Multiphysics (coupling) between Deep Geothermal Water Cycle, Surface Heat Exchanger Cycle and Geothermal Power Plant Cycle

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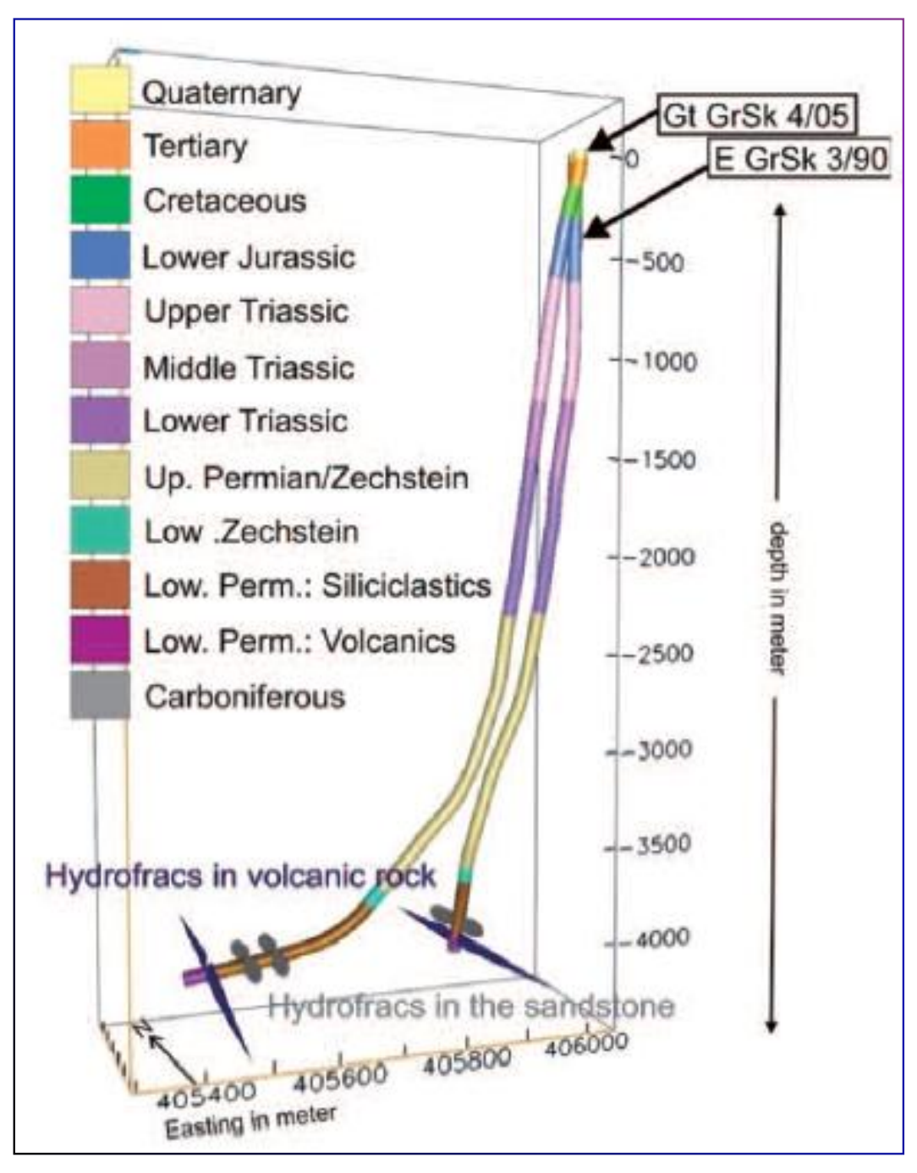
Introduction

Geographical coordinates	52° 54' 0" North, 13° 31' 0" East
Geographical location	Brandenburg, Germany (≈ 50km away from Berlin centre)
Geological setting	Lower Permian of Northeast German Basin (NEGB)
Depth	-3815m - -4247m bsl
Enthalphy, Concept	low enthalphy, Enhanced Geothermal System (EGS)
Rock classification	volcanic rock (Lower Rotliegend), siliciclastics (Upper Rotliegend)
Hydraulic induced fractures	**production well**: water fracture (low permeable volcanic rock), gel-proppant (high permeable sandstone) **injection well**: multi fracture (water fracture cum gel-proppant)
Major components	reservoir, hydraulically induced fractures, natural internal faults (f21n, f28, f29), production well Gt GrSk 4/05 , injection well E GrSk 3/90



