

# **TOUGH3-FLAC3D: A MODELING APPROACH FOR PARALLEL COMPUTING OF FLUID FLOW AND GEOMECHANICS**

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*Submitted to Computational Geosciences*

## **ABSTRACT**

The recent development of the TOUGH3 code allows for a faster and more reliable fluid flow simulator. At the same time, new versions of FLAC3D are released periodically, allowing for new features and faster execution. In this paper, we present the first implementation of the coupling between TOUGH3 and FLAC3Dv6/7, maintaining parallel computing capabilities for the coupled fluid flow and geomechanical codes. We compare the newly developed version with analytical solutions and with the previous approach, and provide some performance analysis on different meshes and varying the number of running processors. Finally, we present two case studies related to fault reactivation during CO<sub>2</sub> sequestration and nuclear waste disposal. The use of parallel computing allows for meshes with a larger number of elements, and hence more detailed understanding of thermo-hydro-mechanical processes occurring at depth.

**Keywords:** THM processes; coupled simulator; parallel computing; TOUGH3; FLAC3D

## **1. INTRODUCTION**

The current development of georesources exploitation strongly relies on numerical simulation of the processes occurring at depth. Understanding of the coupled thermo-hydro-mechanical processes is essential to assess properly the changes in system conditions as well as to study the risks associated with the underground exploitation (e.g., loss of circulation; caprock failure; induced seismicity). Model developments and their applications constitute a huge step towards understanding coupled processes. Several numerical simulators are already available in the literature for the study of coupled processes at various levels of complexity. Some models allow for all Thermo-Hydro-Mechanical-Chemical (THMC) couplings.

Examples are: TOUGHREACT-FLAC3D (Taron and Elsworth, 2009; Rutqvist et al., 2014; Rutqvist, 2017), OpenGeoSys (Kolditz et al., 2012), Dumux (Flemisch et al., 2011), COMSOL Multiphysics (COMSOL, 2020). In addition, other simulators have been applied to study partial processes coupling, THM or THC: e.g., Sierra Mechanics (Newell et al., 2017), 3DEC (Itasca, 2016), CODE-BRIGHT (Olivella et al., 1996), CSMP++ (Yapparova et al., 2017; Salimzadeh et al., 2018), PFLOTRAN (Lichtner et al., 2017).

In numerical modeling, the governing equations (conservation laws of mass, momentum and energy) are solved considering the relationship among processes (e.g., coupling of two or more processes), and completed with constitutive laws, initial conditions and boundary conditions. One factor determining the computational effort is the number of simulated THMC coupled processes. Another factor is the numerical scheme. In the literature, the term *monolithic* refers to a scheme in which the physical equations for multiple processes are solved simultaneously, which may be computationally expensive. More loose couplings exist, such as one-way (i.e., a given process influences another, but not vice versa) or two-way sequential (i.e., the different processes are considered in sequence). Such schemes are less computationally intensive and may refer to the same simulator, but often the integration of different codes is used to take advantage of specialized codes and to increase the types of simulated processes (Kulik et al., 2012; Jha and Juanes, 2014; Rutqvist, 2017; Garipov et al., 2018; Li et al, 2020).

Given the complexity of the coupled processes, verification of the numerical approach is often an issue. Analytical solutions are only available for very simplified processes (e.g., only for fully saturated medium), and observations from lab and *in situ* experiments involve significant uncertainties. Benchmarking activities involving code-to-code comparison and validation against analytical solutions and experimental data are often in play for developing numerical models (Blanco-Martín et al., 2015; Garitte et al., 2017; Rutenberg et al., 2018;

Birkholzer et al., 2019). The TOUGH family of codes are commonly applied to model the coupling of fluid flow and heat transport in geological media (Pruess et al., 2012; Jung et al., 2017), and have been extended to consider coupling to geomechanical processes. In particular, several TOUGH-based geomechanical codes have been developed to solve THM problems (Rutqvist, 2017), among which TOUGH-FLAC is the most widely used, with recent applications featuring inverse modeling (Blanco-Martín et al., 2016; Rinaldi et al., 2017) and finite strain deformation (Blanco-Martín et al., 2017). Since its initial development in the late 1990s (Rutqvist et al., 2002), TOUGH-FLAC has been applied to study geomechanical aspects of CO<sub>2</sub> sequestration, nuclear waste disposal, enhanced geothermal systems, underground gas storage and compressed air energy storage, gas production from hydrate-bearing formations, induced seismicity, as well as for the implementation and the study of constitutive equations (Rutqvist, 2017 and references therein).

The most common version of TOUGH-FLAC accounts for the two-way sequential coupling of TOUGH2 (Pruess et al., 2012) for the simulation of non-isothermal, multi-phase and multi-component fluid flow with upgraded versions of FLAC3D (e.g., ver.4/5, Itasca, 2011) for solving the mechanical equilibrium. The equations for fluid flow and geomechanics are solved sequentially, and the approach is unconditionally stable, using the fixed-stress split sequential scheme: the flow sub-problem is solved first with a fixed total stress field, which is then modified in the subsequent geomechanics sub-problem by using modified variables from the flow step (Kim et al., 2011).

Despite the wide use of TOUGH-FLAC coupled simulations in the literature, applications are often limited to a relatively small computational domain, with a number of elements usually smaller than 50,000. In this work, we moved one step forward by coupling for the first time the newly developed TOUGH3 (Jung et al., 2017) with versions 6.0 and 7.0 of FLAC3D (Itasca, 2017), hence implementing a parallelized version of the well-known coupled



simulator. The coupled simulator integrates all the new functionalities of TOUGH3, including the use of PETSc solvers, together with the improved solver performance in FLAC3Dv6/7 as well as the possibility of using Python scripting compared to the FISH programming embedded in previous versions of FLAC3D. After verifying the correctness of the approach comparing the simulation results with an analytical solution and with the previous version, we evaluate the performance of the newly developed approach. Finally, we present results of two case studies, aimed at understanding the potential for fault reactivation during CO<sub>2</sub> sequestration and the evolution of stress and strain during nuclear waste disposal in a deep geological repository.

Although specific for TOUGH-FLAC, the results of the current manuscript can be generalized to the entire community working on sequential coupling for studying coupled processes. The sequential coupling of two codes both running in parallel is not trivial, and it represents a novel computational approach. We demonstrate that the use of a fast wrapper (i.e., Python-based) can help to strongly reduce the computational speed.

## **2. MATHEMATICAL FORMULATION AND SINGLE CODE PERFORMANCE**

### **2.1 Mass and energy balance equations of the fluid**

The fluid flow formulation described in here, closely follows the description in TOUGH2/3 User's guide (e.g., Pruess et al., 2012). For nonisothermal, multiphase, multicomponent flow, the mass of each component  $k$  can be generally written as summing over the fluid phases:

$$M^k = \phi \sum_{\beta} S_{\beta} \rho_{\beta} \chi_{\beta}^k \quad (1)$$

where  $\phi$  is porosity,  $S_{\beta}$  is the saturation of phase  $\beta$ ,  $\rho_{\beta}$  is the density of phase  $\beta$ , and  $\chi_{\beta}^k$  represents the mass fraction of component  $k$  in phase  $\beta$ .

The advective flow for the  $k$ -component is given by the sum over the phases:

$$\mathbf{F}_{adv}^k = \sum_{\beta} \chi_{\beta}^k \rho_{\beta} \mathbf{u}_{\beta} \quad (2)$$

where  $\mathbf{u}_{\beta}$  is the volumetric flux derived from the Darcy's law:

$$\mathbf{u}_{\beta} = -\kappa \frac{\kappa_{r\beta}}{\eta_{\beta}} (\nabla p_{\beta} - \rho_{\beta} \mathbf{g}) \quad (3)$$

where  $\kappa$  is the absolute permeability.  $\kappa_{r\beta}$ ,  $\eta_{\beta}$ , and  $p_{\beta}$  are the relative permeability, the viscosity and the pressure of the phase  $\beta$ , respectively.  $P_{\beta} = P + P_{c\beta}$ , where  $P$  is the pressure of a reference phase (here, gas) and  $P_{c\beta}$  is the capillary pressure.

Mass transport can also occur via diffusion and hydrodynamic dispersion, expressed through Fick's law in the general form:

$$\mathbf{F}_{dis}^k = - \sum_{\beta} \rho_{\beta} \bar{\mathbf{D}}_{\beta}^k \nabla \chi_{\beta}^k \quad (4)$$

where  $\bar{\mathbf{D}}_{\beta}^k$  is the hydrodynamic dispersion tensor depending on the porous medium dispersivity, the Darcy velocity, the coefficient of molecular diffusion, and the phase-dependent tortuosity.

The mass balance equation can be written in the general form for each component  $k$ :

$$\frac{\partial M^k}{\partial t} + \nabla \cdot (\mathbf{F}_{adv}^k + \mathbf{F}_{dis}^k) = r^k \quad (5)$$

with  $r^k$  being the change term denoting sinks and sources.

Similarly, the energy conservation equation, accounting for heat propagation and fluid flow, can be written as:

$$\frac{\partial M^h}{\partial t} + \nabla \cdot \mathbf{q}^h = Q \quad (6)$$

where  $Q$  represents the energy gain/loss from sink and sources,  $\mathbf{q}^h$  is the heat flow, and  $M^h$  is the accumulation term. This latter takes into account the internal energy per unit volume as:

$$M^h = (1 - \phi)\rho_R C_R T + \phi \sum_{\beta} S_{\beta} \rho_{\beta} u_{\beta} \quad (7)$$

where  $T$  is the temperature,  $\rho_R$  and  $C_R$  are the rock density and specific heat, and  $u_{\beta}$  is the specific internal energy of the phase  $\beta$ .

