Thermo-Hydraulic Modeling of the Northern Upper Rhine Graben using OpenGeoSys

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1. Introduction

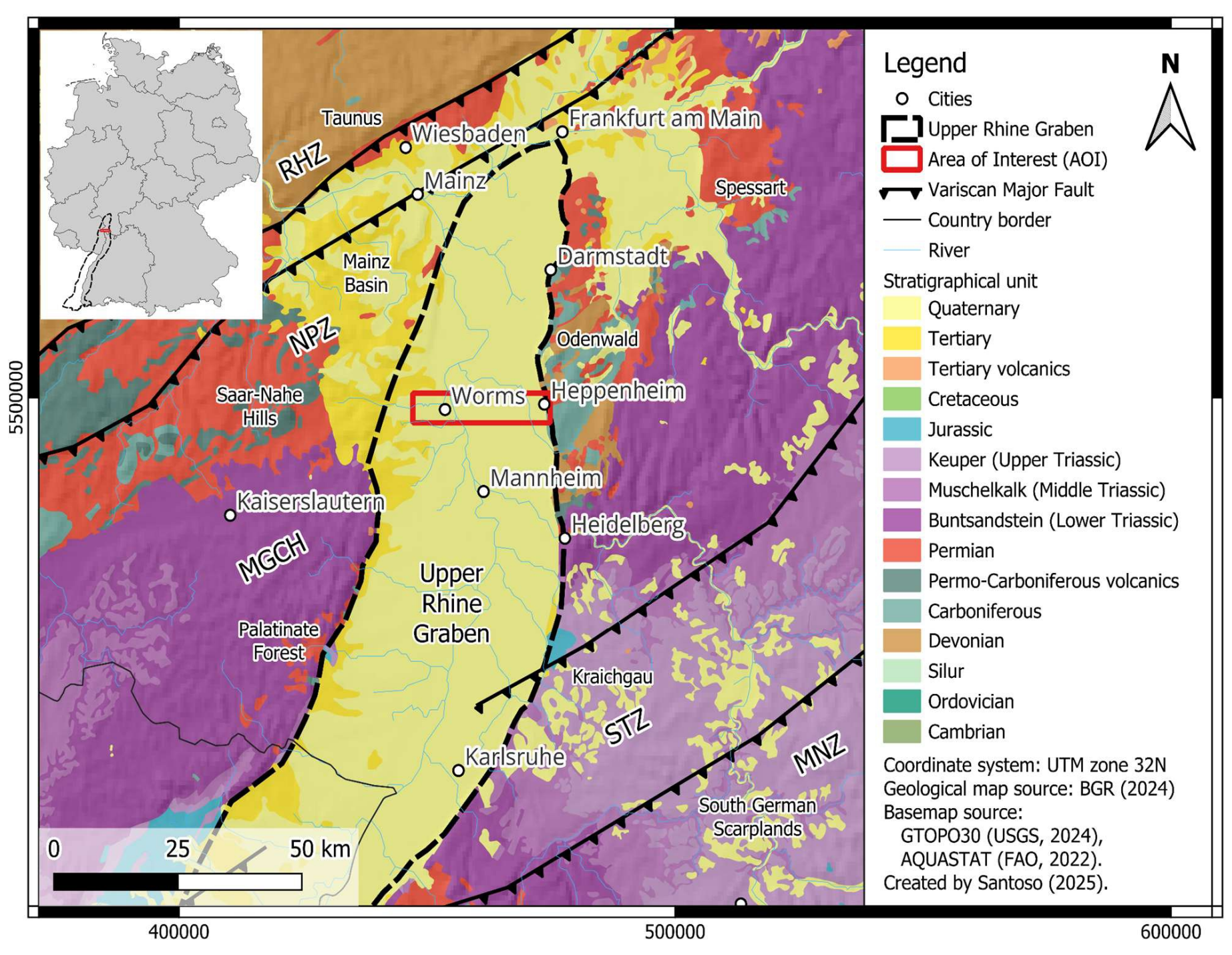
Efficient geothermal reservoirs require high permeability, elevated geothermal gradients, and active fluid flow to ensure sufficient wellhead temperature and productivity. The Upper Rhine Graben (URG) provides favourable conditions with positive temperature anomalies and permeable fault zones driving hydrothermal convection [1]. Coupled Thermo-Hydraulic (TH) simulations using the open-source software OpenGeoSys (OGS) [2] can help predict these convection cells. The 3D geological model is based on the Artemis [3], GeORG [4], Hessen 3D 1.0 & 2.0 [5][6], and DGE-ROLLOUT [7] projects.

