

MUFITS:

A Universal Reservoir Simulator
for Numerical Modelling, History
Matching and Optimization
of Multicomponent Flows
in Porous Media

www.mufits.imec.msu.ru



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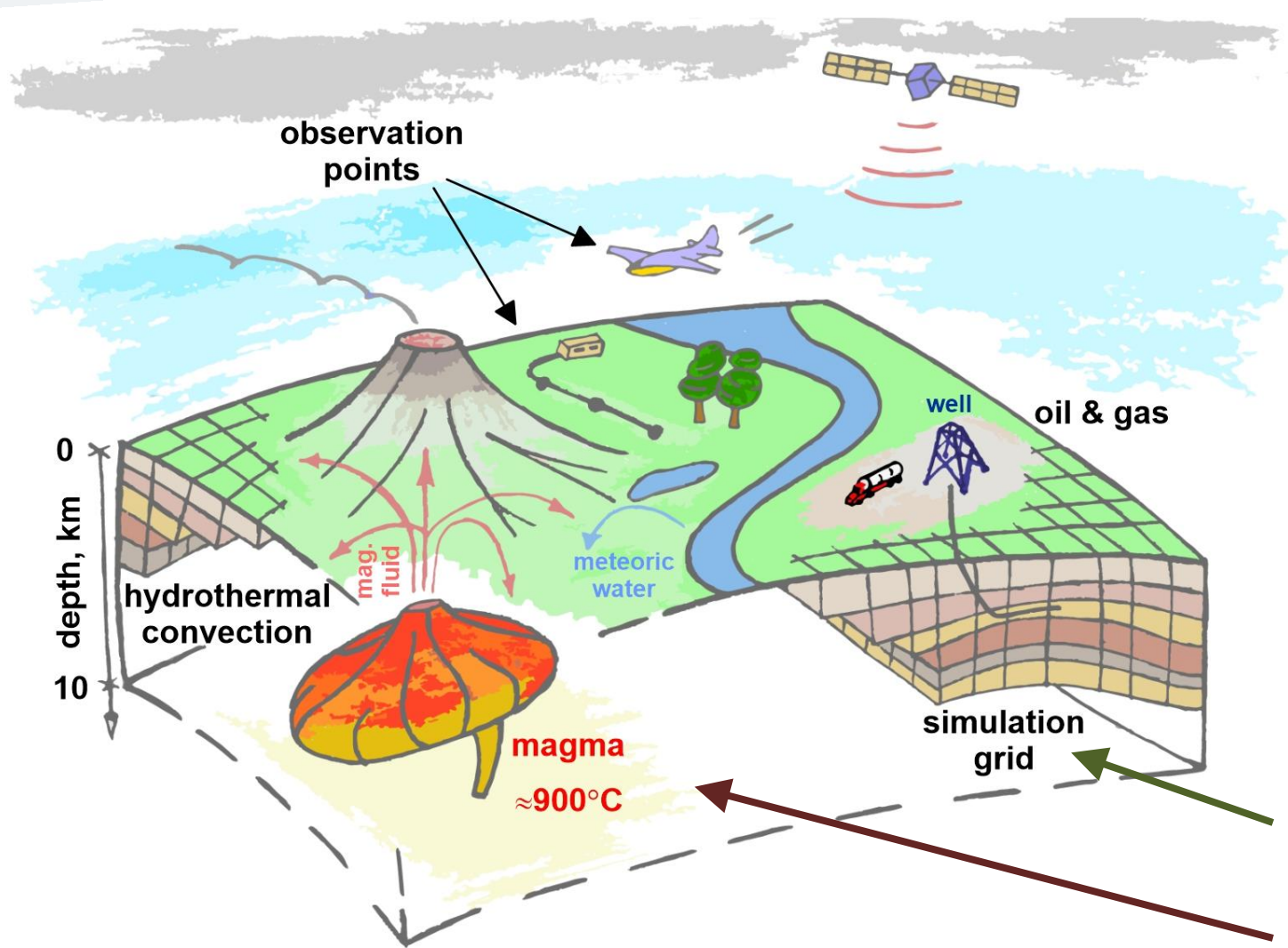
Goal

Development of the universal software package allowing for

- thermo-hydro-mechanical modelling of multicomponent flows at low and high supercritical temperatures.
- history matching to various observable parameters and optimization of such flows.

Potential applications:

- Low-temperature processes (petroleum reservoirs or subsurface gas storage)
- High-temperature flows and associated chemical and mechanical phenomena (hydrothermal & magmatic systems)



Architecture of the software

The software consists of three computer programs with fully compatible interface

Utilities program

- Input data preparation
- Simulation control unit (SCU) for history matching and optimization
- Auxiliary calculations

Hydrodynamic simulator

- Numerical modelling of the non-isothermal flows in porous media and wellbores
- Includes several EoS modules for predicting the fluid properties

Geomechanical simulator

- Modelling the stresses, strains, and displacements in saturated porous media (elastic and plastic deformations)
- Calculating the associated changes of porosity and permeability

New

is being developed by Ivan Utkin



EoS modules

Hydrodynamic simulator

BLACKOIL

(Black-oil modelling including the wet gas option)

GASSTORE

(Modelling gas storage in saline aquifers)

MAGFLUID

(Describes the fluid phase diagram by simplexes)

Coming
soon

BINMIXT

(Modelling binary mixture flows at near-critical conditions)

SIMPLMOD

(Modelling the flows of a simple 1-phase fluid)

ADDPHASE

(Adds an additional fluid phase to the other modules)

T2EOS1

(Modelling non-isothermal flows of water and steam)

COMPS

(Compositional module based on a cubic equation of state)

New

ADDCOMPO

(Adds an additional fluid component to the other modules)



Key modelling options

Hydrodynamic simulator

Dual porosity

DUALPORO

Dual permeability

DUALPERM

Multi-porosity

MINC

Gravity drainage

GRAVDR

modelling fractured reservoirs

Ductile creep of hot rock

DUCTILE

Dynamic fractures

DYNFRACK

modelling
brittle-ductile transition

Hydrodynamic dispersion
and molecular diffusion

MECHDISP

Horizontal wells

MUSEGWEL

Isothermal modelling

ISOTHERM

Thermal conduction

HCROCK

Gravity changes

GRAVIMET

New

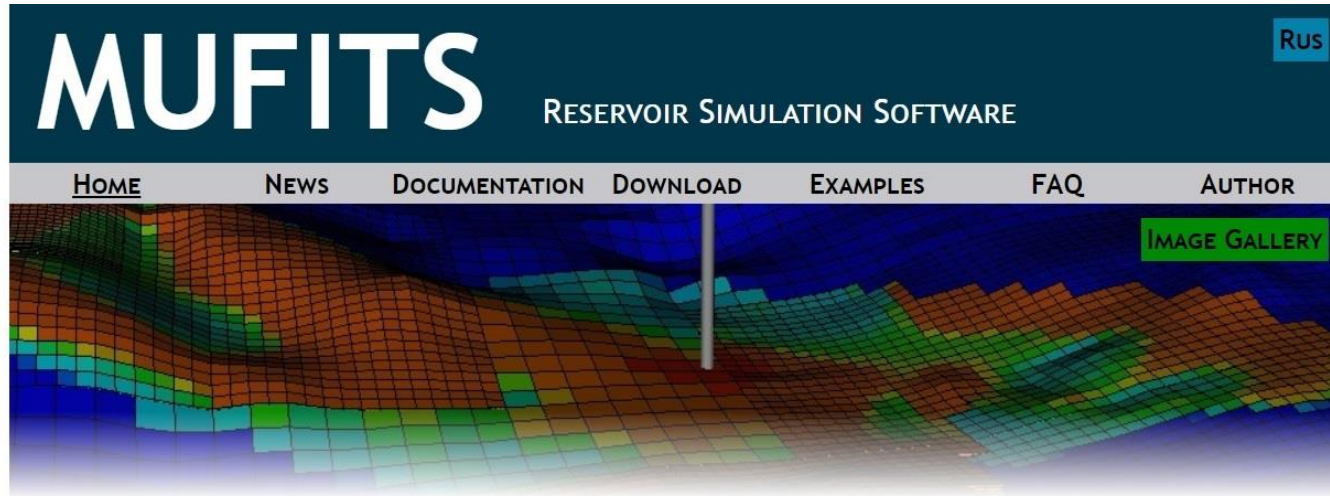
Ground displacement

GRDDISP

New

are calculated in
Observation points

Website: www.mufits.imec.msu.ru



MUFITS is a noncommercial reservoir simulator for analysis of non-isothermal multiphase multicomponent flows in porous media. The simulator is designed for parallel compositional simulations using both laptops and supercomputers. MUFITS can accommodate geologic, petrophysic and thermophysic data of the real-world complexity.