The heat flow due to conduction and fluid advection is given by:

$$\mathbf{q}^h = -\lambda \nabla T + \sum_{\beta} h_{\beta} \mathbf{F}_{\beta} \quad (8)$$

where  $\lambda$  is the thermal conductivity,  $\mathbf{F}_{\beta} = \rho_{\beta} \mathbf{u}_{\beta}$  is the mass flow rate for the phase  $\beta$ , and  $h_{\beta}$  the corresponding specific enthalpy.

TOUGH3 solves the mass and energy balance equations by means of an integral finite difference method for space discretization with a first-order fully implicit time formulation. Each time step involves the calculation of the Jacobian matrix as well as the solution of the equations using Newton-Raphson iterations. The time steps are automatically adjusted given the convergence rate. A comprehensive description can be found in the TOUGH2/3 User's guide (Pruess et al., 2012; Jung et al., 2018).

## **2.2 Mechanical formulation**

Mechanical equilibrium is calculated by solving the momentum equation, that can be expressed as

$$\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{b} = \rho \frac{d\mathbf{v}}{dt} \quad (9)$$

where  $\boldsymbol{\sigma}$  is the Cauchy stress tensor,  $\mathbf{b}$  is the vector of body forces per unit mass, and  $\mathbf{v}$  is the velocity. By neglecting the inertial terms, and using the indexing notation, the equation above reduces to  $\sigma_{ij,j} + \rho b_i = 0$ .

The relation between stress and strain is then provided by a constitutive equation, linked to the nature of the medium being deformed. The coupling between fluid flow and deformation

is described by the Biot's theory of poroelasticity. The total stress (negative for compression) is affected by the equivalent fluid pore pressure  $p_{eq} = \sum_{\beta} S_{\beta} p_{\beta}$ :

$$\sigma_{ij}^{tot} = \sigma_{ij}^{eff} - \alpha p_{eq} \delta_{ij} \quad (10)$$

where  $\alpha$  is the Biot's coefficient and  $\delta_{ij}$  is the Kronecker's delta. The constitutive equation for a given  $\beta$  phase relates the variation in fluid content  $\zeta_{V/V;\beta}$  to the pore pressure  $p_{\beta}$ , saturation  $S_{\beta}$ , mechanical volumetric strain  $\varepsilon_{vol}$ , and temperature  $T$ :

$$\frac{1}{M_{\beta}} \frac{\partial p_{\beta}}{\partial t} + \frac{\phi}{S_{\beta}} \frac{\partial S_{\beta}}{\partial t} = \frac{1}{S_{\beta}} \frac{\partial \zeta_{V/V;\beta}}{\partial t} - \alpha \frac{\partial \varepsilon_{vol}}{\partial t} + \alpha_T \frac{\partial T}{\partial t} \quad (11)$$

with  $\alpha_T$  representing the undrained thermal coefficient and  $M_{\beta}$  being the Biot modulus, expressed as:

$$M_{\beta} = \frac{K_{\beta}}{\phi + (\alpha - \phi)(1 - \alpha) K_{\beta}/K} \quad (12)$$

where  $K_{\beta}$  being the bulk modulus of the phase  $\beta$  and  $K$  the drained bulk modulus.

The changes in fluid content are related to changes in porosity as:

$$d\phi = A(\alpha, \phi, K) dp + B(\alpha_T) dT + \Delta\phi \quad (13)$$

with  $\Delta\phi$  being a porosity correction term due to mechanical deformation (Kim et al., 2012).

This provides a simple approach for sequential coupling of fluid flow and mechanical calculation, such as the fixed-stress split sequential method (Kim et al., 2009; 2011). In addition to porosity, other flow variables such as permeability  $k$  and capillary pressure  $P_{c\beta}$  may be affected by mechanical changes (Rutqvist et al., 2002; Rutqvist, 2017).

Plastic deformation can be accounted for by using a failure criterion  $f(\sigma_n) = 0$  and decomposing the strain increment into the sum of elastic and plastic parts. For the latter its direction is specified as being normal to a potential surface  $g(\sigma_n) = \text{constant}$  and following a flow rule:

$$\Delta \varepsilon_i^p = \lambda \frac{\partial g}{\partial \sigma_i} \quad (14)$$

where the subscript  $i$  refers to the increment in strain/stress and  $\lambda$  is a constant depending on the chosen constitutive equation.

FLAC3D solves the mechanical problem by means of an explicit finite difference approach, in which the laws of motion are discretized at the nodes and the resulting system of equations solved by explicit finite difference in time (Itasca, 2017). In the coupling with TOUGH, the mechanical formulation is always run to equilibrium every time step. Mechanical equilibrium is reached when the ratio between the maximum unbalanced force magnitude and the average applied force magnitude falls below a threshold limit. For time-dependent deformation the coupling needs to be adapted accordingly (Blanco-Martín et al., 2015).

### **2.3 Single codes parallel computing performance**

TOUGH3 is parallelized by means of MPI, while FLAC3D uses threaded operations. The most current version of FLAC3D runs on both Linux and Windows-based systems. For a Windows-based system, to make use of the MPI parallelization provided in TOUGH3, the code can be compiled in Cygwin or Windows Subsystem for Linux (Windows 10 and 11). Each of the two codes was evaluated separately on various machines. The speed increase was calculated with respect to the single MPI process/thread calculation. Results are shown in Figure 1. We evaluated TOUGH3 on three different hardware configurations: (1) a 2x6-core Windows workstation equipped with CPUs Intel Xeon E5-2643 (24 threads) at 3.40 GHz and with 64 GB RAM; (2) a 32-core virtual workstation with AMD EPYC 7742 at 2.25 GHz and equipped with 64 GB RAM; (3) a Linux cluster (<https://scicomp.ethz.ch/wiki/Euler>) with limited request for this work up to 32 cores (potentially to much larger number) for comparison with the other hardware configurations. For a simulation with 50,000 elements,

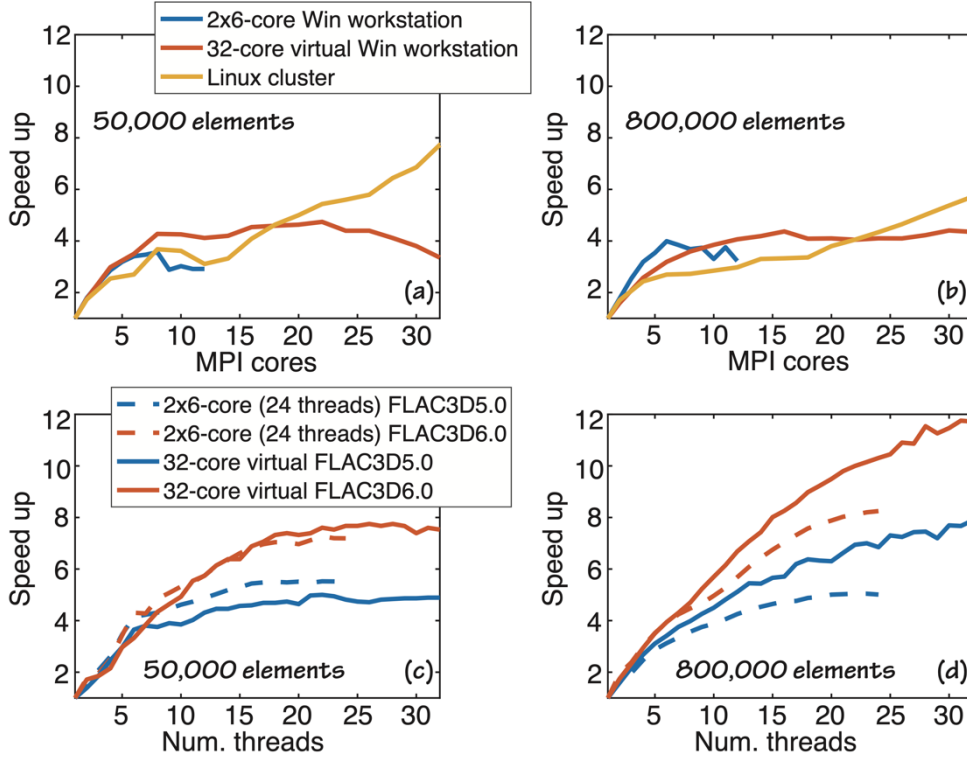


Figure 1. Performance evaluation (speed up) for the individual codes on various hardware configurations. (a,b) TOUGH3 performance on three hardware configurations (2x6-core Windows workstation, 32-core virtual workstation, Linux cluster) for a computational mesh with 50,000 and 800,000 elements, respectively. (c,d) FLAC3D version 5 and version 6 performance on two hardware configurations (2x6-core Windows workstation, 32-core virtual workstation) for a computational mesh with 50,000 and 800,000 elements, respectively.

we noticed for TOUGH3 a plateau in performance when reaching roughly half of the available cores on the Windows workstations, with a speed increase of about 4 (Fig. 1a). On a Linux cluster the increase is observed up to the limit number of cores (increase up to 8-fold). Figure 1b shows the performance of TOUGH3 for a simulation with 800,000 elements: the speed increase is similar to the smaller mesh, although with the performance on the cluster being more similar to what observed on the Windows workstations. FLAC3D was evaluated for two versions (5 and 6) only on the windows workstations, allowing for 24 and 32 threads, respectively. Figures 1c and 1d show the speed increase, with the version 6 being sensibly faster than version 5, and with slightly better performance on the virtual workstation with 32 cores/threads. In this latter we observe an 8-fold and 12-fold increase for a simulation with 50,000 and 800,000 elements, respectively.

