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Fault reactivation during fluid production, modelled as a multi-physics multi-scale instability

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Abstract. During fluid production in carbonate reservoir rock under high Pressure and Temperature conditions, the production-enhanced shear-heating of a creeping fault can lead to a thermal run-away. The reactivation of the fault is then accompanied with a large increase of permeability (by orders of magnitude) due to the dissolution of the rock. As a detrimental consequence for the industry, pressure equilibrates between the two compartments of the reservoir delimited by an initially sealing fault. To model such behavior, we present a three-scale framework implementing a THMC fault reactivation model. The framework links the three different scales of the problem: (a) the poro-elastic reservoir (km) scale, where faults are treated as frictional interfaces with the equivalent friction law being determined from the meso-scale; (b) the thermo-poro-chemo-visco-elasto-plastic fault at the meso-scale (m), encompassing all the physics at hand; and (c) its chemo-mechanically altered pore structure at the micro-scale (μm), where meso-scale properties (like permeability) are upscaled. In the present approach, the multiscaling approach allows us to replace the common use of empirical laws to the profit of upscaled physical laws. The framework is used to simulate the fault valve behavior appearing during induced reactivation coming from the production scenario next to a sealing fault.

1 Introduction

Faults are critical features of many reservoirs because their potential lower permeability may induce reservoir compartmentalization. Fault behavior carries an essential aspect for the design of any energy application, from traditional petroleum and gas accumulation and production, to CO_2 storage or geothermal energy. Fault reactivation can therefore be dramatic, yet fluid production is known to induce stress changes in the reservoir that can be large enough to reactivate indeed nearby "dormant" faults (Segall, 1989). Interestingly, following the reactivation of a fault, pressure equilibration between the two sides of the fault can sometimes be observed. A sealing fault then becomes a flow path, which can provoke leakage of the reservoir into the adjacent compartment (Wiprut, 2000) or fluid invasion leading to early water breakthrough (Dos Santos, 2014). Both cases are extremely detrimental and can render a reservoir completely non-operable at engineering time-scales, irrespective of the type of application. It may also become dramatic for companies in case hydrocarbon reach the sea bottom.

The consequences of such scenarios are becoming increasingly more expensive as petroleum exploration is targeting deeper reservoirs, due to the depletion of conventional resources. Operational costs are indeed increasing rapidly with depth and understanding fault reactivation with pressure equilibration becomes an important topic. Fortunately, as temperature and pressure increase, rocks behave in a more ductile manner, making the problem more tractable from a physical perspective for some specific faults, which behavior is heavily controlled by P,T conditions and material properties, rather than geometry and heterogeneity.

In this context, we focus in this contribution on faults with mineralogies that are prone to dissolution/precipitation reactions triggered by temperature increase during slip (i.e. chemically active). In particular, we illustrate this general behavior with a case study on carbonate rocks, as a typical example of deep reservoirs in Brazil. Fault reactivation in this context can provoke an increase of permeability high enough to break the seal integrity of a reservoir. The reactivation of such chemically active faults can be modelled with the chemical shear zone model of Alevizos et al. (2014), which extends the traditional rate and state friction approach to chemically active, rate and temperature dependent ductile rocks. That theory has been successfully applied to explain the temporal evolutions of current subduction zones (Veveakis et al., 2014), as well as spatial features of exhumed carbonate thrusts (Poulet et al., 2014a), all requiring specific temperature conditions involving depths of several

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kilometres (Poulet et al., 2014a) for episodic reactivation events to take place. The same model can also lead to one-off events much more easily, in environments with much lower forces involved (Poulet et al., 2014b). Considering this type of reactivation, a substantial permeability increase can get generated during fault slip by chemical dissolution.

