Geo-Meta Ensemble Framework for Pore Pressure Prediction

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Introduction

- Critical Safety Challenge: Pore pressure prediction prevents drilling blowouts and \$10M+ losses per incident
- The Gap: Current models achieve >95% R^2 on validation but collapse to <75% on new wells [1,4].
- Our Solution: Geo-meta ensemble combining six architectures with physics-informed features and SHAP-validated geological feature importance.

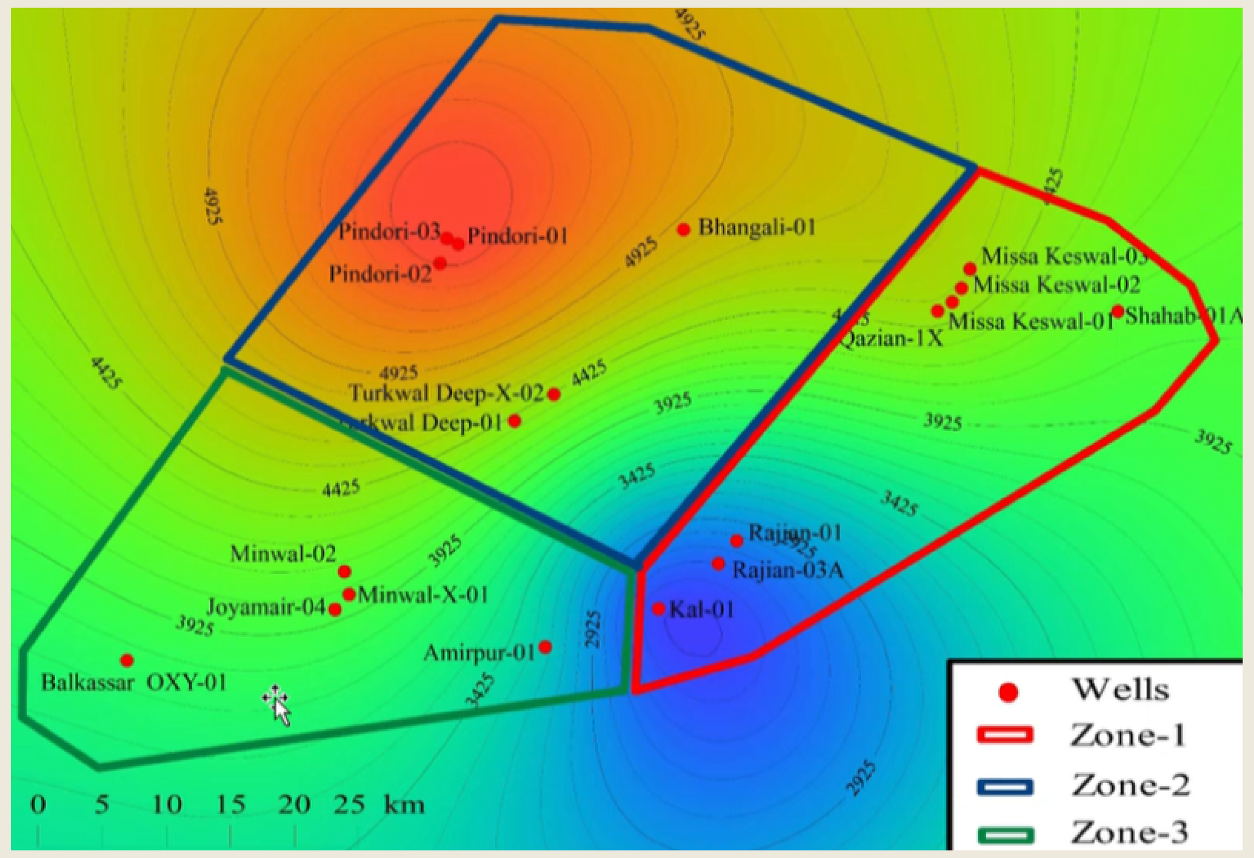

Fig. 1: Study area showing 20 wells distributed across 3 geological zones in Pakistan's Potwar Basin, highlighting diverse pressure regimes and formation heterogeneity.

Problem Statement

- Domain shift: Models fail when geological conditions change between training and deployment[2].
- Flawed Evaluation: 78% of the literature uses sample-level splits, masking true generalization failure[1].
- Class imbalance: Underpressured zones (13.8%→16.2%) poorly predicted, risking formation damage.

Methodology

- Multi-Architecture Ensemble Design: Implemented six diverse models (DFNN, CNN [2,3], RNN-LSTM, Random Forest, XGBoost, Transformer) on 294,930 samples with physics-informed features (Eaton ratio, pressure gradients)[4], after removing outliers and imputing missing values using geological constraints.
- Combined model predictions through four aggregation strategies (Simple/Weighted Average, Top-3 Models, Ridge Stacking) with data stratified by pressure regimes (normal/abnormal), while employing SHAP analysis to validate geological feature importance and ensure physically-consistent decision boundaries.

