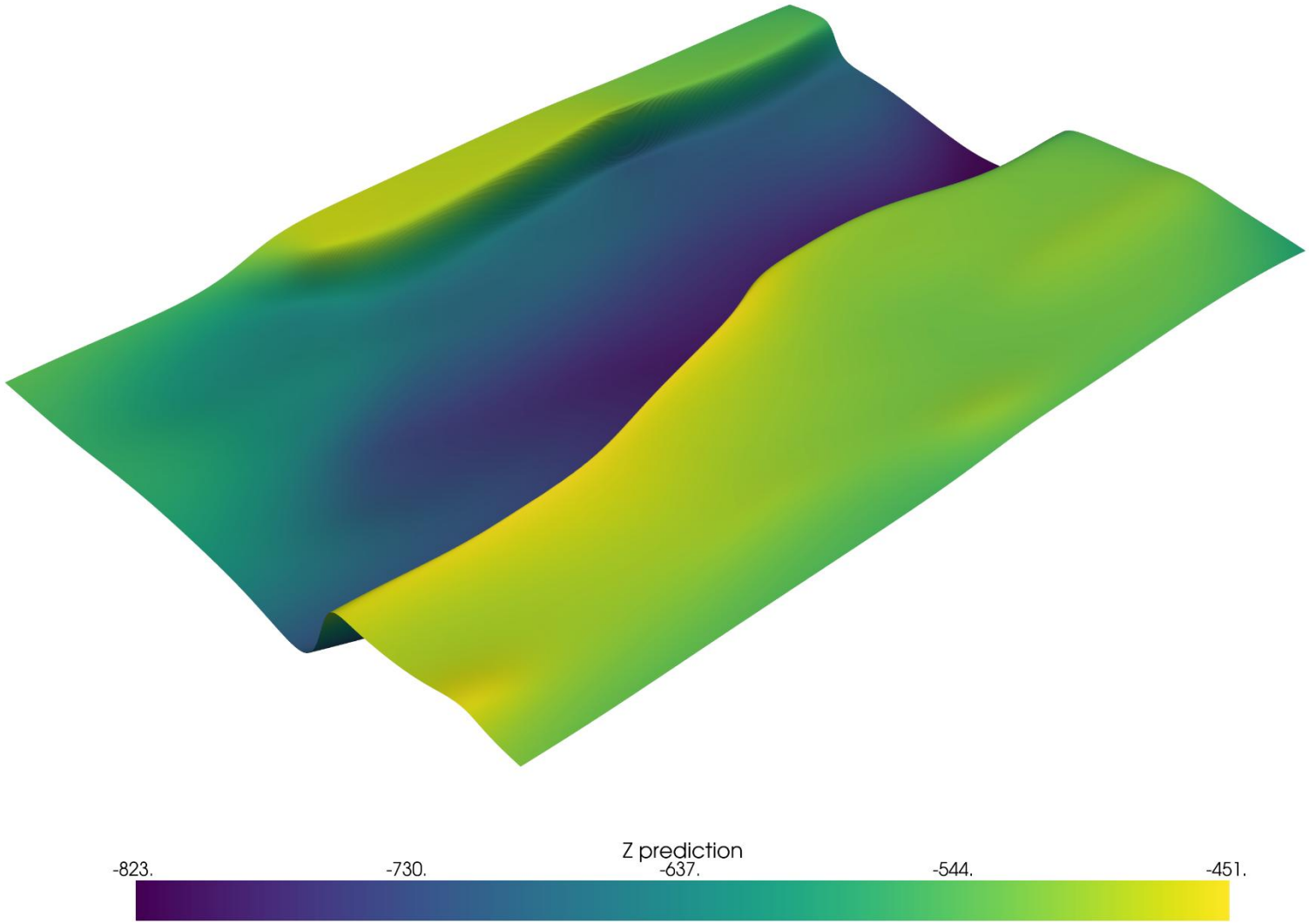
Top Karbon – Pennsylvanium Rheinberg



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