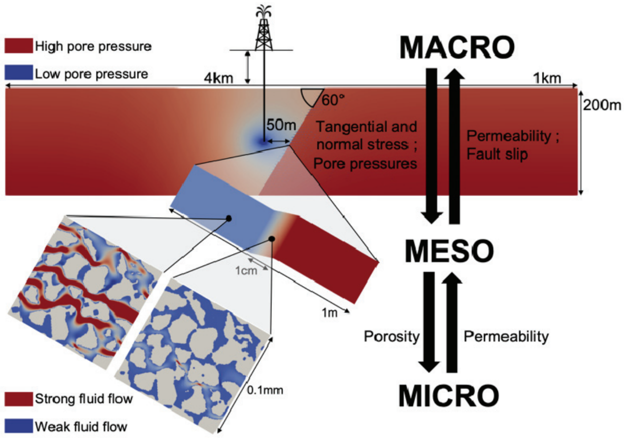

Fig. 1. Schematic of the fault's three different scales, displaying the apparent scale separation, and their couplings.

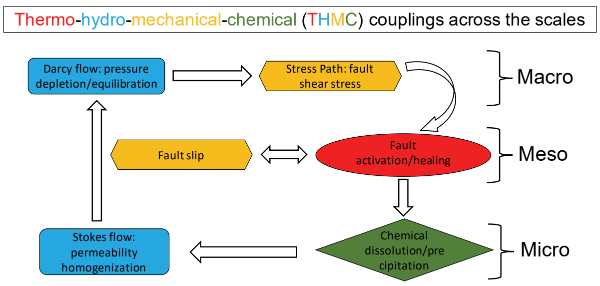

Fig. 2. Diagram showing a simplified loop of coupled scales and physics allowing for fault reactivation and healing. A blue box represents a hydraulic mechanism; yellow is mechanical; red is thermal; green is chemical.

2 Three-scale THMC framework

The physical model, which describes the fault at a meter-scale, does not take into considerations the perturbations of pressure that can affect the fault and cannot describe the fault in its entirety. To account for the role of the outer domain (reservoir) on the stresses acting on the fault, we use a multiscale approach with three scales of consideration, displayed in Fig. 1. Given the large difference of length scales between the considered km-wide reservoir and the comparatively thin fault core (meter-wide or less), a scale separation between those two coupled features is possible. The simpler reservoir system is modelled as a poro-elastic domain. The fault is treated at this scale as an interface solving for a discontinuity of displacement due to the slippage of the fault and a discontinuity of pressure due to the sealing capability of the fault. The full behavior of the fault is modelled separately from the reservoir, with the chemical shear zone model, solving for the mass, momentum and energy balance with a set of constitutive laws (Alevizos et al., 2014). In this multiscale model, the pressure depletion simulated at the reservoir-scale is transferred to the interface and applied as a boundary condition for the fault-scale system. The complex behavior of the fault is in turn upscaled into an interface law at the reservoir-scale that links the stress state of the fault to its response in terms of slippage and permeability and allows to solve for the pressure equilibration across the reactivated fault, happening in the reservoir. This two-way coupling is summarised in Fig. 1 and 2. The micro-scale (μm) is added for the refinement of the permeability evolution. The change of porosity stemming from chemical dissolution/precipitation and computed at the meso-scale is transferred to the micro-scale. An erosion algorithm is used to spatially distribute this porosity change on the 3D rock microstructure. The permeability is then upscaled to the meso-scale from the flow computation on the deformed microstructure, simulated following the methodology introduced by Lesueur et al. (2017). More details on each scale and their couplings can be found in (Lesueur et al., 2020).

The framework is simulated with the Finite Element Method. It is tightly coupled and parallel at every scale, and the scales between them are staggered, with the nested scheme being solved at every time-step of the meso-scale. The different systems of equations are solved with REDBACK (Rock mEchanics with Dissipative feedBACKs) (Poulet et al., 2017), based on the Multiphysics Object-Oriented Simulation Environment (MOOSE) (Gaston et al., 2009), a platform designed to solve highly non-linear multiphysical problem in a tightly coupled manner, taking advantage of the solver capabilities of the underlying PETSc library (Balay et al., 1997). In particular, this FE3 framework is enabled by the use of the multiapp capability of MOOSE that manages the distribution of embedded applications (called *subapps*) automatically and the transfer functions that can pass information to each *subapp*.

