Modelling fluid flow in complex 3D fault networks

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SUMMARY

Faults play a critical role in controlling the movement of mineralising fluids and the resulting formation of mineral deposits. Numerical models are useful for understanding fluid pathways through faults and their host rocks. However, the heterogeneous and multi-scale nature of fault zones can make numerical modelling a challenge, and studies applied to specific locations tend to be expensive as they require custom-built models of complex 3D geometries. Here, we present a series of tools to investigate fluid flow in fault zones at various length-scales. We introduce tools to automate rapid building of 3D meshes, on which Finite Element simulations can be run efficiently. The fault core and surrounding damage zones can be modelled as flat or volumetric features, depending on their scale and permeability characteristics. We highlight the impact of these fault components on fluid flow localisation, and consider specifically three aspects of fault networks: a map of intersecting fault traces, the effect of varying dip of non-planar faults, and the impact of intersecting damage zones. The numerical tools enable rapid investigation of scenarios involving complex fault networks as commonly observed in sedimentary basins.

Key words: numerical modelling, fault, damage zone, permeability.

INTRODUCTION

Fault zones play a critical role in the formation of mineral deposits as they strongly impact the movement of mineralising fluids through the crust. The complex structures of fault zones are conceptually described by a fault core surrounded by damage zones. The damage zones are characterised by fractures at multiple scales decaying away from the fault core (Mitchell and Faulkner, 2009). These fault zone components account for the main impacts of faults on fluid flow, which can be captured from a modelling perspective by assigning appropriate permeability values.

One of the challenges with modelling fluid flow in fault zones is to account for the extreme permeability contrasts involved in geometric features with different length-scales (Bense et al., 2013). The definition of faults and fault zones is indeed large enough to include anything from single fractures to massive fault zones in the Earth's crust. It is important to note that different fluid flow behaviours can also be observed in time within the same fault zone, as the effective stress conditions evolve and faults reactivate for instance (Louis et al., 2019).

The permeability of a fault zone can be represented by a combination of permeability profiles across the damage zone and fault core. A typical profile of the damage zone would consist of fine breccia, coarse breccia, pulverised rocks, fractured rocks and intact rock far away (Mitchell et al. 2011). The corresponding permeability can be conceptually linked to the damage intensity. The behaviour of the fault core can range from an open fracture to a fluid flow barrier, for example with clay smearing. Thus, depending on the relative widths and permeabilities of the core and damage zones, the fault zone can act as a fluid conduit, a barrier, or a combined conduit-barrier system.

While the conceptual behaviours of specific fault zones might be reasonably well understood qualitatively, a quantitative analysis of fluid flow in fault networks remains a numerical simulation challenge. In this contribution, we present approaches to model fault zones at various scales using the Finite Element Method. We highlight some of the interesting impacts of fault zones on fluid flow localisation with examples inspired by fault networks in the southern McArthur Basin, northern Australia.

METHODS

We base our study on the Finite Element Method. This allows us to develop fluid flow components that can later be coupled with mechanical and thermal processes. We use the open-source REDBACK simulator (Poulet et al., 2017), based on the Multi-physics Object Oriented Simulation Environment (MOOSE; Gaston et al., 2009) and its PorousFlow module (Wilkins et al., 2020) for the modularity and ease of development it provides.

Our aim is to handle the fault core and damage zone components of each fault in a modular way at different scales (m to 100's km). At small scales it is possible to represent the fault core and damage zones as volumetric features, which can be meshed with 3D volumes in a traditional continuum manner. As the scale increases, however, the fault core becomes too small to be treated as a volumetric region. In this case, we take an equivalent discrete approach (illustrated in 2D in Fig. 1) on a conformal mesh where the fault traces form part of the mesh, but where fault cores are considered infinitely thin. We follow Lesueur et al. (2020) to impose a Darcy flow constraint across the fault core with a user-provided permeability and fault core thickness. This allows us to capture pore pressure discontinuities at low permeability fault cores without having to mesh those features explicitly. When the damage zones themselves also become negligible compared to the overall size of the model, we use a similar approach to capture the behaviours of the entire fault zone as “flat” elements within the mesh (see Fig. 1), accommodating their impact on fluid flow through constraints at the Finite Element level (Poulet et al., 2021).

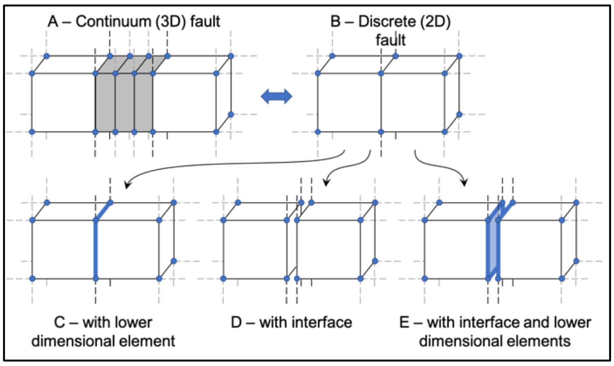

Figure 1. Various approaches to meshing a fault, modified from (Poulet et al., 2021). (a) Continuum approach to model a fault with finite thickness; (b) fault represented as a discrete (flat) surface which can be handled in the following three ways: (c) a lower dimensional element; (d) an interface between duplicated nodes (shown translated for visualisation purposes); (e) combination of (c) and (d).