MUFITS has several EOS modules for prediction PVT properties of reservoir fluids:

- BINMIXT module for modelling nonisothermal three-phase flows of binary mixtures. The properties are specified by the thermodynamic potential of the mixture, which is calculated before hydrodynamic simulations. The potential is used in conditional extremum problem, which corresponds to the entropy maximum condition in thermodynamic equilibrium. By using this formulation, MUFITS can determine single-, two-, and three-phase equilibriums of the mixture under sub- and supercritical conditions. The primary variables are the pressure, the mixture total enthalpy and the composition. The system singularities in the vicinity of critical thermodynamic conditions are eliminated if these variables are used. Therefore, the simulator can avoid dramatic timestep cuts for hydrodynamic simulations under near-critical conditions.
- BLACKOIL module for modelling petroleum reservoirs using extended Black-oil approach. The module is capable of single-phase,

**The simulator is a free academic software available for
download from its webpage**

Further information

The simulator is supplemented with

- Comprehensive [Reference manual](#)
- Simulation [Examples](#)



**The software updates
are published
at ResearchGate**



Compositional module (COMPS)

Hydrodynamic simulator / COMPS

Can deal with non-isothermal flows

Algorithms for modelling flows of the multicomponent fluids whose properties are predicting with a cubic EoS.

EoS coefficients can be loaded from the library

Built-in library of EoS coefficients
(includes sections for different EoS types)

PR3 (Peng-Robinson EoS with volumes shift)

SRK3 (Soave-Redlich-Kwong EoS)

Another section can be created by user

EoS coefficients can be explicitly specified by user

EoS coefficients can be exported in a standard format

External files

External files

- ✓ The module can deal with mixtures consisting of an arbitrary number of components including H_2O , CO_2 , H_2S , N_2 , CH_4 , C_2H_6 , C_3H_8 , and other hydrocarbons.
- ✓ The single-phase and two-phase equilibria of vapor-liquid type can be simulated.



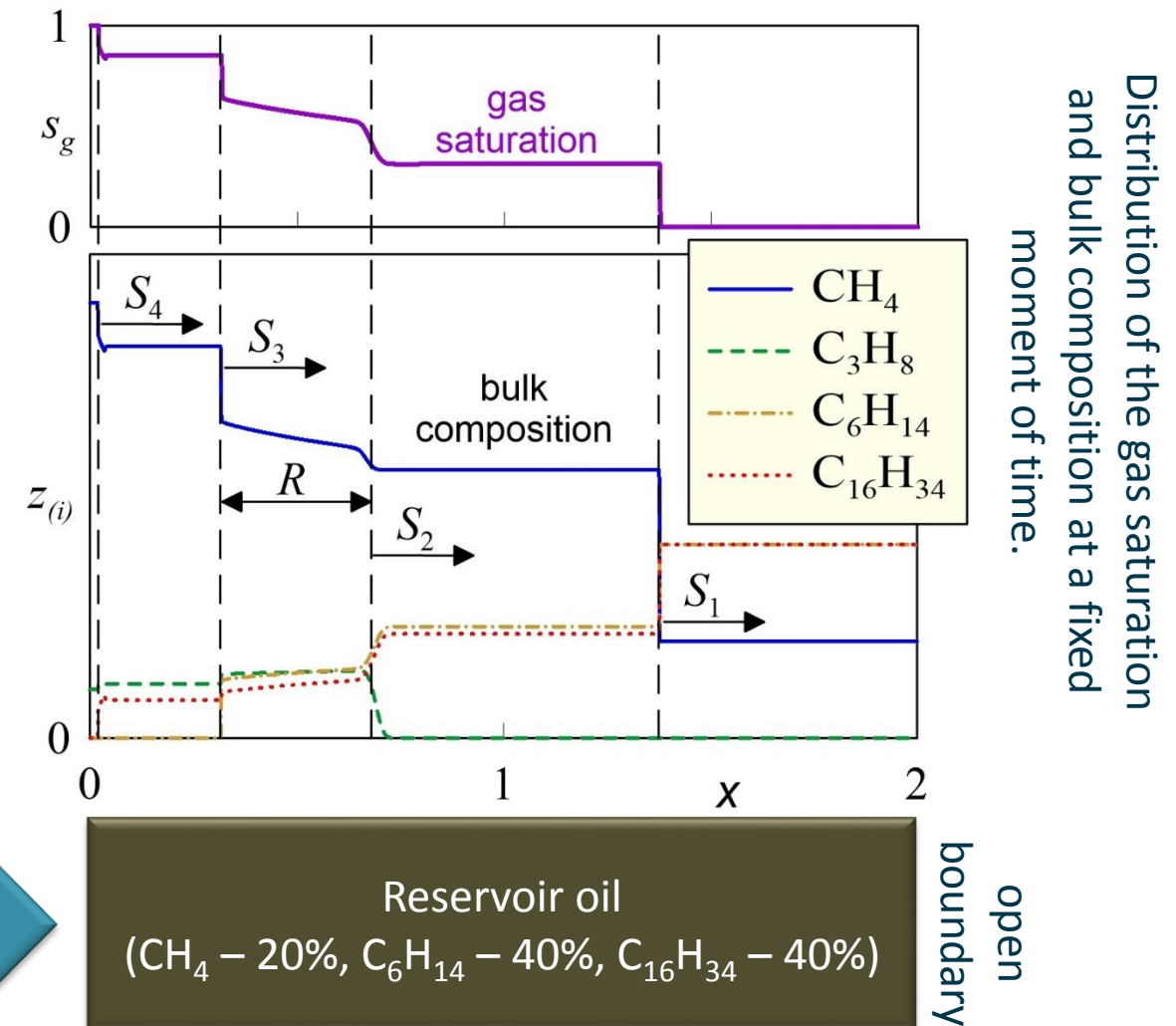
Modelling multi-contact displacement of oil

For demonstrating the COMPS module, we consider a 1-D study of miscible displacement in a porous medium. At $t=0$, the reservoir is saturated with a three-component mixture in liquid state that should be regarded as a proxy for a realistic oil. This liquid is displaced by a hydrocarbon gas (methane + propane) injected through the boundary $x=0$. The gas injection results in a complicated flow pattern (S_4 - S_3 - R - S_2 - S_1) consisting of several displacement fronts (S), a Riemann wave (R), and constant states (-) propagating from $x=0$ into the reservoir. The example demonstrates compositional effects related to the different displacement efficiency of different components.

See details at

<http://www.mufits.imec.msu.ru/example-comps-test-a.html>

Injected gas
(CH_4 – 90%,
 C_3H_8 – 10%)