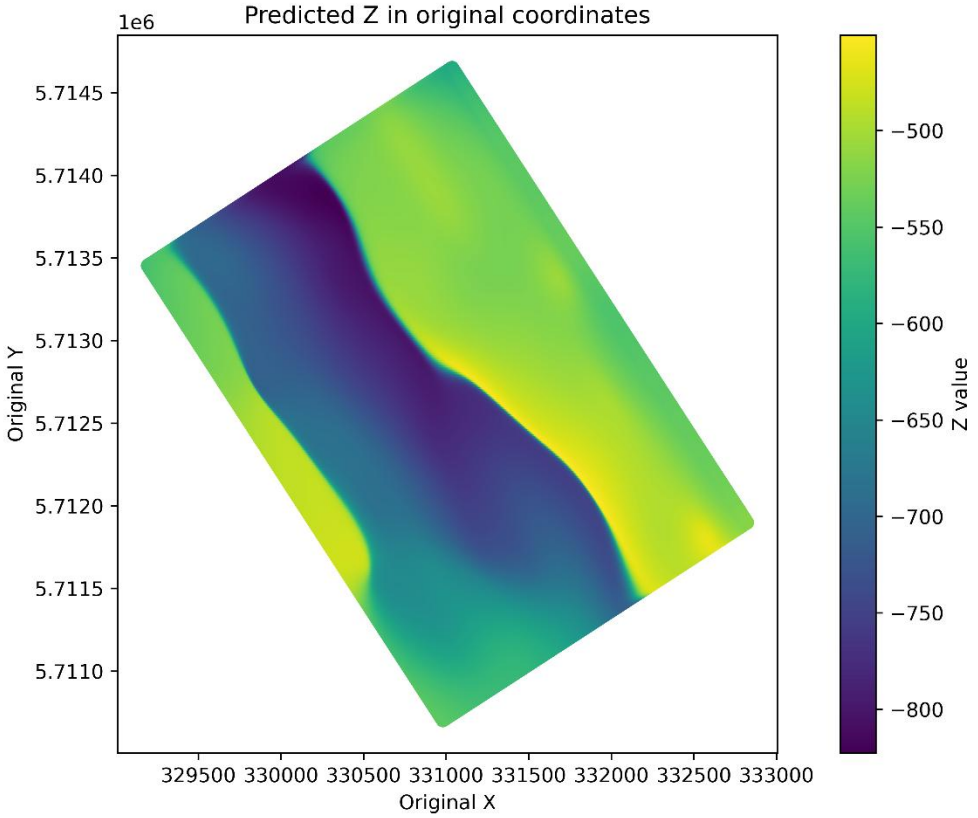
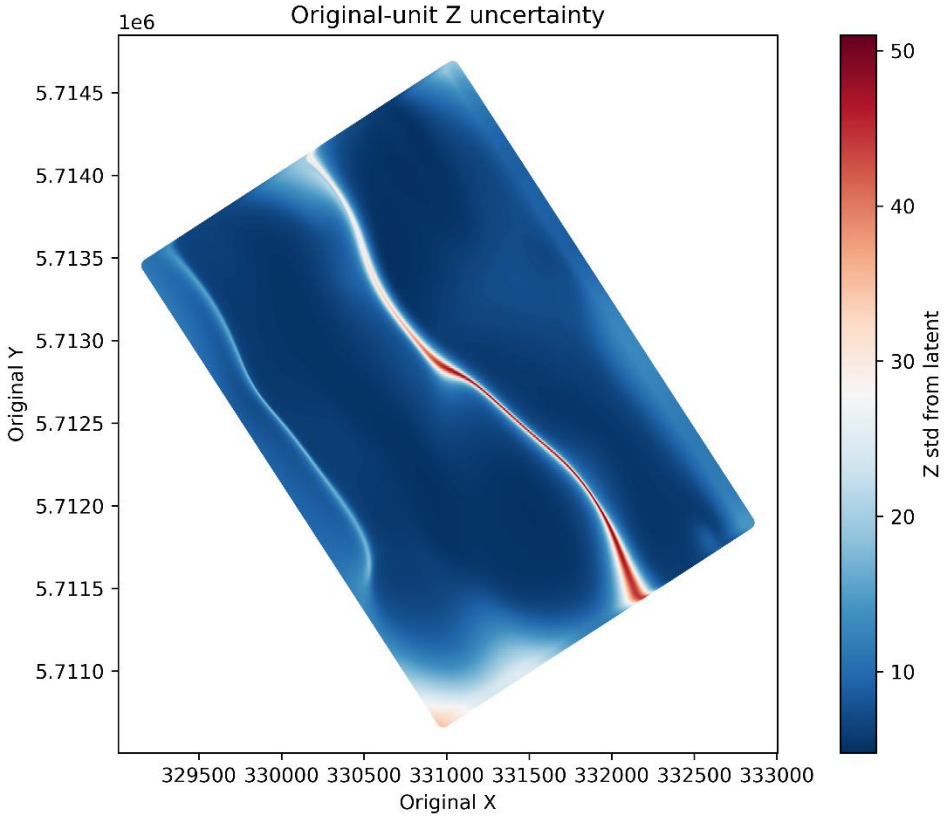
Uncertainty Map Top Karbon – Pennsylvanium Rheinberg