2. Goals

- Creating a **workflow** for integrating 3D geological model from Petrel into OGS
- Performing **coupled 3D TH simulations** of the Northern URG
- Predicting and analyzing the development of **hydrothermal convection cells**

3. Geological and Model Setting

- **Location:** Worms to Heppenheim
- **Overburden:** Cenozoic Rocks, Rotliegend
- **Basement:** Mid-German Crystalline High



Coordinate system: UTM zone 32N
Geological map source: BGR (2024)
Basemap source:
GTOPO30 (USGS, 2024),
AQUASTAT (FAO, 2022).
Created by Santoso (2025).

Figure 1: *Geological map of the Northern URG (RHZ: Rhenohercynian Zone, NPZ: Northern Phyllite Zone, MGCH: Mid-German Crystalline High, STZ: Saxothuringian Zone, MNZ: Moldanubian Zone). Coordinate system: ETRS89 / UTM zone 32N.*

Mesh type: 3D structured hexahedral mesh
Geometry size (N-S, W-E, depth): (6, 28, 5) km
Voxel res. (Δx, Δy, Δz): (100, 100, 100) m
BCs: **Top:** Dirichlet BC ($T = 9.5$ °C , $p = 1$ bar)
Bottom: Neumann BC ($q = 80$ mW/m²)
Sides: Neumann BC (no-flow)

Total nodes:
822,324 nodes
Total elements:
789,450 voxels
Total simulated time:
105,000 years

4. Basic Physics and Parametrization

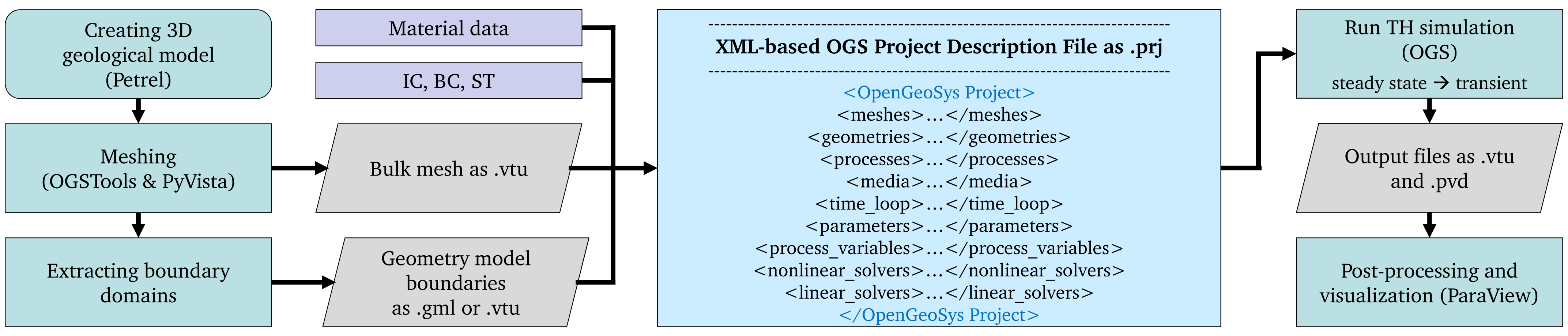
Coupled TH processes: $\left(\varphi(\rho c)_f + (1-\varphi)(\rho c)_s\right)\frac{\partial T}{\partial t} = \nabla \cdot \left(\boldsymbol{\lambda}\nabla T - (\rho c)_f \mathbf{v_D} T\right) + S$ **Darcy Law:** $\mathbf{v_D} = -\mathbf{K}\frac{\partial h}{\partial x_i}$, $\mathbf{K} = \mathbf{k}\frac{\rho_f \mathbf{g}}{\mu_f}$