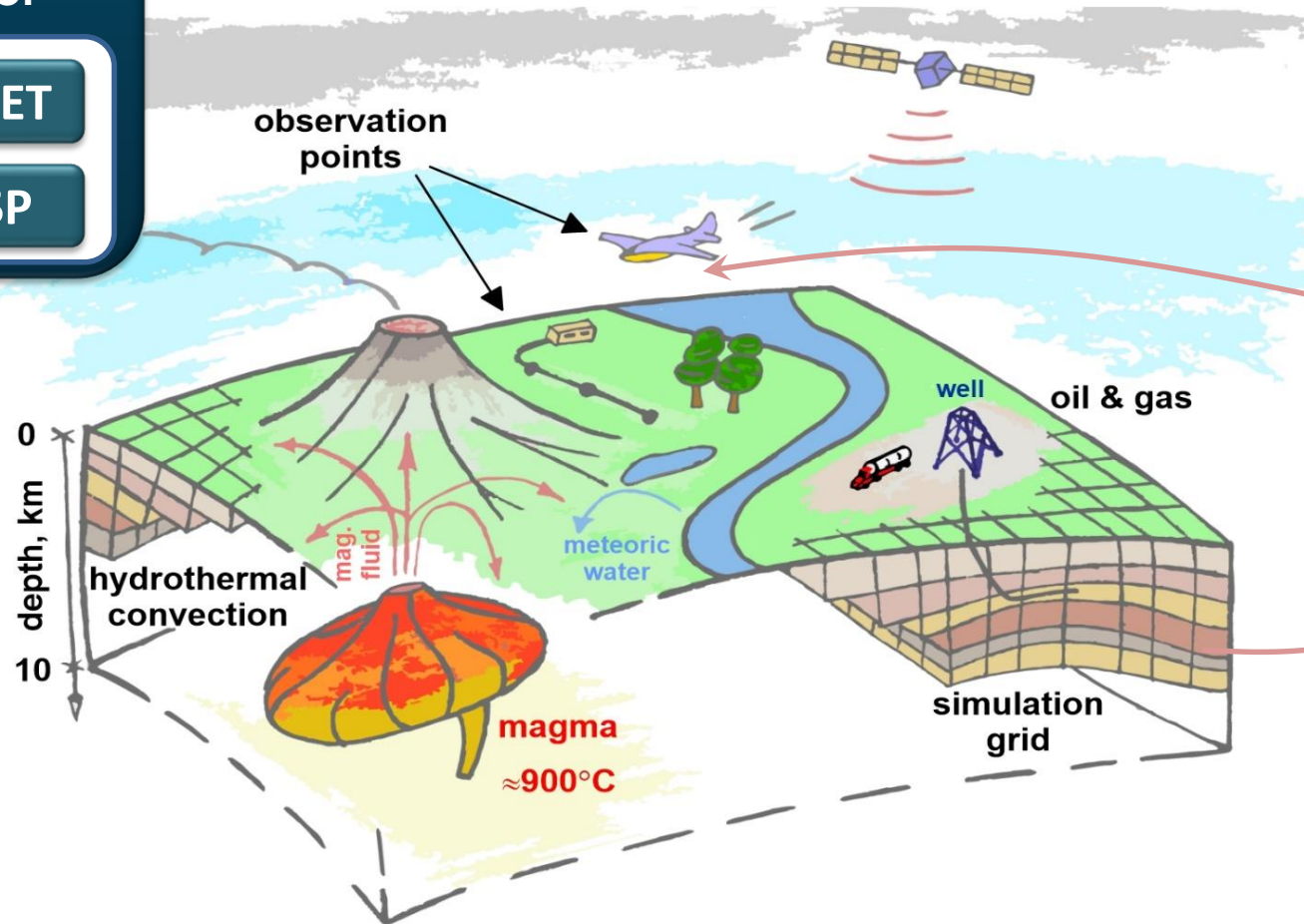
Modelling gravity changes and ground displacement

(using the built-in capabilities of the hydrodynamic simulator)

Hydrodynamic
simulator

GRAVIMET

GRDDISP



A new primitive 'Observation Point (OP)' of the reservoir models is introduced for reporting the observable parameters. Every OP is characterized by 3 coordinates in space.

The observable parameters are reported by summing the contributions from every grid block to parameters at OPs.

The gravity changes and ground displacement are calculated against a reference state that can easily be defined by user by the SETDGRAV and SETREFPT keywords, respectively.

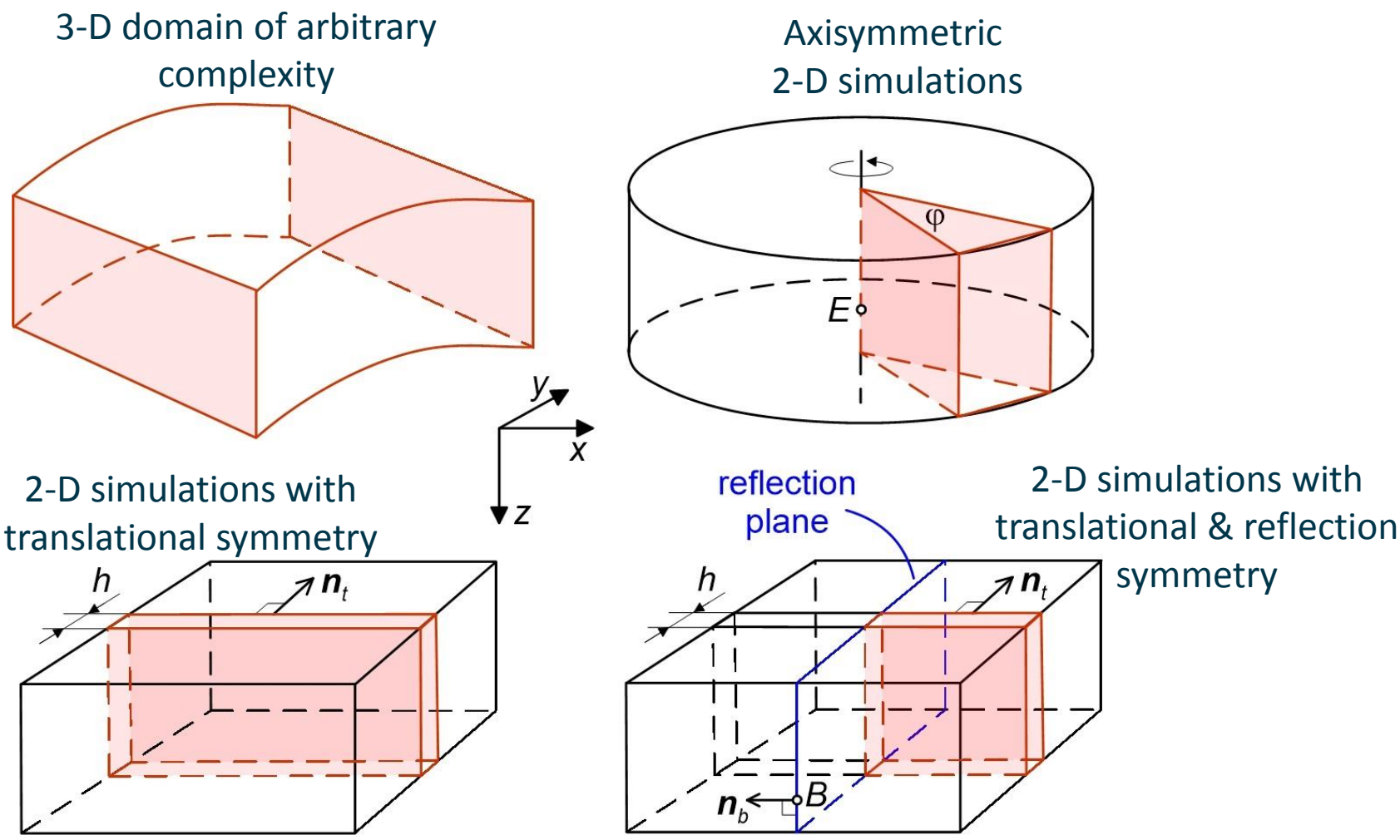
Hydrodynamic simulator

GRAVIMET

GRDDISP

The developed modelling options are generally designed for 3-D simulations with domains of arbitrary complexity. However, in the case of 2-D simulations with the symmetries shown on the right, the simulator can automatically account for other parts of 3-D space that do not belong to the domain.

Domain symmetries



The simulation domain (red) occupies a region of the subsurface reservoir (black)

Equations for modelling the observable parameters

Gravity changes **GRAVIMET**

According to Newton's law of universal gravitation, the gravity change in every OP is calculated using the following equation:

$$\Delta g = \sum_{i=1}^N \gamma \frac{(\rho_i - \rho_{i,0})V_i}{|\mathbf{r}_i - \mathbf{r}_o|^3} (\mathbf{r}_i - \mathbf{r}_o)$$

where Δg is the gravity change, N is the number of grid blocks in the simulation, γ – is the gravity constant, ρ is the bulk density of the saturated porous medium, ρ_0 is the reference bulk density, V is the volume of the grid block, \mathbf{r}_i is the position vector of the i th grid block, \mathbf{r}_o is the positions vector of OP, and the subscript i denotes parameters of the i th block.

Ground displacement **GRDDISP**

The built-in model for ground displacements is restricted by the following assumptions:

- ✓ The mechanical properties of the saturated porous medium are homogeneous.
- ✓ The top boundary of the domain corresponding to Earth's surface is flat, horizontal, and free of stresses.
- ✓ The domain for modelling the displacement is the semi-infinite region filled with elastic medium.