### **3. COUPLING APPROACH**

The main modifications of the approach compared to the previous versions are:

1. Use of TOUGH3 with parallel computing and use of FLAC3Dv6/7, both allowing for faster calculation.
2. Use of binary instead of ASCII exchange files. This is particularly important when dealing with computational domains containing a large number of elements.
3. Use of a flag system to keep FLAC3D mechanical state into memory. In the previous formulation, a new instance of FLAC3D was called at each time step. At a given flow time step “i”, the full mechanical state was saved to a binary file and loaded back at the time step “i+1” and solved for mechanical equilibrium with the new hydraulic solution from TOUGH3. In the new approach, the FLAC3D model state is only loaded at the beginning of the simulation (i.e., for the initial conditions), then FLAC3D is paused during TOUGH3 execution and the model state kept in the memory, thereby avoiding overhead caused by restoring/saving the mechanical state at each TOUGH3 time step.
4. Use of Python routines to read/write coupling files in FLAC3D. Through the use of NumPy (Harris et al., 2020), this can produce up to 34× faster execution (10× in average) in variable allocation compared to the previously used FISH scripting (Itasca, 2017).

The approach proposed here is general and can be applied in both Windows and Linux environments. All the coupled simulations presented here were carried out on the virtual workstation that allows using up to 32 MPI processors/threads.





TOUGH3, FLAC3D computes the mechanical equilibrium to a predefined convergence threshold. In general, the fluid flow problem and the mechanical problem are treated independently regarding the convergence. This approach is quite stable for poroelastic problems, but it may require an appropriate choice of time stepping when including time-dependent deformation (e.g., creep). Beck et al. (2020) compared the single-iteration against multi-iteration coupling and found that the solution may be different, although the uncertainty linked with the coupling equation is certainly much larger than that caused by the numerical implementation of the sequential solving of the equations. Figure 2a shows the numerical scheme for the coupling in time between the two codes, while Figure 2b provides details of the coupling for each time step.

For each time step, before starting the iterations for solving the fluid flow sub-problem, TOUGH3 invokes a subroutine to gather the arrays from all the MPI processes. Such arrays (pressure, temperature, saturation and capillary pressure) are written to file `TOU_FLA` by the `IOProcessor`, together with a flag (1). The `IOProcessor` performs this entire stage in serial, while all the other  $n$  MPI processes are idle. During this process, FLAC3D is idle waiting for the flag to change. Then, FLAC3D (i) reads the `TOU_FLA` file (in serial), (ii) solves for mechanical equilibrium (in parallel), and (iii) writes the `FLA_TOU` file to transfer data to TOUGH3 (in serial), and modifies the flag (2). At this stage, the subroutine invoked previously by TOUGH3 is waiting for FLAC3D to finish execution, then the `IOProcessor` serially reads the flag and the `FLA_TOU` file and distributes the variables/properties (bulk modulus, Biot's coefficient, strain, and stress) to all  $n$  MPI processes.

Finally, the parallel computing can restart with the calculation of mechanically-induced changes of flow properties and with continuation of the flow iterations to finish the current time step. When TOUGH3 is at the last time step, it will issue a flag (3) that FLAC3D will interpret and save the final state in a binary file. The mechanical state as well as the flow

variables can also be saved at predefined times during execution. The use of Python routines within FLAC3D allows for easier handling of arrays (e.g., mapping of a given variable or extra post-processing computation), and also for handling and personalizing the entire output functions, making redundant the use of standard TOUGH3 output functions.

## **4. VERIFICATION AND PERFORMANCE**

### **4.1 Analytical solution**

An analytical solution can be derived for a Terzaghi-like problem (Lux et al., 2015). The problem here is part of the BenVaSim initiative to verify and benchmark several numerical codes (Rutenberg et al., 2018). While being a simplified numerical exercise, the model setup physically resembles a dam construction in a flooded drift with a pore pressure gradient allowing water flowing through the host rock. As the current approach is based on previous versions, more verifications can be found elsewhere (Blanco-Martín et al., 2017).

The model is one dimensional, fully saturated 10 m–long domain with displacement completely fixed in  $y$ - and  $z$ - directions and at  $x = 10$  m (Fig. 3a). The initial pressure and total stress in the model are set to 0.1013 MPa. Pore pressure is 1 MPa at the left boundary ( $x = 0$  m), and 0.1013 MPa at the right boundary ( $x = 10$  m). A total stress of 1 MPa is applied at time  $t=0^+$  at  $x = 0$  m. The base case scenario accounts for a porous and low-permeability material (porosity  $\phi = 0.15$ ; permeability  $\kappa = 10^{-20}$  m<sup>2</sup>) with stiff and deformable matrix (Young's modulus  $E = 8$  GPa; Biot's coefficient  $\alpha = 1$ , and Poisson's ratio  $\nu = 0$  to allow for 1D problem). Variations to the base case account for compressible grains (Biot's coefficient  $\alpha = 0.75$ ) and for very soft material (Young's modulus  $E = 150$  MPa). Both TOUGH3 and FLAC3D convergence thresholds are set to  $10^{-7}$ .

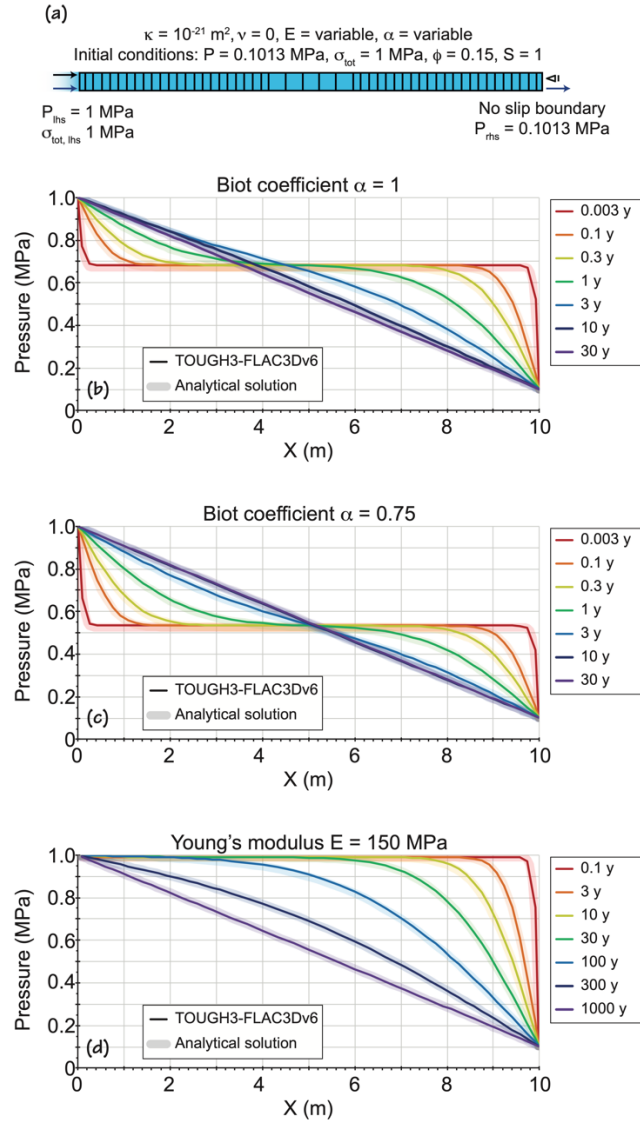


Figure 3. Verification of the coupling approach with an analytical solution in a low-permeability environment. (a) Computational domain and boundary conditions; (b) Base case scenario; (c) Compressible grains (Biot coefficient  $\alpha = 0.75$ ); (d) Soft matrix (Young's modulus  $E = 150 \text{ MPa}$ ).

Figure 3b shows the profiles of the pore pressure at different times comparing the numerical (solid line) and the analytical (shaded line) solutions. Results show that for different times, the developed approach is able to match the analytical solution, with only minor differences mostly related to space discretization (50 elements for the 10 m long domain). The initial pressurization of the system (undrained response at 0.003 y) is somewhat larger than the analytical solution due to coarse time discretization, while the steady state is well matched (at 30 y for the base case scenario). A more compressible grain will result in less undrained

pressurization (Fig. 3c), while the soft matrix will result in much larger deformation, allowing for larger porosity decrease in the matrix, and larger pressure increase during the undrained response (Fig. 3d). As it can be seen, the numerical approach is in good agreement with the analytical solution also for more critical scenarios.

