

Milestone

2.2 Digital Twins for three scales created and calibrated with observed data

Report information	
Work package	2 (Digital Geothermal Reservoir Twin)
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Approval	Federica Lanza
Status	final
Dissemination level	internal
Will the data supporting this document be made open access?	Yes, when publishing the Deliverable 2.3
If No Open Access, provide reasons	Currently, these are initial models that need to be calibrated and updated
Delivery deadline	30.11.2025
Submission date	30.11.2025
Intranet path	General/D.Milestones/ and WP2/Milestone_2_2_data

Summary

To investigate the effect of physical changes in reservoirs on seismic wavefields, we need geothermal poroelastic reservoir twins on three scales: microscale (micrometers – millimeters), mesoscale (centimeters - meters), and macroscale (meters to kilometers). Aiming to constrain the interaction between observed seismic velocity changes and in-situ stress and strain variations induced by hydraulic stimulations and fluid, we derive high-resolution models on these three scales.

1) Microscale (resolution: micrometers, dimension: millimeters)

On the microscale, CT images of reservoir rocks have been created based on a geological driven segmentation workflow. Segmentation is the process of assigning gray-scale intensities, a result of X-ray computed tomography scans, to the corresponding mineral phases. The resulting geometrical model with assigned phases consists of a 400^3 voxel subvolume with a resolution of $7\ \mu\text{m}/\text{voxel}$ (Fig. 1) and can be found in the Milestone folder on the project Teams. These will be used to calculate effective properties and investigate any poroelastic effects or anisotropy that will be used as an input to the mesoscale models.