Given that these assumptions are satisfied, the displacements are calculated by employing an analytical solution for the centre of compression (or dilatation) placed in the interior of the semi-infinite solid ([Mindlin, 1936](#); [Mindlin and Cheng, 1950](#)). Every grid block is considered such a centre of compression, and the total displacement in OP is obtained by summing contributions from all grid blocks. See details of this model in

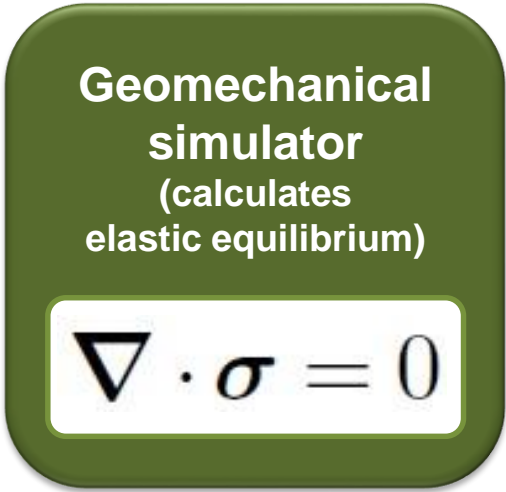
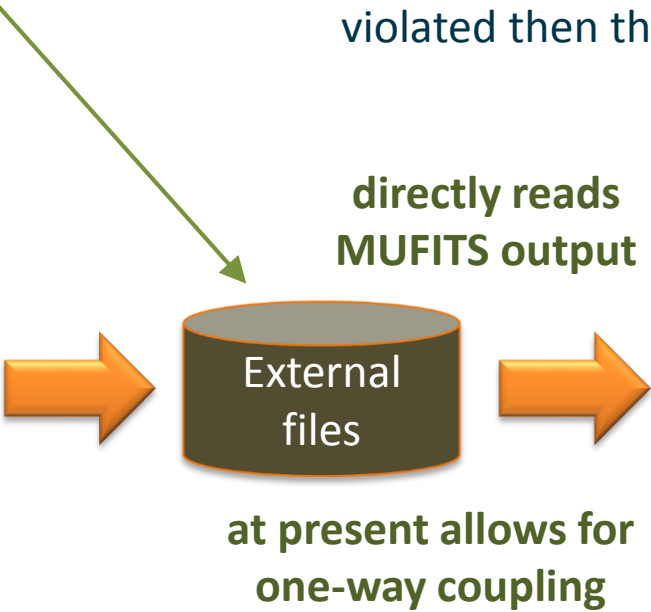
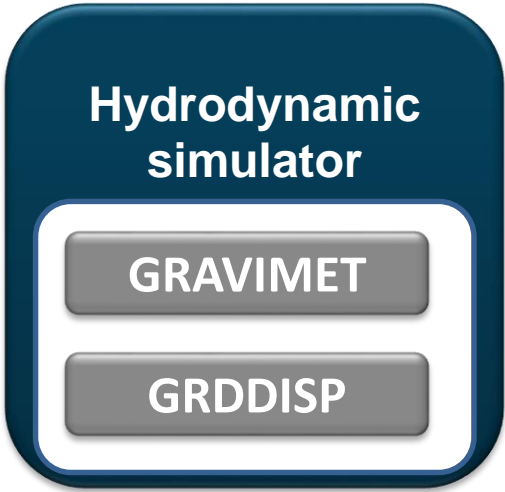
- ✓ [Rinaldi et al. Phys Earth Planet. Inter. 178 \(2010\) 155-161](#)
- ✓ [Afanasyev & Utkin \(2020\). To be submitted](#)



Geomechanical code

The files contain distributions of P and T

If the assumptions of the built-in model for ground displacement (GRDDISP) are violated then the displacements can be simulated in the geomechanical module



- ✓ is an open-source MATLAB application.
- ✓ available for download at <https://github.com/utkinis/THM2D-U>.
- ✓ can deal with heterogeneous mechanical properties.
- ✓ can deal with rectilinear and radial grids.

τ – total stress deviator

ε – strain tensor

P – fluid pressure

T – temperature

b – Biot-Willis coefficient

K – drained bulk modulus

K_s – bulk modulus of the solid phase

α_s – thermal expansion coefficient

subscript 0 – reference parameters

$\sigma_{ij} = \tau_{ij} - P_{tot}\delta_{ij}$

$P_{tot} - P_{tot,0} = -K\varepsilon_{kk} + b(P - P_0) + \alpha_s K(T - T_0), \quad b = 1 - \frac{K}{K_s},$

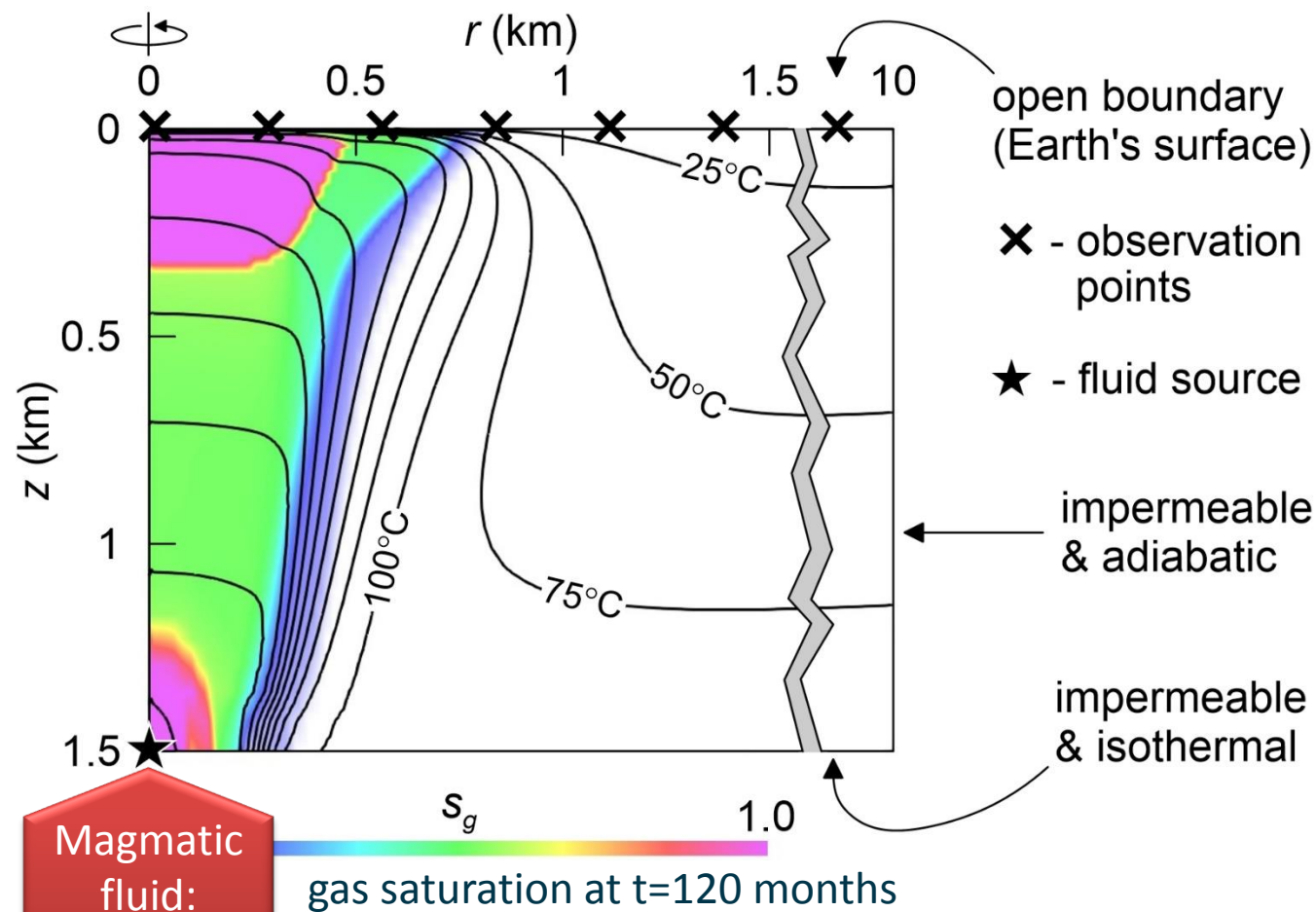
$\tau_{ij} - \tau_{ij,0} = 2\mu(\varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}), \quad i, j = 1, 2, 3.$

