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COMPUTER SIMULATION OF GEOTHERMAL RESERVOIRS IN THE PANNONIAN BASIN, EASTERN EUROPE

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ABSTRACT

Geothermal reservoir modelling is a technology that has become standard over the past decade in Eastern Europe. If sufficient information is available on a geothermal field, it is often possible to construct numerical models of the reservoir and use these models to simulate field performance under a variety of conditions. Perhaps the most important, and most challenging, part of this process is the integration of information gathered by all the geoscientific disciplines leading to development of the conceptual model. The success of any reservoir modelling exercise is dependent upon the flow of high quality information from the basic data collection phase, through the conceptual modelling phase, to the simulation process. This flow of information must go both ways, as the modelling process is an iterative one, often requiring numerous reconstructions and reinterpretations.

This paper reveals the particularities of numerical simulation of geothermal reservoirs nestled in the Pannonian Basin using modern reservoir engineering tools. Modelling results for several types of geothermal reservoirs are summarized , with special attention to general procedures for model development; calibration, and production simulation forecasts.

1. INTRODUCTION

Many Central and Eastern European (CEE) Countries have significant low-enthalpy (50-120°C) geothermal resources suitable for direct heat utilisation: space heating, culinary water heating, greenhouse heating, fish farming, aquaculture, etc.

Until the 1970s, these resources were only partially used, mainly for health and recreational bathing. The use of natural hot springs in the Precarpathian area and in the Pannonian Basin has been known since the time of the Roman Empire when Pannonia and Dacia provinces had famous health spas: Aqua Pannonicae (Vienna), Austria, Aquincum (Budapest), Hévíz Lake in Hungary, and Geoagiu, Herculane, and Felix Spas in Romania. The practice of geothermal health bathing continued in the Middle Ages during the Hungarian Kingdom and the Ottoman domination. During the last hundred years geothermal health bathing has flourished, especially in Hungary and Romania but also in Slovenia, Croatia, Serbia, Bulgaria and Slovakia.

Geological exploration for hydrocarbon resources carried out after World War II, particularly following the oil crisis of the early 1970s, gave a significant impulse to the identification and utilisation of geothermal resource in this part of Europe.

During early geothermal exploration and development, reservoir engineering was primarily involved with documentation of well outputs and their physical characteristics such as temperature and pressure; the potential of geothermal resources encountered by the wells was only briefly assessed.

2. GEOLOGICAL OUTLOOK

The Pannonian Basin was formed as a result of southward subduction of oceanic lithosphere. The rising contact of the mantle with the crust resulted in crustal thinning by extension and erosion. This caused a higher than average heat flow in the region, due to the closer proximity of the hotter mantle. The subsidence, which took place mainly in Neogene-Quaternary time, resulted in sedimentation of sandstones, clays and marls. These Pannonian formations overlie rocks of Miocene age or older. The latter are often referred to as basement, and include limestones, dolomites, sandstones, and conglomerates, as well as various igneous and metamorphic rocks.

3. RESERVOIR SIMULATION PROCEDURE

Published reservoir modelling studies (e.g., Economides and Ungemach, 1987) have helped to establish some general simulation procedures:

1. Selection of block structure and layout that best suits the conceptual model size and shape.
2. Initial selection of reservoir and fluid parameters that best match the observed conceptual model.
3. Iterative refinement of model parameters in order to provide the best match to observed reservoir behaviour under exploitation.
4. Further refinement of the model in order to reproduce the observed pre-exploitation state of the reservoir. These models are run over extremely long simulation times in order to confirm that the model approaches stability under observed reservoir conditions.
5. The best model is used to predict the reservoir behaviour throughout the expected project life under a variety of exploitation conditions.

4. CASE STUDIES

4.1. Simulation of the Tomnatic Geothermal Reservoir, Romania

The Tomnatic geothermal area is located in the Western Plain of Romania. This area is structurally part of the southeastern region of the Pannonian Basin.

