AMPHOS 21
SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

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Groundwater flow in the fractured system surrounding a nuclear waste repository

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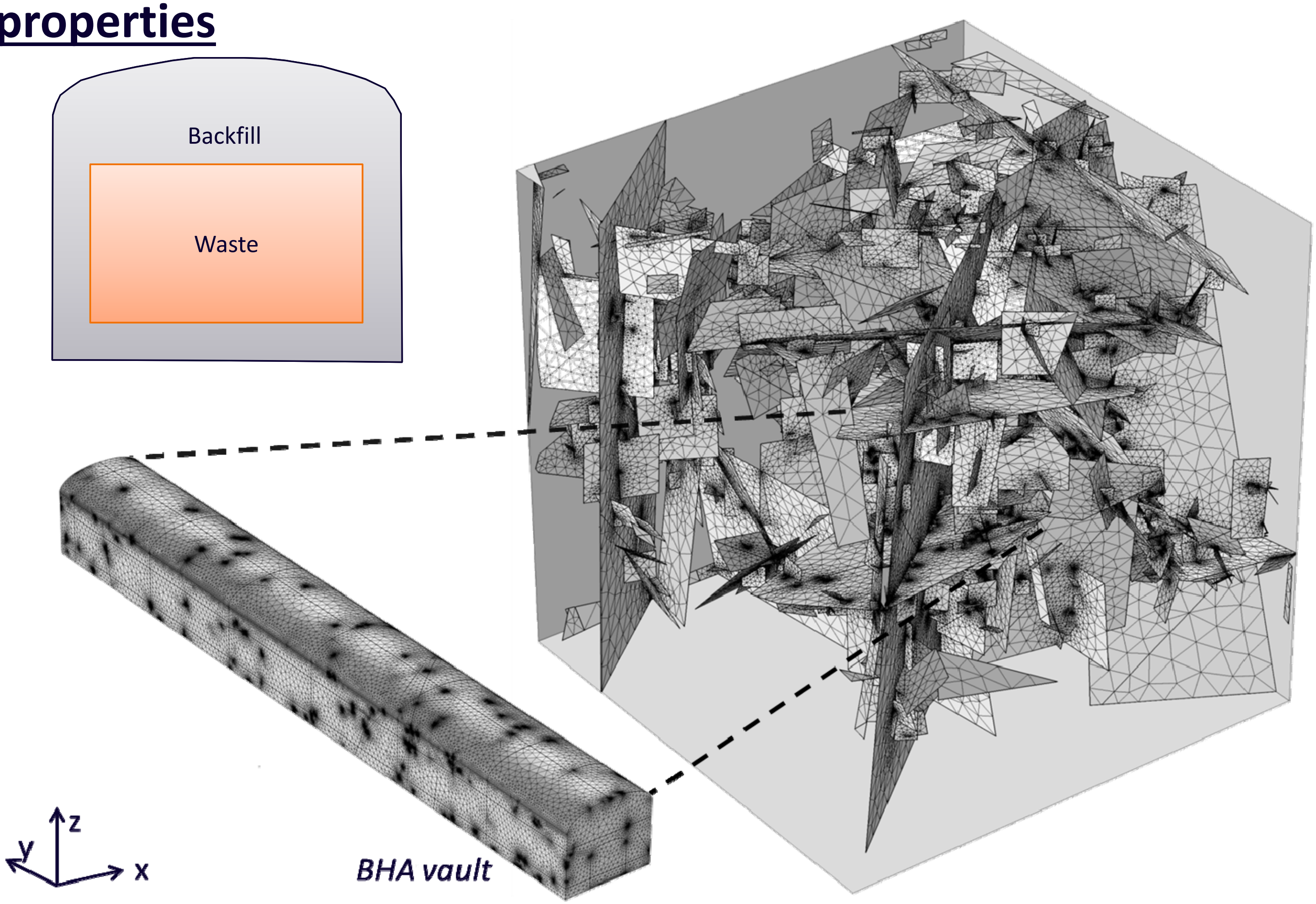
Geometry & Hydraulic/Transport properties

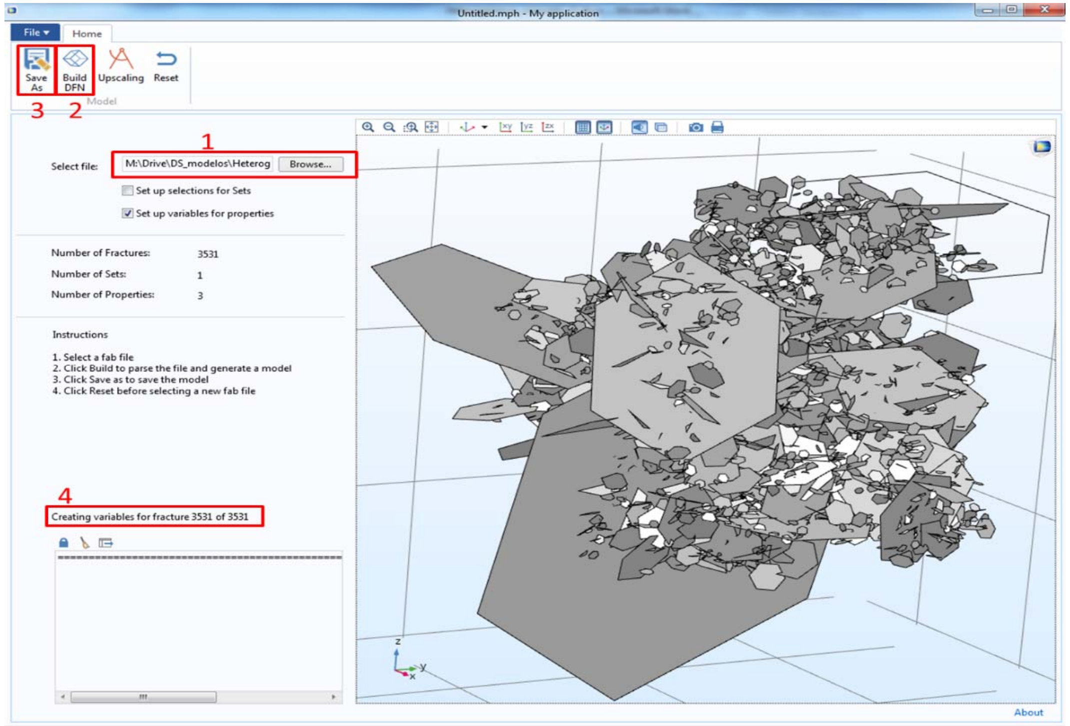
- The model considers a generic nuclear waste vault imbedded in the centre of a Discrete fracture network formed by 7,200 fractures.
- The domain is a cube of 400 meters length.
- The waste vault is formed by two materials: An homogenised waste surrounded by a low permeable backfill.
- The FEM used in the simulations is formed by 1,801,850 triangular elements and 1,963,025 tetrahedra.



