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Quantification of fluid migration via faults requires two-way coupled hydromechanical simulations

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Abstract

Subsurface storage of fluids triggers pressure and volume changes in reservoirs, caprocks and faults. In this context, hydraulic fault conductivity can increase by several orders of magnitude, promoting upward migration of reservoir fluids into shallow freshwater aquifers. In the present study, we compared one-way and two-way hydromechanical couplings to quantify the impacts of subsurface fluid storage on fluid migration via a fault. Our simulation results emphasize the requirement of two-way coupled hydromechanical simulations, since neglecting petrophysical changes in the one-way coupling leads to an underestimation of fault pressure gradients, and thus fluid migration.

Keywords: Subsurface fluid storage; fault fluid migration; fault reactivation; hydromechanical simulations; one-way coupling; two-way coupling

1. Introduction

Utilization of the geological subsurface for greenhouse gas storage is practiced for many decades worldwide at pilot- to industrial-scale, e.g., [1-3], and is likely to become even more important in the near future to meet current climate and energy policy objectives [4]. However, fluid injection into the subsurface, e.g., into a saline aquifer for long-term storage induces pressure elevation, and thus spatial and temporal changes in the recent stress field. These in turn can adversely affect the mechanical behavior of reservoirs, caprocks and faults. Effective stresses altered by

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pore pressure changes in a fault and its vicinity can facilitate fault slip and dilation, and hence enhance or establish new hydraulic flow paths for formation fluids as a result of porosity and associated permeability increases [5-7]. In the present study, we set up a 2D structural model based on the geology of a prospective storage site in the German Federal State of Brandenburg, and applied one-way and two-way hydromechanical coupled simulations to assess the impacts of geological subsurface storage on fault integrity and fault fluid flow (Fig. 1).

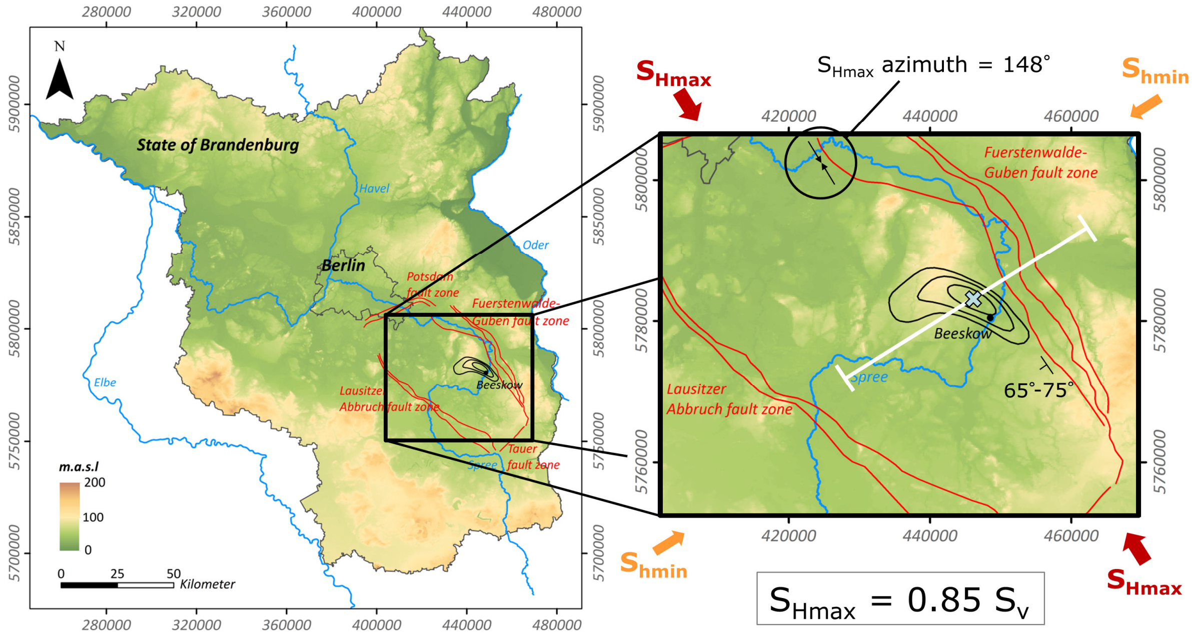

Fig. 1. Model set up based on a prospective storage site in the German Federal State of Brandenburg (left). White cross-section in the right figure indicates the extent of the 2D structural model used in our coupled hydromechanical simulations. Fluid injection (white cross) occurs into the top of a Mesozoic anticline structure (outlines indicated). Maximum horizontal stress orientation is derived from wellbore breakout analyses at the Fuerstenwalde-Guben fault zone [8]. A classical normal faulting regime was assumed in all simulations. Axis labels show UTM-coordinates (spatial reference: EPSG projection 32632 - WGS84 / UTM zone 33N). National borders, isolines and rivers derived from [9], digital terrain model from [10].