Darcy's Law Physics Interface

Permeability, *k*, [m^2], is selected to specify the capacity of materials of f21n, f28 and f29 to transmit flow. Darcy's velocity, u, [m/s] :

$$\mathrm{u} = -\frac{k}{\mu}(\nabla p + \rho g \nabla D) \qquad (1)$$

Hydraulic conductivity, *K*, [m/s], is selected to define a combination of fluid permeability, *k*, [m^2] and dynamic viscosity, μ, [Pa·s] of each geological layer or the reservoir. Darcy's velocity, u, [m/s] :

$$\mathrm{u} = -\frac{K}{\rho g}(\nabla p + \rho g \nabla D) \qquad (2)$$

The approximate solution from Darcy's Law is expected to be continuous along the boundary between adjacent elements,

Continuity equation: $$\frac{\partial}{\partial \mathrm{t}}(\rho \epsilon_p) + \nabla \cdot (\rho \mathrm{u}) = Q_m \qquad (3)$$

Using COMSOL Multiphysics, homogenization of the porous and fluid media into a single medium is the alternative approach applied. Darcy's Law is combined with continuity equation, for instance (1) and (3) becomes (4).

$$\frac{\partial}{\partial \mathrm{t}}(\rho\varepsilon) + \nabla \cdot \rho[-\frac{k}{\mu}(\nabla p + \rho \mathrm{g} \nabla \mathrm{D})] = Q_m \qquad (4)$$

Time deriavative term of (4) is expanded to get (5). Porosity, ε and density, ρ are defined as functions of pressure, p, chain rule is applied to get (6).

$$\frac{\partial}{\partial \mathrm{t}}(\rho\varepsilon) = \varepsilon\frac{\partial\rho}{\partial \mathrm{t}} + \rho\frac{\partial\varepsilon}{\partial \mathrm{t}} \qquad (5)$$

$$\varepsilon\frac{\partial\rho}{\partial \mathrm{t}} + \rho\frac{\partial\varepsilon}{\partial \mathrm{t}} = \varepsilon\frac{\partial\rho}{\partial \mathrm{p}}\frac{\partial \mathrm{p}}{\partial \mathrm{t}} + \rho\frac{\partial\varepsilon}{\partial \mathrm{p}}\frac{\partial \mathrm{p}}{\partial \mathrm{t}} \qquad (6)$$

Definition of fluid compressibility (7) is inserted to the right hand side of (6) in order to rearrange to arrive at (8)

$$X_f = \left(\frac{1}{\rho}\right)\left(\frac{\partial\rho}{\partial \mathrm{p}}\right) \qquad (7)$$

$$\frac{\partial(\rho\varepsilon)}{\partial \mathrm{t}} = \rho\left(\varepsilon X_f + \frac{\partial\varepsilon}{\partial \mathrm{p}}\right)\frac{\partial \mathrm{p}}{\partial \mathrm{t}} = \rho \mathrm{S}\frac{\partial \mathrm{p}}{\partial \mathrm{t}} \qquad (8)$$

Final governing equation is $$\rho \mathrm{S}\frac{\partial \mathrm{p}}{\partial \mathrm{t}} + \nabla \cdot \rho[-\frac{k}{\mu}(\nabla \mathrm{p} + \rho \mathrm{g} \nabla \mathrm{D})] = Q_m \qquad (9)$$

Heat Transfer in Fluid Physics Interface

Volume fraction of reservoir solid material, θ_p, [1] takes the value of θ_p = 1 - ε, with different λ, [W/m*K] of each geological layer, heat transfer in reservoir solid material in a stationary state is (10) and that in a time dependant state is (11).

$$\rho C_p \mathrm{u} \cdot \nabla T = \nabla \cdot (\lambda \nabla T) + Q$$

$$\lambda = \lambda_{eq}$$

$$\lambda_{eq} = \theta_p \lambda + (1 - \theta_p)\lambda \qquad (10)$$

Temperature solution from a stationary state is implemented as initial temperature for a time dependant state with a *m* number of nodes in the mesh, in the form of interpolated function, *int*, of depth, as shown in (12).