Description	Material	K (m/s)	De (m²/s)	ϕ	Reference
Waste domain	Homogenized	$1.0\cdot10^{-7}$	$3.5\cdot10^{-10}$	0.30	(SKB 2014)
BHA vault backfill	Bentonite	$1.0\cdot10^{-13}$	$1.4\cdot10^{-10}$	0.43	(SKB 2010)

Geometry & Hydraulic/Transport properties

- The discrete fracture network (DFN) form part of a regional characterization of the host-rock that was generated using Connectflow (Hartley L and Holton D, 2003).
- The fracture network generated is characterized by heterogeneous hydraulic and transport properties such as transmissivity, storativity and aperture.
- The DFN is imported in Comsol using a custom utility app.



Select file: M:\Drive\DS_modelos\Heterog

☐ Set up selections for Sets

☑ Set up variables for properties

Number of Fractures: 3531

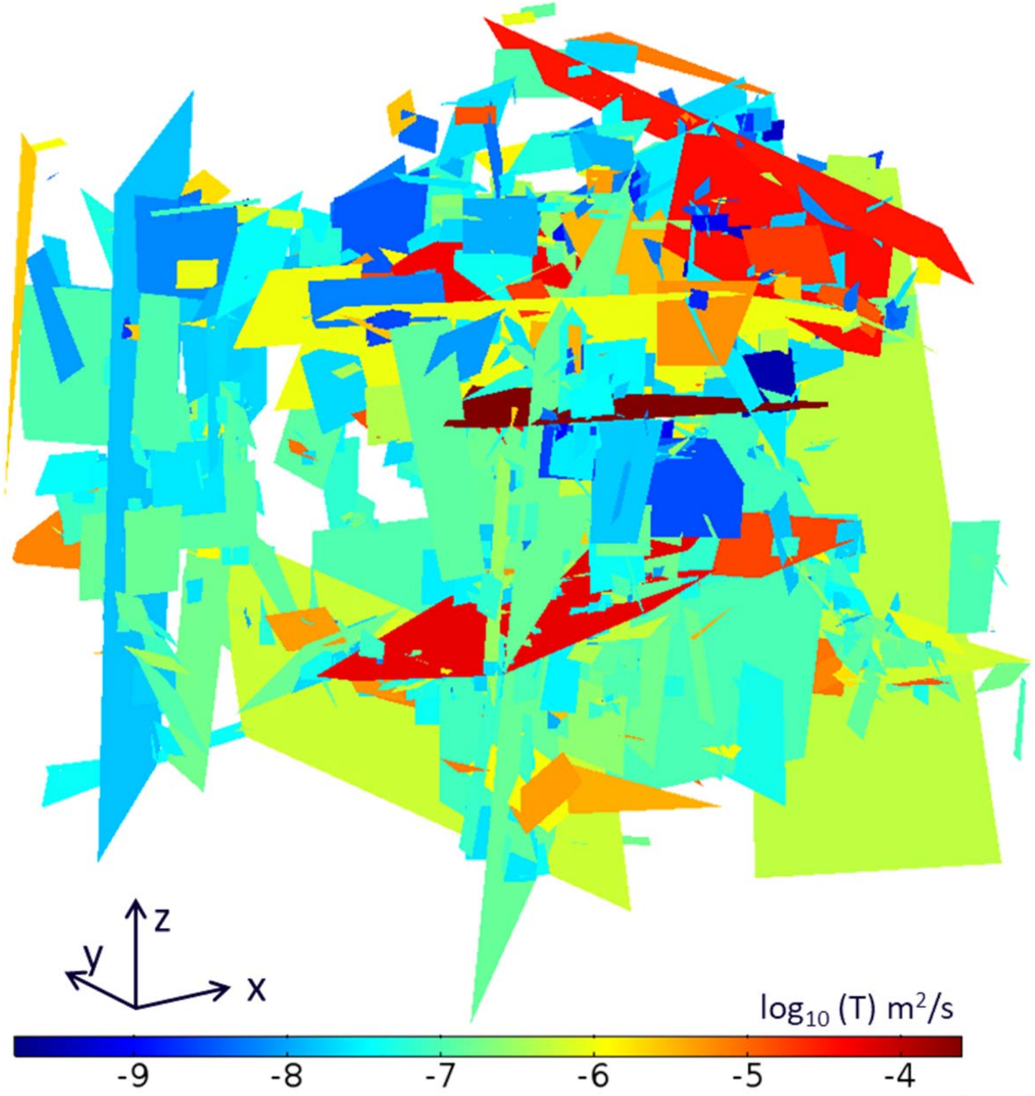
Number of Sets: 1

Number of Properties: 3

Instructions

1. Select a fab file
2. Click Build to parse the file and generate a model
3. Click Save as to save the model
4. Click Reset before selecting a new fab file

Creating variables for fracture 3531 of 3531



Governing equations

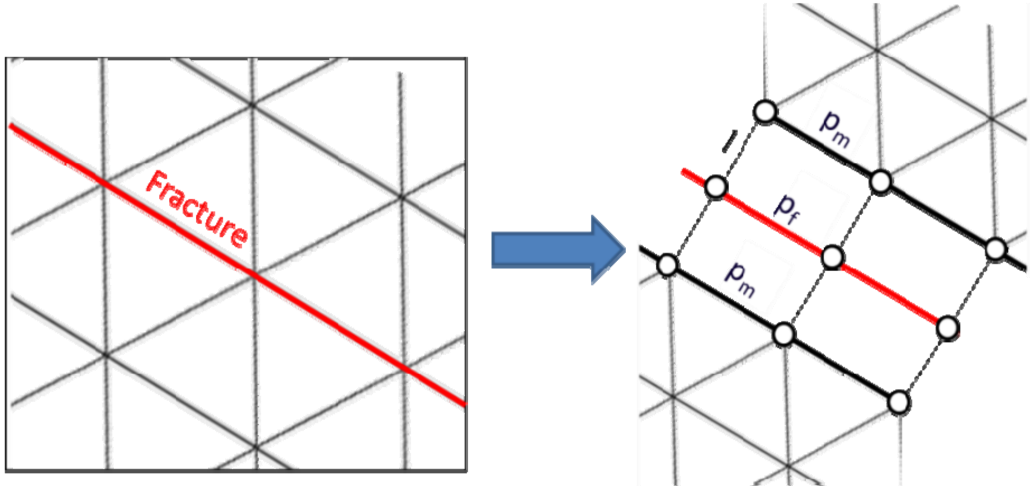
Groundwater flow

Porous media

$$\begin{cases} \rho S \dfrac{\partial p_m}{\partial t} + \nabla\rho\left[-\dfrac{k}{\mu}(\nabla p_m + \rho g \nabla z)\right] = Q_m \\ u = -\dfrac{k}{\mu}(\nabla p_m + \rho g \nabla z) \end{cases}$$

Fracture media

$$\begin{cases} d_f \dfrac{\partial}{\partial t}(\phi_f \rho_f) + \nabla_T(\rho q_f) = d_f Q_m \\ q_f = -\dfrac{k_f}{\mu} d_f(\nabla_T p_f + \rho g \nabla_T z) \end{cases}$$



- The coupling between both equations is carried out by a source/sink term with the following form:

$$\begin{cases} Q_m = -\alpha(p_m - p_f) \\ Q_f = -\alpha(p_f - p_m) \end{cases} \quad \text{where} \quad \alpha = \frac{k}{\mu} \cdot \frac{1}{l}$$

- α is a parameter that evaluates the connection between the two domains (matrix and fracture).
- Groundwater flow is solved in steady state by imposing the fluid pressure coming from a regional hydro model in the external boundaries .