Table 1: *Overview of thermo-petrophysical properties of each modeled geological unit for the TH simulation. Summarized by Santoso (2025) based on several projects: GeORG, Hessen 3D 1.0 & 2.0, DGE-ROLLOUT, IMAGE, AMPEDEK.*

ID	Modeled Unit	Dominant Lithology	φ_{eff} [%]	k [m²]	ρ_s [kg m⁻³]	c_s [J kg⁻¹ K⁻¹]	λ [W m⁻¹ K⁻¹]	S [μW m⁻³]
1	Young Cenozoic	Marl, sandstone, sand	17.2	$3.26 \cdot 10^{-15}$	2250	978	2.30	1.0
2	Niederroedern	Marl, limestone	18.2	$1.02 \cdot 10^{-14}$	2300	978	2.25	1.0
3	Froidefontaine	Marl, limestone	13.7	$1.48 \cdot 10^{-15}$	2300	978	2.25	1.0
4	Pechelbronn	Marl, limestone, dolostone	14.5	$2.82 \cdot 10^{-15}$	2300	978	2.60	1.0
5	Base Tertiary	Claystone, sandstone	15.7	$2.66 \cdot 10^{-14}$	2250	1000	2.60	1.0
6	Rotliegend	Sandstone, andesite	8.9	$7.24 \cdot 10^{-15}$	2430	758	2.21	1.0
7	Basement	Granitoids, gneiss	3.6	$1.82 \cdot 10^{-16}$	2630	648	2.71	1.8
8-10	Fault Zones		25.0	$1.00 \cdot 10^{-13}$	2000	1000	2.00	1.0

List of symbols:
$\boldsymbol{\lambda}$: thermal conductivity [W m⁻¹ K⁻¹]
T: temperature [k]
∇T: temperature gradient [K m⁻¹]
$\mathbf{v_D}$: Darcy velocity [m s⁻¹]
$\mathbf{K}$: hydraulic conductivity [m s⁻¹]
$\partial h/\partial x_i$: hydraulic gradient [–]
$\mathbf{k}$: intrinsic permeability [m²]
$\mathbf{g}$: gravitational acceleration [m s⁻²]
ρ: density [kg m⁻³]
μ: dynamic viscosity [Pa s]
c: specific heat capacity [J kg⁻¹ K⁻¹]
φ: effective porosity [–]
S: radiogenic heat production [μW m⁻³]
t: time [s]
s: solid rock material
f: fluid material

5. Workflow



Creating 3D geological model (Petrel)
Meshing (OGSTools & PyVista)
Extracting boundary domains
Material data
IC, BC, ST
Bulk mesh as .vtu
Geometry model boundaries as .gml or .vtu