In both coupling approaches, two independent simulators calculate either fluid or rock dynamics, whereby the information exchanged between both depends on the chosen coupling method. Our one-way coupling implementation considers pore pressure changes calculated by the flow simulator as input to the hydromechanical simulator to determine effective stresses and calculate grid point velocities. In our two-way coupling implementation, the flow simulator receives a feedback from the hydromechanical simulator in case of altered hydraulic properties due to volumetric strain increments [6, 11-13]. One-way coupled simulations generally reduce the complexity of the computational implementation; however, hydromechanical effects on fluid flow are likely to be underestimated without taking into account mechanically induced porosity and permeability changes, affecting fluid flow and pore pressure propagation.

2. Model setup and parameterization

The 2D structural model used in our coupled one-way and two-way hydromechanical simulations has a total lateral extent of 40 km and a thickness of 5 km. It is set up along a cross-section in the southeastern part of the Federal State of Brandenburg, running through the top of a Mesozoic anticline structure and perpendicular to the Fuerstenwalde-Guben fault system, representing a major fault system in this region (Fig. 1). The model consists of five geological units, including one saline storage aquifer (Detfurth Formation in the Middle Buntsandstein), an overlying secondary aquifer (Lower Muschelkalk) as well as basement and caprock units. Further, it comprises the anticline structure with the injection well location at its top at 1,090 m depth as well as one fault zone, representing the fault segment of the Fuerstenwalde-Guben fault system lying closest to the well location at a distance of 4.5 km (Fig.1 and Fig. 2).

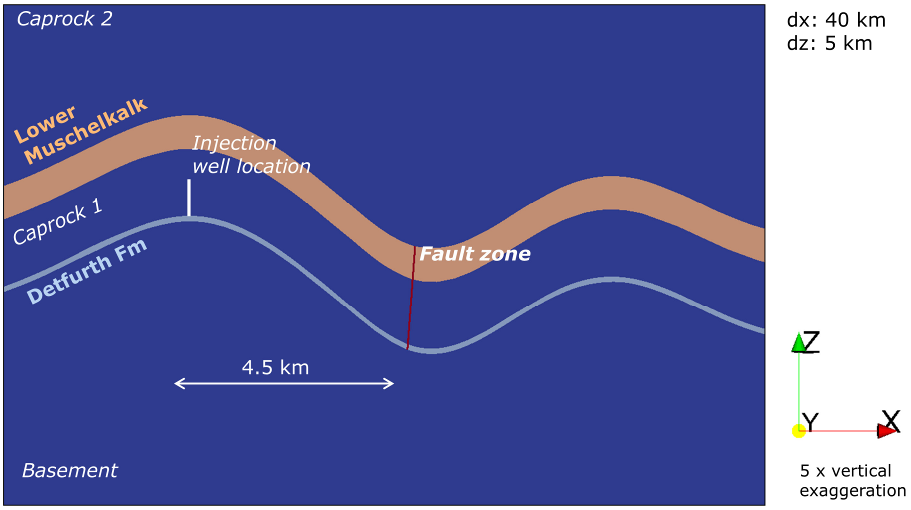

Fig. 2. Section of the structural 2D model applied in both coupling approaches. The model comprises an anticline structure and one fault zone at a distance of 4.5 km to the injection well.

We assume that the fault connects the storage aquifer with an overlying secondary aquifer, enabling fluid migration from the Detfurth Formation into the shallower aquifer (Lower Muschelkalk). According to Sedlacek [14], maximum allowable pressures in porous aquifers in Germany are determined by a gradient of 1.65 bar / 10 m (Fig. 3). Hence, bottomhole pressure is not allowed to exceed 180 bar at 1,090 m depth during the entire injection period in both coupled simulation approaches.