Governing equations

Conservative transport

The coupling between both domains is analogous to the flow coupling.

- Two transport equations:

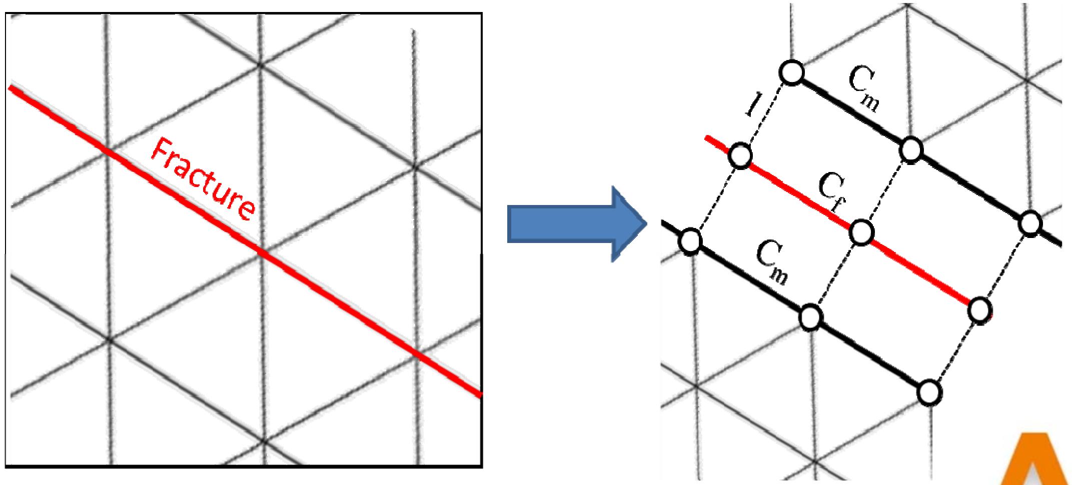
Porous media $$\left(\phi + \rho_b k_{p,i}\right)\frac{\partial c_i}{\partial t} + \left(c_i - \rho_p c_{p,i}\right)\frac{\partial \phi}{\partial t} + u\nabla c_i = \nabla\left[(D_d + D_e)\nabla c_i\right] + R_i$$

Fracture media $$d_{fr}\left(\frac{\partial \rho_b c_{p,i}}{\partial t} + \frac{\partial \phi_f c_i}{\partial t} + \nabla_t\left(D_{e,i}\nabla_t c_i\right) + u\nabla_t c_i\right) = d_{fr}R_i + n_o$$

- The coupling between both equations is carried out by a source/sink term with the following form:

$$\begin{cases} Q_m = -\beta(C_m - C_f) \\ Q_f = -\beta(C_f - C_m) \end{cases} \quad \text{where} \quad \beta = D_e \cdot \frac{1}{l}$$

- The transport is solved in a transient simulation of 500 k years.
- The simulation considers an initial release of 1 mol/m^3 in the waste domain.



Governing equations

First order decay

The simulation considers one conservative tracer and three different radionuclides that are affected by first order decay and linear sorption

Exponential decay equation:

$$c(t) = c_o e^{-\lambda t}$$

Partial derivative form of the decay term:

$$\frac{\partial c}{\partial t} = -\lambda c$$

First order decay and transport parameters

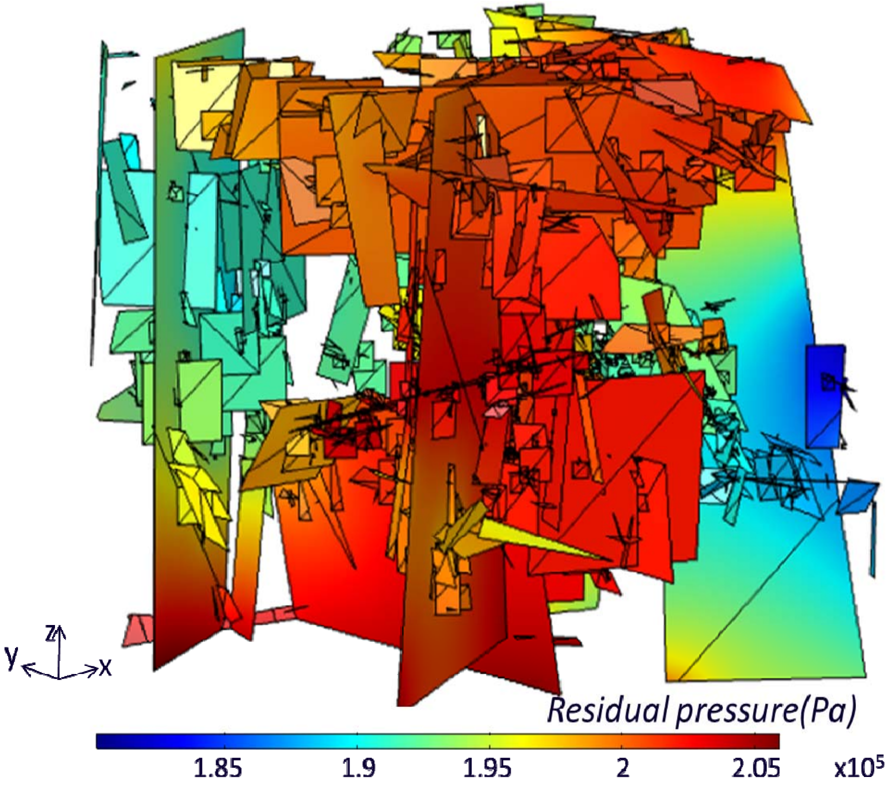
Three radionuclide are considered:

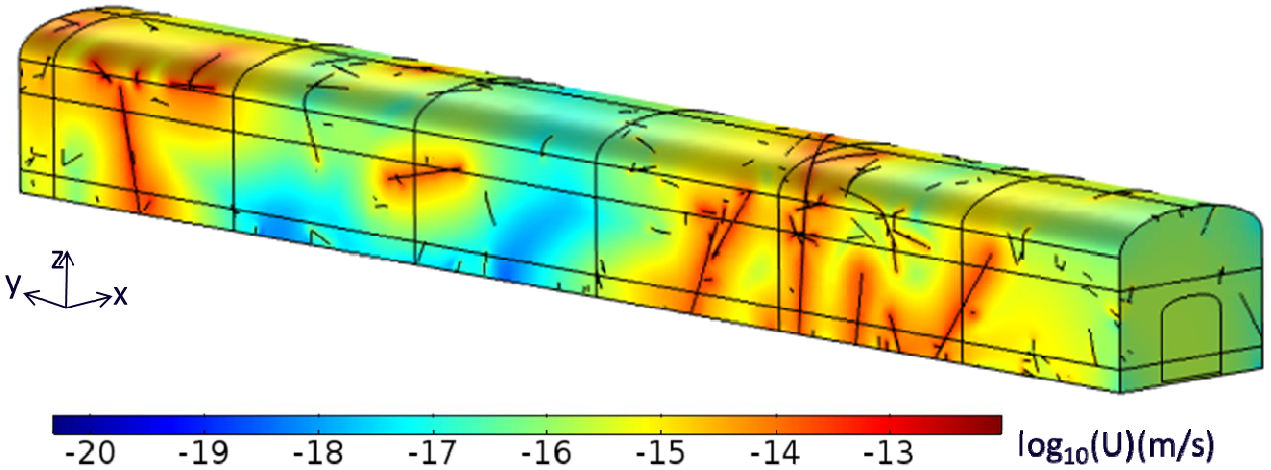
- Cl^{36}: Small decay and no-sorption.
- Mo^{93}: Quick decay and no-sorption.
- Cs^{135}: Small decay and high sorption.