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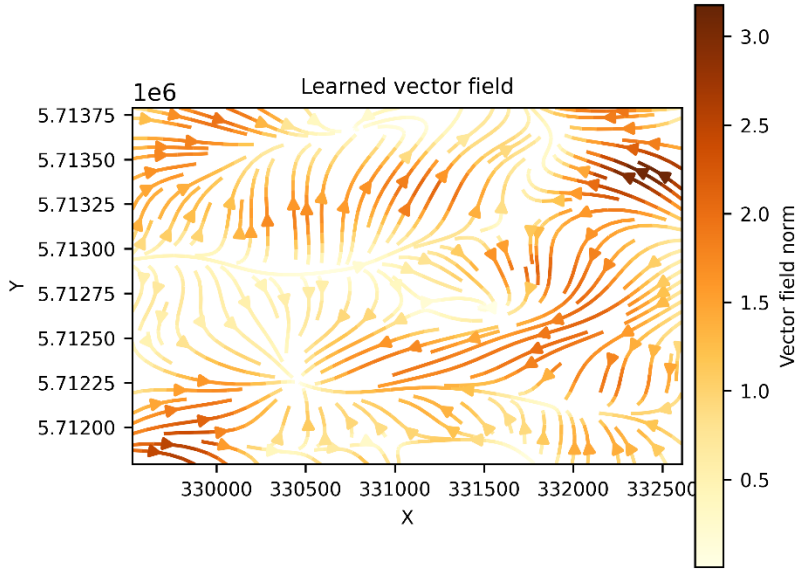
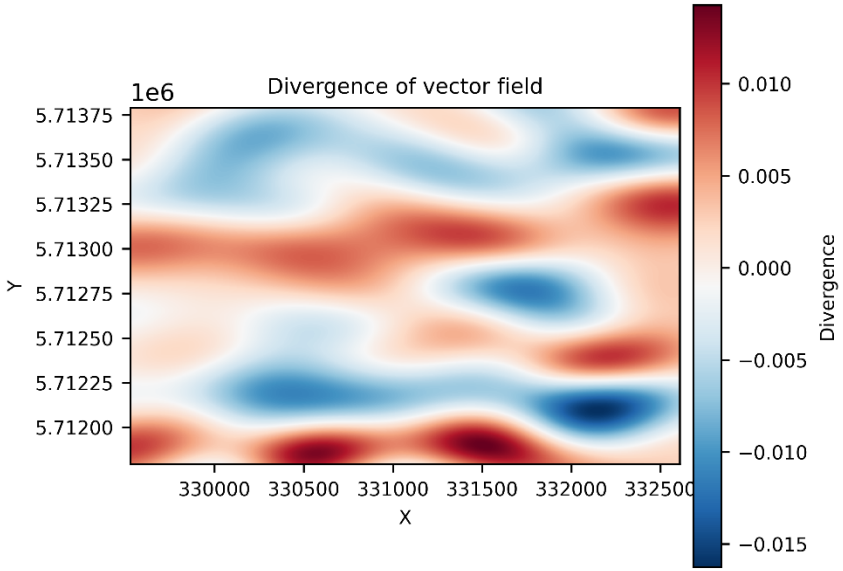
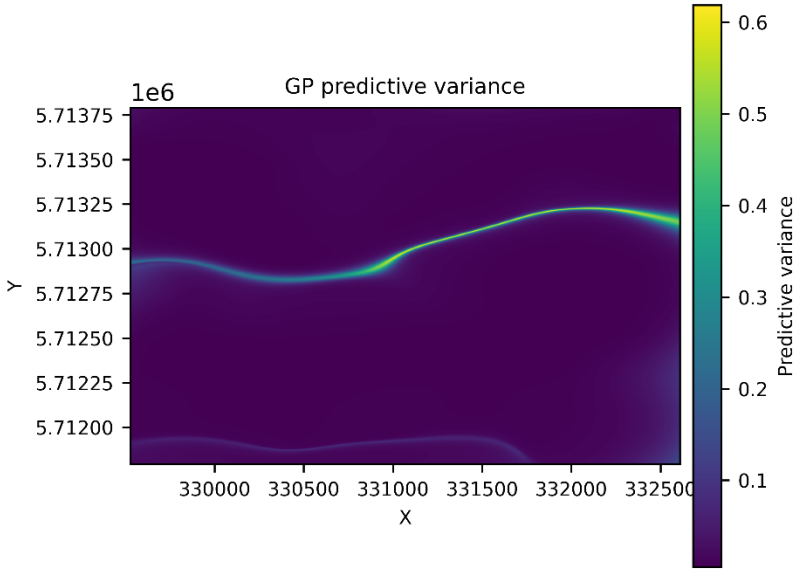
Vector Field | Divergence | Variance | Top Karbon – Pennsylvanium Rheinberg