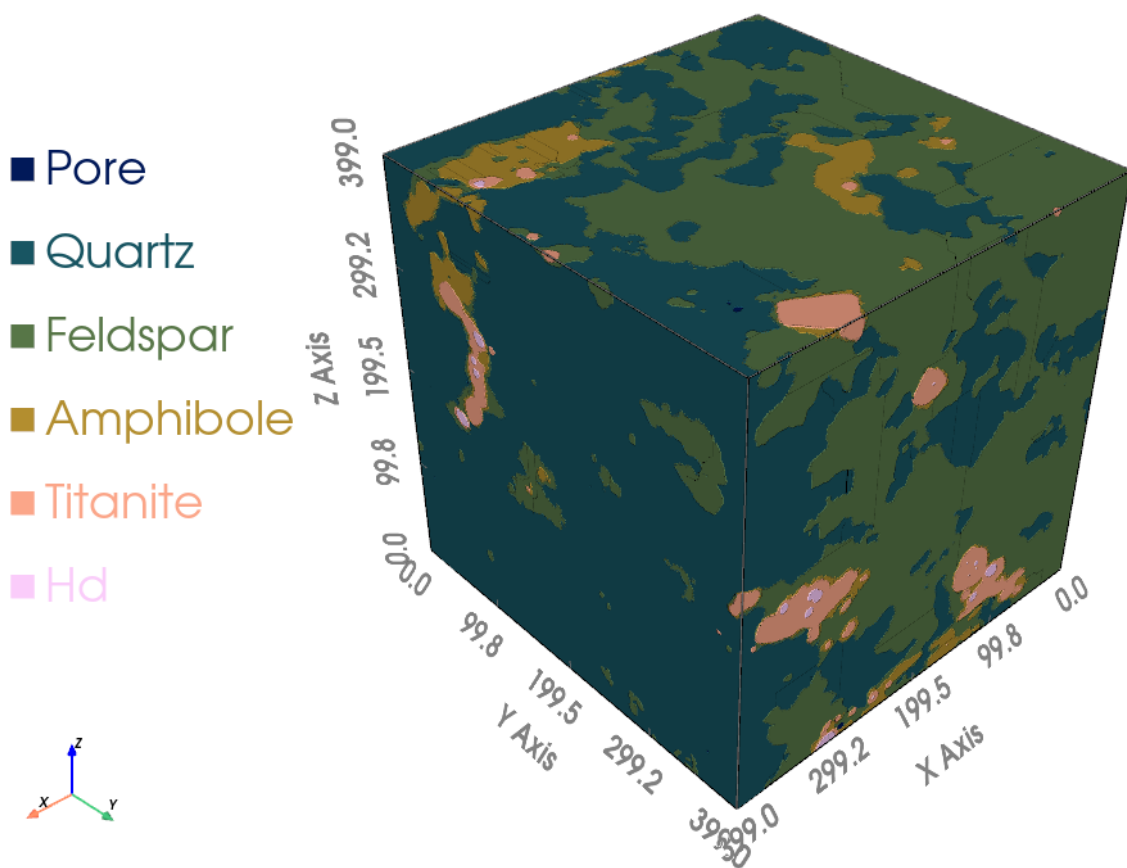


Figure 1: Segmented 400^3 voxel subvolume of FORGE granite from XRCT data. Five mineral phases (Quartz, Feldspar, Amphibole, Titanite and High-density minerals) were identified. Microporosity remains largely unresolved.

2) Mesoscale (resolution: centimeters, dimension: meters)

Hydraulically induced fractures are known to interact strongly with pre-existing flaws such as cracks, joints, and faults (in the following, we use the term flaw to describe these). These discontinuities influence fracture propagation, fluid-flow pathways, and the redistribution of stress and pore pressure, and therefore also affecting the associated seismic response. Depending on their mechanical properties, in-situ stress conditions, injection rate, flaws' orientation and spatial distribution, pre-existing flaws may cause the hydraulic fracture to cross, be arrested, dilate, become reactivated, or undergo offset crossing.

To capture these processes, 3D mesoscale models are constructed that efficiently reproduce different patterns of heterogeneity and anisotropy in rocks, including isotropy, transverse isotropy, rotated anisotropy, as illustrated in Fig. 2. At this scale, the influence of natural discontinuities on hydraulic-fracture development can be represented explicitly and the resulting mesoscale responses are upscaled to inform the reservoir-scale velocity and THM models/simulations. The upscaled information includes the homogenized stiffness tensor, velocity anisotropy, effective permeability tensor, and transmissivity. This facilitates a DFN-guided anisotropy description at large scale. In addition, mesoscale simulations also provide pressure-fracture opening and pressure-permeability relationships that can be directly incorporated into the reservoir-scale constitutive behavior.

The models of dimension (100m x 100m x 100m) are discretised by 8 million voxels of size 50 cm. fractures are represented as 0.5 m thick numerical penny shape crack with diameter of 9 m (aspect ratio of 0.055). The mean fracture area per volume is $0.0525 \text{ m}^2/\text{m}^3$ for configurations (a-e) and $0.1575 \text{ m}^2/\text{m}^3$ for configuration (f). The fracture orientations are assigned using a Bingham distribution in which a concentration matrix is constructed from the prescribed fabric tensor. The eigen vector of the fabric tensor control the preferred orientation axes and the eigen values control the strength of alignment. This procedure yields a statistically consistent set of fracture normal reflects both the anisotropy and intensity encoded in the fabric tensor. Furthermore, the mesomodels exhibits periodic boundary which can be served as building blocks to construct efficiently a larger model.

It is important to note that the hydraulic and mechanical properties assigned to the mesoscale representative volume elements (RVEs) and the smeared penny-shaped cracks are calibrated to correspond to physical apertures in the millimeter range. As a result, consistency with field observations and microscale fracture characteristics can be ensured.

The voxel data for all models are available in the Milestone folder on the project Teams. Each subfolder corresponds to one configuration and includes:

- a **CSV file** containing the voxel-wise phase information,
- a **VTI file** of the meso-model for direct visualization,
- a **README.txt** with the relevant geometric details of the penny-shaped cracks.

in addition, a **Python script** for reading and processing the CSV data is also included.