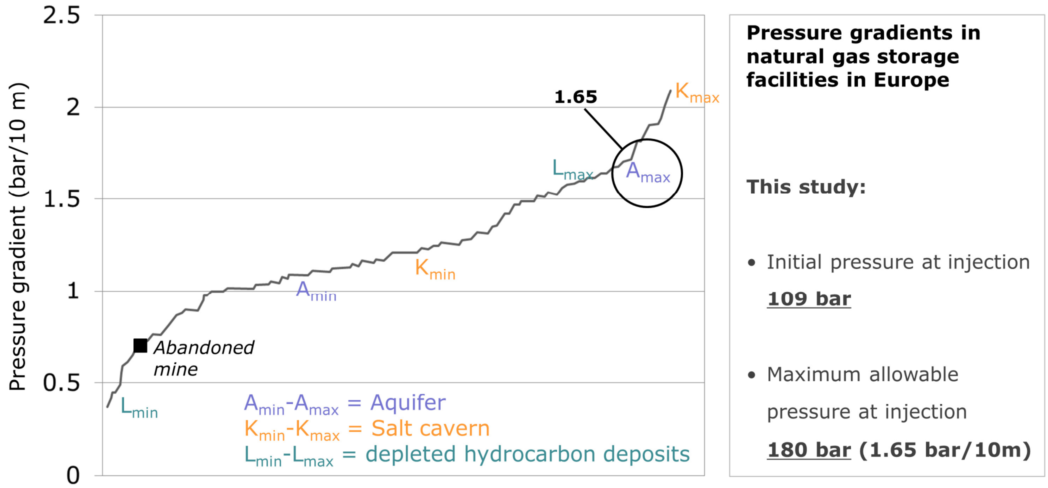

Fig. 3. One-way and two-way hydromechanical simulations are evaluated for a maximum allowable pressure at the injection well of 180 bar, corresponding to a pressure gradient of 1.65 bar / 10 m after Sedlacek [14].

We applied our flexible simulation framework [15] for model implementation and to handle the coupling between the reservoir simulator MUFITS (BLACKOIL module) [16-17] and the geomechanical simulator FLAC^{3D} [18] to carry out simulations for 20 years of injection. According to the dip angle and direction of the Fuerstenwalde-Guben fault as well as breakout analyses from a wellbore in its northern part, a maximum horizontal stress orientation parallel to the fault trace with a normal faulting regime and a maximum horizontal stress (S_{Hmax}) to vertical stress (S_v) ratio of $S_{Hmax} = 0.85\ S_v$ were assumed for the hydromechanical simulations. The fault is parameterized to be mechanically weak compared to its host rocks (Table 1).

Table 1. Applied hydromechanical parameters are derived from Nagelhout and Roest [19], Ouellet et al. [20], Kempka et al. [21] and Tillner et al. [22]. In the hydromechanical simulations, the fault zone is represented by weak planes (ubiquitous joints), embedded in an elastoplastic material.

	Caprock 2	Lower Muschelkalk	Caprock 1	Detfurth Formation	Basement	Fault zone
Porosity *(-)*	-	0.2	-	0.17	-	0.05
Permeability *(m^2)*	-	2.0×10^{-13}	-	4.0×10^{-13}	-	1.0×10^{-16}
Young's modulus *(GPa)*	4.1	26	31	27.7	60	5
Poisson's ratio *(-)*	0.43	0.18	0.29	0.26	0.19	0.29
Friction angle *(°)*	30	23	20	25	30	31
Cohesion *(MPa)*	5	5	5	5	5	0
Tension *(MPa)*	0.95	5	5	5	5	0
Dilation angle *(°)*	0	0	0	0	0	10
Density *(kg/m^3)*	2,059	2,658	2,362	2,453	2,698	2,362

In both coupling approaches, the pressure distribution obtained from the flow simulations is transferred to the hydromechanical simulator for selected time steps; however, only in the two-way coupling, a permeability increase, resulting from volumetric strain increments is calculated using Equations 1 and 2 [23-24] and considered in the next fluid flow simulation time step.