3 Geological Setup

We focus on the problem of a chemically active sealing fault near criticality embedded in a carbonate reservoir under extension. In accordance with the Andersonian depiction of a typical extensional setting, the fault is dipping at 60º (Anderson, 1905). The reservoir, located at four kilometres depth, measures two hundred metres in height and stretches horizontally far beyond the fault. We select therefore a zone of 1 km centred on the fault of interest. With the cap rock above and an impermeable layer below, the reservoir is hydraulically sealed at the top and bottom boundaries. In comparison to the 10% porosity and 10 mD permeability of the reservoir, the pre-existing carbonate fault act as a seal with a porosity of 3% (Sulem and Famin, 2009) and a permeability of 0.01 mD. The fault core has a thickness of several tens of the average grain size, around 1 cm (Papanicolopulos and Veveakis, 2011) and is modelled at the meso scale within 1m of its surroundings. We model the pre-existence of this fault core with a lower strength (16 MPa) than the reservoir (80 MPa). All other properties than the strength and permeability are considered identical in the reservoir and the fault. The reservoir is modelled as an elastic medium with a Young modulus of 20 GPa and a Poisson ratio of 0.2. We impose on the layer the lithostatic overburden stress corresponding to four kilometres depth and we select a vertical to horizontal stress ratio of 2.3 for the reservoir to be in the extensional regime. The pore pressure is initialised with the weight of the hydrostatic column.

Given the low background geological strain rate, we assume no lateral displacement of the reservoir during the relatively short time scale of production of a few years. This common hypothesis results in a uniaxial strain loading condition for the reservoir (Jaeger, 2007). Vertical uplift from a fault slip can propagate far away from the source, sometimes hundreds of kilometres, as Scholz (2002, Fig. 5.3) showed for the Nankaido earthquake of 1946. Since this contribution focuses on the local repercussions of the fault reactivation on its environment, we choose to model only a 1 km long section of the reservoir and the vertical slip of the fault is accommodated uniformly across the bottom boundary of the domain on either side of the fault as can be seen in Fig. 4c&d. Capturing the effects of the fault slip at the larger scale would require further specific assumptions about the fault surroundings and falls outside the scope of this generic study. The reservoir is filled with overpressurised oil, of density 0.8, at an initial pore pressure of 40 MPa. Even though the fault permeability is very low, geological times have allowed for the reservoir to equilibrate the pressure on both sides of the fault. From this initial state, we are investigating in the next section the fault reactivation scenario in the case of the production from a well drilled through the reservoir located very close to the fault.

4 Pressure equilibration induced by reactivation of deep carbonate faults

The system displays two important phases: the fault reactivation and the deactivation/healing.

4.1 Production-induced fault reactivation

We consider a production well located at 50 m from the fault, as seen on Fig. 1. Initially, the pore pressure is equilibrated on both sides of the fault, despite its low permeability. The simulation starts when oil production begins from the well with a prescribed flow rate. Initially, the pressure starts decreasing on the left compartment of the reservoir only, as the fault acts as a seal. Fig. 4a shows the undisturbed pressure distribution across the fault at this early stage of production.

This decrease in pore pressure can potentially lead to fault reactivation, under certain conditions linked to the stress path followed during production and material properties, which can easily be understood with a simple analytical approach. Following the uniaxial strain conditions of the setup considered, known to match field observations of reservoir stress paths (Engelder and Fischer, 1994), the evolution of shear stress $\Delta\tau$ in elasticity can be analytically computed from the variation of pore pressure Δp_f as $\Delta\tau = -\Delta p_f \frac{1\text{-}K}{2}$, with K=$\frac{\Delta\sigma_H}{\Delta\sigma_V}$. This ratio K was introduced by Teufel et al. (1991) to characterise field observations of reservoir stress paths and is expressed as K=$\frac{\nu}{1\text{-}\nu}$. For the common model of Coulomb failure criterion used to describe the reactivation of faults, $\tau = c + \mu(\bar{\sigma} - p_f)$. Therefore, if $\frac{1\text{-}K}{2}$ is superior to the friction angle of the fault, then reactivation will ultimately occur (Nacht et al., 2010). Our scenario falls under such a case where the shear stress non-intuitively augments with production as pore pressure drops, as seen on Fig. 3b before point A.