XML-based OGS Project Description File as .prj

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<linear_solvers>...</linear_solvers>
</OpenGeoSys Project>
```

Run TH simulation (OGS)
steady state → transient
Output files as .vtu and .pvd
Post-processing and visualization (ParaView)

Figure 2: *Simplified workflow for integrating 3D geological model from Petrel into OGS (IC: Initial Condition, BC: Boundary Condition, ST: Source Term).*

6. Results and Discussion

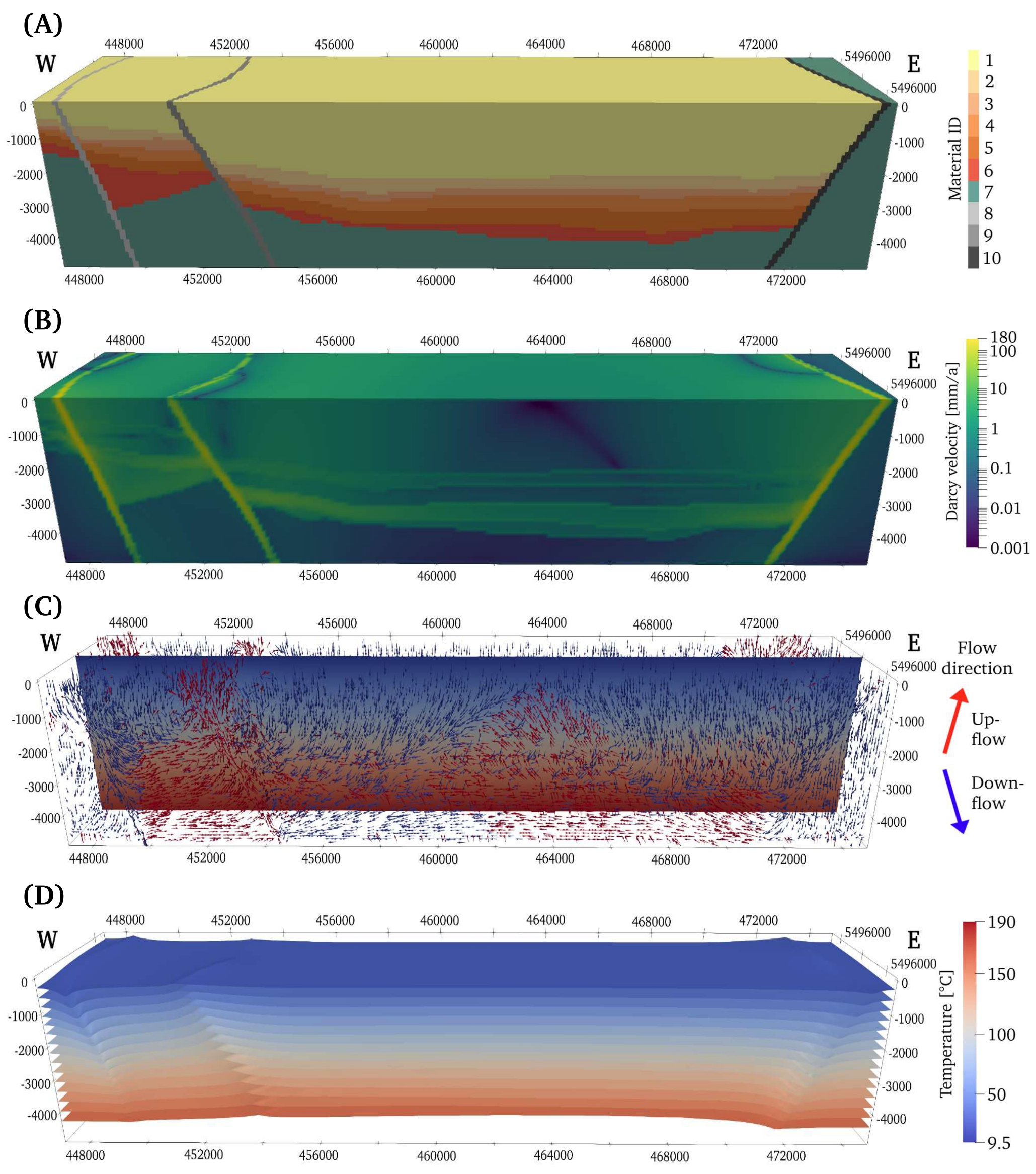
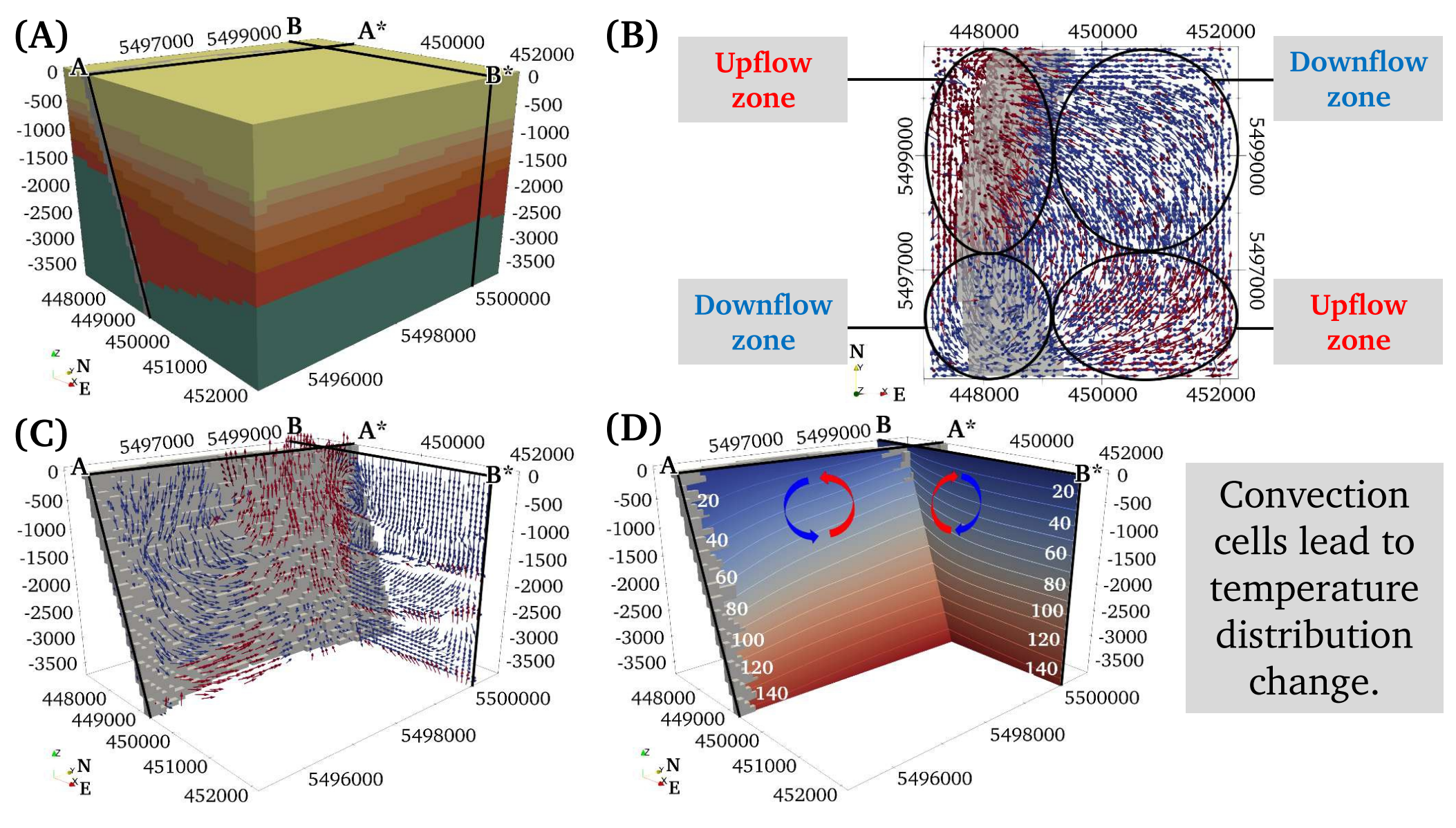


Figure 3: *Results of the transient 3D TH simulation after 75,000 years of simulated time: (A) material IDs of the modeled geological units, (B) Darcy velocity in mm/a, (C) fluid flow direction with a W-E cross-section of the temperature distribution in°C, (D) temperature isoplanes in °C.*



Convection cells lead to temperature distribution change.

Figure 4: *Zoom of Figure 3 in West Boundary Fault: (A) material IDs, (B) fluid flow direction from top view, (C) fluid flow direction of cross-sections A-A* and B-B*, (D) temperature distribution of cross-sections A-A* and B-B* with conceptual convection cells.*

7. Conclusion and Outlook

Conclusion:

- Development of **hydrothermal convection cells** within and around fault zones
- Positive temperature anomaly ⟷ **upflow** zone
- Negative temperature anomaly ⟷ **downflow** zone
- Highest Darcy velocity in fault zones (**5.0 – 180 mm/a**)

Outlook:

- Simulation with different mesh types
- Fill data gap and more accurate parametrization (lab measurements, borehole data)

Literature

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