$$\rho C_p \frac{dT}{dt} + \rho C_p \mathrm{u} \cdot \nabla T = \nabla \cdot (\lambda \nabla T) + Q$$

$$\lambda = \lambda_{eq}$$

$$\lambda_{eq} = \theta_p \lambda + (1 - \theta_p)\lambda$$

$$\rho C_p = (\rho C_p)_{eq}$$

$$(\rho C_p)_{eq} = \theta_p \rho_p C_{p,p} + (1 - \theta_p)\rho C_p \qquad (11)$$

$$\sum_{i=1}^{m} int\,(x, y, z)\, T_0 \qquad (12)$$

Numerical Model

Using COMSOL Multiphysics, deviated Gt GrSk 4/05 is represented by 1D Bézier curve, as well as E GrSk 3/90. f21n, f28, f29 and four major hydraulically induced fractures are represented by 2D linear curve extrusion from workplanes.

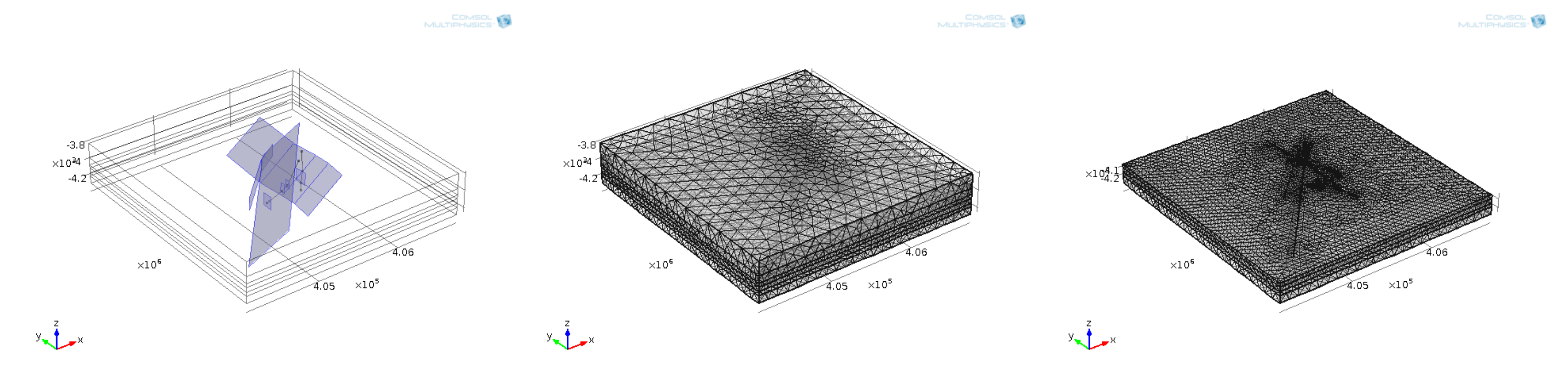


Figure 1. 2D geometries are discretized into triangular mesh elements and 3D geometries into tetrahedral mesh elements

Results

Within Groß Schönebeck framework, aperture, d_{fr}, [m], of hydraulically induced fractures is 2.28E-04m. Elbe Base Sandstone layer of the North German Basin possesses the highest permeability, k_r, [m^2], 7.90E-15m^2.