The fault is initially in a creeping regime, with negligible displacement rate at engineering time scales, yet produces heat from internal friction. The increase of shear stress/heating leads eventually to thermal runaway (Regenauer-Lieb and Yuen, 1998), passed a critical value. The sudden increase in temperature from the fault reactivation triggers a calcite decomposition reaction which dramatically increases the permeability of the fault, allowing pressure equilibration between both sides of the fault. The thermal runaway is capped due to the endothermic nature of the chemical reaction (Veveakis et al., 2010; 2017), which stops the temperature instability and keeps the fault in a stable, activated state. The reactivation of the fault happens around t≈500 days, jumping between points A1 and A2, on the transient evolution of pore pressure, fault permeability, slip and shear stress plotted in Fig. 3. The permeability increase leads to a loss of sealing capability of the fault and lets fluid invade the reservoir. Consequently, the pore pressure on the left-hand side of the fault suddenly jumps (see Fig. 3a), as a result of pressure equilibration to a lower differential across the fault.

4.2 Fault deactivation and healing

The slippage of the fault results at the macro-scale in a horizontal elastic relaxation of the reservoir. Indeed, in the context of a normal fault, with the reservoir in extension, the fault slippage results in the hanging wall moving downwards. Due to the fixed lateral boundaries of the reservoir, this movement translates in a shortening of both compartments of the reservoir, relieving part of the extensive stress of the reservoir. This stress drop tends to bring back the fault towards a deactivated state, competing with the pressure depletion which keeps it activated. Given the difference of rates of those two processes, with pressure diffusing much slower than the fault slips, the stress decreases faster than the strain rate increases. This relaxation decreases the shearing stress at the fault, which corresponds to tracing downwards the highest branch of Fig. 3b from the reactivated state (point A2). After a sufficient decrease, the stress reaches a low enough value (point B1) where the fault cannot remain in its activated state and returns to the lower branch of the S-curve (drop from point B1 to B2). The temperature and slip velocity return to their initial value and the fault goes back to its initial slow creep regime. Correspondingly, the permeability goes back to its initial low value (see Fig. 3d) as the reversible temperature-activated calcite decomposition reaction switches from forward to reverse direction. The chemical dissolution responsible for the large increase of permeability gives way to its opposite reaction, which heals the fault by precipitating calcite at its core.

For the generic scenario selected, the whole reactivation event lasts for 250 days. Note the small thickness of reservoir leads the slip to propagate to the limits of the domain and the whole reservoir therefore accommodates the same vertical displacement jump as the fault. The fact that the reactivated fault splits the whole reservoir leads to an artificially increased period of slip. Considering a much deeper section of the reservoir, as well as its 3D nature, would be required to model appropriately a more precise duration of the whole slip event. This example illustrates nonetheless the ability of the approach to capture the physical couplings responsible for the activation, permeability increase and deactivation. Note that in any case we do expect a longer opening compared to a brittle fault slip, as it is an important characteristic of ductile faults, along with the aseismic nature of the slip.

5 Conclusions

With more than half of global gas reserves held in carbonate reservoirs, chemical fault reactivation represents a major case study that will only become more relevant as reservoir operations are getting increasingly deeper. The chemical shear zone model incorporated in our multiscale framework showcases the possibility of fluid invasion across a reactivated fault that could happen during production of deep carbonate rocks. The fault behaviour at such temperatures can be explained predominantly by the physics of the processes involved, contrary to shallower brittle fault where geometry and material heterogeneity control the behaviour of brittle failures. This allows our model to be more predictive towards the detection of fault reactivation and this study showcases the importance of monitoring for example the temperature of deep faults. The consideration of the micro-scale in the multiscale framework comes as an effort to link the field of data-driven science to physics-based modelling in the sense that the microstructural data, collected to characterise rock properties, is used quantitatively for physical modelling in this contribution, in a dynamical hydro-chemical simulation to simulate the transient evolution of permeability with deformation.

