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Numerical Modelling of the Mechanical and Fluid Flow Properties of Fault Zones - Implications for Fault Seal Analysis

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SUMMARY

Existing fault seal algorithms are based on fault zone composition and fault slip (e.g., shale gouge ratio), or on fault orientations within the contemporary stress field (e.g., slip tendency). In this study, we aim to develop improved fault seal algorithms that account for differences in fault zone composition as well as deformation conditions under which the fault zone developed. The influence of composition and deformation conditions on the fluid flow properties of fault zones is investigated using discrete element simulations and laboratory experiments (cf. companioning paper by Giger et al.) of samples consisting of a low-permeability clay or shale layer, embedded in porous sandstone. A combination of discrete element and finite difference models is used to upscale the results and investigate the evolution of fault zone architecture and fluid flow properties of outcrop-scale faults. The fault seal algorithms are tested in a case study using finite element models of reservoir-scale faults.

The fluid flow properties of fault zones play a crucial role in exploration and production of hydrocarbons, CO_2 sequestration and geothermal energy production. The integrity of fault seals is usually assessed by analysing clay or shale content and the amount of fault slip (e.g., shale gouge ratio analysis, Yielding 1997), or by determining fault orientation within the contemporary stress field (e.g., critical stress analysis, Wiprut and Zoback 2000). Composition-based techniques for analysing fault seal integrity do not generally account for the stress field under which faults develop, while stress-based techniques do not generally account for fault rock composition. Moreover, neither of these techniques account for differences in fault zone architecture, which plays an important role in determining the fluid flow properties of fault zones (Cain et al. 1996). The evolution of fault zones and related changes in fluid flow properties depends on the interplay between fault zone composition, stress conditions, and fault slip (e.g., Fisher and Knipe 2001, Takahashi 2003). Despite the shortcomings of existing fault seal analysis techniques, both composition-based and stress-based techniques have proven to be successful in predicting fault sealing or leaking in specific field cases (Wiprut and Zoback 2000, Yielding 2002). Therefore, fault seal analysis may be improved if composition- and stress-based techniques are combined in new algorithms that take into account fault zone composition, stress conditions and fault zone architecture.

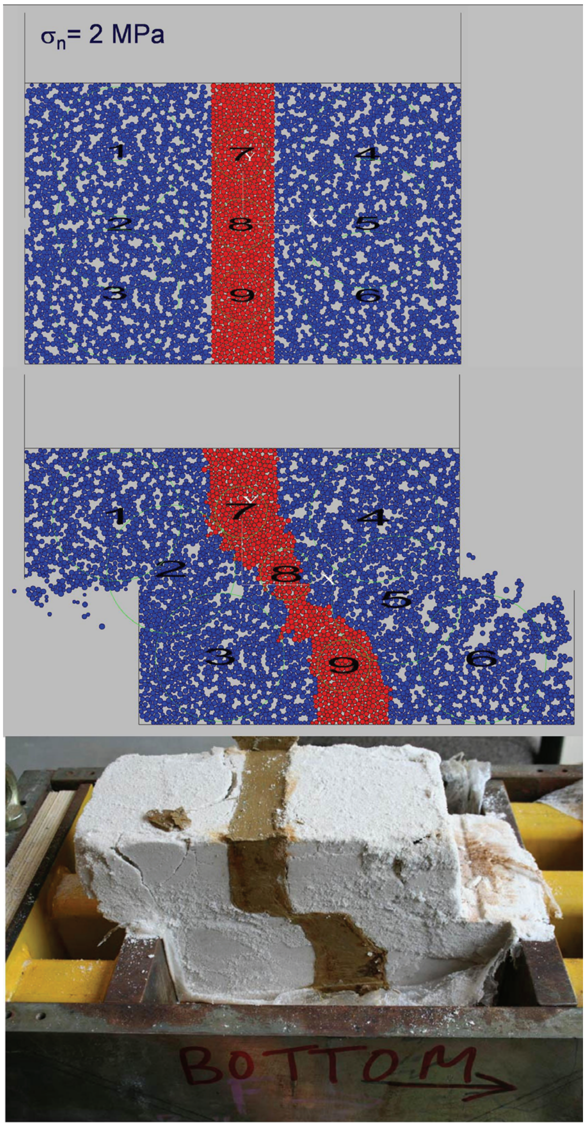

Figure 1 *Discrete element simulation reproducing the clay-smear structure produced in an analogue direct shear experiment of a sandstone-claystone-sandstone sequence.*

The aim of this study is to develop such algorithms, capable of predicting fault permeability for reservoir rocks of different composition and varying deformation conditions. The algorithms are based on fluid flow properties of simulated (sample-scale) fault zones for different compositions, stresses, pore pressures and fault displacements. A combination of micromechanical discrete element models, physical experiments and reservoir-scale finite element models is used to study changes in fluid flow properties during fault zone evolution.

In the experiments fault zone evolution was simulated by deforming large (~4-18 dm^3) sample blocks consisting of a pre-consolidated clay layer in between two synthetically cemented quartz sand layers (c.f. the companioning paper by Giger et al., this volume). The sample blocks were deformed in direct shear using a shearbox, creating a fault zone perpendicular to the sandstone-clay-sandstone layering (Fig. 1). The experiments were used to investigate the 3D fault architecture, clay smear structures, and associated fluid flow properties in detail. Two-dimensional micromechanical models were developed using a discrete element package that simulates porous rocks by stacked circular discs of different radius (Particle Flow Code).

The models allow simulation of bulk mechanical behaviour, realistic fracture development, and fluid flow in porous rock. The discrete element models are used to reproduce the experimental results, and, after calibration of the model parameters, to extend the results to a larger range of fault rock compositions, fault displacements, stresses and pore pressures. Finite difference models (FLAC) of meso-scale (outcrop-scale) fault zones with simple geometries were used for upscaling the sample-scale results and testing fault seal integrity for different production scenarios. The fault sealing algorithms were tested in a real field case using reservoir-scale finite element models.

The results show that although the discrete element models are limited to 2D, clay smear structures and mechanical behaviour observed in 2D sections through the deformed sample blocks perpendicular to the fault zone can be closely reproduced using the discrete element models. Fig. 1 shows a comparison between a 2D discrete element simulation (100 mm fault displacement, ~2 MPa normal stress) and an experiment using a pre-consolidated weak natural clay in between cemented quartz sand layers for 61 mm fault displacement. The following observations can be made based on comparison of several (direct shear and triaxial) experiments and 2D simulations: (1) Material properties (unconfined compressional strength, bulk modulus, Poisson's ratio, porosity) for the sand- and claystone are closely reproduced in the simulations, (2) clay smear structures such as local segmentation and thickening or thinning of the clay layer depend on the material parameters of the sand- and claystone and are reproduced in the experiments, (3) the stress distribution in the shearbox results in local compaction and dilation and associated variation in porosity and permeability. The differences in predictions of fault zone permeability between existing fault sealing algorithms and the new algorithms are illustrated for the field case.

It can be concluded that in order to accurately assess the integrity of fault seals, fault sealing algorithms are required that account for fault rock composition and properties as well as stress conditions. Although composition- or stress-based fault sealing algorithms both can have predictive success in some settings, algorithms that account for both composition and stress conditions are wider applicable and can better predict fault zone permeability.

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