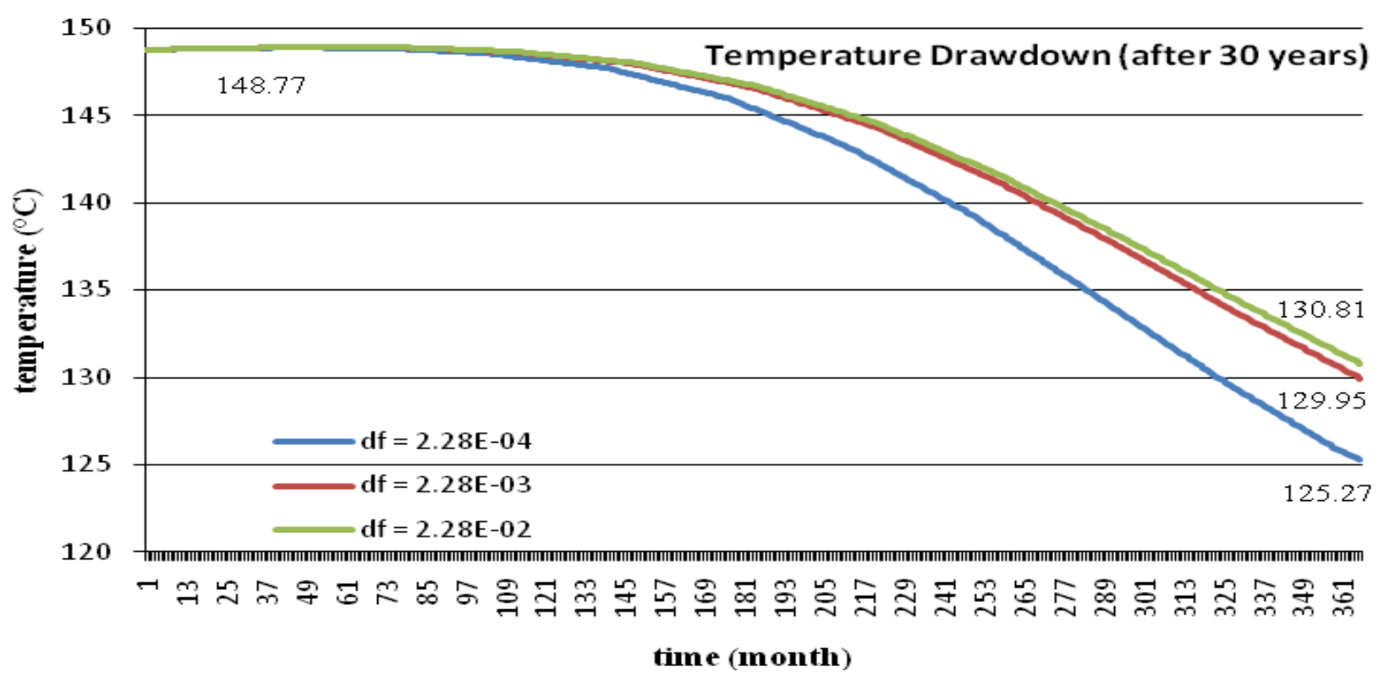


Figure 2. If aperture of internal faults zone, d_f, [m] = d_{fr}, production temperature drawdown is 23.50°C and is reduced with the increment in d_f, from d_f = 10*d_{fr} to d_f = 100*d_{fr}, by 4.68°C and 7.34°C respectively