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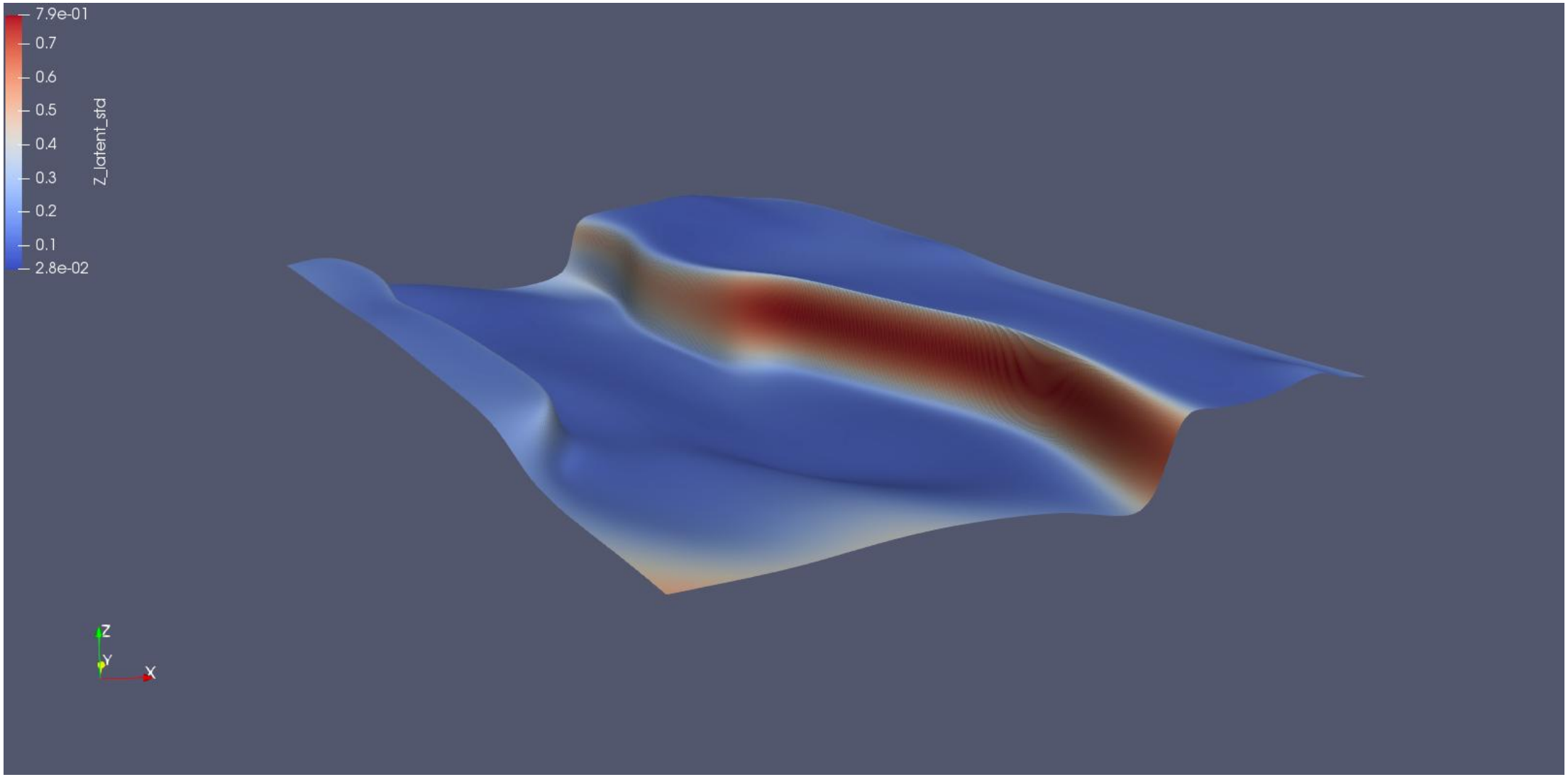
Uncertainty Top Karbon – Pennsylvanium Rheinberg



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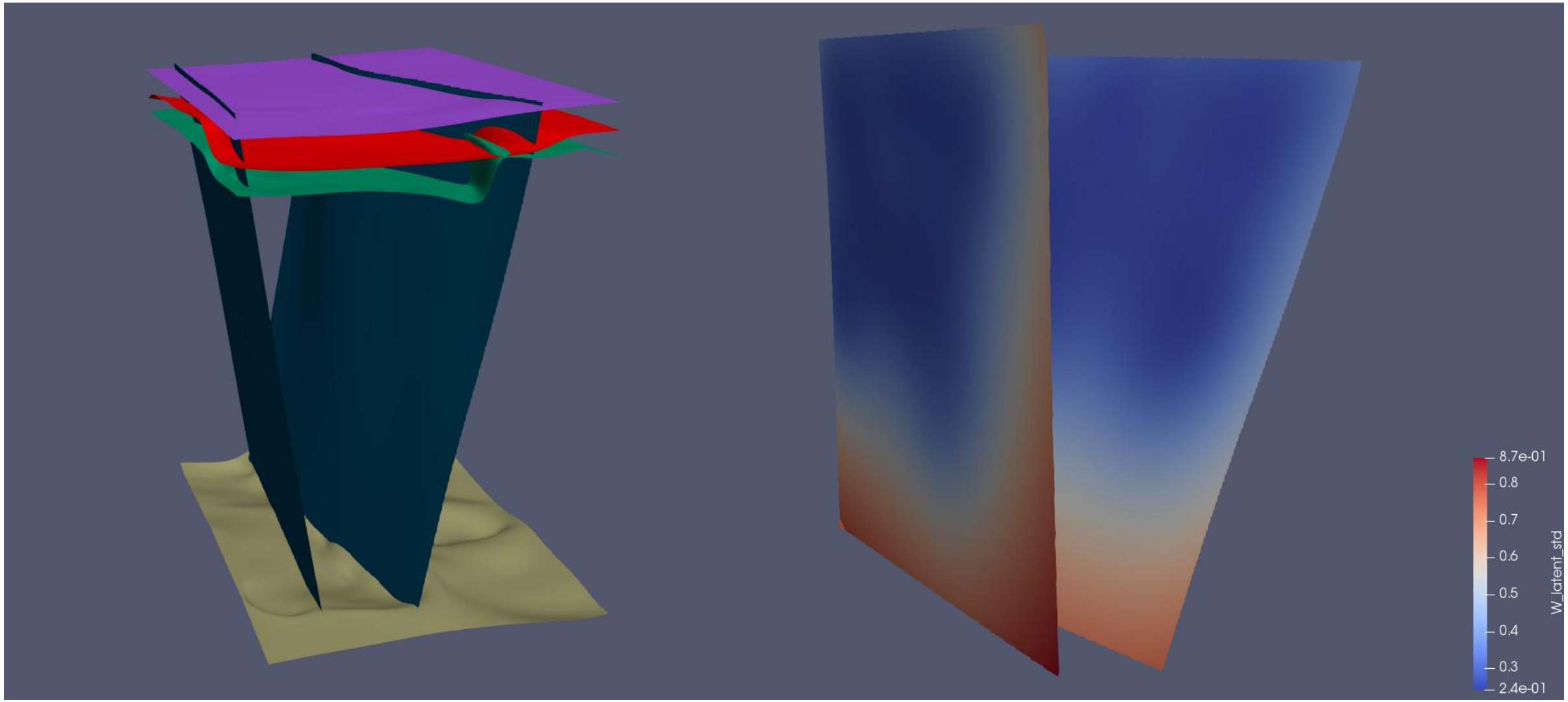
Geological Model (Surfaces) Rheinberg