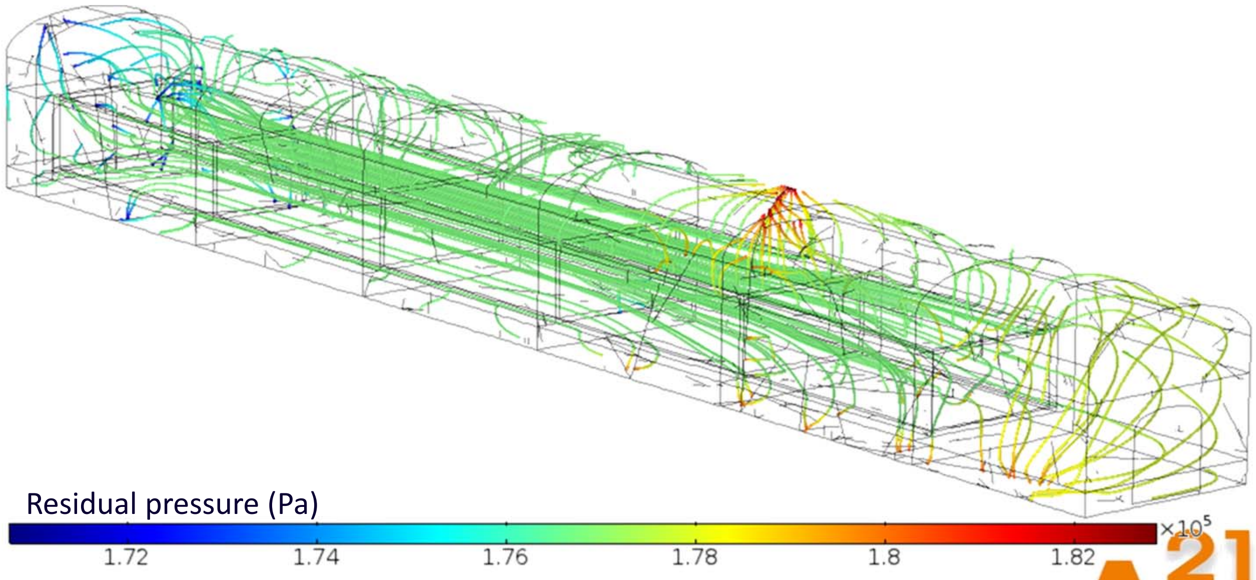
Isotope	**Kd m³/kg**		**Half life (y) $T_{1/2}$**
	Backfill	**Bedrock**	
Cl^{36}	0	0	3.01E+05
Mo^{93}	0	0	4.00E+03
Cs^{135}	1.10E-01	0	2.30E+06

Groundwater flow

Water pressure field coming from a regional hydrogeological model is imposed over the edges of the boundaries. The groundwater flow field is solved in steady state. Regional groundwater flow streams from West to East.