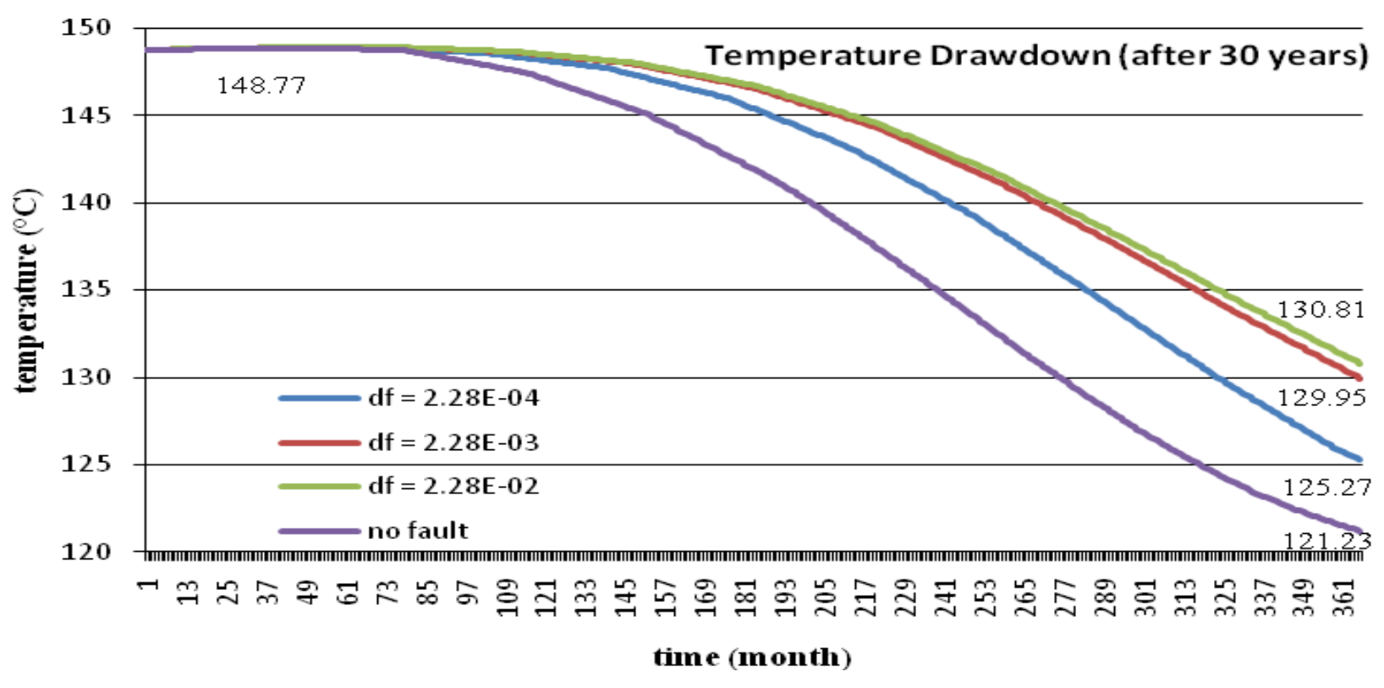


Figure 3. A drawdown in production temperature of 27.54°C in a non fault system and 23.50°C in a faulted system after 30 years. The latter production temperature drops from 148.77°C to 125.27°C

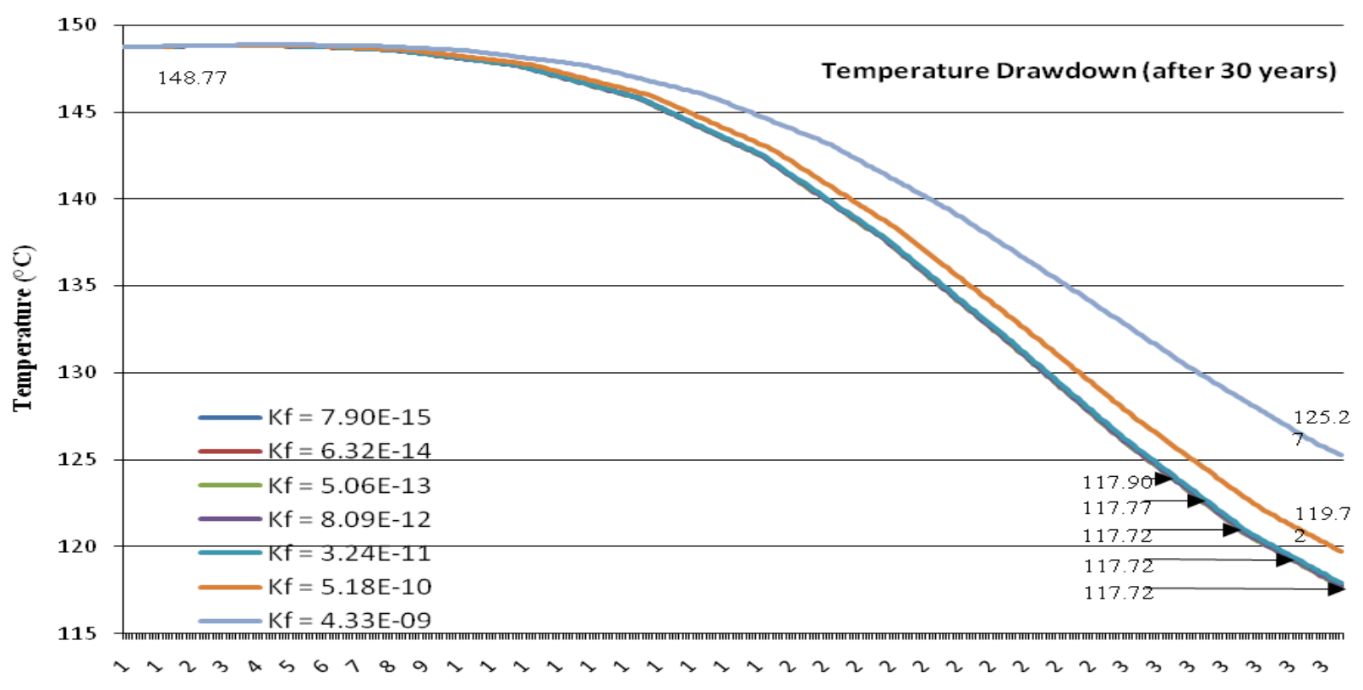


Figure 4. When d_f = d_{fr} and *k*, [m^2] of f21n, f28 and f29, k_{fr} = 4.33E-09m^2, production temperature drawdown increases with the decrease in *k* of internal fault zones, k_f,for instance 29.05°C when k_f = 1.02E-01*k_{fr}. It stays constant gradually when k_f approaches k_r