Constitutive equations

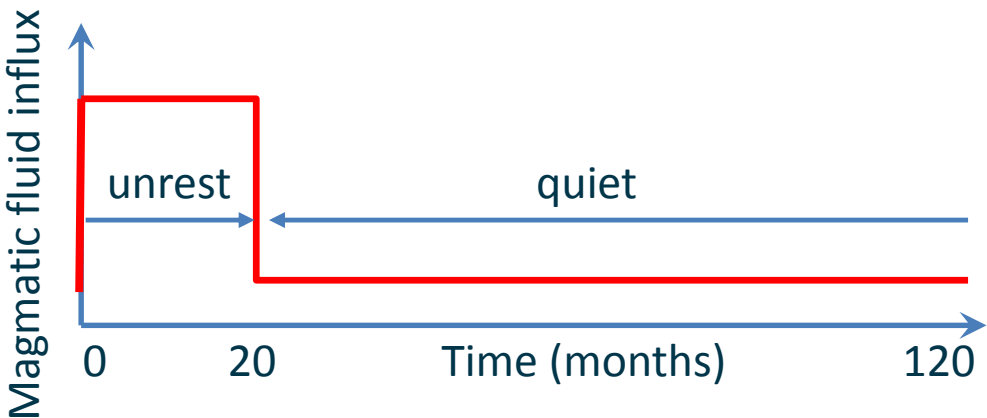
See details in [Afanasyev & Utkin \(2020\)](#)

Modelling hydrothermal activity at Campi Flegrei

(Problem statement for the hydrodynamic modelling)



To validate the simulator, we consider the axisymmetric study of hydrothermal activity at Campi Flegrei. During the unrest ($t < 20$ month), the system is inflated what results in the gravity changes and ground displacement. The flow and observable parameters were broadly investigated by [Chiodini et al. \(2003, 2016\)](#), [Todesco et al. \(2003, 2004\)](#), and [Rinaldi et al. \(2010, 2011\)](#), among others. Thus, the simulation results are well constrained, and they can be used for benchmarking.

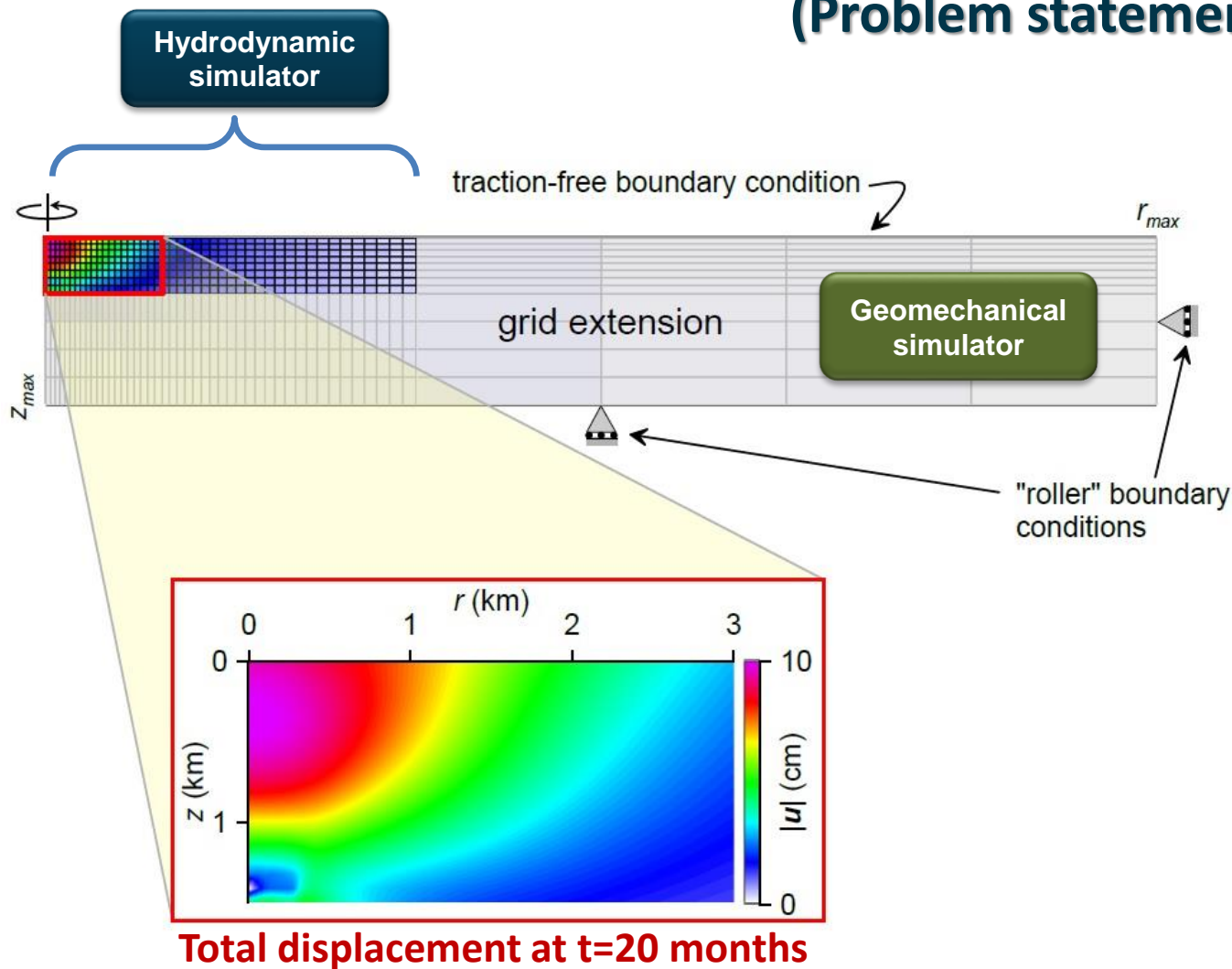


See details in:

- ✓ [Rinaldi et al. JVGR 207, 93-105 \(2011\)](#)
- ✓ [Afanasyev & Utkin \(2020\). To be submitted](#)

Modelling hydrothermal activity at Campi Flegrei

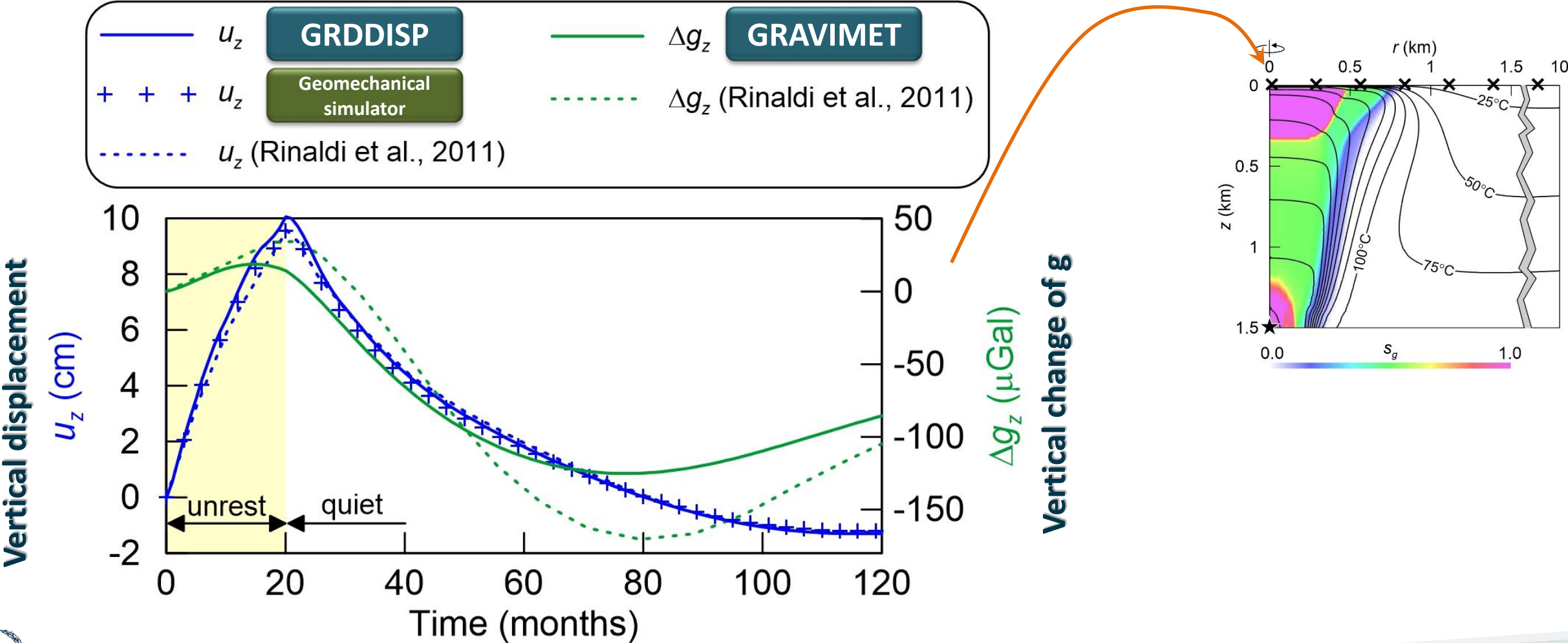
(Problem statement for the geomechanical modelling)