In the Tomnatic geothermal area, the Upper Pannonian aquifers are exploited at present. The lower limit of these aquifers is the contact with the Lower Pannonian formation. The upper limit is arbitrarily defined because of the intercalated permeable formations which are present up to the surface. The most important aquifers are located in the bottom part of the Upper Pannonian formations. The porous permeable reservoirs are multi-layered, confined, and have high permeability contrasts; they consist of sandstone and siltstone interbedded with clay and shale, at depths of 1.4 to 2.0 km. Structurally, the layers are almost horizontal within the area. Hydrologic communication exists only between wells that are opened at the same depths. This fact is demonstrated clearly in this area where three productive intervals are defined and these are opened by different groups of wells. The temperatures of the productive zones are varying between 70°C and 95°C in the lower part of the reservoir. The reservoir pressure is uniform hydrostatic throughout the reservoir. The geothermal water, which is bicarbonate-sodium-chloride type with dissolved gases, especially methane (Gas Water Ratio=0.8-1.3 Nm^3/m^3) and total dissolved solid content (TDS) of 4 to 6 g/l, does not show variation in composition with time, proving the hydrologic unity of the entire multi-layered reservoir.

Broadly the reservoir may be considered as horizontal, with infinite extent and without recharge.

Eight wells were drilled in the area. From the geophysical logging and the continuous coring programs carried out during drilling, three productive intervals were defined. Along with the wells that penetrated them, these intervals are listed below.

- interval RA:-1860m to -2000m opened by well 4633 for production and well 4637 for monitoring.
- interval RB:-1690m to -1850m opened by well 1564 for production and well 1565 for monitoring.
- interval RC:-1490m to -1670m opened by well 1566 for production and well 1567 for monitoring.

Well 1574 is drilled to the -2000m depth but is not opened at any of the above intervals. This well initially was proposed for reinjection into the interval RA.

Reservoir model

The aim of the reservoir simulation carried out for this area was to find a model that can match the observed exploitation drawdown and temperatures (Antics, 1992).

The general-purpose geothermal reservoir simulator MULKOM (developed at Lawrence Berkeley National Laboratory by Karsten Pruess in 1982) was employed to carry out the simulation.

Based on the available geological data for the reservoir, the first step in the simulation was to set up the conceptual model. Reservoir parameters were assigned to the model based on the field measurements. It was considered that there was enough field data to start directly with a 3D model. Assuming that the reservoir is of infinite extent and without recharge, an area of 100 km^2 (10kmX10km) around the wells was considered.

The next step was to divide this area into blocks. Around the wells a finer grid (250m×250m) was chosen for a better approximation of the behaviour in this area. The grid is symmetric, containing square blocks with increasing size from the middle part to the outer part of the area (Figure 1). In vertical profile, nine layers were considered. Layers RA, RB, and RC are the productive layers corresponding to intervals A, B and C. Layers CA and CB are confining layers. Layers PA, PB, and PC are the layers corresponding to the upper part of the model up to the surface. The next step was to assign rock parameters to the selected layers. It was considered that the layers are horizontal and do not show anisotropy in permeability and porosity. The modelling was started with the assumptions presented above. The rock parameters assigned to the layers are presented in Table 1.

Simulation runs

The idea of natural-state modelling is to set up an approximate structure based on the conceptual model with a heat input at the bottom. Heat sources were assigned in layer BB (Lower Pannonian age) to each of the blocks, giving a uniform heat flow of 90 mW/m^2. The simulation was carried out over a very long period of time (5.0E+13s) corresponding to the development of the system over geological time.

The final steady-state conditions of the natural-state model were considered as initial conditions for the production model. The main objective at this stage was to match the observed drawdown in the wells. A time step of 2 months was considered appropriate for simulation. Smaller time steps would have increased computer time. The time step of 2 months can cover in good conditions both the production period (7 months) and the recovery period (5 months). Several trial and error runs were performed until the best fit was obtained.

Because the wells are producing in a cyclic manner, there is a cyclic variation, in time, of the pressure drawdown. They exhibit increasing values when the wells are producing and decreasing values when the wells are shut off. The general trend of the pressure drawdown is increasing with time. The reservoir pressure does not recover to its initial value while the wells are shut off.