## **4.2 Comparison with previous simulator**

In order to verify the validity of TOUGH3-FLAC3Dv6/7, we compared results with the previous TOUGH2-FLAC3Dv5 (Blanco-Martín et al., 2017). We checked the results for variables such as injection pressure and temperature as well as the uplift of the top boundary. We account for a 3D computational domain ( $10 \text{ km} \times 10 \text{ km} \times 4 \text{ km}$ ) fully saturated and with homogeneous hydraulic properties (constant permeability  $\kappa = 5 \cdot 10^{-15} \text{ m}^2$ , initial porosity  $\phi = 0.1$ , rock grain density  $\rho_R = 2550 \text{ kg/m}^3$ , fluid density dependent on pressure and temperature as default for TOUGH3, rock grain specific heat  $C_R = 800 \text{ J/kg } ^\circ\text{C}$ , heat conductivity  $\lambda = 2.0 \text{ W/m } ^\circ\text{C}$ ). For simplicity, we assume a constant permeability, while the porosity changes as described in Eq. 13. The model ranges from a depth of -2 km to -6 km, and the top and bottom boundaries, as well as the boundaries at  $x = y = 10 \text{ km}$ , are open to fluid flow. The boundaries at  $x = y = 0 \text{ km}$  are closed and allow for symmetry. Mechanically, we assume a poroelastic material (Young's modulus  $E = 10 \text{ GPa}$ , Poisson's ratio  $\nu = 0.25$ , Biot's coefficient  $\alpha = 1$ ), with the top and side boundaries ( $x = y = 10 \text{ km}$ ) at fixed stress conditions, with rollers for all the other boundaries. We assume initial hydrostatic gradient for pore pressure, geothermal gradient for temperature ( $30 \text{ } ^\circ\text{C/km}$ ), and lithostatic gradient for stresses. We simulate 60 days of cold-water injection ( $T = 10 \text{ } ^\circ\text{C}$ ) in a saturated medium with variable rate (30 days at  $30 \text{ kg/s}$ , 20 days at  $60 \text{ kg/s}$ , and 10 days at  $90 \text{ kg/s}$ ), followed by 40 days of shut-in period for a total simulation time of 100 days. The injection region is at a

depth of 4 km and extends over a region  $50 \text{ m} \times 50 \text{ m} \times 50 \text{ m}$ . For both simulations, we use a mesh with  $\sim 46,500$  elements. Porosity changes depend on the bulk modulus and on the total volumetric strain, when larger than  $10^{-4}$ . The FLAC3D mechanical ratio between the maximum unbalanced force magnitude and the average applied force magnitude is set to  $10^{-7}$ . The TOUGH3 convergence criterion is set to  $10^{-5}$ .

As shown in Figure 4, the two approaches are in extremely good agreement, with differences in pressure in the order of some Pa, minor differences in temperature, and differences in uplift in the order of some microns.

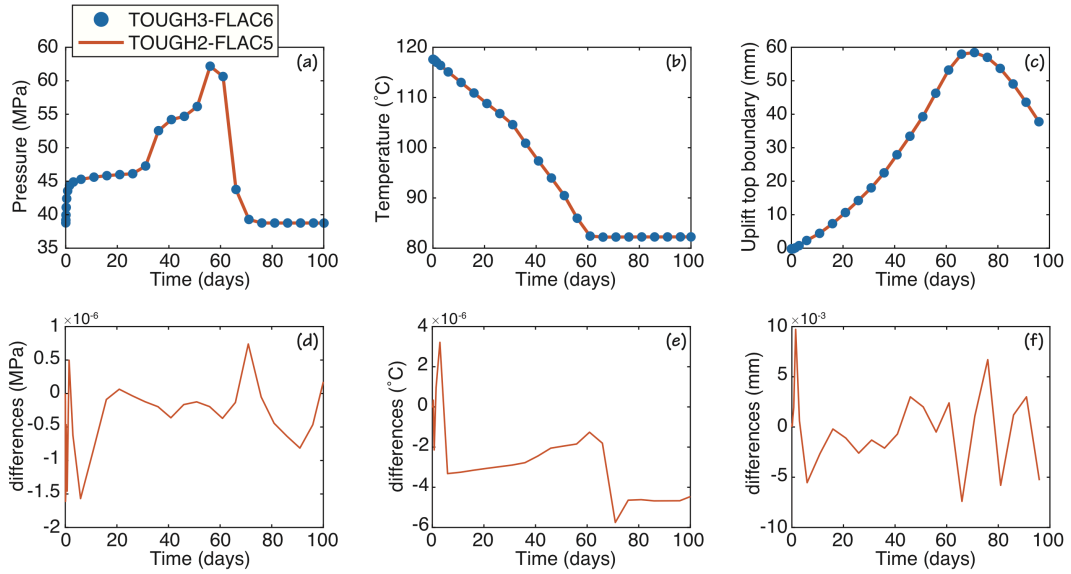


Figure 4. Comparison between TOUGH2-FLAC3Dv5 (red line) and TOUGH3-FLAC3Dv6 (blue dots) for pressure near the injection point (a), temperature near the injection point (b), and uplift of the top boundary (c) for a mesh with 46,464 elements. (d-f): differences between the two approaches.

### 4.3. Performance Tests

Figures 5a-b show the performance of TOUGH3-FLAC3Dv6 compared to the previous version and to serial execution as a function of the number of threads and for various sizes of the computational domain. We varied the number of threads in FLAC3D and the number of cores in TOUGH3 accordingly (each core allows for two threads). For each computational domain, we have created similar initial conditions (via steady state simulation), to avoid

biases on the final simulation, which is the same as what was described in Section 4.2. Some differences may arise for small meshes in the final displacement, which depends on the exact position of the monitoring point, defined as the nearest to the position  $x=300$  m,  $y=300$  m, and  $z=-2000$  m (supplementary material, Fig. S1). For a single MPI process/thread, the code is 1.5x faster compared to the previous version only owing to better I/O handling and use of Python in FLAC3D. Due to parallelization overhead (communication and domain decomposition), the speed up clearly depends on the size of the mesh, with an increase of up to  $2\times$  faster for a coarse mesh with 4,000 elements and up to  $5\times$  faster for a relatively fine mesh with 800,000 elements. Interestingly, for all the cases the performances does not improve after reaching 16 cores/threads. This is consistent, however, with the performance observed for TOUGH3 on the same hardware configuration (Fig. 1a-b). This could be due to conflict with the operating system processes, as the scaling for TOUGH3 is better on standard cluster. FLAC3D is not affect by this behavior, so in general we obtain a better performance in terms of speed-up for TOUGH3-FLAC3D compared to TOUGH3-only, although the absolute running time is much smaller for the latter.

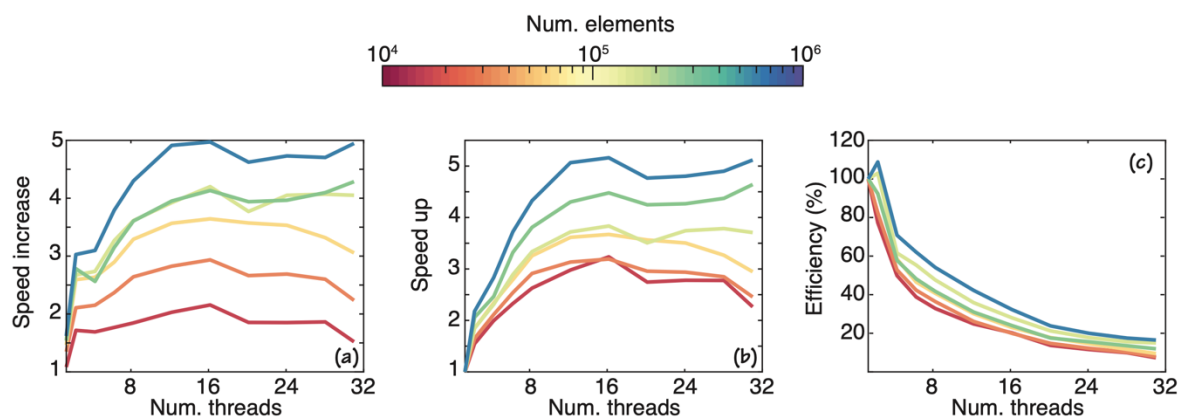


Figure 5. (a) Speed increase for TOUGH3-FLAC3Dv6 compared to TOUGH2-FLAC3Dv5 as a function of the number of threads for different mesh sizes (colormap). (b) Speed up of the current approach (execution time for a single thread compared to multi-thread) as a function of number of threads for different mesh sizes (colormap) (c) Efficiency of TOUGH3-FLAC3Dv6 for different mesh sizes (colormap)

## 5. CASE STUDIES

### 5.1 Fault reactivation during CO<sub>2</sub> sequestration

The model presented here closely follows previous works addressing the same topic (Rutqvist et al., 2016). A three-dimensional model was already proposed by Rinaldi et al. (2015), who addressed the effect of the well orientation on induced seismicity and CO<sub>2</sub> leakage through the fault. Here, thanks to the faster solver, we introduce a further complication in the model, which is the presence of a multiple fault system (Fig. 6). A similar model was also employed for studying the natural seismicity occurring at Matsushiro, Japan (Cappa et al., 2009), but here the much larger number of elements allows for better details. We simulate a 3D computational domain 10 km × 10 km × 3 km with 91×165×74 elements in the three directions (total of about 1 million elements). The two fault zones strike N90° and N180° while dipping 90° and 80°, respectively, and intersect at the center of the computational domain, assuming the north is oriented in the y-direction. (Fig. 6). Injection occurs in a 100 m thick reservoir, bounded by

