E04

Emergent Distributions of Stress and Strain in Fault Damage Zones

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SUMMARY

Simulation models of faulting based on realistic poro-plastic geomaterials develop complex but well-ordered strain patterns that are very similar to those observed in natural fault damage zones. The stress states in the simulations are complex, and exhibit substantial changes during the faulting process. The material properties of the materials in the FDZs are significantly altered as the deformation progresses. None of the current approaches to predicting fault stability or fault sealing is compatible with the conditions revealed by these simulations. There is a need to re-consider the basis for making such predictions to determine where the current methods might be approximately right, and where new methods are required.

Real faults, when observed in outcrop, are usually expressed as finite-thickness zones that define a region which contains deformationally-altered fault-rock materials. Such fault damage zones often exhibit self-organised patterns of high- and low-strain components that comprise fault-parallel lozenges of rock which are arranged *en echelon* within the FDZ. Geomechanical models of FDZs, using both experimental studies and numerical simulations, reproduces similar patterns of strain, with those patterns emerging as the models evolve during accumulation of fault offset. Thus, there are strong similarities between what we observe in nature and what happens in fault models. Because of this similarity, such fault-zone models can be considered as proxies for the natural processes that we wish to better understand, and they may be able to provide information about the spatial and temporal arrangements of evolved mechanical states associated with the faulting process. Here, we summarise the main outcomes of our modelling work and the key concepts that can be derived from our geomechanical analysis of the faulting process.

The essential theme underpinning fault evolution is that rocks are geomaterials which exhibit key characteristics: their deformation behaviour is governed by mean stress; yielding (which is the onset of permanent straining) can occur in either hardening or softening modes, so mechanical properties profoundly evolve when deformation occurs; and localization (concentration of large strains into small volumes) is a typical outcome. In a geomechanical system involving a faulting process, the occurrence of localization leads to a significant alteration of the stress state, with major changes in magnitudes and orientations of the principal stresses. These evolved conditions are quite different from the oft-assumed stress states associated with faulting, which means that we need to re-consider the basis for some of the rules-of-thumb about fault sealing and fault stability.

We illustrate our main points by presenting two model configurations whose outcomes provide key insights into the faulting process. The first model is based on a single-layer of uniform geomaterial which is subjected to a shearing deformation across the layer. In response to the loading, the layer develops a complex, but well-ordered zone of deformation that contains lozenges of high- and low-strained materials whose new mechanical properties are quite different from those in the initial state (Fig. 1). Those regions which undergo softening experience a reduction in magnitudes of the stress components (and hence also a reduced mean stress), while the regions with a hardening response see increases in stress levels. The evolved strain state is also heterogeneous, with volumetric strains (associated with porosity changes) and distortional strains (mainly shearing). During the deformation of this shear zone, the stress and strain distributions are spatially complex, with significant alterations of deformation state at any particular location in the region.

The second model configuration considers a similar layer of uniform material, but with an initial discontinuity crossing it that is defined to have a classical friction response. When this model is loaded, the pre-existing discontinuity does indeed experience slip, but not uniformly. In addition, the regions adjacent to the slip surface develop fault-parallel lozenges of high- and low-strained materials similar to those that emerge from the shear zone example described above (Fig. 2). The evolved stress states around the zone are as complex as those seen in the previous model.

These two model configurations both lead to the development of an emergent region of deformation that has characteristics that are similar to FDZs as are seen in nature. We suggest that the deformation process revealed by the models can provide insights into how a natural fault might develop. We propose that a real fault would lead to important alterations of the local stress state during the deformation, which undermines the basis of predictions formulated from a Coulomb approach to fault stability linked to a perceived regional stress regime. Even in later times, when the deformation-related stresses may have relaxed, the different material stiffnesses associated with the altered materials will continue to cause local stress perturbations under any subsequent loading arrangement (even if the fault remains "dead"). The conceptual premise of stress-based predictions of fault responses is not secure.

Predictions abut fault-related fluid flow need to acknowledge the characteristics of the spatial distribution of strains. Both volumetric and distortional strains should impact on the petrophysical properties of the FDZ rocks. The expected heterogeneity of flow properties within an FDZ needs to be carefully considered in terms of how to approximate the fault effects and simplify the flow simulation, as are often required when considering reservoir-scale flow scenarios.

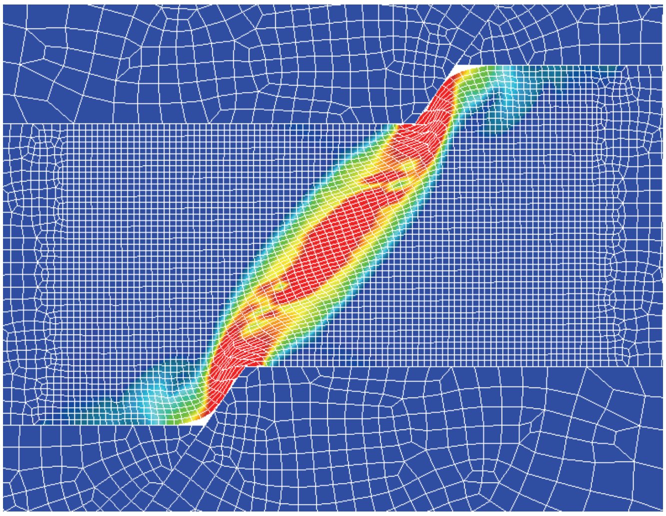

Figure 1 *Illustration of mesh and calculated equivalent plastic strain (a scalar that depends on both volumetric and distortional strain components) for a model where a shear deformation is imposed onto a previously-uniform layer (where the mesh is smaller). The regions above and below are used to cause the shear loading. Dark blue indicates no plastic strain, while hotter colours depict increasing magnitudes of strain.*

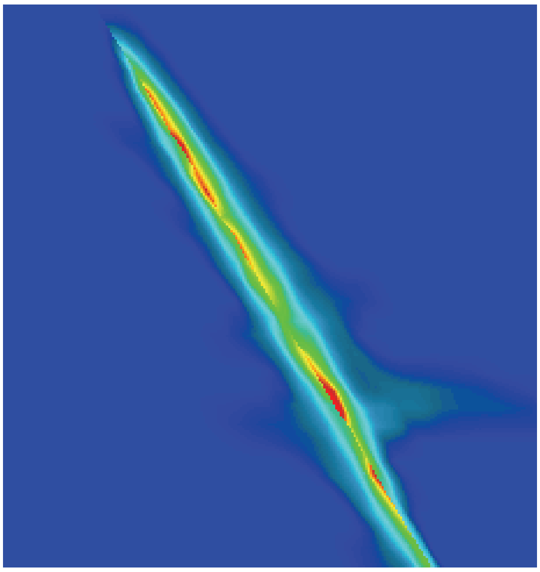

Figure 2 *Portion of a reverse-fault model illustrating the distribution of equivalent plastic strain that develops around a frictional discontinuity surface during loading of the system. Colours as defined in Figure 1.*