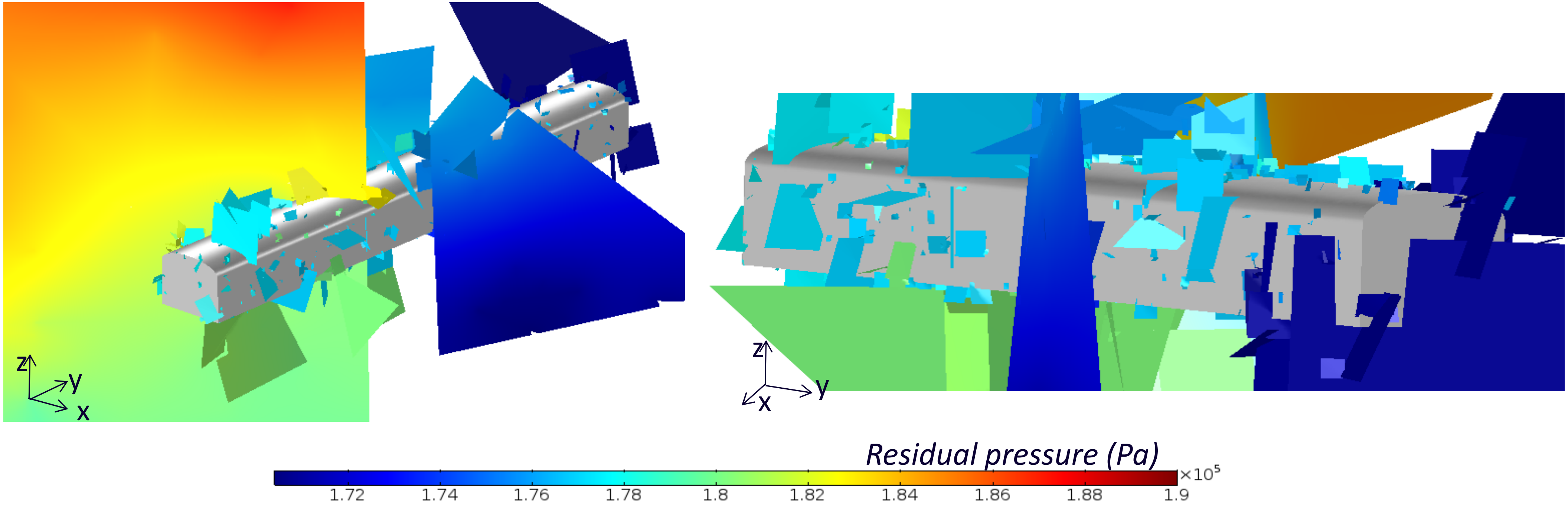




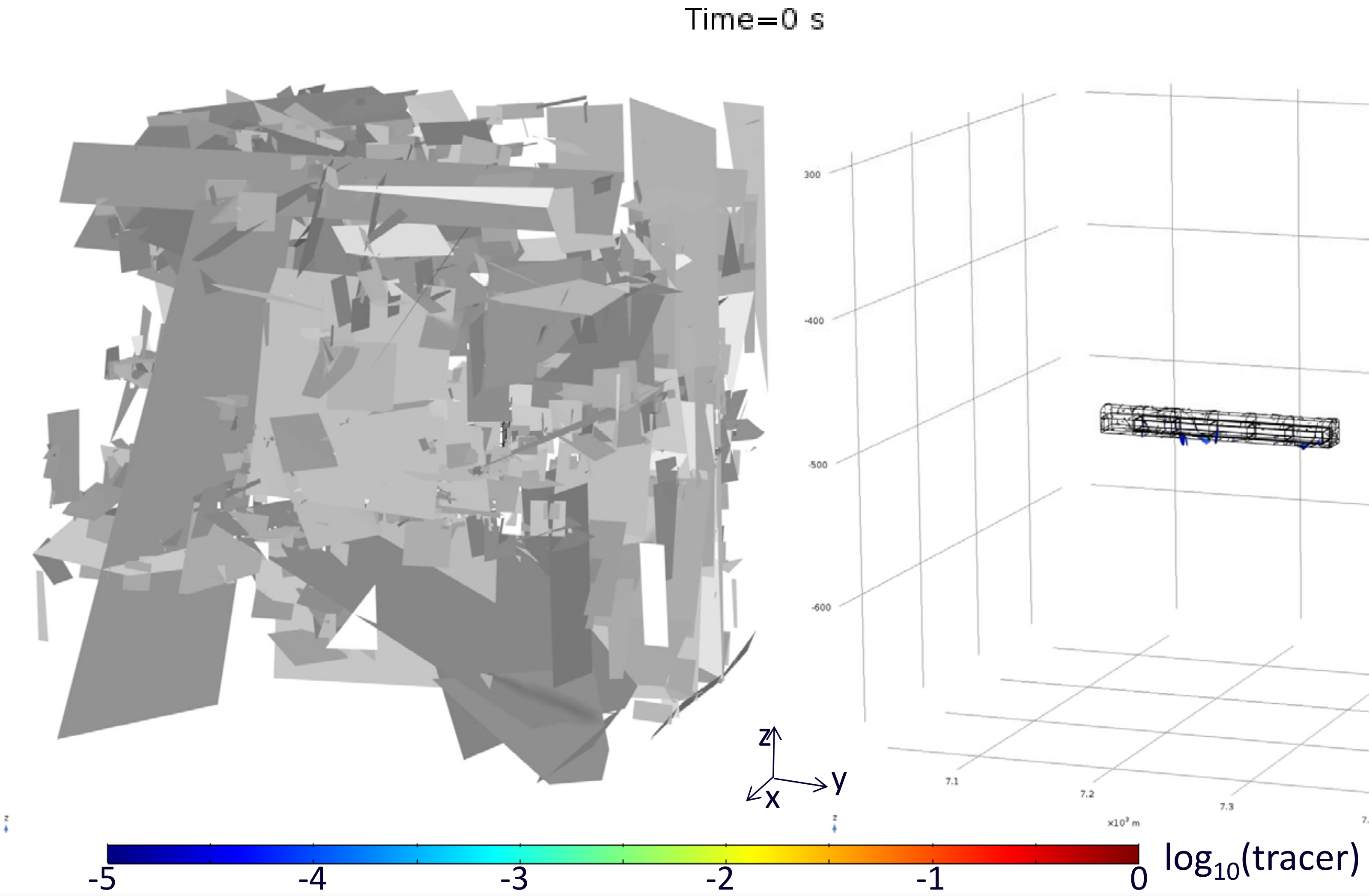


Groundwater flow

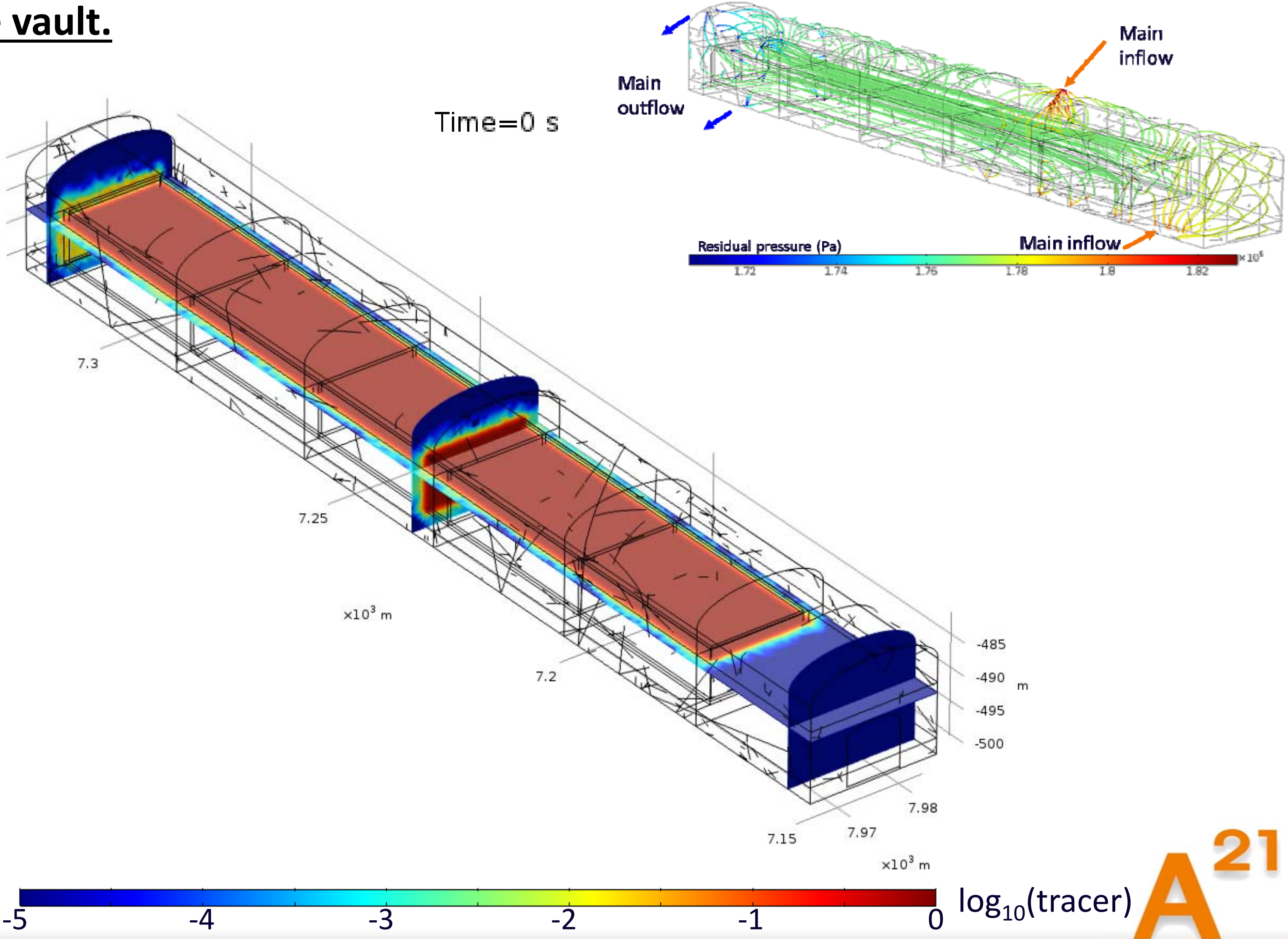
Regional groundwater flow streams from West to East. However, the groundwater through the vault is from South to North due to the local connectivity of the fractures.