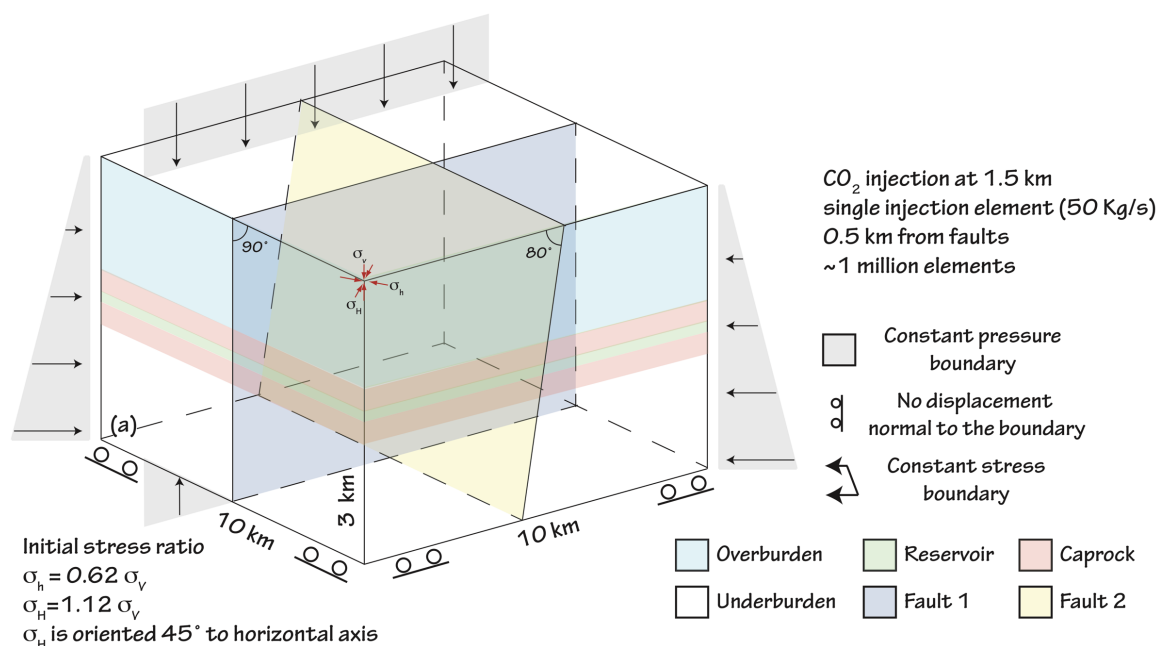


Figure 6. Computational domain for the study of fault reactivation during CO<sub>2</sub> injection.

two 150 m thick caprock formations, at a distance of 500 m from each fault (at a single point  $x = 4500$  m,  $y = 4500$  m,  $z = -1500$  m), and with a constant rate of 50 kg/s (1.6 Mt/y) for a total of 3 years. Initial conditions account for hydrostatic pressure and geothermal gradient, and the simulation is considered isothermal (i.e., temperature is only needed to calculate the fluid viscosity and density). Initial stress follows a strike-slip regime, with both maximum and minimum principal stresses horizontal. The maximum horizontal stress ( $\sigma_H$ ) is oriented N45° with a stress ratio  $\sigma_H/\sigma_V = 1.12$ , while the minimum horizontal stress ( $\sigma_h$ ) has a ratio of  $\sigma_h/\sigma_V = 0.62$ , with the vertical one ( $\sigma_V$ ) being the lithostatic stress. Boundaries are all open to fluid flow with constant lithostatic stress and hydrostatic pore pressure, except for the bottom where the displacement normal to the boundary is null. The system is initially fully saturated with brine, with retention curves for capillary pressure and relative permeability following van Genuchten (1980).

For the sake of simplicity, we do not include permeability changes at this stage, as we focus on the reactivation of the faults. Permeability changes are instead more relevant when studying CO<sub>2</sub> leakage (Rinaldi et al., 2014). We account for the full hydro-mechanical coupling by modeling porosity changes as function of the volumetric strain and pore pressure.

We assume for all rock formations elastic rheology, except the core of both faults, which follows a strain-softening ubiquitous-joint model with frictional law depending on the accumulated plastic strain (Cappa and Rutqvist, 2011). Both elastic and hydraulic properties for the different domains are listed in Table 1. The simulation execution time with the given setup is comparable to a similar case in 2D and single fault for the previous version of the simulator (some hours).



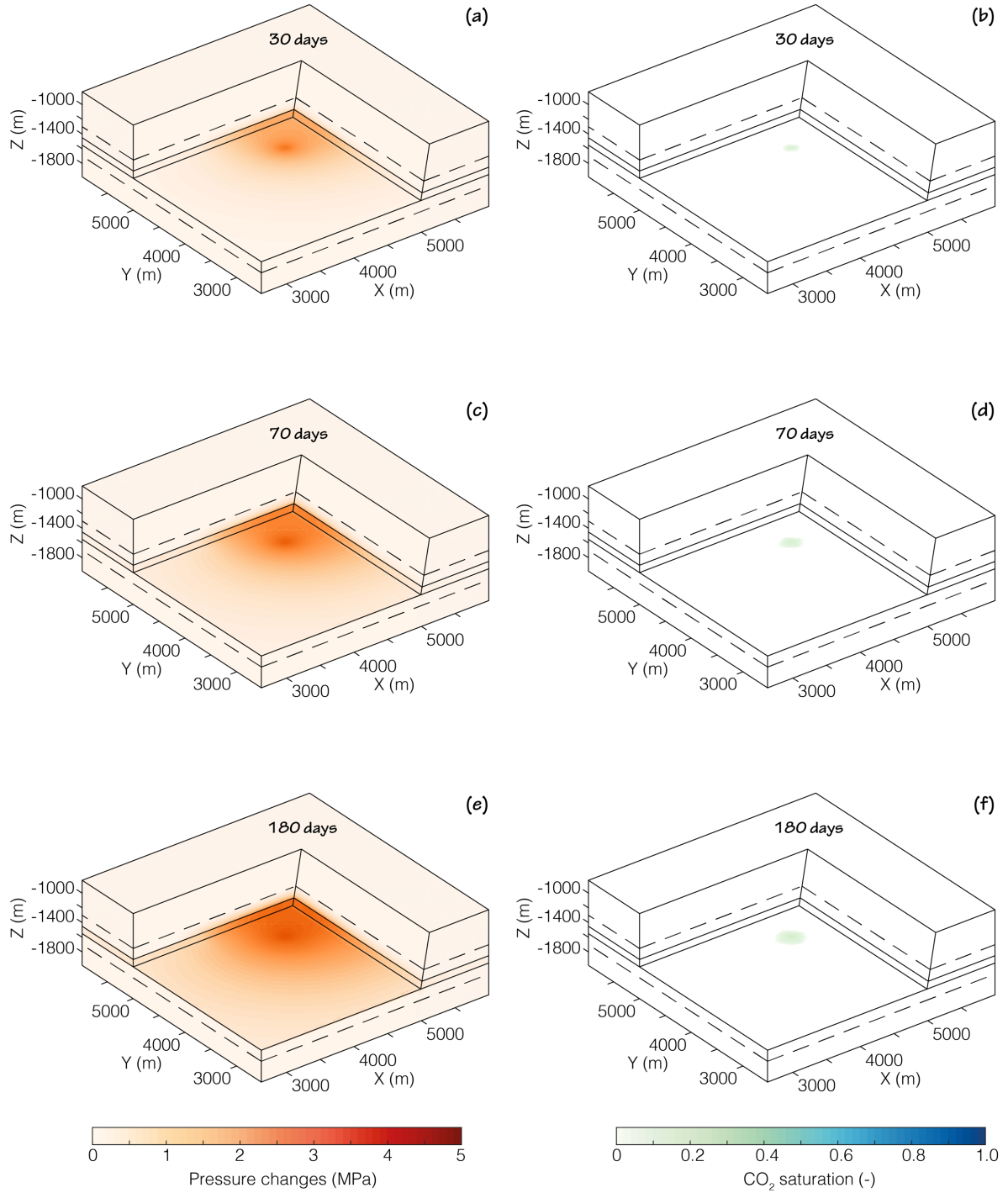
Table 1. Hydraulic and mechanical properties for the different domains in the CO<sub>2</sub> injection case study

|  | <b>Reservoir</b>  | <b>Caprock</b>    | <b>Overburden</b> | <b>Underburden</b> | <b>Damage zone</b> | <b>Fault core 1</b> | <b>Fault core 2</b> |
|--|-------------------|-------------------|-------------------|--------------------|--------------------|---------------------|---------------------|
| Permeability (m <sup>2</sup> )             | 10 <sup>-13</sup> | 10 <sup>-19</sup> | 10 <sup>-14</sup> | 10 <sup>-18</sup>  | 10 <sup>-15</sup>  | 10 <sup>-17</sup>   | 10 <sup>-17</sup>   |
| Porosity                                   | 0.1               | 0.1               | 0.1               | 0.1                | 0.1                | 0.1                 | 0.1                 |
| Rock density (kg/m <sup>3</sup> )          | 2260              | 2260              | 2260              | 2260               | 2260               | 2260                | 2260                |
| Residual CO <sub>2</sub> saturation (-)    | 0.05              | 0.05              | 0.05              | 0.05               | 0.05               | 0.05                | 0.05                |
| Residual liquid saturation (-)             | 0.3               | 0.3               | 0.3               | 0.3                | 0.3                | 0.3                 | 0.3                 |
| van Genuchten (1980), p <sub>0</sub> (kPa) | 19.9              | 621               | 19.9              | 621                | 19.9               | 19.9                | 19.9                |
| van Genuchten (1980), m (-)                | 0.457             | 0.457             | 0.457             | 0.457              | 0.457              | 0.457               | 0.457               |
| Young's modulus (GPa)                      | 10                | 10                | 10                | 10                 | 10                 | 5                   | 5                   |
| Poisson's ratio                            | 0.25              | 0.25              | 0.25              | 0.25               | 0.25               | 0.25                | 0.25                |
| Peak/residual friction angle (°)           | -                 | -                 | -                 | -                  | -                  | 31/29               | 31/29               |
| Dilation angle (°)                         | -                 | -                 | -                 | -                  | -                  | 10                  | 10                  |

Pressure evolution and CO<sub>2</sub> plume are shown in Figure 7. Results show that the pressurization of the reservoir is quite fast with changes up to 4 MPa near the injection point. Both faults start pressurizing right after injection starts, and less than 5 MPa are needed to reactivate both faults, with reactivation time depending on the fault strength (or actually on the fault orientation with respect to the state of stress). The CO<sub>2</sub> plume is still confined close to the injection, extending up to 200 m when both faults are reactivated.

