FLOW SIMULATIONS OF GEOMECHANICAL MODELS OF FAULTING

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ABSTRACT
Modern geomechanical simulation techniques – based on the finite element method, and using an advanced poro-plastic material description – produce numerical outcomes that are in good agreement with experimental models of faulting processes, and that also agree with outcrop observations of natural fault damage zones. The correspondence between these independent investigation methods enables us to suggest that the geomechanical numerical simulation approach can serve as a useful proxy for reality, even though there is no way to prove that the simulation results are correct. In compensation, however, the geomechanical simulation results provide spatial and temporal information that cannot be obtained from physical models or outcrops. Specifically, the simulation outcomes contain a complete characterisation of the mechanical state at all points of a model as it evolves. Here, we show how the progressive deformed states of simulation models can be used as input to create flow simulations that enable us to examine the flow consequences of faulting. To transform the mechanical state to petrophysical properties, we develop algorithms based on the state of strain – since it is the texture of the rock that is altered by strain, and it is the same texture that controls the flow properties. Our algorithm has a primary dependence on the volumetric strain, since this determines whether permeability is increased or decreased; additional dependencies can be introduced to account for the directionality introduced by distortional strains. Single-phase flow simulations reveal how variations in the rock mechanics behaviours are ultimately expressed in terms of flow system differences. We illustrate the development of fault seals and reservoir flow barriers, and the impact of faulting on caprock seals.

INTRODUCTION
This study is part of a programme of investigations aimed at creating new understanding of the deformation processes operative during the development of fault damage zones. It is commonly observed that natural faults are not perfect slip surfaces, but, instead, have regions around the fault (damage zones) that exhibit elevated levels of deformation with

associated alterations of the petrophysical properties of the rocks. We are using geomechanical simulations and experimental studies to learn more about how such deformed regions develop as a result of the fault movement. In this paper, we will use a single model configuration to illustrate how the resulting deformed state can be interrogated to make predictions about the altered petrophysical properties that evolve during deformation events.

FAULT DAMAGE ZONE MODELS

The example selected for this paper reveals the process interactions that occur during the development of an imposed shear zone, and how a damage zone evolves from an originally uniform material. Our prototype is an experimental model that involves the shear deformation of an initially-intact rock sheet caused by the sliding of rigid blocks above and below (Fig. 1). The experiment is conducted under confining pressure, so the rock material behaves much as it would do in the subsurface (albeit that the experiment is of small size, so there is little opportunity to consider multi-scale interactions or significant internal heterogeneities). During the experiment, the rock sheet develops a localised shear zone whose width and characteristics are dependent on the confining pressure and the lithology of the rock material. In the example shown (which is typical of other experiments), the damage zone develops a nested arrangement of lozenge-shaped regions that are highly strained and lying within the overall shear zone.

It is not possible to determine the complete mechanical state of the deforming rock during the experiment. Even after the experiment is concluded, we can – at best – only determine the final strain distribution, from which we might be able to infer deformation processes and former states. In order to gain more understanding of the progressive deformation processes, we employ a geomechanical simulation approach that enables us to recover the complete history of the mechanical state throughout the simulated deformation process. The simulation tool is called SAVFEM™ (Applied Mechanics Inc.), and it is capable of reproducing the complex responses of rock materials (Couples et al 2007), including localisation, dilation/compaction, and softening/hardening. The simulation of the shear zone model reproduces the observed pattern of strain (Fig. 2).

PERMEABILITY PREDICTIONS

The similarity of the experimental and numerical models leads us to suggest that the simulation results can be used as a proxy for reality. In other words, we can use the calculated mechanical state (strain or stress) throughout the deformation process to calculate derived quantities from which additional predictions can be made. Here, we illustrate the use of the results as an input from which we calculate the deformed permeability distribution resulting from the deformation. In order to make it easier to see the relevance of the results, we simulate a comparable model in which the thickness of the layer is increased (from the experimental dimension of 5mm) to 50m. The spatial distribution of strain is essentially identical in the re-scaled model.