$$\phi = 1 - (1 - \phi_0) e^{-\Delta e_v} \quad (1)$$

$$k = k_0 \left(\frac{\phi}{\phi_0} \right)^n \quad (2)$$

In Equations 1 and 2, ϕ_0 and k_0 are the initial porosity and permeability, respectively, Δe_v the volumetric strain increment and ϕ and k porosity and permeability at a given stress state. As discussed by David et al. [23], the porosity sensitivity exponent n can range from 3 to 25 in high- (e.g., sandstone) and low-permeable rocks (e.g., claystone), respectively. In our conservative modelling approach, we assume that all model boundaries are closed for fluid flow and n is equal to 3 in the storage and secondary aquifers, model basement and caprocks, whereas n is equal to 25 in the fault elements to account for a maximum pressure response, increasing the hydraulic conductivity of this potential fluid migration pathway. A free top surface boundary and zero displacement normal to bottom and lateral boundaries as well as impermeable caprocks and basement rocks are assumed in both simulation runs.

3. Hydromechanical simulation results

In both coupling approaches and under the assumption of a maximum allowable pressure of 180 bar at the injection well, pressure at the base of the fault increases by about 68 bar until the end of injection, corresponding to a pressure gradient of 1.41 bar/10 m (Fig. 4b).

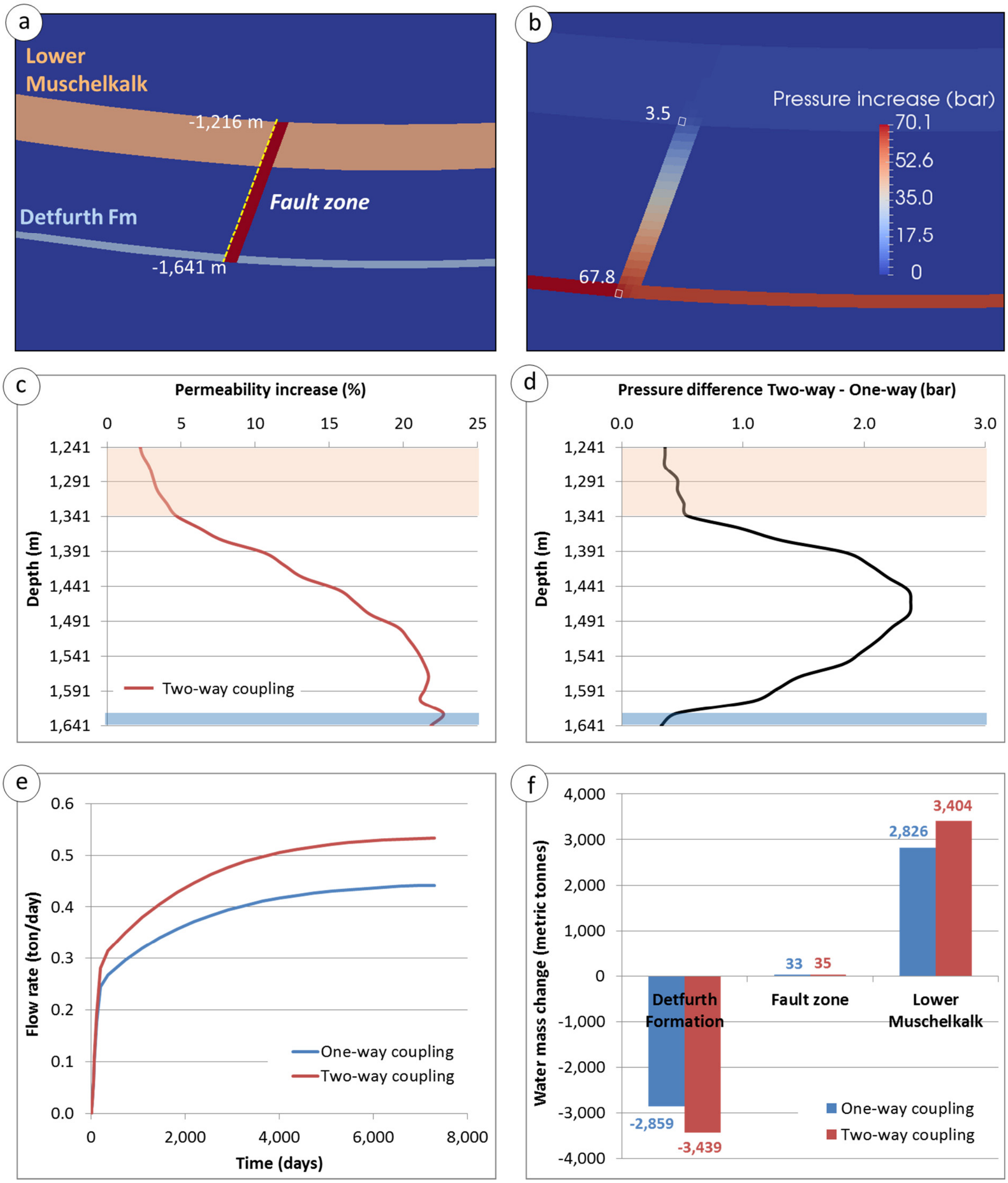

Fig. 4. (a) Close-up view of near-fault area with yellow dashed line, representing the location of the pressure and permeability profiles. (b) Pressure increase in the fault and its vicinity and (c) permeability increase along the fault in the two-way coupling. (d) Pressure difference between two-way and one-way coupled simulations along the fault. (e) Formation fluid flow rate from the fault into the secondary aquifer. (f) Relative formation fluid mass changes in the storage aquifer (Detfurth Formation), fault zone and secondary aquifer (Lower Muschelkalk). Figures (b), (c), (d) and (f) represent the simulation time at 20 years.

Consequently, altered effective stresses and induced volume changes in the fault lead to a maximum fault permeability increase in the two-way coupling from initially 1.0×10^{-16} m^2 to 1.3×10^{-16} m^2 at the base of the fault, corresponding to almost 23 % (Fig. 4c). At the top of the fault in the upper part of the secondary aquifer permeability increases by at least 2 %.

Pressure propagation and thus fluid migration via the fault is facilitated in the two-way coupling scheme, where simulated pressures in the fault elements are about 2.4 bar higher at the maximum, compared to those achieved with the one-way coupling after 20 years of injection (Fig. 4d). Consequently, the water flow out of the fault and into the secondary aquifer progressively increases in the two-way coupling after about 70 days of injection (Fig. 4e). About 0.1 tons of water per day are additionally displaced out of the storage aquifer into the secondary aquifer after 10 years of injection. Until the end of injection, additional 578 tons of brine reach the secondary aquifer, which corresponds to an increase in the displaced fluid amount by 20 % (Fig. 4f).