Figure 8 shows how the rupture starts occurring on Fault 1 (the vertical blue fault, Fig. 6), and it is followed several days after by reactivation on Fault 2 (the dipping yellow fault, Fig. 6). This is consistent with the state of stress, according to which Fault 1 is favorably oriented for shear activation. Given the frictional law in the ubiquitous joint model, the friction angle

drops in the ruptured area (i.e., the one where plastic strain accumulates) from the peak value ( $31^\circ$ ) to the residual ( $29^\circ$ ). Reactivation on Fault 1 occurs after only 30 days of injection with maximum slip of 0.6 cm (Fig. 8a-b), and it is followed by the reactivation on Fault 2 after 70



*Figure 7.* Distribution of pressure changes (a,c,e) and CO<sub>2</sub> saturation (b,d,f) after 30, 70, and 180 days of injection operations.

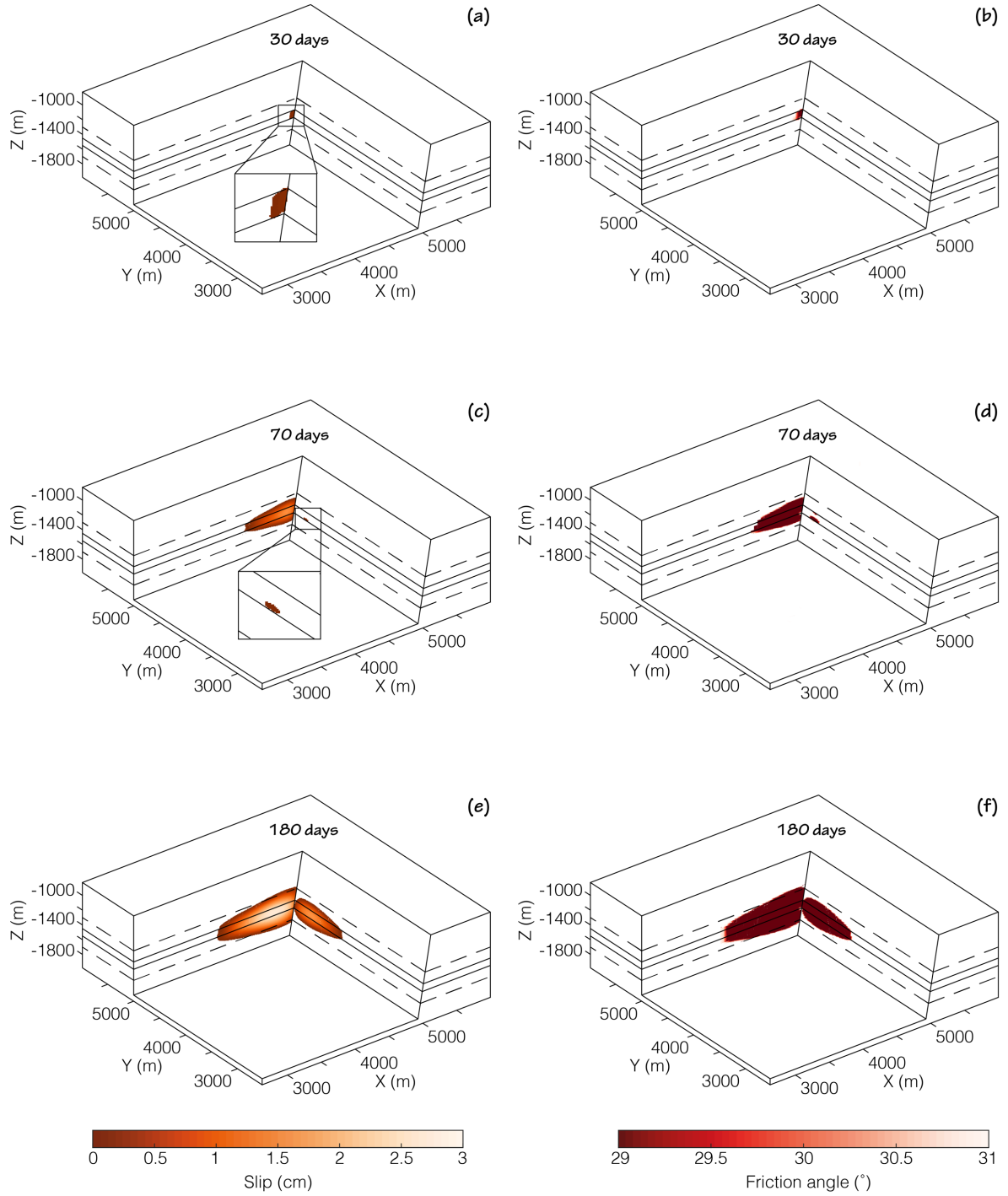


Figure 8. Distribution of plastic slip (a,b,c) and friction angle (d,e,f) at 30, 70, and 180 days of injection.

days of injection with a maximum slip of 0.2 cm, which involves only a small minor patch on the fault plane (Fig. 8c-d). Worth to note that while the injection continues, the rupture continues extending on the two faults, reaching a maximum extent after 180 days of injection, which is much shorter than the total injection time of 3 years. The rupture area is

larger on Fault 1 given the more optimal orientation for shear rupture with respect to the stress field.

## **5.2 Potential for fault reactivation during geological nuclear waste disposal**

The model presented in this section aims at understanding the stress and strain changes occurring at depth in a nuclear waste geological repository. We simulate the heat generated by several, parallel nuclear waste emplacement tunnels located in argillaceous clay host rock, i.e., following the Swiss concept for geological nuclear waste disposal (NAGRA, 2016). The use of a refined mesh allows for more details. Figure 9a shows the  $10 \text{ km} \times 10 \text{ km} \times 5.5 \text{ km}$  three-dimensional computational domain, with  $113 \times 102 \times 86$  elements in the three directions and starting at the ground surface. We simulate conditions during 2000 years after nuclear waste disposal in a repository located in a clay layer with anisotropic permeability at a depth of 700 m, and embedded within two seal formations as well as under- and overburden. Thanks to symmetry, we simulate only a quarter of the domain, and simulate 13 half-length tunnels. Each tunnel has a length of 450 m and the tunnels are 50 m apart. Each element of the tunnel has a finite volume with a heat source variable in time (Fig. 9b), and is connected to two elements of the main computational domain (Fig. 9a). The boundaries at  $x = 0 \text{ m}$  and  $y = 0 \text{ m}$  are closed to fluid flow and have null displacement normal to the boundary to simulate symmetry. The other boundaries are open to fluid flow and have constant lithostatic stress and hydrostatic pore pressure, with the exception of the bottom boundary where the normal displacement is blocked, and the pore pressure is set to  $\sim 54 \text{ MPa}$ . Initial conditions follow hydrostatic and geothermal ( $30 \text{ C}^\circ/\text{km}$ ) gradients, while we impose normal stress conditions with the lithostatic vertical

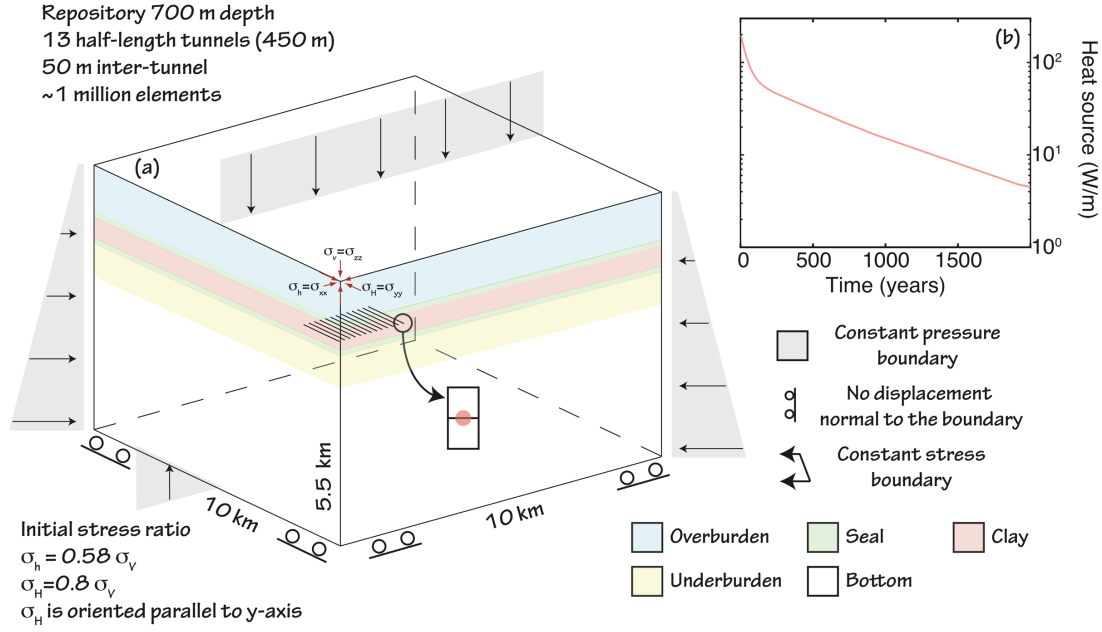


Figure 9. Computational domain for the study of potential fault reactivation during geological nuclear waste disposal.

stress ( $\sigma_v$ ) being the maximum principal stress and with  $\sigma_{xx} = \sigma_h$  as minimum principal stress. We impose stress ratios  $\sigma_h / \sigma_v = 0.58$  and  $\sigma_H / \sigma_v = 0.8$ . We simulate full thermo-hydro-mechanical coupling by assuming that the porosity depends on strain, pressure, and temperature. We neglect at the current stage any permeability variation as a function of the stress field. For simplicity, all the layers follow an elastic rheology, and we varied only the hydraulic properties (Table 2). We use here single-phase conditions, assuming that the tunnels are already fully saturated at hydrostatic pressure conditions after emplacement, i.e., ignoring some of the short-term re-saturation processes that may take tens of years (Rutqvist et al., 2014) as well as potential gas generation (Fall et al., 2014; Shaw, 2015). The full 2000 years are simulated in a bit more than 2 hours.