The exploited geothermal water is used directly in space heating of 7.5 ha of greenhouses. The requirement of the greenhouses is for 41 kg/s water at a minimum of 70°C in the colder part of the winter (October-February) and 29 kg/s in the other period (March-April). This flowrate can be obtained from the actual producing wells without exploiting the wells that are used for monitoring. It was assumed that the whole amount of waste geothermal water at a return temperature of 30°C is reinjected in well 1574. It was also assumed that the injection flowrate is changing at the same time with the production flowrate, and that the well can receive the whole amount of the waste geothermal water.

The results of the simulation show that the reservoir pressure will increase by 8 bar in the interval RA (Figure 2), by 4.2 bar in interval RB, and by 2.2 bar in interval RC (not shown in figures). The temperature will decrease after 25 years in the injection block and in the four blocks which are on the sides of the injection block. No significant temperature change can be observed in the other blocks and layers. Since all the reinjection tests in the neighbouring areas were unsuccessful, the present simulation of this situation should be considered as a purely theoretical one.

4.2. Simulation of the Oradea Geothermal Reservoir, Romania

The Oradea aquifer is located in Triassic limestones and dolomites, at depths of 2,200-3,400 m, within an area of about 113 km^2, and is exploited by 12 wells, with a total artesian flow rate of 140 l/s geothermal water, with well head temperatures of 70-105°C. There are no dissolved gases, and TDS is lower than 0.9-1.2 g/l. The water is of calcium-sulphate-bicarbonate type, with no scaling or corrosion potential. The reservoir is bounded by faults. There are also internal faults in the reservoir, dividing it into four blocks. The central block is elevated relative to the northern and southern blocks (see Figure 3). The internal faults do not produce discontinuities in the circulation of the water in the reservoir. The main circulation is from the northeastern part of the reservoir, along preferential pathways represented by the fault system at the boundary. There is a continuous flow of water towards its natural discharge at Felix Spa. The terrestrial heat flow is about 90 mW/m^2. The geothermal gradient varies between 2.6-4.1 °C/100m. Properties such as ionic composition, high radioactivity and the content of rare gases, indicate an active circulation along paths partially in contact with the crystalline basement. The water is about 20,000 years old, the recharge area being in the Western Carpathian Mountains 20-30 km East of Oradea.

Reservoir model

The main aim of the reservoir simulation carried out for the Oradea geothermal reservoir was to set up a numerical computer model which is able to match the pressure drawdown and temperatures observed during exploitation and to predict pressure and temperature trends in the reservoir for future development schemes.

The computer code employed for simulation is TOUGH2 PC version.

Based on the available data, a 2D computer model was considered for the Oradea geothermal reservoir. The assumptions used for modelling are presented below:

- the reservoir is situated at 2,400 m below sea level;
- the reservoir is one horizontal layer, with a constant thickness of 900 m;
- the reservoir is closed at the north, south and west;
- the eastern boundary was set as a constant pressure boundary at 246.9 bar and 70°C;
- the internal faults of the reservoir have not been considered in the simulation.

The reservoir was divided into 1,934 elements. A regular grid of 200×200 m (Figure 3) was set up in the production area, in the outer portion of which an irregular grid was set up. At the eastern boundary of the reservoir, a block with a volume of zero was set up to simulate the constant pressure boundary of the reservoir. In order to assign double porosity behaviour to the model, the primary grid was pre-processed with the MINC (Multiple Interacting Continua) procedure of the simulator. It was considered that there are two interacting media, the matrix and the fracture, and the type of flow in the reservoir is mainly fracture flow. It was assumed that the fracture represents 10% of a unit volume of rock, and that the fractures have 100m spacing. After pre-processing, a model with 3,869 elements resulted. The producer/injector blocks were not discretised in order to simulate accurately the well within the producer block. The permeability structure of the fractures in the reservoir was assigned based on the contour map of the permeability distribution (Figure 4) obtained from interpretation of well test data obtained from an intensive campaign carried out in 1995. The well tests consisted of buildup and drawdown tests for each well in the area.

Simulation runs

The computer model has been calibrated on the measurements carried out during the interference test of 1984. It is worth mentioning that these were the only reliable measurements done during the production of the reservoir (that began in 1974; Antics, 1997).