Having modelling strategies in place to account for different scales of fault zone elements, we start accounting for geometrically realistic fault zones and produce 3D meshes for regions of interest. For this purpose, we developed a workflow using GMSH (Geuzaine and Remacle, 2009), along with its OpenCascade engine to handle topological operations. This step results in the generation of tetrahedral meshes from georeferenced 1D fault traces in ARCGIS format (Fig. 2). The script allows us to produce 3D meshes, with faults either considered as 3D volumes or as 2D surfaces embedded in 3D volumes, and programmatically handle the tagging of all regions and surfaces of interest, including fault intersections.

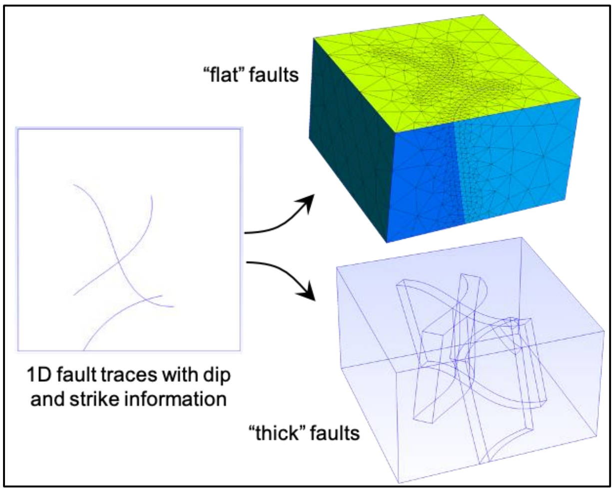

Figure 2. Illustration of building 3D meshes from 1D fault traces at the surface, along with thickness, dip and dip direction information for each fault. The faults can be represented by 2D elements (flat faults) or 3D elements (thick faults).

Subsequently, we developed a method to include anisotropic permeability within fault zones based on user-provided longitudinal and transverse permeability values, which are then transformed geometrically for each mesh element to follow the shape of the fault. The workflow considers permeabilities for each fault separately (Fig. 3). This allows us to handle fault intersections in different manners, for example by selecting the overprinting order of the faults, or potentially by implementing more complex fault intersection behaviours.

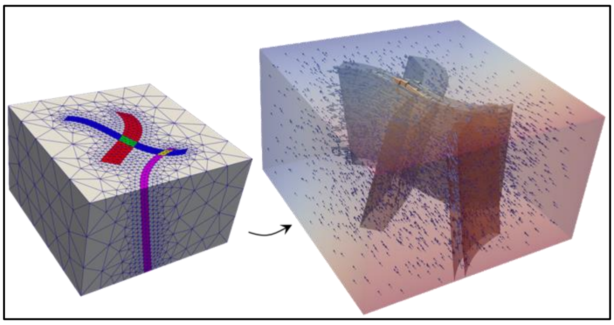

Figure 3. Example of fluid flow pathways through intersecting faults with anisotropic permeability. Overprinting relationships are represented by assigning appropriate permeability values to fault intersections.

RESULTS

The new methodology allows us to investigate fluid flow in faulted environments at different scales. Here we present three examples inspired by the southern McArthur Basin. These examples illustrate the possibilities our new modelling approach provides to address exploration-related questions.

First, it is now possible to rapidly generate 3D meshes that would take weeks to create manually (Fig. 4). This provides an interesting opportunity to study fluid flow through complex fault networks inferred from surface geology.

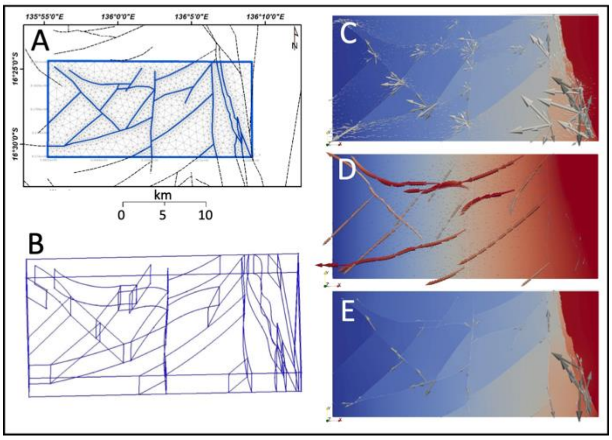

Figure 4. Example of a 3D fault network created by vertical extrapolation of surface fault traces from part of the McArthur Basin. (A) Fault map and surface mesh; (B) 3D model; (C, D, E) horizontal fluid flow through the fault network with different fault permeability scenarios: barrier, conduit and combined conduit-barrier, respectively. Contours indicate pore pressure, arrows indicate fluid flow.