We all appreciate that there is a strong (but not universal) co-variance between porosity and permeability. These two properties are both dependent on the characteristics of the pore system, which we use to develop a transformation algorithm that predicts changes in permeability as a function of changes in porosity. Volumetric strain (dilation or compaction) is the mechanical equivalent of porosity change (increase, decrease). The geomechanical simulation is, in fact, based on a formulation in which volumetric strain is a key parameter (we represent rocks as poro-plastic materials), so there is a strong basis for making predictions of permeability change as a consequence of the calculated deformation.

For the flow simulations reported below, we use a simple predictor in which the non-directional permeability is determined by a factor that is multiplied by the original (un-strained) permeability of the material. The factor of proportionality is determined by simple relationships:

$$k / k_o = c\ \varepsilon_v \qquad (\varepsilon_v \geq 0) \qquad (1)$$

$$k / k_o = a\ e^{(\varepsilon v/b)} \qquad (\varepsilon_v < 0) \qquad (2)$$

where k is the new (deformed) permeability, k_o is the original (un-strained) permeability for that material, ε_v is the plastic (permanent) volumetric strain (positive values are dilational), and a, b, and c are constants that enable a calibration to specific data. As the material experiences compactional volumetric strain, its porosity decreases, and its permeability declines. Where the material dilates, it experiences an increase in permeability.

Using the prediction approach defined in Equations (1) and (2), we can calculate the deformed permeability of a shear-zone model like the one illustrated in Figures 1 and 2. The shear zones possess an *en echelon* arrangement of high-strain regions (noted above) which are characterised by mostly compactional volumetric strains, but with strongly-localised regions with high shear strains (Fig. 3). The overall zone is surrounded by a sheath of (slightly) dilated material. At earlier stages of the calculated deformation, we can see the sheaths of dilated material propagating inwards from the margins of the layer. The magnitudes of the compactional strains, and the spatial complexity of their pattern, also evolve as the deformation progresses. The mechanical state, and its associated properties (such as permeability, as illustrated here), is strictly dependent on the evolution of the deformation. It is not the case that the later deformation (or property distribution) is simply a scaled-up version of an earlier state. The non-linearities of the deformation process preclude any effort to generate a universal model that can predict the complexities at all stages of the deformation.

FLOW SIMULATIONS

Here, we illustrate the flow consequences of deformation. To increase the utility of the results, we use a similar geomechanical model, but we introduce layering within the initially-intact material. The layer contacts are mechanically welded in the example shown here, but they have contrasting material properties ("strong" and "weak" in general terms, although we do not have space here to describe the complete material characteristics; see Quijano (2004) for further information). This initial heterogeneity leads to interesting patterns in the permeability distributions that impact the flow of fluids.

The flow results illustrated here consist of single-phase simulations that use a mixed finite-element method similar to that described in Ma et al (2006; 2007). We illustrate two flow cases using the same geomechanical simulation model. In one (Fig. 4), the flow regime is associated with the breach of a caprock seal due to faulting. This model assumes that the middle layer is a low-permeability material that is separating high-pressure and low-pressure regions below and above, respectively. As the faulting occurs, the seal is progressively breached because of the dilational sheaths that develop around the main damage zone. This case illustrates an along-fault situation even though the across-fault flow would be restricted (see below).

The second case examines the situation where progressive faulting is associated with the creation of a fault seal. Here, we imagine the flow regime to represent a case with flow occurring from left to right (Fig. 5). As the shear zone develops, the flow becomes progressively restricted, and there is an increase in the pressure gradient in the region near the fault. It is important to note that the maximum flux is depicted by the same-length arrows in each plot, but that there is a major reduction in absolute value of the flux as the fault zone grows (about three orders of magnitude).

CONCLUSIONS

Geomechanical simulations, which use a modern poro-plastic material description, are capable of replicating the deformation processes operating in realistic scenarios. We assume that the geomechanical simulations can serve as proxies for reality in the case of natural deformations, for which we can observe only limited rock exposures, and only the final configuration. By developing a predictor for permeability, we can transform the calculated mechanical state to a permeability distribution, and then use that as input to flow simulations. Thus, it is possible to gain insights into how deformation can affect fluid flow, and especially, how the effects develop during progressive stages of deformation.