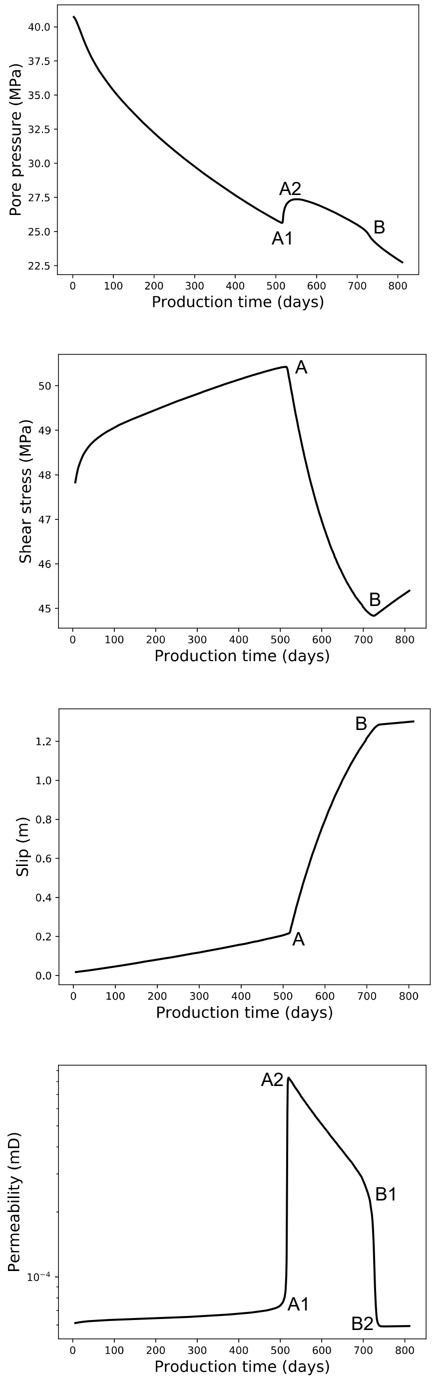

Fig. 3. Outputs of an event of chemical fault reactivation induced by reservoir production, following the setup of Sec. 3.

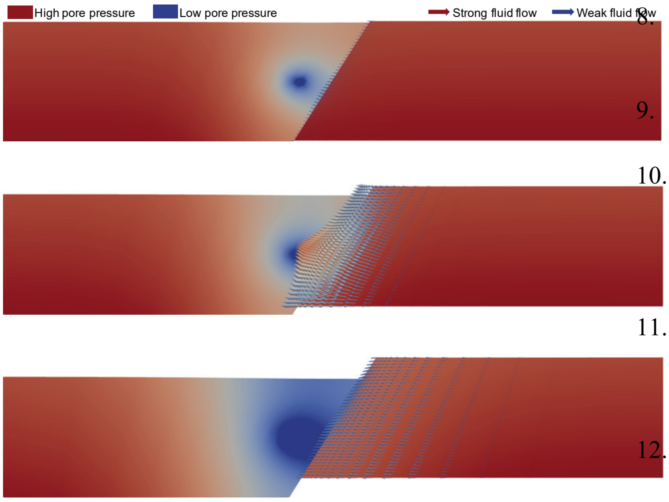

Fig 4. Pressure distribution in the reservoir and fluid velocity in the right-hand-side compartment at different times during the reactivation event. The arrows size is proportional to the magnitude of the fluid velocity. Displacements are magnified by 30 times for visualisation purposes. The effect of the reactivation and corresponding permeability increase is observed on the pressure depletion across the fault.

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