We apply an extended grid to reduce the influence of the boundary conditions on the elastic equilibrium.

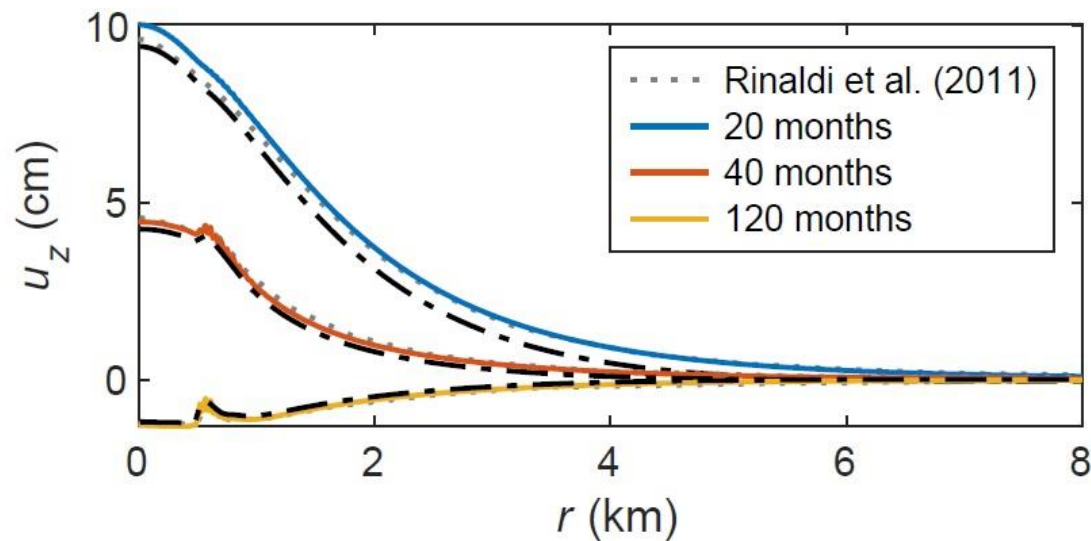
A three times larger domain along both r and z axes produces satisfactory agreement between the built-in model and the geomechanical simulator. Herewith, the mesh outside the domain for hydrodynamic modelling should not be very dense. A coarse grid like such as that shown in the figure is sufficient

Gravity changes and displacements at the centre

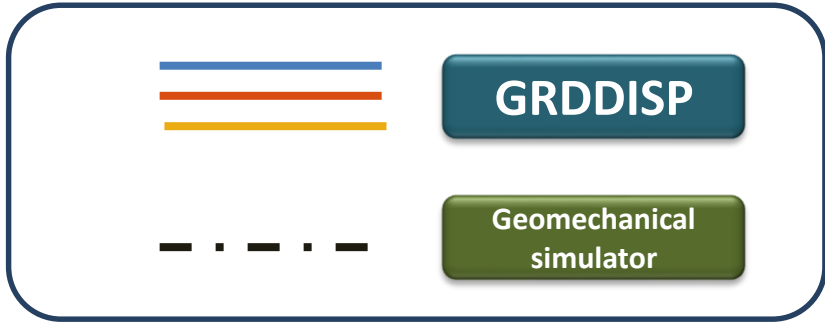
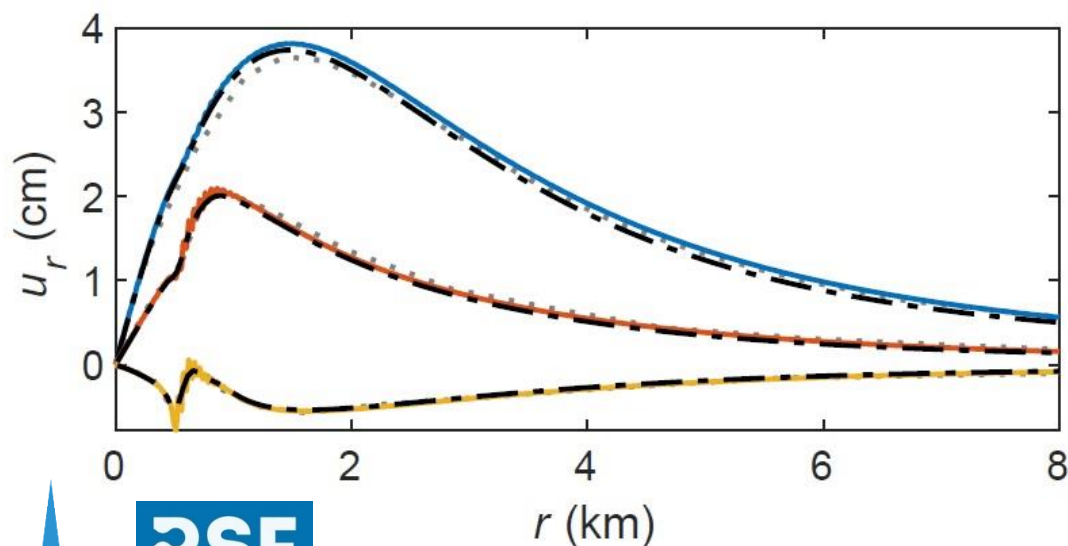