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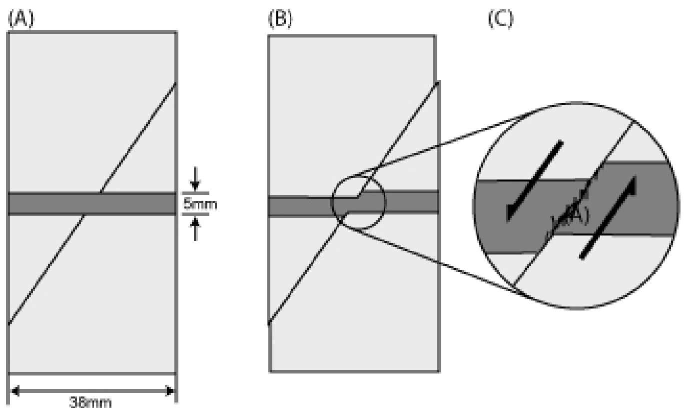

Figure 1: Experimental design for shear zone models. Radial pressure (acting outside of a jacket) establishes an initial state, then axial displacement causes steel blocks to displace. (A) Pre-deformation configuration, showing section of cylinder (light-grey steel blocks, with pre-cut, lubricated surface) and the rock disk (dark grey). (B) Configuration after shortening. The steel blocks slip and force the rock disk to deform. (C) Localised distribution of deformation in rock disk.

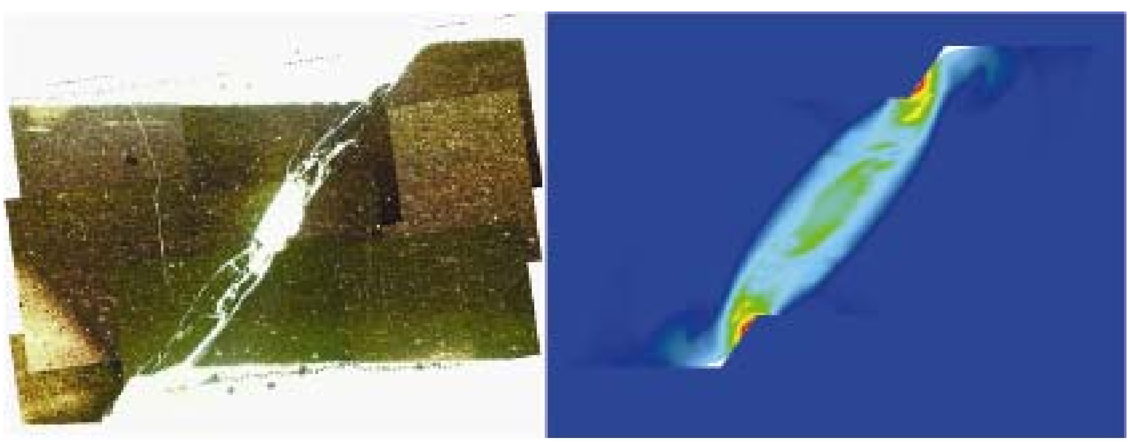

Figure 2: (Left) Composite photomicrograph of mudstone with shear zone, resulting from experimental deformation as illustrated in Figure 1. (Right) Geomechanical simulation of the experimental model. Warmer colours indicate higher levels of effective plastic strain. Note the similarity between the experiment and simulation, especially in terms of the en echelon arrangement of deformation.

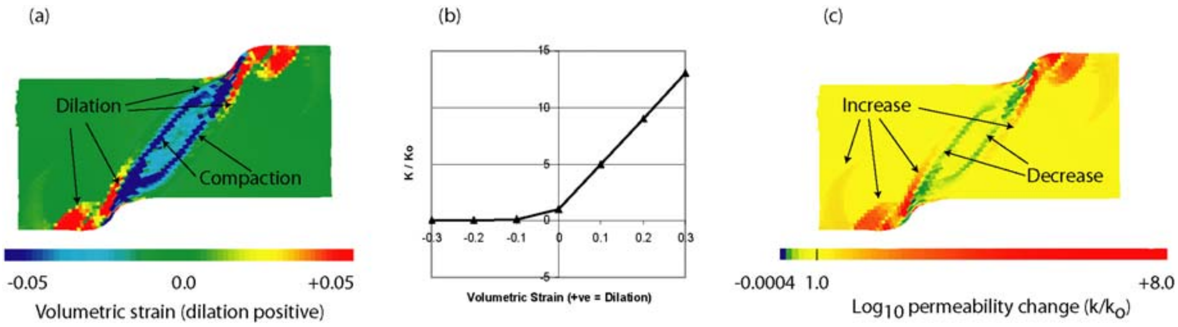

Figure 3: Volumetric strains and permeability prediction for the shear zone model.