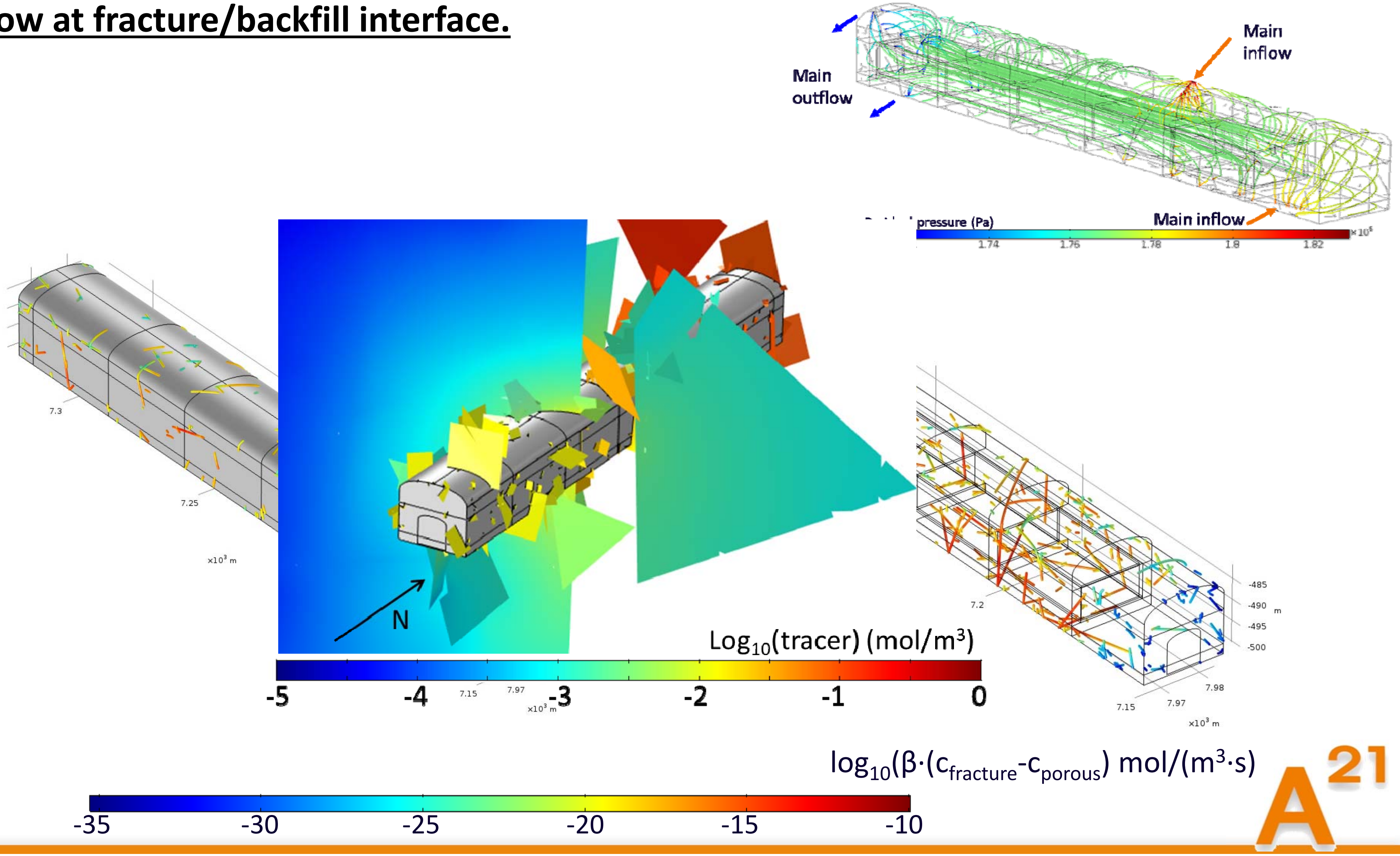
Tracer evolution in the fractures.



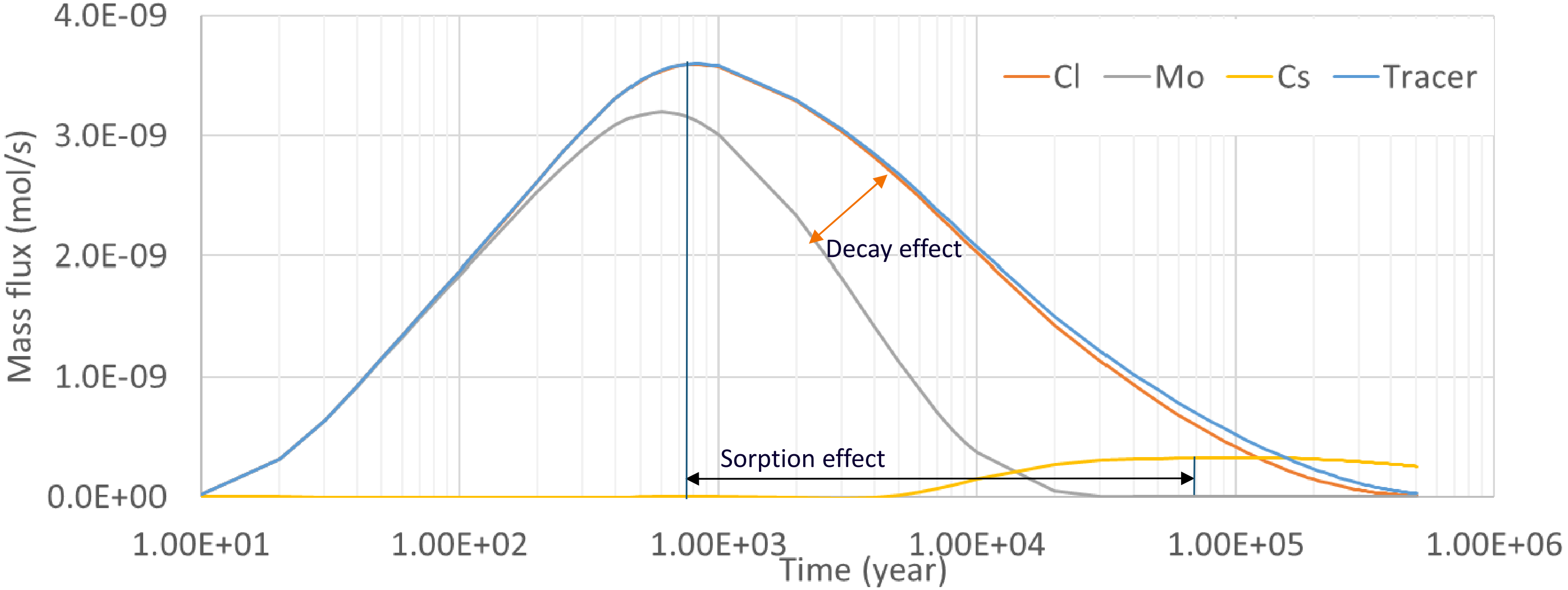
Tracer evolution in the vault.



Mass flow at fracture/backfill interface.