It is important to note that neither shear nor tensile failure are observed in any of the fault elements in both simulation runs during the entire simulation time, since the induced pore pressure increase is too low to trigger weak plane or rock matrix failure, supporting the applied limitation of the maximum allowed bottomhole pressure. Hence, permeability increase in the two-way coupling only results from volumetric changes induced by the pore pressure increase, and not additionally from fault dilation.

4. Discussion and conclusions

Fluid injection into the geological subsurface induces pressure and volume changes in reservoirs, caprocks and faults. In this view, hydraulic fault conductivity can be significantly increased and trigger upward migration of reservoir fluids into shallow freshwater aquifers. We compared one-way and two-way hydromechanical coupling approaches, aiming at the quantification of fluid migration via a fault. Our simulation results demonstrate that two-way coupled hydromechanical simulations are required when fluid flow pathway properties are likely to change due to geomechanical effects. Applying a one-way coupling instead of a two-way one in our simulation study underestimates fluid migration into the upper aquifer by about 20 %, even though neither fault shear nor tensile failure are induced by the resulting pore pressure increase.

This finding is not only crucial for the quantitative assessment of fluid leakage via faults, but also of relevance for, e.g., wellbore integrity assessments. Considering the relevance of effective fault damage zone volumes for brine displacement into freshwater aquifers [25], two-way coupled hydromechanical simulations allow to represent the dynamics between variations in fault zone volume depending on pore pressure propagation and fault fluid flow, increasing complexity but also reliability of quantitative risk assessments on freshwater salinization.

Further, it has to be taken into account that two-way coupled hydromechanical simulations require substantially more computational time, especially when fluid mass balance has to be preserved, since several iterations may be required considering mass conservation by adjusting pore compressibility or source and sink terms in the respective model elements. In this context, preliminary comparisons of deviations between one-way and two-way coupled models can become extremely useful in arriving at an acceptable trade-off between simulation result accuracy and computational time.

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