Figure 10 shows the temperature and pore pressure distribution at different times of evolution. Thermal effects are slower and only few  $^{\circ}\text{C}$  changes are observed 10 years after emplacement in the near repository region (Fig. 10a), but the temperature changes are large enough to enable so-called thermal pressurization, a phenomenon known to occur when

Table 2. Hydraulic and mechanical properties for the different domains in the deep geological repository case study. Note that for the clay layer, we assume anisotropic permeability.

|  | Soil              | Overburden        | Seal              | Clay                                | Underburden       | Bottom            |
|--|-------------------|-------------------|-------------------|-------------------------------------|-------------------|-------------------|
| Permeability ( $k_h/k_v$ ) ( $m^2$ )                     | $10^{-14}$        | $10^{-15}$        | $10^{-17}$        | $3 \cdot 10^{-19}/6 \cdot 10^{-20}$ | $10^{-17}$        | $10^{-18}$        |
| Porosity   | 0.1               | 0.1               | 0.05              | 0.074                               | 0.01              | 0.01              |
| Rock density ( $kg/m^3$ )                                | 2430              | 2430              | 2430              | 2430                                | 2430              | 2430              |
| Thermal conductivity ( $W/m \text{ } ^\circ C$ )         | 3.2               | 3.2               | 3.2               | 3.2                                 | 3.2               | 3.2               |
| Specific Heat ( $J/kg \text{ } ^\circ C$ )               | 920               | 920               | 920               | 920                                 | 920               | 920               |
| Young's modulus (GPa)                                    | 8                 | 8                 | 8                 | 8                                   | 8                 | 8                 |
| Poisson's ratio  | 0.27              | 0.27              | 0.27              | 0.27                                | 0.27              | 0.27              |
| Linear thermal expansion coefficient ( $^\circ C^{-1}$ ) | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-5}$                   | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-5}$ |

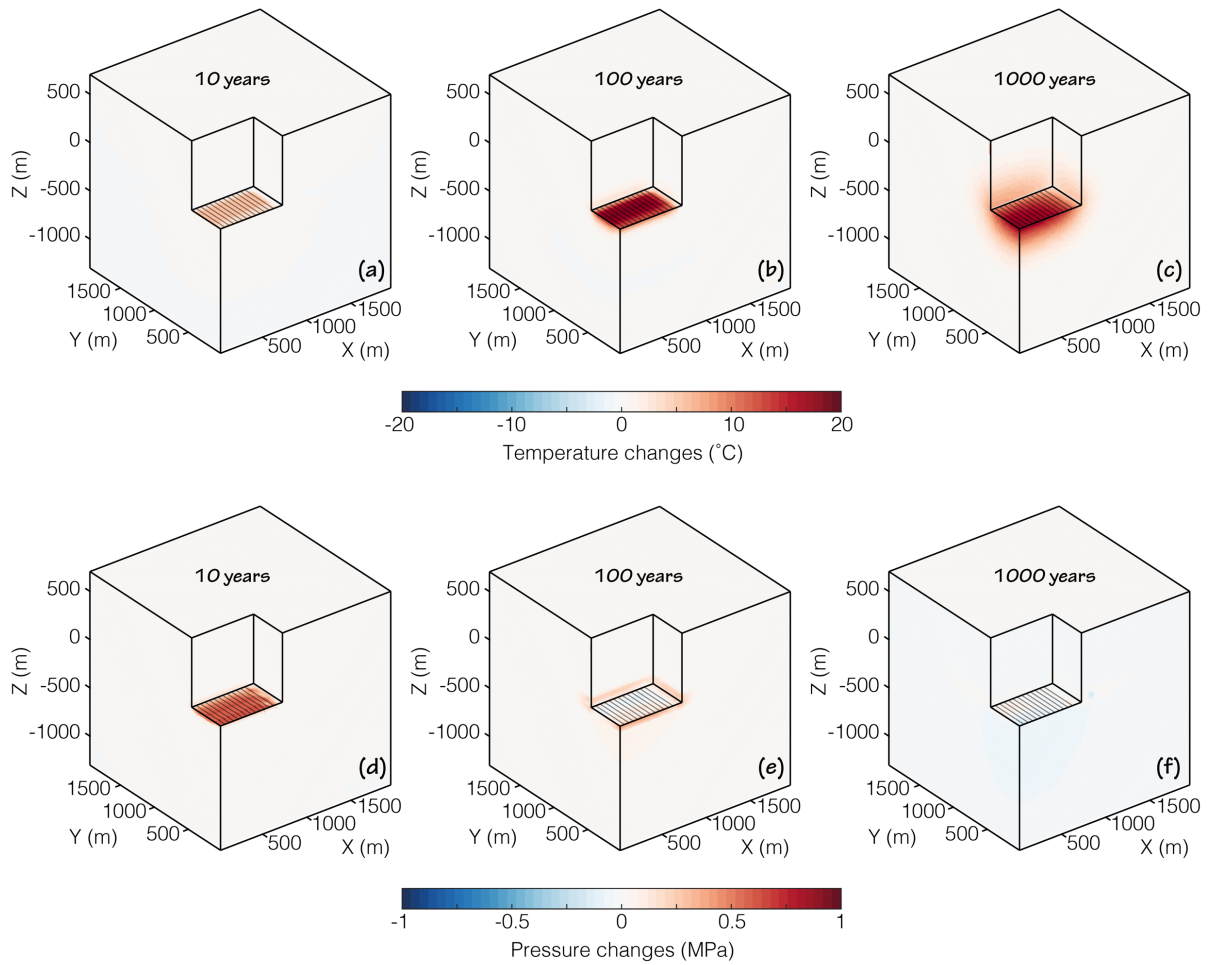
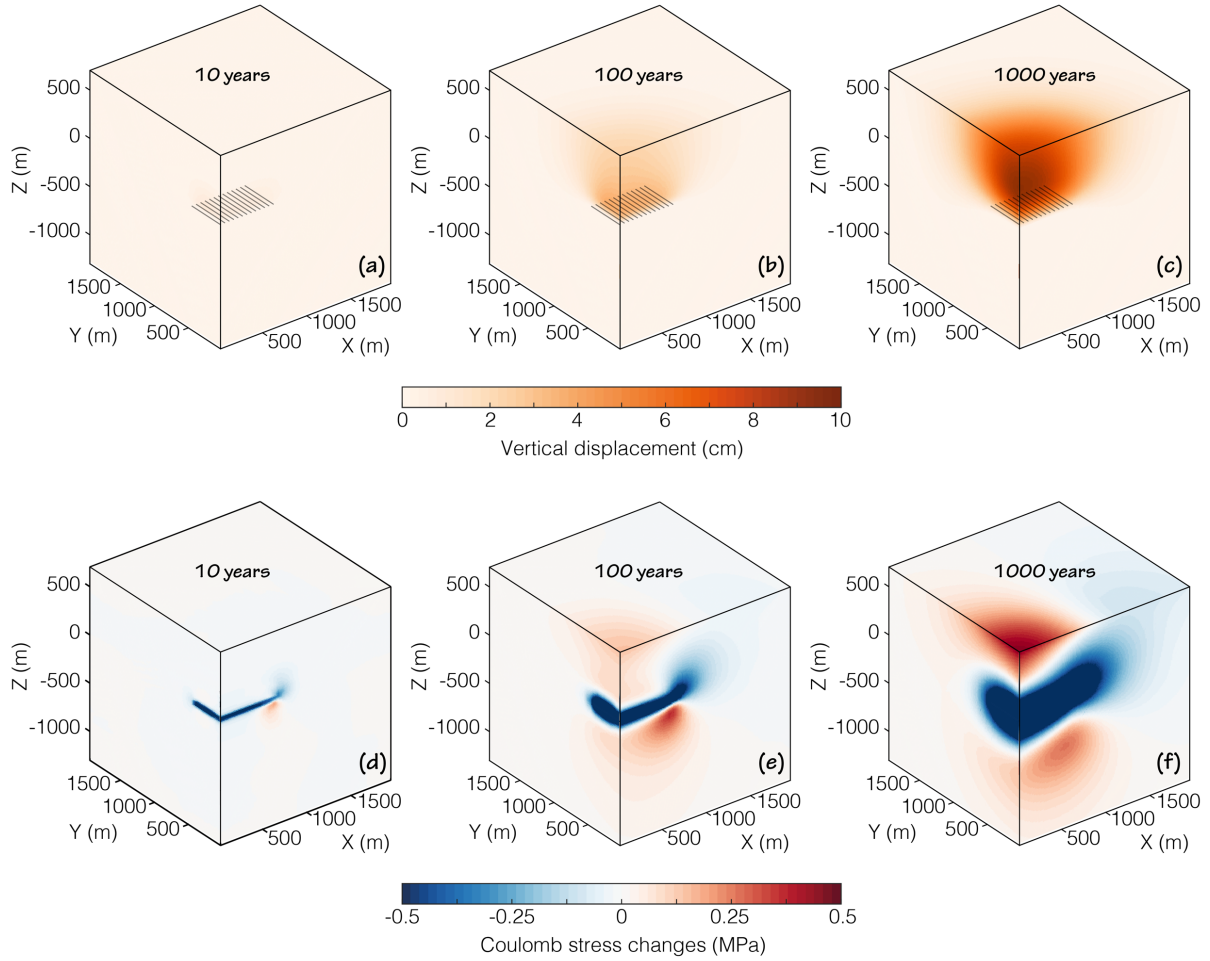


Figure 10. Distribution of changes in temperature (a,b,c) and pressure (d,e,f) in a deep geological repository for the storage of nuclear waste 10, 100, and 1000 years after emplacement.

heating pore fluids in low permeability rocks, such as shale (Gens et al., 2007; Ghabezloo and Sulem, 2009; Zhang et al., 2017). In this case, the thermal pressurization causes a relatively small pore pressure increase of about 1 MPa (Fig. 10d). The domain remains fully saturated.