For the FORGE model, mechanical and hydraulic properties of the rock matrix can be found at:

<https://utahforge.com/data/>

<https://gdr.openei.org/submissions/1162>

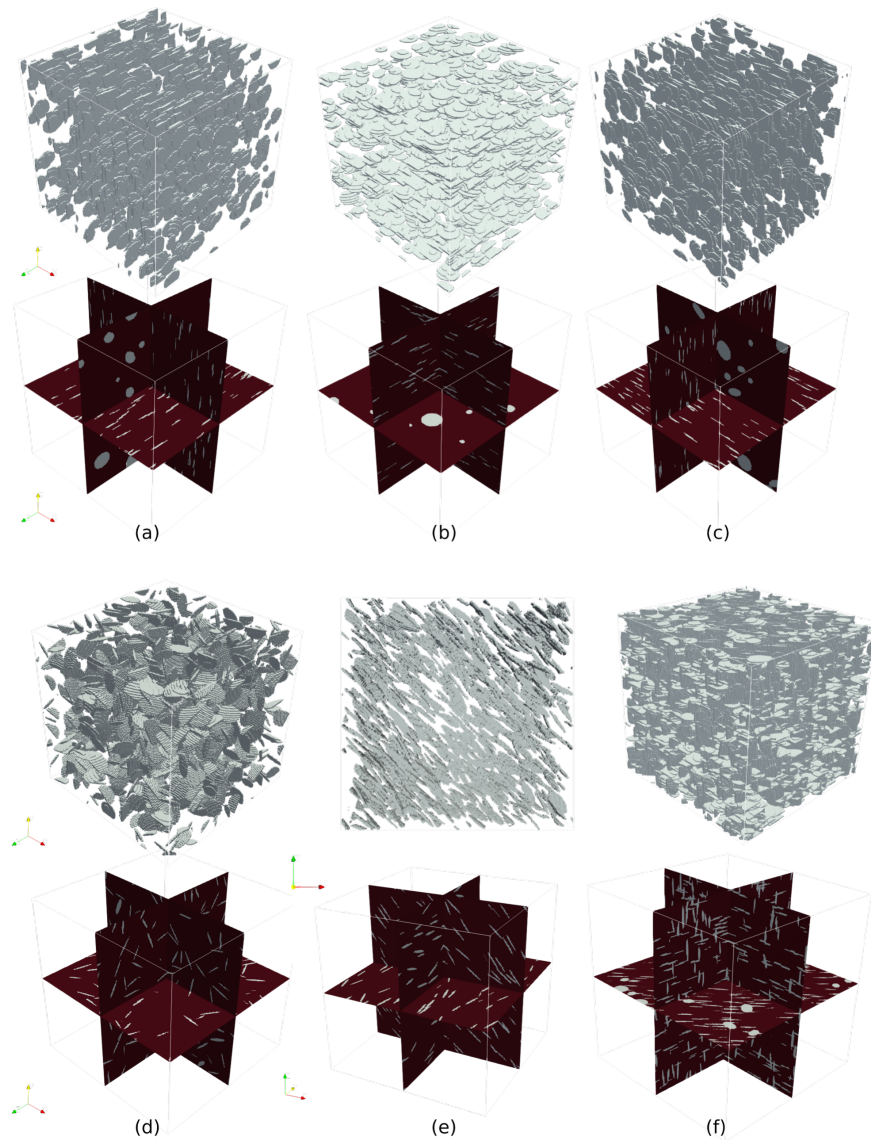


Figure 2: Visualisation of meso models of different fracture network configurations: (a-c) transverse isotropy (d) isotropy (e) rotated transverse isotropy (f) mutually orthogonal crossing-fracture configuration.

3) Macroscale (resolution: meters, dimension: kilometers)

On the mesoscale, the influence of natural discontinuities on hydraulic-fracture development can be represented explicitly, and the resulting mechanical and hydraulic properties are upscaled to inform the reservoir-scale velocity and THM models. The upscaled information includes the homogenized stiffness tensor, velocity anisotropy, effective permeability tensor, and transmissivity. The homogenization operations are important to speed up simulations of mechanical changes caused by fluid injection and will be used to update the macroscale model. On the macroscale, a composite three-dimensional model of seismic wave velocities exists for the FORGE site (<https://gdr.openei.org/submissions/1585>). This model was created in the DEEP project and calibrated using onset times of P and S waves recorded on temporary nodal deployments. A python script is included with the needed input data to create models at different resolutions and for

different applications in different file formats. Using the input from the micro- and mesoscale, we will update this macroscale model with effective property changes (elastic parameters, anisotropy, scattering coefficient) to simulate the effect fluid injection has on the seismic wave propagation.

