Multiphysics Deep Learning for Spatiotemporal Carbon Storage Prediction Under Geological Uncertainty

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1. Introduction

Safe geological CO2 storage requires rapid prediction of plume migration, geochemical alteration, and pressure-induced deformation under uncertain geological conditions. Full coupled reservoir-geochemistry-geomechanics simulation provides physically rich information, but repeated simulation is costly for scenario screening and real-time risk assessment. This study presents an AI-enabled workflow that transforms coupled simulation outputs into standardized learning datasets and predicts CO_2 plume, pH distribution, and subsidence with uncertainty information.

2. Methodology

The workflow starts from subsurface data, reservoir simulation models, geochemical reactions, and a geomechanical model. Forty-eight coupled scenarios were generated using Latin hypercube design, well-operation parameters, permeability anisotropy, and 3D geostatistical realizations. The full simulations required approximately 96 hours. CMG-format outputs were converted into standard map-based datasets. Input features include porosity, horizontal/vertical permeability, net pay, net pore volume, and pressure; output targets include gas saturation/CO2 plume, pH, and vertical displacement. Forty-five scenarios were used for training and three unseen scenarios were retained for blind testing. GNN, CNN, and MLP models were compared and combined as an ensemble to provide mean, standard deviation, and P10-P50-P90 uncertainty maps.

3. Results and Discussion

The ensemble predictions reproduce the dominant spatial evolution of CO2 saturation, pH change, and deformation while quantifying predictive uncertainty. The highest uncertainty appears near plume boundaries and zones with strong geochemical or mechanical gradients. This behavior is important because these regions are often related to monitoring interpretation, pressure management, and geomechanical risk. The uncertainty maps therefore provide more decision value than a single deterministic prediction.

4. Conclusions

The proposed framework provides a compact digital-twin pathway that links geological uncertainty, coupled multiphysics simulation, AI surrogate prediction, and uncertainty visualization. It can reduce dependence on repeated full-physics simulations and support rapid screening of storage safety, monitoring response, and operational design for CO2 storage projects.

References

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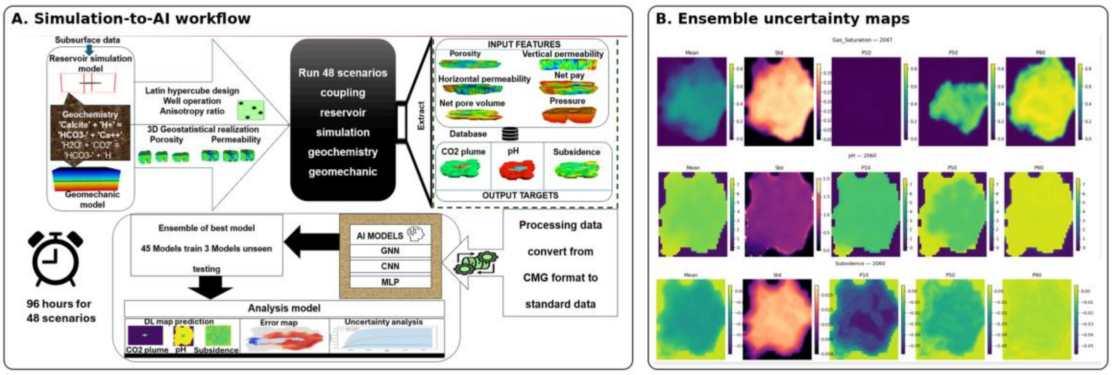

Fig. 1 Integrated workflow linking coupled simulation, data conversion, AI surrogate modeling, and uncertainty-aware maps for CO2 plume, pH, and subsidence prediction.