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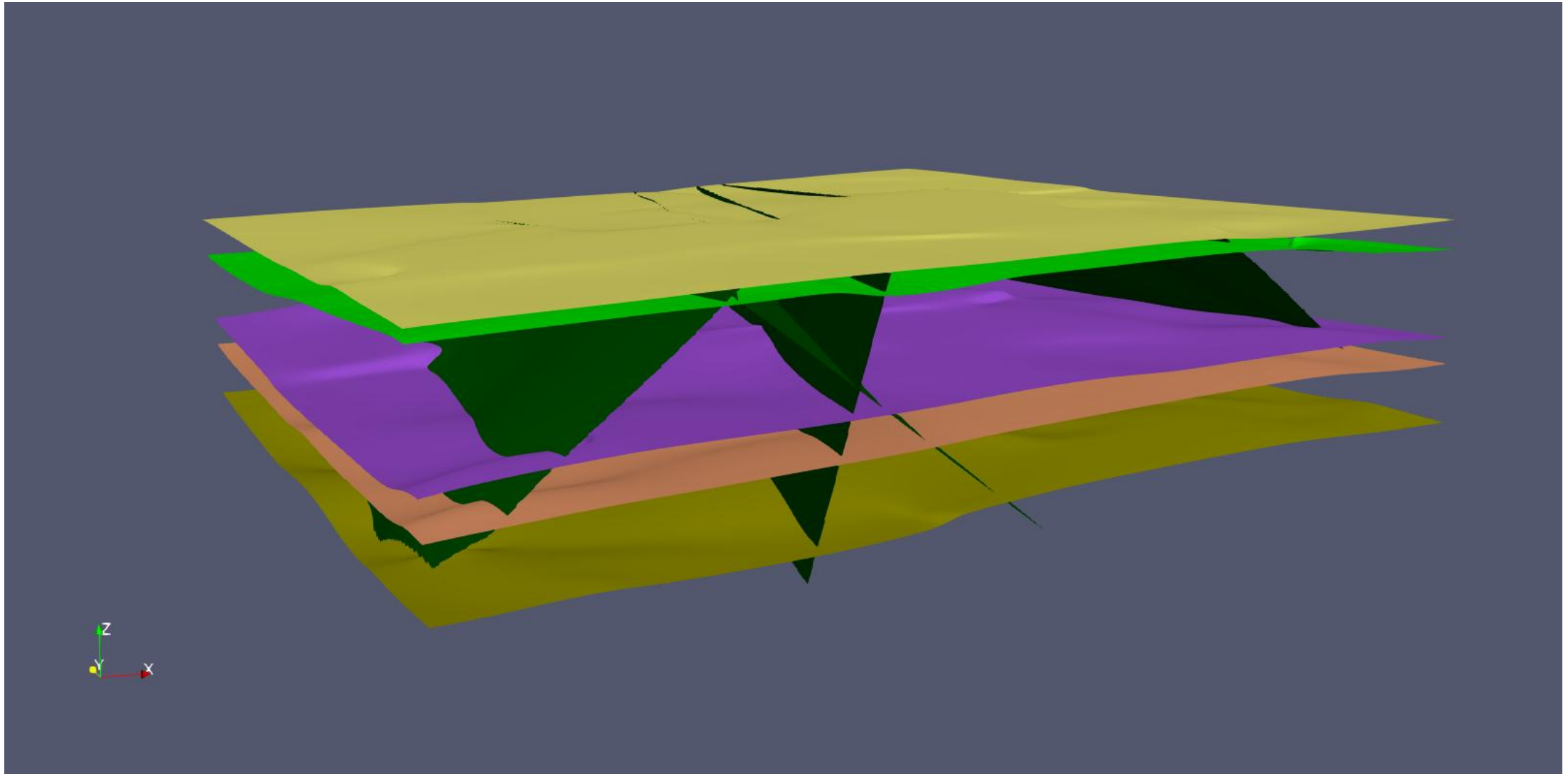
Geological Model (Surfaces) Prosper Haniel