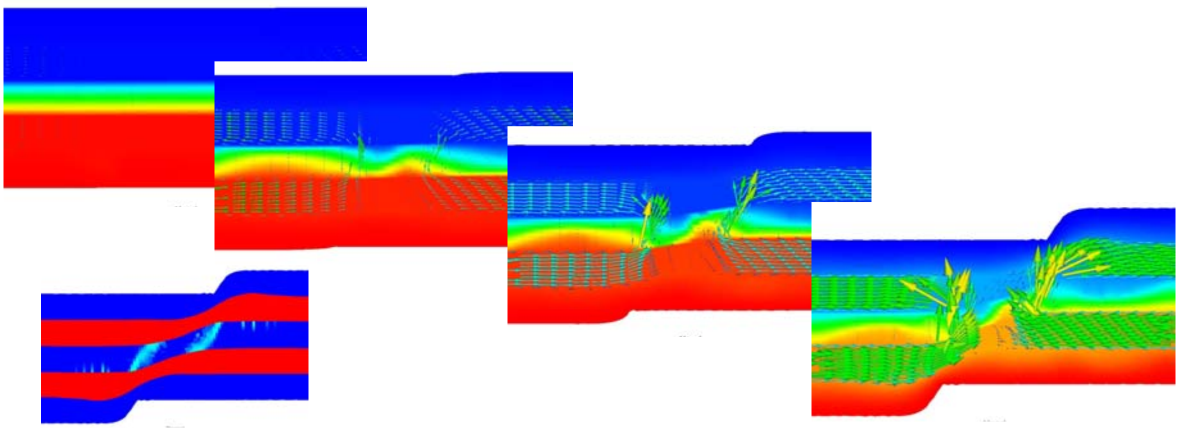

Figure 4: Sequence of flow simulation outcomes using a multi-layer shear zone model, illustrating progressive changes in flow system as shear zone develops. This flow regime addresses the breach of a caprock seal. Arrows are Darcy flux, and background colour is pressure field. Inset shows final perm distribution.

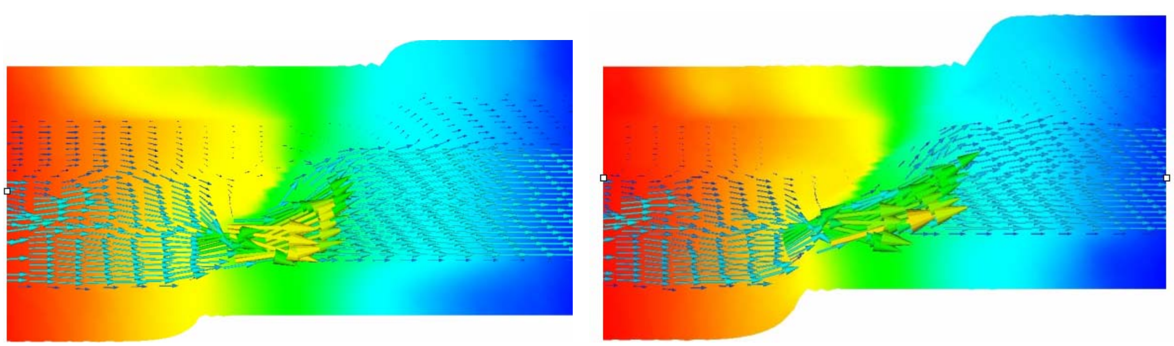

Figure 5: Two flow simulations at increasing shear offset. This flow regime is representing the development of a fault seal, with flow occurring from left to right. The maximum flux in the right image is about two orders smaller than in the left image.