Breakthrough curves at the facture/backfill interface



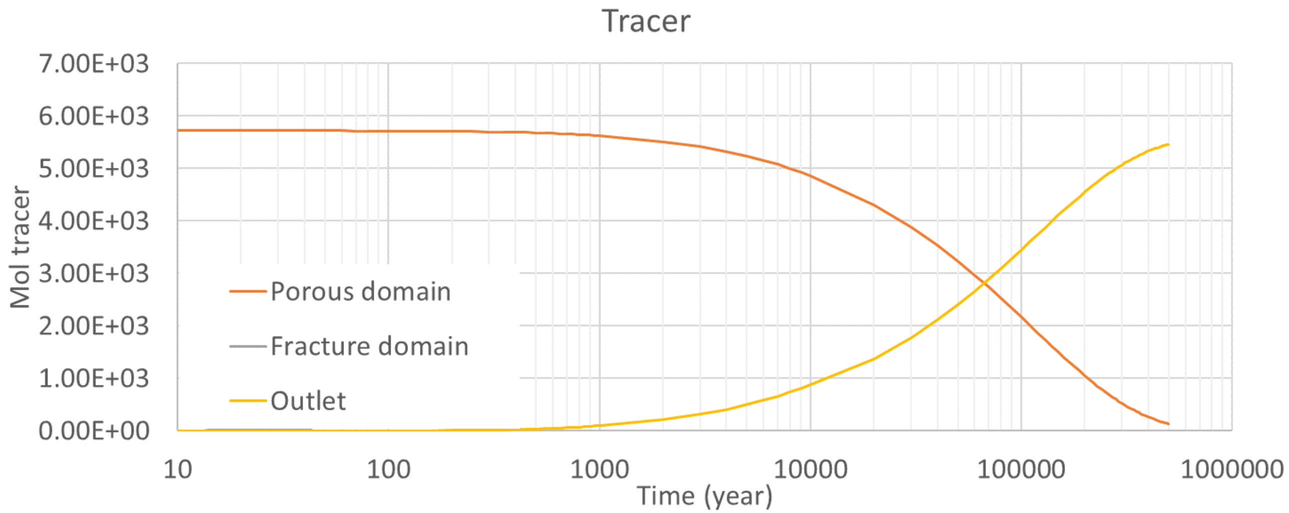
- Maximum release of tracer is observed at 8,000 years of simulation.

- The decay has an important effect in the release of Mollydenum whereas it is not important in the case of the Chloride.

- The higher Cesium sorption capacity produces a delay in the release of around 7000 years

Temporal evolution of the dissolved tracer in the different domains

- Temporal evolution of the dissolved mass in the different domains



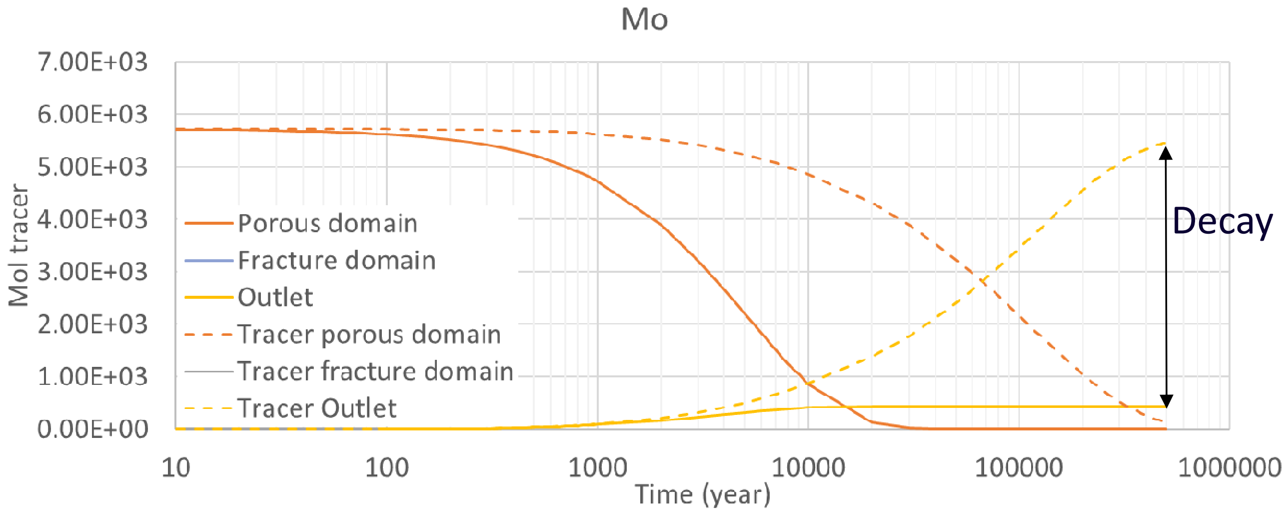
- The tracer spends around 1000 years to cross the backfill.

- The residence time in the fractures in very small due to the high velocities of the groundwater.

- All the tracer released leaves the modelled domain after 500,000 years.

Temporal evolution of the dissolved Molybdenum in the different domains

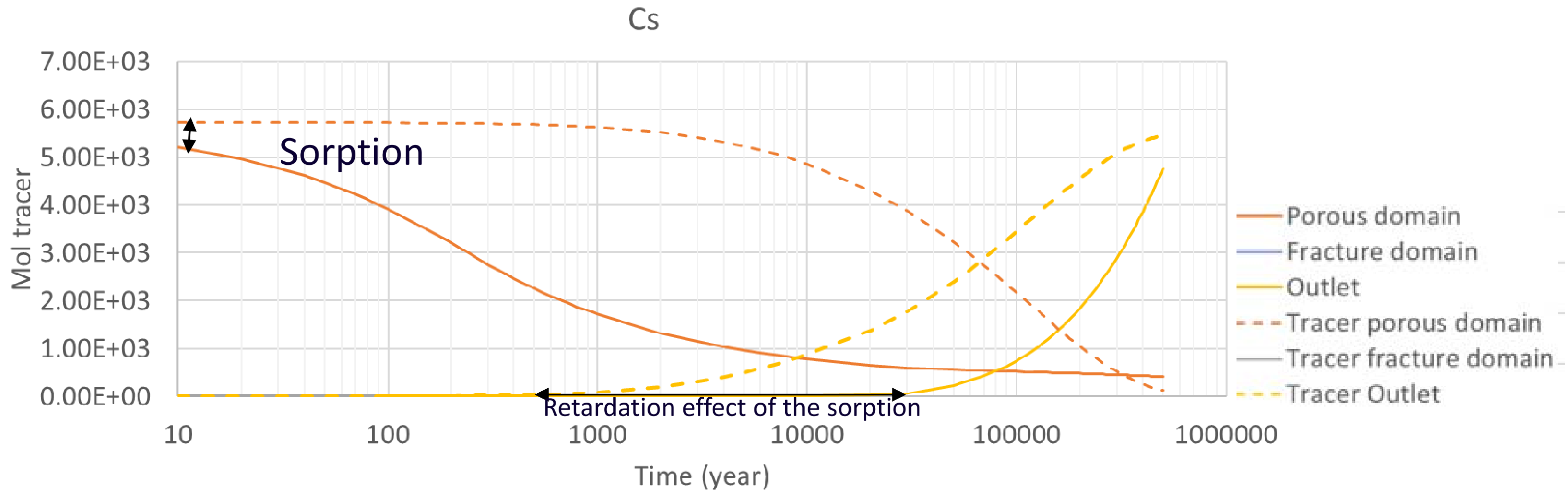
- Temporal evolution of the dissolved mass in the different domains



- The tracer spends around 1000 years to cross the backfill.
- The residence time in the fractures in very small due to the high velocities of the groundwater.
- All the tracer released leaves the modelled domain or has been decayed after 500,000 years.
- The higher half-life of the Molybdenum almost decay all the mass before leaving the domain.