Several simulations have been carried out in order to calibrate the model. Parameters such as permeability structure of reservoir, fracture spacing, and boundary conditions were modified. Two separate simulation runs were carried out: one simulation for constant pressure boundary conditions at the eastern side of the reservoir and one simulation for closed reservoir. After calibration, the simulation was continued for the 1984-1995 period. These simulations were based on the production history of each well. The simulations showed that the reservoir behaved in stable fashion during the past 11 years of exploitation.

The development schedule assumes that the utilisation will be developed to maximum by installing electrical downhole pumps in 8 wells and reinjecting in 6 wells. Reinjection will be carried out in 4 selected production wells and in 2 injection wells to be drilled in the future. By employing this scheme, the exploitation will be carried out by the operation of 8 doublets in the Oradea area. Four of the doublets will be using only two injection wells, a single well being used to inject the spent geothermal water from two doublets. The production/injection schedule is presented in Table 2.

The simulation has been performed for a period of 30 years. For the first 10 years, the chosen time step was 30 days and after 10 years it was changed to 120 days.

The simulation shows that the reservoir pressure distribution will be stable at its initial value, except the blocks in the northwestern part of the reservoir, which have lower permeabilities. The temperature in the injection blocks will decrease during 30 years of exploitation from their initial value close to the injection temperature. However, there will be no thermal breakthrough between the injection and the production blocks.

4.3. Simulation of the Overpressured Geothermal Reservoir, Nagyszénás, Hungary

The Nagyszénás area belongs to the southern belt of the Békés Basin i.e. to the Battonya-Pusztaföldvár Mesozoic Trough. The first exploratory wildcat oil well was completed in 1954 at a depth of 3009m. During 1978-1988 six more exploratory wells were drilled in the area with final depths of 2800-4200m. These wells confirmed the existence of medium-high enthalpy overpressured geothermal resources below a depth of 3000m. The steam blow-out of Fábiánsebestyén 4 well and the flow test of well Nagyszénás 3 (Nsz3) confirmed that geothermal overpressured resources occur in fractured Mesozoic formations in the area and may be suitable for power generation exist.

Overpressuring in basement rocks, most of which are fractured, may be caused by: (i) aquathermal heating and (ii) thermally generated carbon dioxide in the basement rocks simultaneously with downward migration of fluids from overpressured Miocene and lower Pannonian basal marl and argillaceous marl.

Reservoir model

The preliminary numerical simulation studies carried out for the Nagyszénás area were addressed mainly to reservoir evaluation i.e.: lateral extent, thickness and volume, tectonic features, governing boundary conditions, and porosity/ permeability patterns. The main idea was to set up a numerical model that can reproduce the recorded reservoir pressure build-up behaviour after the flow test carried out in 1991 (Antics, 1998).

The computer code employed for simulation was TOUGH2 PC version.

Based on the available geological model and rock properties a 3D model was set up considering that the productive geological formation belongs to Lower Triassic. From the cross section of the area and the results of the magneto-telluric survey the reservoir considered has a rectangular shape with the dimensions of 15x2km and thickness of 950m. The grid set-up is shown in Figure 5. For simplicity the grid describes in vertical direction only the part between 3050-4000m corresponding to the Lower Triassic formation. Furthermore it was assumed that in plan view the well is located in the centre of the grid and in the centre of the third layer in vertical direction.

With respect to permeability / porosity structure of the grid four models were considered:

1. Uniform model with constant thickness of 950m (labelled Uni1)
2. Uniform model with constant thickness of 50m (labelled Uni2)
3. Fractured model consisting of one vertical fracture from East to West 50m wide and 950m thick interacting with the rest of porous medium. The porosity of the fractured medium is higher than of the porous medium (labelled Fra1)
4. Fractured model consisting of one vertical fracture from East to West 50m wide and 950m thick interacting with the rest of porous medium. The porosity of the fractured medium is the same as of the porous medium (labelled Fra2)

The main assumption for each model is that the reservoir is sealed on each side.

The main properties of the four models considered are shown in Table 3. For the case of fractured models, where no separate properties are listed for the fractured and the porous medium they are assumed to be the same.