Ground displacement at sequential times

Vertical displacement

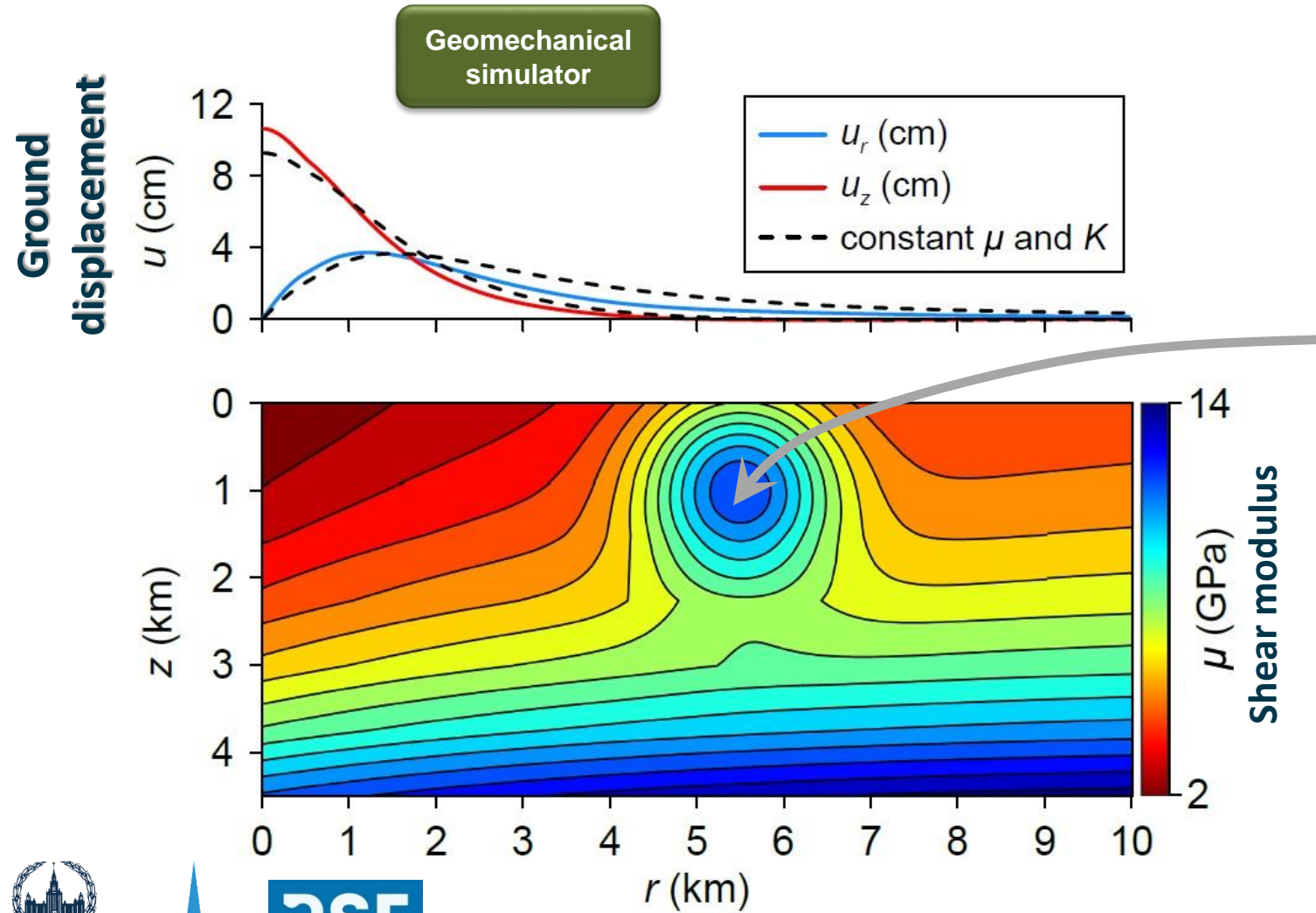


Horizontal displacement



The agreement between the simulation results confirms correct implementation of the simulation algorithms

Modeling ground displacement in a heterogeneous reservoir



To demonstrate the capabilities of the geomechanical code, we simulate the hydrothermal activity in heterogeneous reservoir when the assumptions of the built-in model are violated.

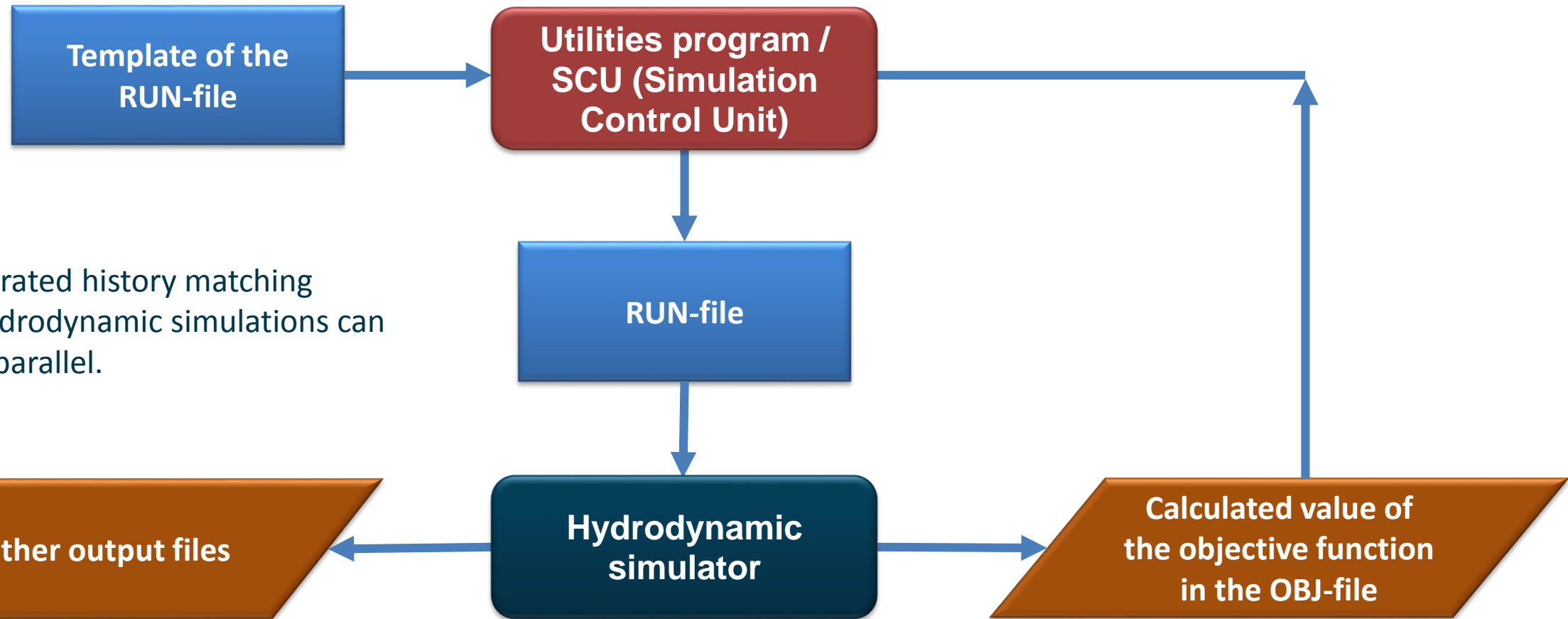
Stiffer material modelling the caldera rim at Campi Flegrei (other parameters are identical to those in the homogeneous study).

The displacements in the heterogeneous reservoir differ from those in the homogeneous reservoir, although the deviation does not exceed 20%.

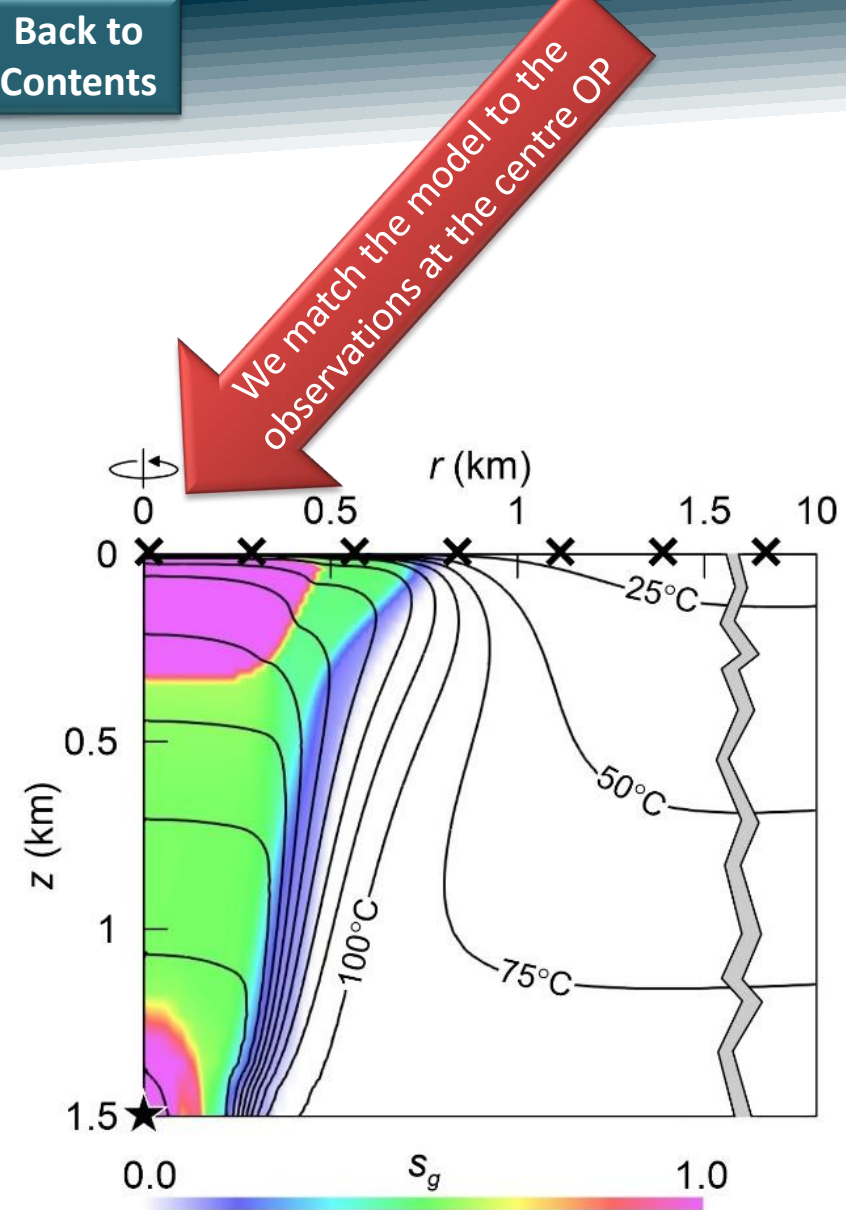
History matching & optimization

The objective function and the parameters to be matched (or optimized) are specified in the template.