At later stages, temperature changes start distributing in the domain up to several hundreds of meters outside the repository after 1000 years (Fig. 10c). At the same time, the pressure changes are diffused in the low permeable clay formation, and only minor changes are observed after 1000 years (Fig. 10f).

The temperature changes due to the heat generated by the nuclear waste can be responsible of quite large deformation at the ground surface, up to several cm uplift after 1000 years (Fig. 11a, b, and c). We also evaluated the potential for fault reactivation. Starting from the changes in the full stress tensor, we evaluate the Coulomb Stress change as  $\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta p)$ , where  $\Delta\tau$  is the change in shear stress,  $\Delta\sigma_n$  is the change in normal stress,  $\Delta p$  is the change in pore pressure and  $\mu$  is the friction coefficient, with the convention of stresses negative for compression. Shear and normal stresses are calculated for faults striking parallel to the tunnels and with 80° dip angle toward the repository (i.e., strike N180°). Figures 11d-f show how the repository itself is undergoing negative Coulomb stress changes, meaning that failure is hindered. At early times, the thermal pressurization is causing only more compression and stabilizing faults in the near repository region (Fig. 10d). Failure of the considered fault orientation is, however, favored at greater depth, where more seismogenic faults could be present. This is linked to the shear transfer caused by temperature changes, and it is then particularly relevant when the thermal effect starts distributing outside the clay formation (e.g., at 100 or 1000 years – Fig. 11e-f). These results are valid for steeply dipping faults and are well in agreement with a recent 2D study on fault reactivation during disposal of nuclear waste at depth (Urpi et al., 2019).



*Figure 11.* Distribution of vertical displacement (a,b,c) and Coulomb stress changes (d,e,f) in a deep geological repository for the storage of nuclear waste 10, 100, and 1000 years after emplacement. Coulomb stress is calculated for faults dipping  $80^\circ$  and striking  $N180^\circ$ , assuming the north is oriented in the  $y$ -direction.

## **6. CONCLUSION AND FUTURE OUTLOOK**

We coupled for the first time the recently released TOUGH3 with FLAC3Dv6/7. The results are well in agreement with analytical solutions and with the previous version of the simulator (TOUGH2-FLAC3Dv5). The coupled code can now use all the new functionalities of TOUGH3, including, among others, the flexibility of a Fortran 90 code and the use of PETSc. Together with the claimed improved solver performance, FLAC3Dv6/7 includes an internal link with Python scripting, which provides an average  $10\times$  faster I/O and variables assignment performance compared to the FISH programming embedded in FLAC3Dv5.



The removal of some bottlenecks, thanks to the use of binary files rather than ASCII, and the removal of save/restore operations for FLAC3D, largely helped in improving the performances of the coupled approach. The current coupled code allows up to 4-fold increase in execution speed for a two 6-core processors workstation compared to the previous version for a mesh with about 800,000 elements.

The possibility to run problems with very large number of elements in the computational mesh will enable a more detailed description of the thermo-hydro-mechanical processes occurring at depth. We have provided in this work two examples: one relates to fault reactivation during CO<sub>2</sub> sequestration, and the second one relates to nuclear waste disposal. For the first test case, we were able to simulate reactivation of intersecting faults during injection operations. The example highlights the time of induced fault reactivation for each fault. In the second test case, we demonstrate the use of the approach to simulate multiple emplacement tunnels at high details. Albeit simplified, the example shows the evolution of stress and strain in a deep geological nuclear waste repository, including the potential for fault reactivation.

Two main points, somewhat negative, are raised for the sake of completeness:

- It is worth to mention that TOUGH-FLAC is based on the use of commercial software. While the running scripts as well as the coupling may be obtained for reproducibility, a user would still need to acquire the independent licenses for both TOUGH3 and FLAC3D.
- The current coupled code, however, does not provide yet the improved performances that could be desired for High-Performance Computing in clusters. Certainly, a drawback with the use of TOUGH3-FLAC3D is the limitation to run exclusively on dedicated workstations (here tested on Windows-based machines). However, Itasca

plans on releasing a MPI version of their code in the future (Rutqvist, 2017), and the current version of TOUGH3-FLAC3D constitutes a strong base for future coupling.

## **ACKNOWLEDGMENTS**

The research was funded by a research agreement between ENSI and SED and by a Swiss National Science Foundation (SNSF) Ambizione Energy research grant (PZENP2\_160555). Funding for LBNL was provided by the Spent Fuel and Waste Disposition Campaign, Office of Nuclear Energy of the U.S. DOE, under Contract Number DE-AC02-05CH11231. The authors are grateful to Michael Ruthenberg and the BenVaSim community for useful discussions. Comments from two anonymous reviewers helped improving the paper.

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## SUPPLEMENTARY MATERIAL

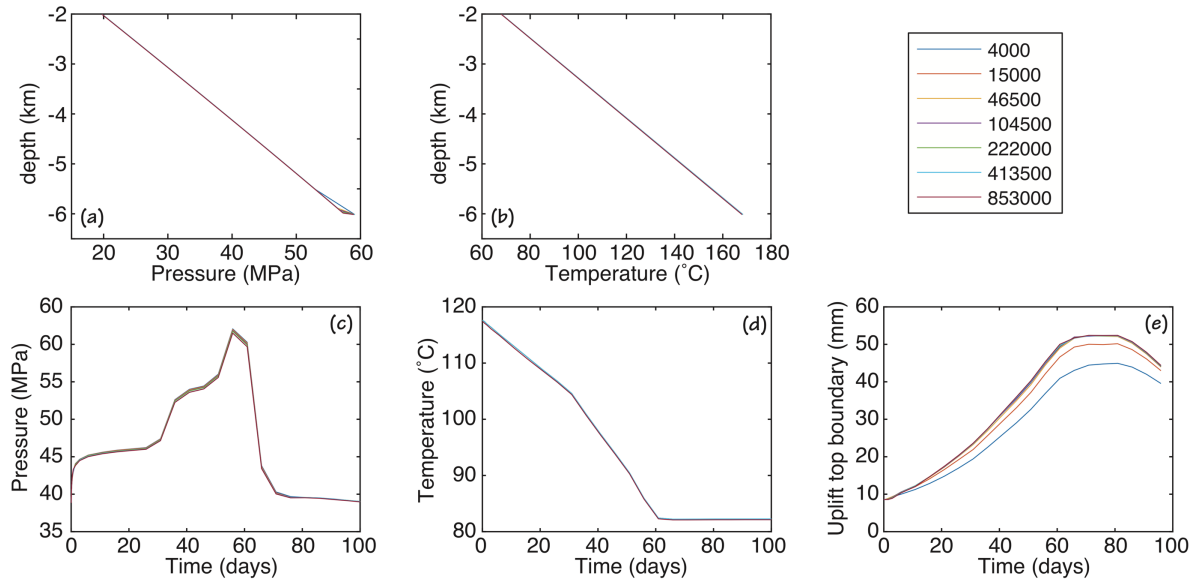


Figure S1. Simulations for different computational domain sizes: (a) Initial pressure; (b) Initial temperature; (c) Pressure evolution; (d) Temperature evolution; (e) Displacement of top boundary.

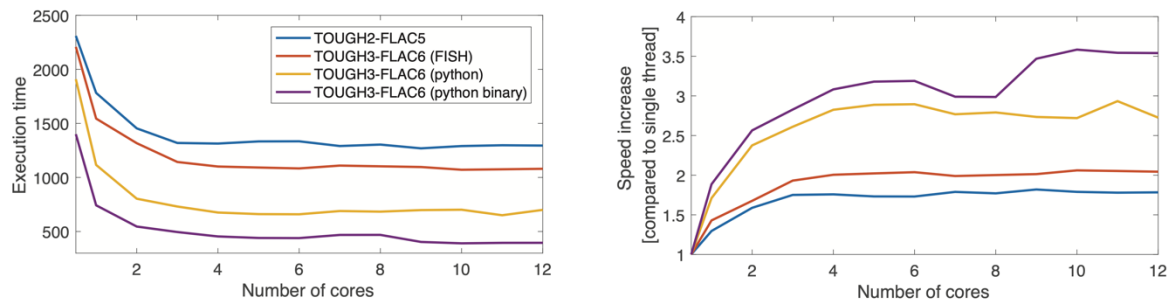


Figure S2. Execution time and speed increase with various versions of the coupling.