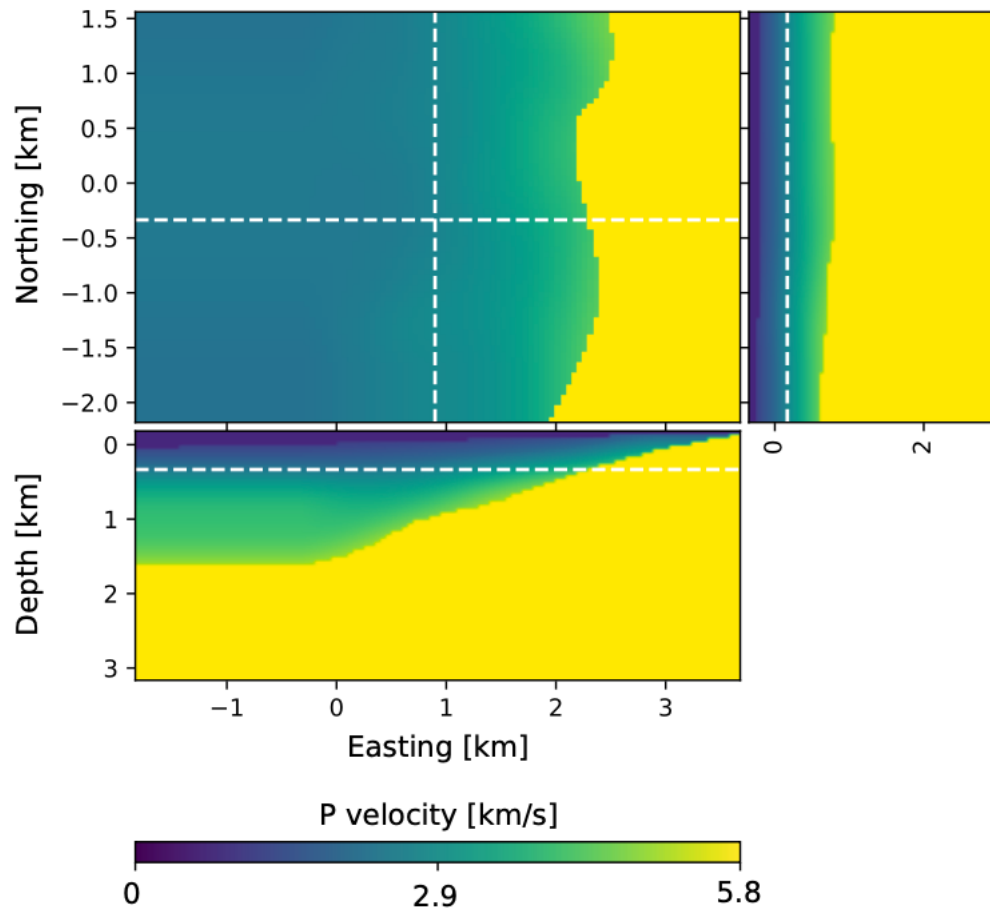


Figure 3 Composite three-dimensional model of seismic velocities at Utah FORGE. Finger et al. (2024), accessible at (<https://gdr.openet.org/submissions/1585>).

Data Access Statement

We provide the three geometrical models (digital twins) for the three scales described above. The files can be found in the internal Teams in: '/WP2/Milestone2.2_data'. They have separate readme files indicating the content and describing the formatting. The macro-scale model can also be found at the GDR repository under <https://gdr.openet.org/submissions/1585>. These models will be updated and further calibrated in the process of the project work and will be made publicly available at the time of submitting Deliverable 2.3.