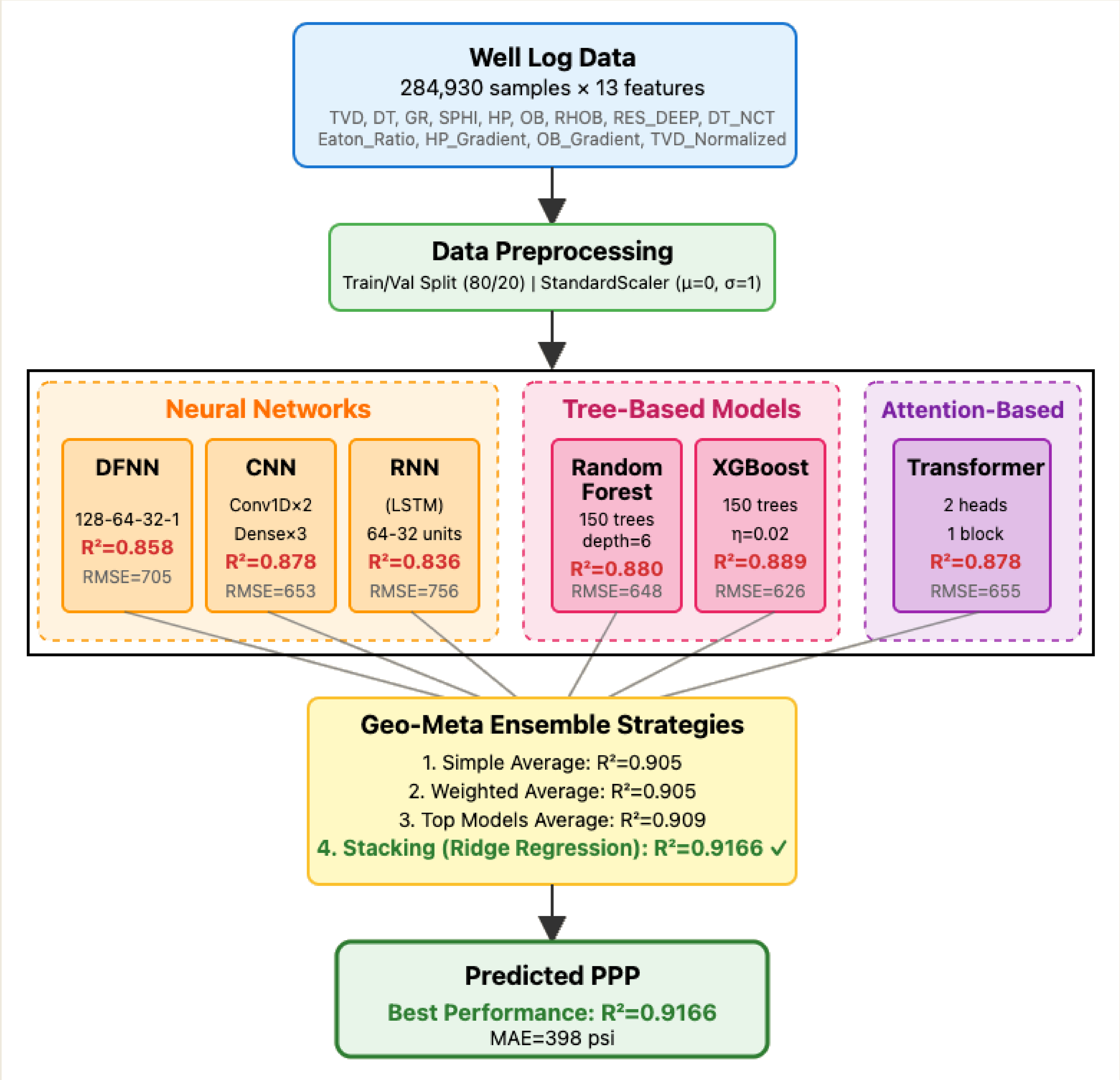

Fig. 2: Multi-architecture ensemble pipeline for pore pressure prediction: Neural networks, tree-based models, and attention mechanisms unified through Ridge regression stacking.

Results

- Achieved R^2=0.9166 and MAE=256 psi on test data (blind wells), demonstrating a significant improvement over individual base models[1,2], with the meta-ensemble leveraging complementary strengths of each architecture.
- The ensemble approach showed consistent performance across varying lithologies and pressure regimes in the 294,930-sample dataset, with SHAP confirming correct geological drivers - overburden stress, Eaton ratio[4], and gamma ray as top features, validating physics-based relationships over spurious correlations.