History matching to the observed gravity changes, ground displacement, and other parameters is possible.



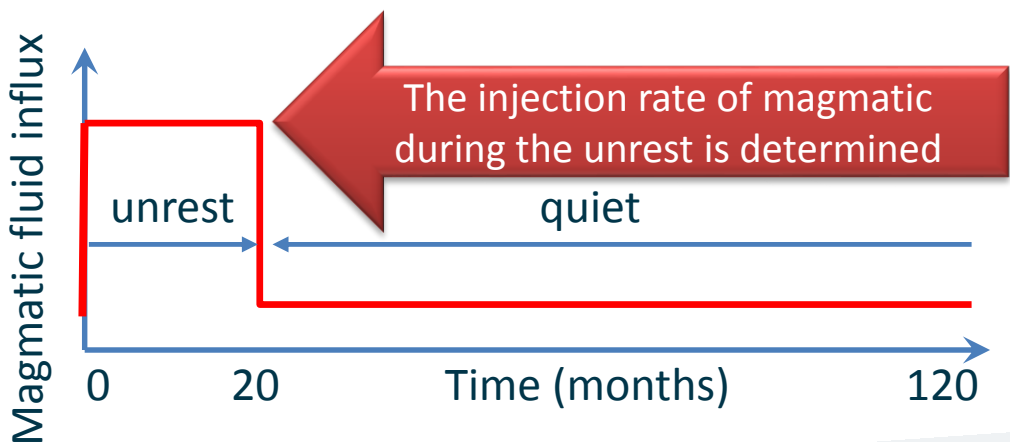
For accelerated history matching several hydrodynamic simulations can be run in parallel.



Example of a history matching study

To demonstrate MUFITS capabilities for history matching, we consider the study of hydrothermal activity at Campi Flegrei. We assume that the injection rate of the magmatic fluid during the unrest event (at $t < 20$ months) is unknown. It is determined by using observations of the gravity changes and vertical ground displacement at the axis of rotation (i.e., at $r=0, z=0$). A proxy for the observations were created by running the reservoir model at 12100 ton/day for the degassing rate.

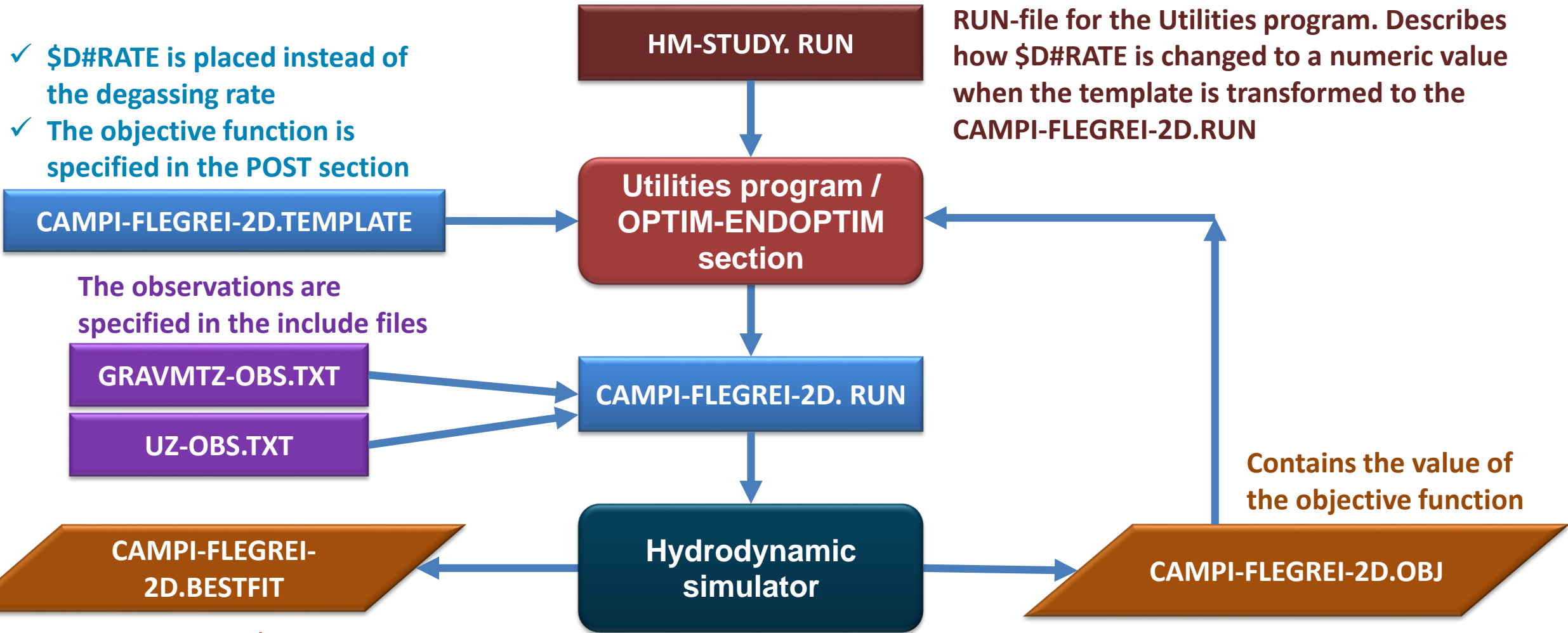
We use a non-gradient method to evaluate an optimal matching to the observations. The history matching study produced the degassing rate of 12136 ton/day which is acceptably close to the original value.



See details here

Review of the input & output files for the benchmark study

- ✓ \$D#RATE is placed instead of the degassing rate
- ✓ The objective function is specified in the POST section



is the RUN-file in that \$D#RATE is replaced by the determined numerical value

Summary

The new development of the software includes:

- ✓ COMPS module for the compositional modelling of multicomponent fluids.
- ✓ Options for modelling gravity changes and ground displacement.
- ✓ Geomechanical code for modelling ground displacement and the stress field.
- ✓ Options for history matching of the reservoir models to the observations of gravity changes and ground displacement.

The simulation results also demonstrate an acceptable accuracy of the semi-empirical built-in model for predicting the ground displacement (GRDDISP). Given that the necessary assumption are satisfied, the displacements predicted by the model are indistinguishable from those predicted by the more comprehensive geomechanical simulations. This makes the built-in option very attractive because it is fast. However, if the assumptions of the semi-empirical model are violated, then the coupling with the geomechanical code remains the only reliable approach for the ground displacement modelling. As we have shown, the domain for the geomechanical modelling should be ~ 3 times larger than that for the hydrodynamic modelling to reduce the influence of boundary conditions on the elastic equilibrium.

Acknowledgements: The authors acknowledge funding from Russian Science Foundation under grant # 19-71-10051.



Supplementary material

Click on the links to download the supplementary material

**Hydrodynamic
simulator**

**Geomechanical
simulator**

Utilities program

Reference manual

**Input data for the
study of activity at
Campi Flegrei
(hydrodynamic)**

**Input data for the
study of activity at
Campi Flegrei
(geomechanical)**

**Input data for the
study of miscible
displacement of oil**

**Draft of the paper with detailed description of the new
options for modelling gravity changes and ground
displacement as well as the benchmark study.**