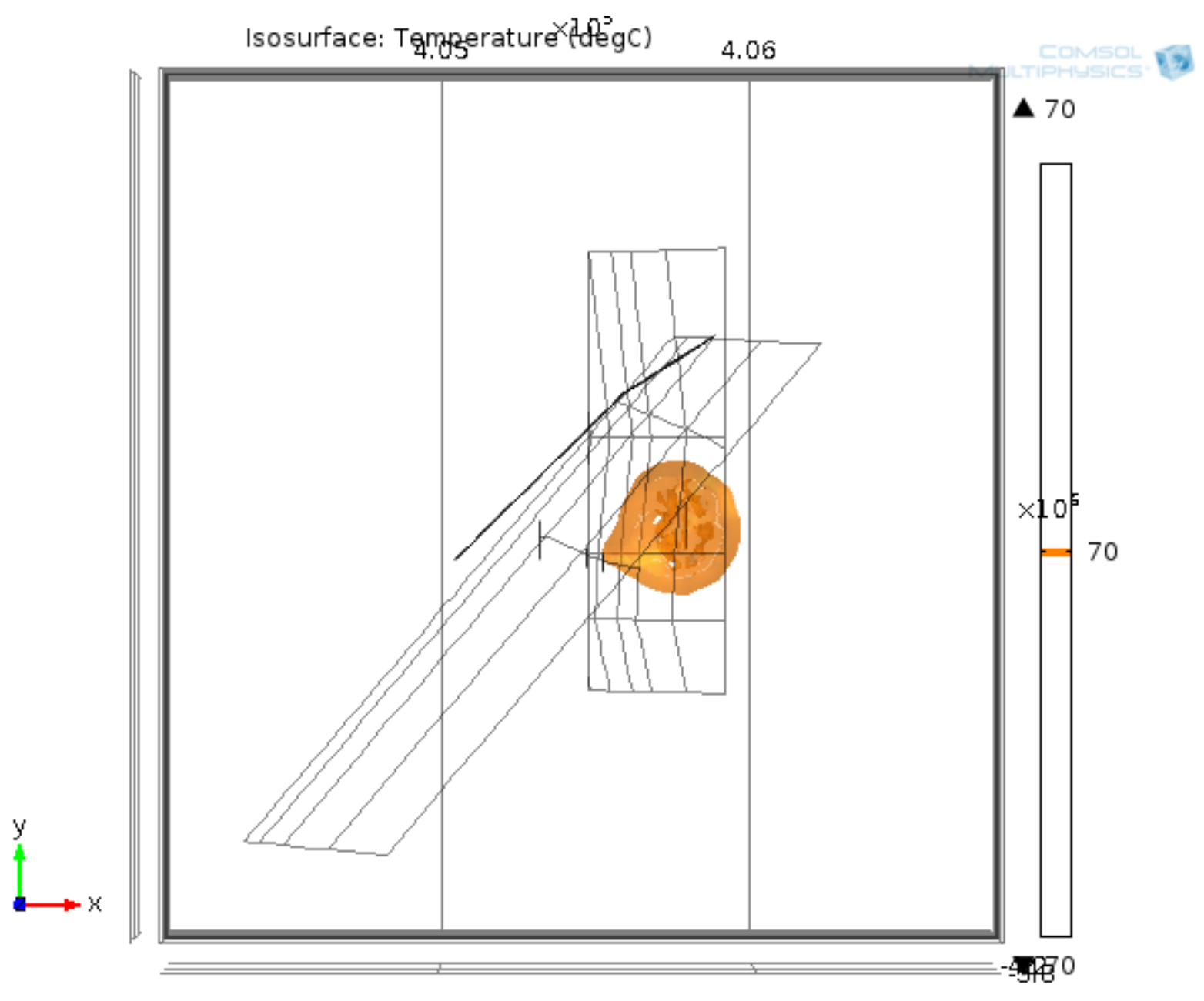


Figure 5. Cold water front (70°C) from E GrSk 3/90 propagates and reaches the second gel-proppant fracture along Gt GrSk 4/05 after 30 years, causing a significant drop of production temperature to 125.27°C

Future Work

Geothermal water cycle will be linked via an interface to surface heat exchanger cycle before another further coupling with the power plant cycle.

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