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Structural Geologic Modelling and Restoration Using the Ensemble Kalman Filter

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Structural restoration using kinematic principles of fault-related folding is a valuable tool in building realistic geological models. Models are, however, typically uncertain and non-unique. While data inversion methods can be employed to find a best-fit model and estimate uncertainty, their use is limited to relatively simple models involving a single fault in two dimensions. In this work, we employ an iterative form of the Ensemble Kalman Filter (EnKF) together with a kinematic model for deformation around normal faults to build and restore three-dimensional structural geologic models. The EnKF is ideally suited to data inversion problems that involve large numbers of model parameters and is frequently used in reservoir simulations, which often do not consider uncertainty in geologic structure. We develop a workflow in which fault geometry, the distribution of slip on a fault, and the geometry of folded horizons are all modelled using the EnKF. The models are constrained by observations of faults and horizons in the present deformed state together with the expectation that horizons should restore flat. We test two modelling approaches: a restoration-based approach in which the model is built in the deformed state and then restored, and a forward modelling-based approach in which the model is built in the restored state and then forward modelled to match present-day data. We test these methods first on a synthetic model involving a single fault and then on a real-world example involving five faults. Both the restoration- and forward modelling-based methods work well for the synthetic model, but forward modelling works best for the more complex real-world case study. The EnKF method provides not only a best-fit model but also an estimate of model uncertainty. The estimation of uncertainty is, however, hindered by the phenomenon of ensemble collapse, which results in underestimation of the uncertainty in model parameters at small ensemble sizes. We employ bootstrap-based localization and covariance inflation to help mitigate this issue and use a dummy parameter to identify whether significant ensemble collapse has occurred. While ensemble collapse remains a challenge in some cases, the EnKF nonetheless shows considerable promise as a tool for building complex many-parameter structural models that are kinematically restorable, and it holds the potential for future integration of structural modelling with other EnKF-based workflows in subsurface modelling.