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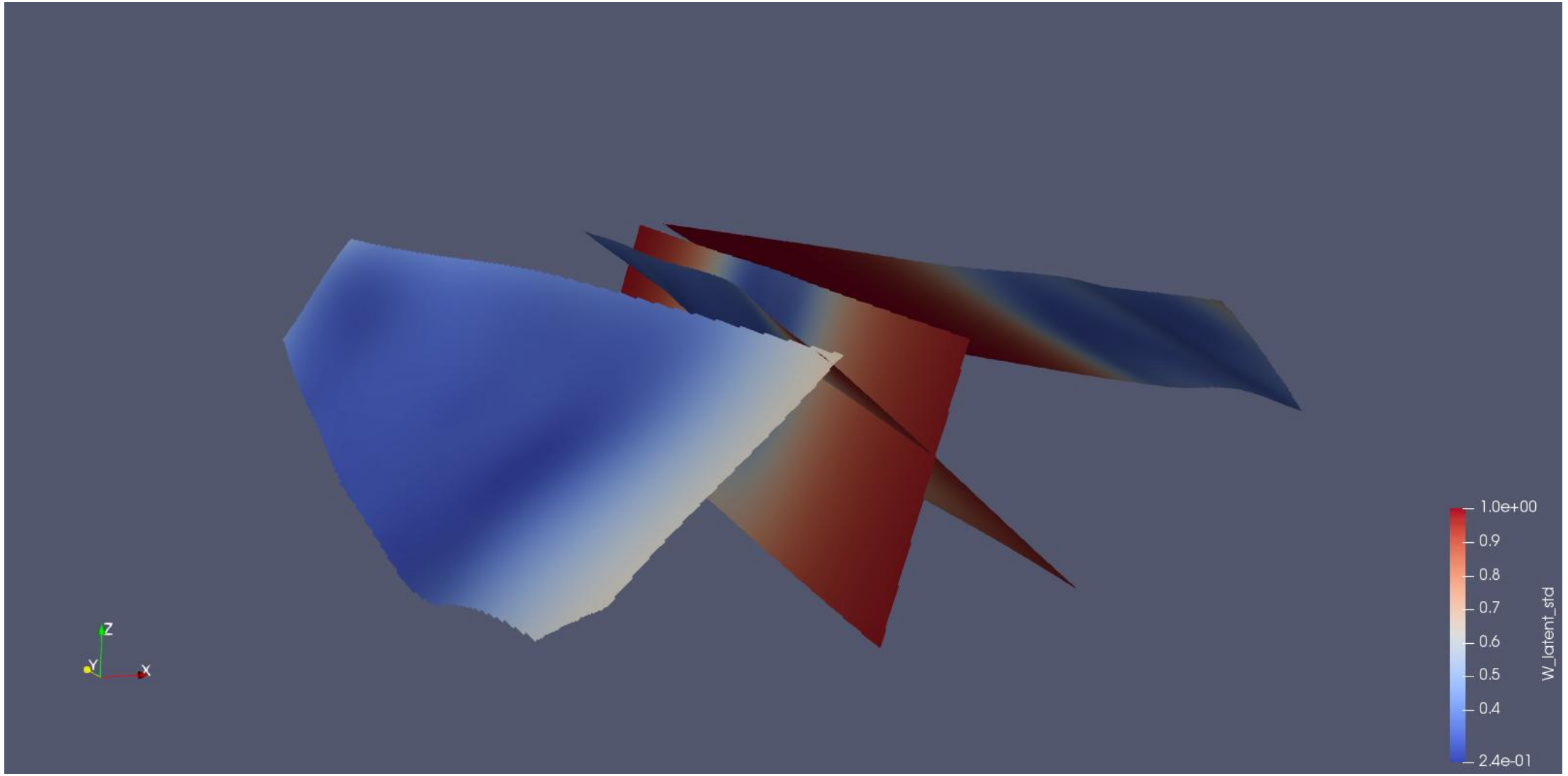