Temporal evolution of the dissolved Cesium in the different domains

- Temporal evolution of the dissolved mass in the different domains

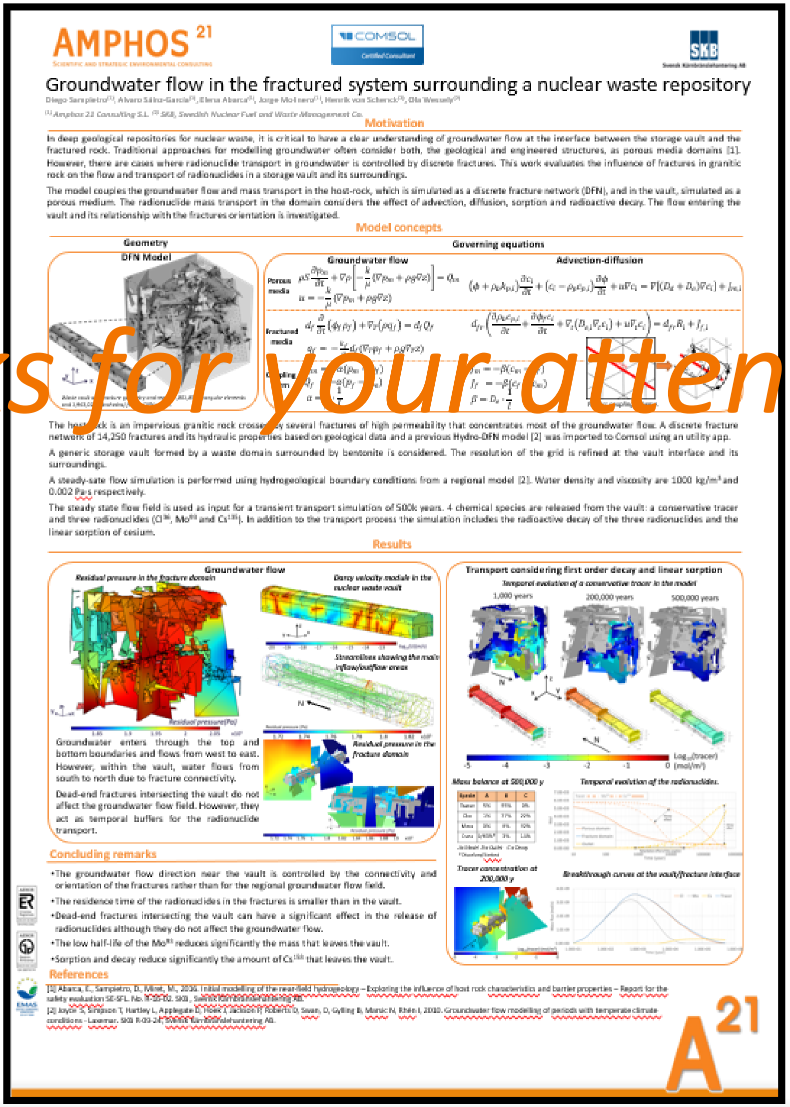


- The tracer spends around 1000 years to cross the backfill.
- The residence time in the fractures in very small due to the high velocities of the groundwater.
- After 500,000 years there is still Cesium sorbed in the backfill.
- The sorption retards around 30,000 years the first arrival of cesium to the model boundaries.

Concluding remarks

- Local groundwater flow crossing the repository is controlled by the connectivity of the fractures.
- The transport of radionuclides in the vault is governed by diffusion and convection whereas the transport in fractures is governed mainly by convection.
- The isolated fractures in contact with the repository doesn't have effect over the groundwater flow system whereas they have an storage effect over the release of radionuclides from the waste through the biosphere.
- The main effective barrier to the movement of the radionuclides is the bentonite backfill. The conservative tracer spends 1,000 years in begin to leave the backfill.
- The residence time of the radionuclides in the fracture domain is very small compared with the one in the backfill.
- The decay of radionuclides decreases the amount of dissolved radionuclides leaving the domain and also decrease the maximum mass flow release in the breakthrough curves evaluated at the fracture/interface.
- The sorption of Cesium retards the first release of Cesium from the vault 30,000 years.

Thanks for your attention



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[1] Amphos 21 Consulting S.L. [2] SKB, Swedish Nuclear Fuel and Waste Management Co.

Motivation

In deep geological repositories for nuclear waste, it is critical to have a clear understanding of groundwater flow at the interface between the storage vault and the fractured rock. Traditional approaches for modelling groundwater often consider both, the geological and engineered structures, as porous media domains [1]. However, there are cases where radionuclide transport in groundwater is controlled by discrete fractures. This work evaluates the influence of fractures in granitic rock on the flow and transport of radionuclides in a storage vault and its surroundings.

The model couples the groundwater flow and mass transport in the host-rock, which is simulated as a discrete fracture network (DFN), and in the vault, simulated as a porous medium. The radionuclide mass transport in the domain considers the effect of advection, diffusion, sorption and radioactive decay. The flow entering the vault and its relationship with the fractures orientation is investigated.

Model concepts

Geometry

DFN Model

Governing equations

Groundwater flow

Advection-diffusion

Porous media

Fractured media

The host rock is an impervious granitic rock crossed by several fractures of high permeability that concentrates most of the groundwater flow. A discrete fracture network of 14,250 fractures and its hydraulic properties based on geological data and a previous Hydro-DFN model [2] was imported to Comsol using an utility app.

A generic storage vault formed by a waste domain surrounded by bentonite is considered. The resolution of the grid is refined at the vault interface and its surroundings.

A steady-sate flow simulation is performed using hydrogeological boundary conditions from a regional model [2]. Water density and viscosity are 1000 kg/m^3 and 0.002 Pa·s respectively.

The steady state flow field is used as input for a transient transport simulation of 500k years. 4 chemical species are released from the vault: a conservative tracer and three radionuclides (Cl^{36}, Mo^{93} and Cs^{135}). In addition to the transport process the simulation includes the radioactive decay of the three radionuclides and the linear sorption of cesium.

Results

Groundwater flow

Residual pressure in the fracture domain

Darcy velocity module in the nuclear waste vault

Streamlines showing the main inflow/outflow areas

Residual pressure in the fracture domain

Groundwater enters through the top and bottom boundaries and flows from west to east. However, within the vault, water flows from south to north due to fracture connectivity.

Dead-end fractures intersecting the vault do not affect the groundwater flow field. However, they act as temporal buffers for the radionuclide transport.

Transport considering first order decay and linear sorption

Temporal evolution of a conservative tracer in the model

1,000 years

200,000 years

500,000 years

Mass balance at 500,000 y

Temporal evolution of the radionuclides.

Tracer concentration at 200,000 y

Breakthrough curves at the vault/fracture interface

Concluding remarks

- The groundwater flow direction near the vault is controlled by the connectivity and orientation of the fractures rather than for the regional groundwater flow field.
- The residence time of the radionuclides in the fractures is smaller than in the vault.
- Dead-end fractures intersecting the vault can have a significant effect in the release of radionuclides although they do not affect the groundwater flow.
- The low half-life of the Mo^{93} reduces significantly the mass that leaves the vault.
- Sorption and decay reduce significantly the amount of Cs^{135} that leaves the vault.

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Any question?

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Additional info