Simulation runs

The initial temperature was considered as 190°C. All models were run first under no flow conditions until hydrostatic equilibrium was reached corresponding to the observed 63.8 MPa at 3165m.

Each model was run for the simulation of the flow test carried out on the Nagyszénás 3 well. The main objective of each simulation was to find a candidate model which is able to reproduce the build-up pressure data recorded at the end of the flow test.

The obtained results lead to the idea that there are two candidate models: Uni2 and Fra1 respectively which closely reproduce the measured data. Another conclusion that can be drawn is that the reservoir's areal extent has been correctly estimated from the geological data, therefore no further sensitivity studies regarding the areal extent of the reservoir are required.

The next step was to examine how the two candidate models Uni2 and Fra1 would describe reservoir behaviour for two long-term production scenarios.

The first scenario assumes that the well would be produced with a flowrate of 16kg/s corresponding to 1MW for 25 years. The purpose of this simulation was also to examine the reservoir behaviour in case of a long term flow test, and to find the ideal duration for a long term flow test (Figure 6).

The second scenario assumes that the well would produce 80kg/s (5MW) for 25 years.

The long-term production simulation for 1MW suggests that out of the candidate models, the reservoir which could sustain 25 years production corresponds to the Fra1 model.

From simulation run results it appears that the ideal duration for the long-term test would be over 100 days. This time would be sufficient to obtain an accurate reservoir response.

None of the models studied provided a production of 5MW for 25years. This suggests that the reservoir in question is a small sealed compartment of Lower Triassic formations.

5. CONCLUSIONS

Data collection for reservoir simulation should be aimed at setting up the best possible model as soon as possible so that it can be used to predict the future behaviour of the reservoir and also to guide further data collection.

It should not be expected that a definitive computer-based geothermal reservoir model can be quickly constructed with meagre data.

The computer codes or reservoir simulators to set up the required models are now available and reservoir engineering expertise to apply them to produce useful models of real reservoirs is also available and is developing rapidly. In particular, for low temperature geothermal reservoirs occurring in the Pannonian Basin, the use of computer codes such as TOUGH2 on PC environments may lead to excellent results at relatively low computer costs.

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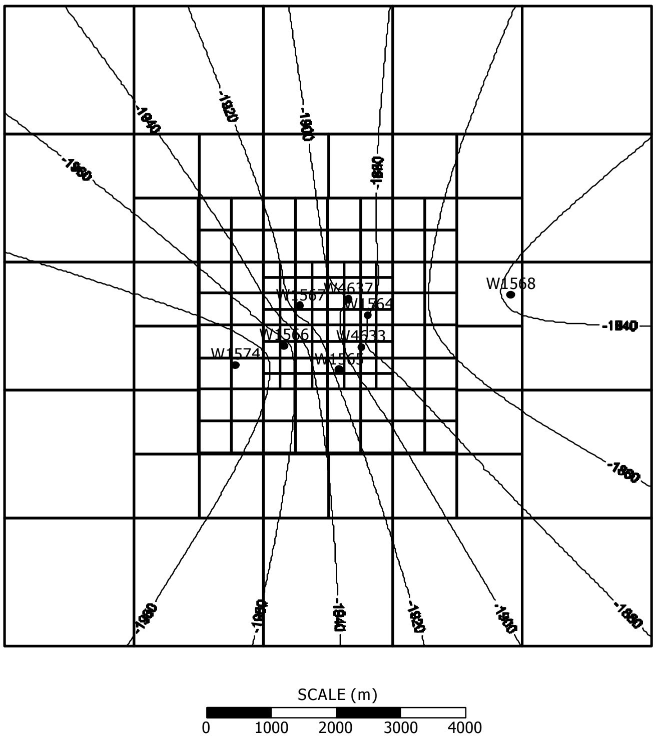