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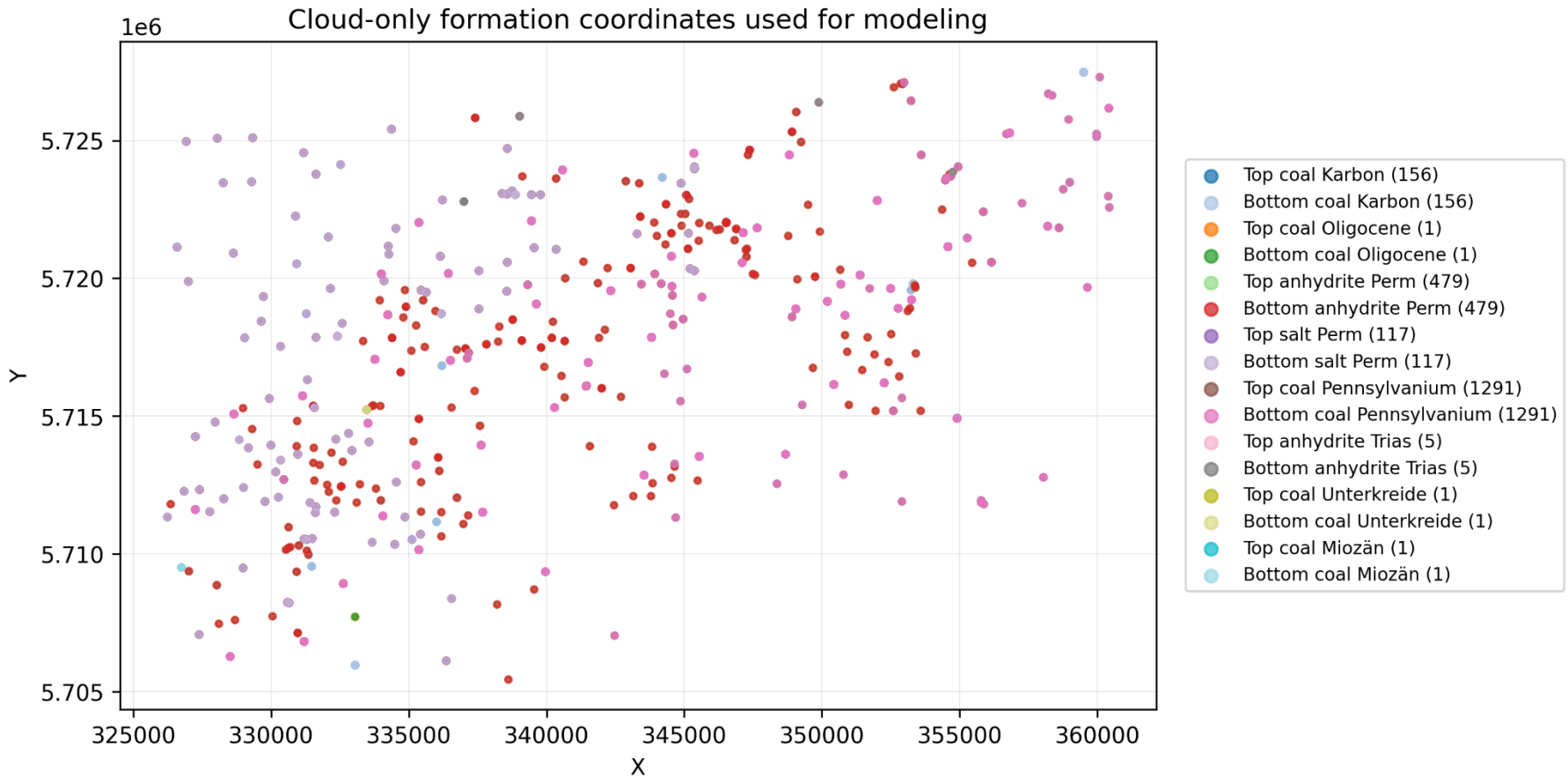
Regional Model

- 01_Bottom_coal_Pennsylvanium_uncertainty.vtp
- 02_Top_coal_Pennsylvanium_uncertainty.vtp
- 03_Top_anhydrite_Perm_uncertainty.vtp
- 04_Bottom_anhydrite_Perm_uncertainty.vtp
- 05_Bottom_coal_Karbon_uncertainty.vtp
- 06_Top_coal_Karbon_uncertainty.vtp
- 07_Top_salt_Perm_uncertainty.vtp
- 08_Bottom_salt_Perm_uncertainty.vtp
- 09_Top_anhydrite_Trias_uncertainty.vtp
- 10_Bottom_anhydrite_Trias_uncertainty.vtp