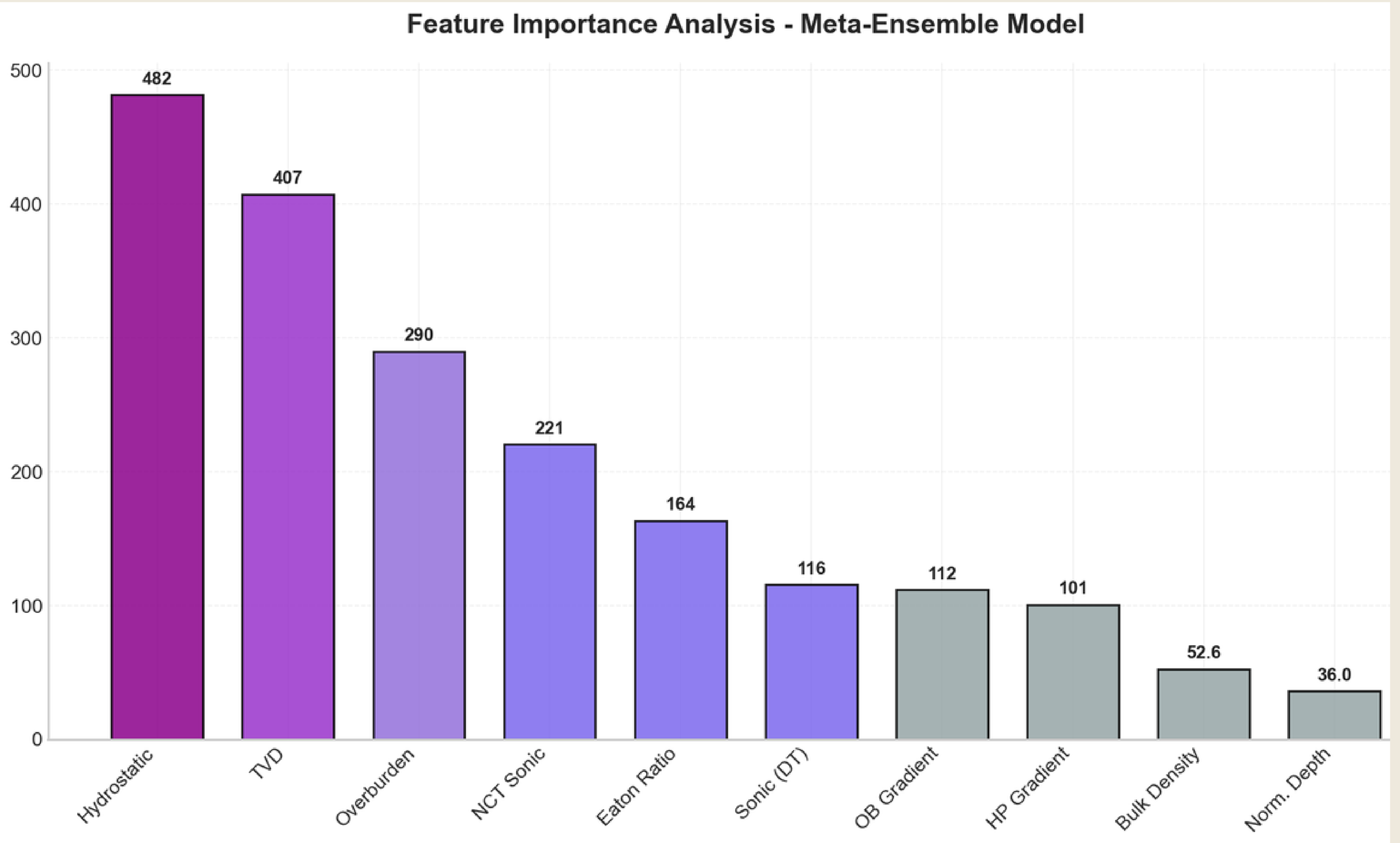

Fig. 3: SHAP analysis reveals physics-informed features dominate model decisions: Hydrostatic pressure (baseline), TVD (depth effect), and Overburden (sediment weight) account for >60% of predictions, validating geological consistency.

Conclusion & Future Work

- Achieved R^2=0.9166 on blind wells with 17.4% pressure regime shift, exposing evaluation flaws in 78% of PPP literature[1] and establishing well-based splitting as the new standard.
- Physics-Informed Real-Time System: SHAP confirms geological validity (shale-pressure correlations)[3,4].
- Expand XAI techniques beyond SHAP (Grad-CAM, LIME, attention visualizations) and look into spatial pressure prediction around drilling locations, enabling real-time geological hazard detection in adjacent formations.

References

[1] Abdulmalek Ahmed, Salaheldin Elkatatny, Abdulwahab Ali, and Abdulazeez Abdulraheem. New model for pore pressure prediction while drilling using artificial neural networks. Arabian Journal for Science and Engineering, 44(6):6079–6088, 2019. [2] Muhammad Raiees Amjad et al. Precise geopressure predictions in active foreland basins: An application of deep feedforward neural networks. Journal of Asian Earth Sciences, 245:105560, 2023. [3] Muhammad Raiees Amjad et al. Beyond the surface: Deep neural networks for subsurface pore pressure estimation. GSA Connect 2025, 57(6), 2025. [4] Glenn L Bowers. Pore pressure estimation from velocity data: Accounting for overpressure mechanisms besides undercompaction. SPE Drilling & Completion, 10(2):89–95, 1995.