Second, while fault traces are readily available from existing geological maps, information about the dip direction, dip angle and fault thickness are less widely available and/or poorly constrained. This geometric uncertainty highlights the importance of having an efficient workflow to generate new meshes representing different geometric scenarios. For example, Fig. 5 illustrates the influence of fault dip on hydrothermal fluid flow in a scenario involving three faults derived from maps of the Glyde sub-basin. In this case the faults were treated as simple fluid conduits represented by flat 2D elements.

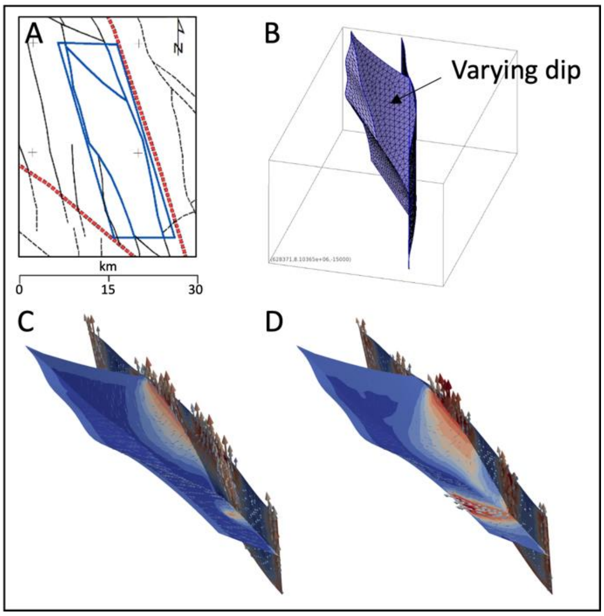

Figure 5. Effect of varying fault dip on hydrothermal fluid flow in three intersecting faults. Faults extrapolated from surface traces in the Glyde sub-basin (A). (B) 3D model showing mesh in the faults. (C, D) Hydrothermal convection in the faults with varying dip on the central fault. Contours indicate temperature, arrows indicate fluid flow.

Finally, we can now explore in detail the effects on fluid flow of two intersecting faults, and the resulting fluid flow focusing effects stemming from the damage zones themselves (Fig. 6). In this 1km long conceptual example, representative of scenarios found in the area (Fig. 4), two slightly dipping permeable layers are intersected by two cross-cutting vertical faults. Fluid flow is imposed on the right-hand side of the lower layer and the steady-state hydraulic solution shown in Fig. 6 illustrates that most of the flow focuses within the faults (green arrows), particularly at the fault intersection where the damage effects compound. A minor part of the flow within the bottom layer (white arrows) crosses through the faults and moves upwards within the damage zones on the other side. The upwards flow within the faults drags in more fluid from the upper layer (red arrows).

CONCLUSIONS

In this contribution, we described new tools to study fluid flow in geologically realistic fault networks. We showed that, depending on the scale of interest, the modelling of the fault cores and their surrounding damage zones requires various approaches to simulate fluid flow in an efficient manner at the Finite Element level. The automated numerical tools developed allow for easy generation of 3D meshes with fault zones represented by volumetric or surface elements. This provides, for the first time, the opportunity to study the effects of fault zones on fluid flow localisation due to three factors: (i) the geometrical layout of fault zones in map view, (ii) the complex geometrical intersections in 3D of non-planar faults, and (iii) the effect of intersecting damage zones.

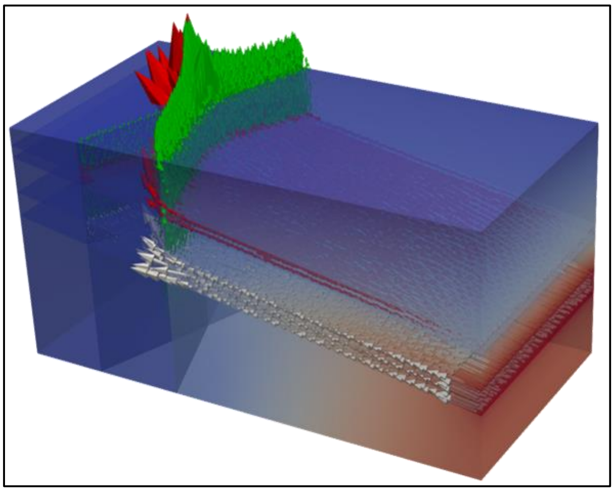

Figure 6. Fluid flow focusing associated with two vertical intersecting faults with a low permeability core and high permeability damage zones, cutting through two shallowly dipping layers with higher permeability than the remaining host rock. Arrows indicate the flow and are coloured by the geological units they are in (white in bottom layer, red in upper layer, green in fault zones).

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