Figure 1: Simulation grid set-up and contour lines at the top of Upper Pannonian

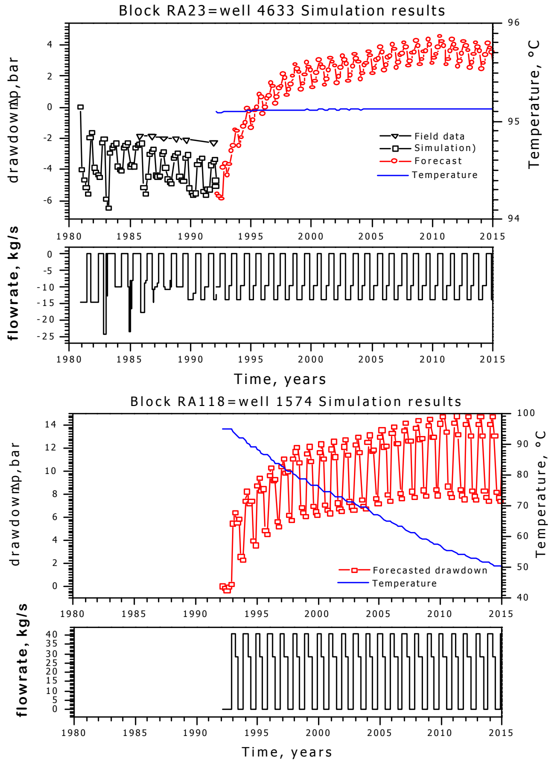

Figure 2: Tomnatic reservoir simulation results

Table 1 Parameters used for the Tomnatice reservoir model

Layer	Middle of layer (m)	Rock name	Poro-sity ϕ	Density (kg/m^3) ρ	Permeability			Thermal conduct (W/mK)	Heat capacity (kJ/kgK)
					k_x (mD)	k_y (mD)	k_z (mD)		
AT	0	ATM							
PC	-250	UPANC	0.1	2500	1	1	1	2.5	1
PB	-750	UPANB	0.1	2500	5	5	5	2.5	1
PA	-1245	UPANA	0.1	2500	15	15	15	2.5	1
RC	-1580	RESEC	0.3	2710	300	300	300	1.45	0.84
CB	-1680	CONFB	0.1	2500	0.03	0.03	0.03	2.5	1
RB	-1770	RESEB	0.3	2710	80	80	80	1.45	0.84
CA	-1855	CONFA	0.1	2500	0.001	0.001	0.001	2.5	1
RA	-1930	RESEA	0.3	2710	94	94	94	1.45	0.84
BB	-2125	LOPAN	0.08	2500	0.01	0.01	0.01	2.5	1

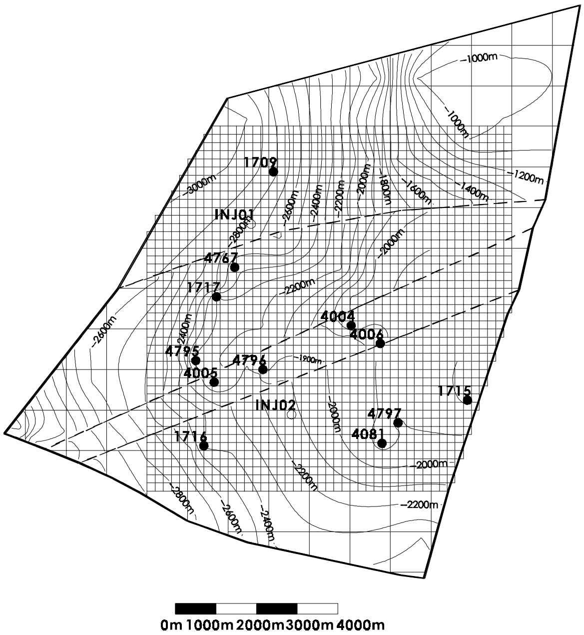

Figure 3: Oradea reservoir simulation grid set-up and contour map at the top of the reservoir

