Loop: An Open-Source Framework for Probabilistic Geological and Resource Modelling

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Efficient and reproducible construction of geologically realistic 3D models of the subsurface is critical for the sustainable management of natural resources — including mineral exploration, groundwater, and waste storage. These models aim to represent geological structures and estimate relevant physical and geochemical properties, while also incorporating and communicating uncertainty at appropriate spatial scales.

We present the current state of the Loop project (github.com/Loop3D), an open-source, interoperable, and probabilistic 3D geological modelling platform designed for efficient and reproducible construction of geologically realistic 3D models. Loop is built around three core Python libraries:

1. map2loop automates the extraction of geological information from regional maps and prepares structured inputs for 3D modelling.
2. LoopStructural constructs structurally consistent 3D geological models using a time-aware parameterization of geological events. Events such as faulting, folding, and intrusion are represented by structural frames — curvilinear coordinate systems defined by three scalar fields that approximate the principal directions of finite strain. These frames are fitted to structural data and combined according to geological history.
3. LoopResources uses the structural frames to guide geostatistical property estimation, enabling the integration of structural controls into resource modelling.

We demonstrate the complete Loop modelling workflow with a case study, from structural model construction through to resource estimation within the structural frame. By performing resource estimation using different structural frame geometries, we explicitly propagate geological uncertainty into the resource model and observe significantly greater variability in estimated resource volumes compared to traditional geostatistical simulations. This added variability reflects uncertainty in the geometry itself — highlighting which parts of the model most influence the outcome. Incorporating these structural uncertainties enables users to identify and prioritise areas where additional data could reduce risk, offering a more informed basis for exploration and development decisions.