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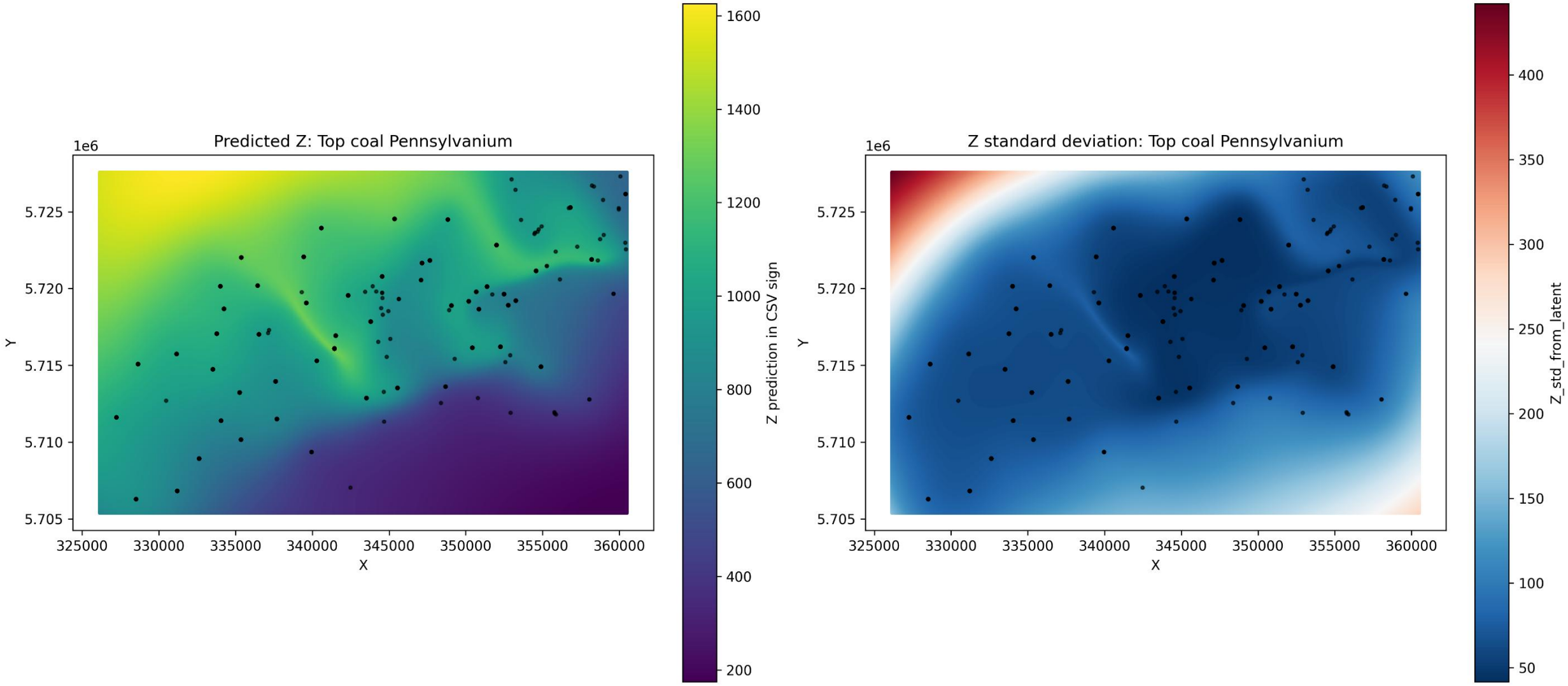
Regional Model



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Next Steps - Conferences

- Future integration with seismic attributes and full seismic cube information opens the possibility for automated geological domain segmentation and stratigraphic classification.
- Extend the methodology from single interpreted surfaces to the full 3-D seismic cube in order to incorporate volumetric spatial information.
- Implement Gaussian Mixture Models (GMMs) combined with Gaussian Process frameworks to identify and classify spatial clusters with similar geological properties.
- Manuscript VGP → Uncertainty quantification on seismic data interpretation (spatial uncertainty) + geological modeling. Compression of information (reduce to the essentials).

Contribution Details

Submission Type / Conference Track: Workshop contribution

ML-Driven Uncertainty-Aware Geological Modeling for Geothermal Exploration from Legacy Seismic Data in the Rhine-Ruhr Area **251**

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Organization(s): 1: Chair of Computational Geoscience, Geothermics and Reservoir Geophysics, RWTH Aachen University; 2: Geological Modeling Laboratory, Federal University of Pampa; 3: Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems (IEG)

Submitted by: **Daniel Satizabal (RWTH Aachen, DE)**, *ID: 3495*
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Topics: Workshop 1: FE-Vorhaben KarboEx2
Keywords: Variational Gaussian Process (VGP), Machine-Learning, Geological Modeling, Uncertainty Quantification, Geothermal Exploration.
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Abstract

The Rhine-Ruhr Area was an important coal mining area in Germany in the past century. In the times of active exploration for coal and salt, 3-D seismic datasets were acquired. Within the KarboEx2-project, these legacy datasets are digitized and reprocessed using modern seismic processing workflows to improve subsurface imaging and to support the characterization of deep geothermal reservoirs through geological modeling and geothermal simulations. In this contribution, we show how surrogate models can be employed to quantify spatially correlated uncertainties in reprocessed legacy seismic data through a Machine-Learning workflow, based on a Variational Gaussian Process (VGP) approach with inducing points implemented in the open-source Python package GeoML.

Uncertainty relates to the spatial position of the input data, which derived from the processing and interpretation of horizons on legacy seismic data. To address this uncertainty, lower-dimensional geological surrogate models may capture spatial correlations between interpretation pick points while allowing them to perform inference, sensitivity analysis, etc.

Our results show that it is possible to create surrogate models efficiently for a range of geological settings – with a balance between the dimension (input points) of the surrogate model and the level of complexity of the original interface. In addition, due to a variational approach, uncertainties in the input data are naturally propagated into the surrogate model and thus into derived geological realizations. We outline how this ML-Driven Uncertainty-Aware modeling approach can be integrated into geothermal exploration workflows, including the uncertainties in the legacy seismic data.

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Annual Conferences

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24th Annual Conference
August 23 - 28, 2026
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2nd Conference on AI for Geological Mapping and Modelling

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