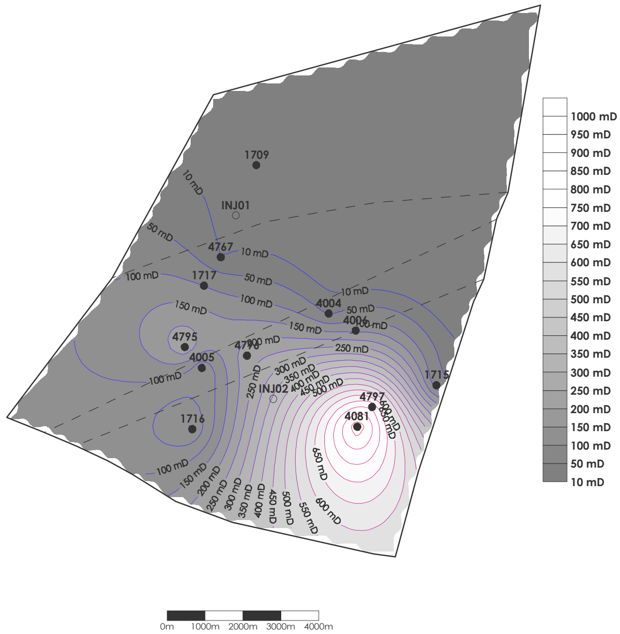

Figure 4: Permeability distribution of the Oradea reservoir model

Table 2: Production/injection schedule for Oradea production forecast simulation

Site	Uses [l/s]			Production		Injection		Injection
	SHW	Other	Total	Well	Q [l/s]	Well	Q [l/s]	Temp.[°C]
Nufărul	32		32	4797	-32	4081	32	30
Ioşia	15	10	25	4767	-25	1717	15	35
	42	10	52		-52		42	35
Arad Highway	10	10	20	4795	-20	4005	20	35
Dacia	5	5	10	4004	-10	4006	5	35
Episcopia	10		10	1709	-10	INJ01	10	40
Airport	5	5	10	1716	-10			
University	10	15	25	4796	-25	INJ02	25	35
Cluj Highway	5	5	10	1715	-10			

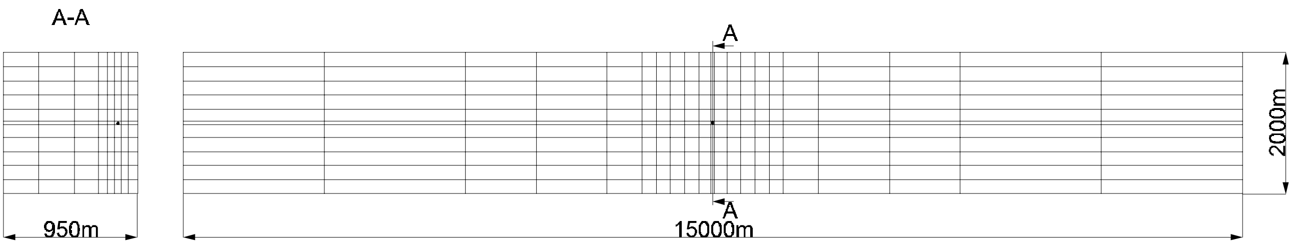

Figure 5: Nagyszénás reservoir model grid set-up

Table 3: Rock properties for the Nagyszénás reservoir model

Parameter	Model	Uni1	Uni2	Fra1	Fra2
Rock density, kg/m^3		2650	2650	2650	2650
Matrix porosity		0.03	0.03	0.03	0.03
Fracture porosity		-	-	0.1	0.03
Matrix permeability, mD		11	11	1	1
Fracture permeability, mD		-	-	11	11
Rock heat conductivity, W/m°C		3	3	3	3
Rock grain specific heat, J/kg°C		1000	1000	1000	1000
Compressibility, m^2/N		10^{-9}	10^{-9}	10^{-9}	10^{-9}

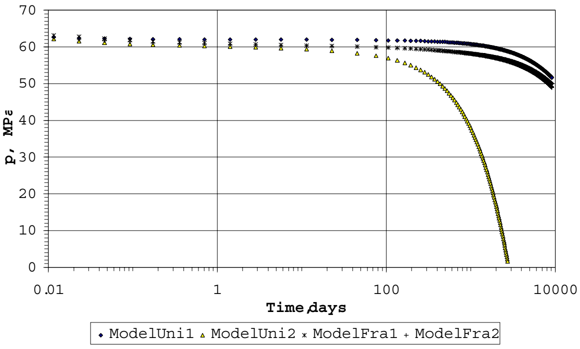

Figure 6: Nagyszenas 1MW simulation results