LOW ENTHALPY GEOTHERMAL RESERVOIR SIMULATION

Miklos ANTICS
GEOPRODUCTION CONSULTANTS (GPC)
Paris Nord 2, 14, rue de la Perdrix, Lot 109, B.P. 50030
95946 ROISSY CDG CEDEX, France
e-mail: m.antics@geoproduction.fr

ABSTRACT

Owing to the exhaustible nature of geothermal resources, sustainable heat mining is of utmost importance in designing and implementing relevant exploitation strategies aimed at reconciling users' demands with reservoir longevity concerns.

Geothermal reservoir simulation is a technology that contributes to the important problem area of sustainable heat mining, and has become standard over the past decade. If sufficient information on the field is available then 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 geo-scientific disciplines leading to the 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 reconstruction and reinterpretation.

The paper reveals the particularities of numerical simulation of geothermal reservoirs nestled in the Pannonian Basin using modern reservoir engineering tools. There are summarised the modelling results of several types of geothermal reservoirs focusing on the general procedures adopted for model development; calibration, and production simulation forecasts.

1. INTRODUCTION

Once a geothermal resource has been identified and the reservoir assessed leading to a conceptual model of the geothermal system, reservoir development and relevant management issues come into play.

In the broad sense, reservoir management is an extension of reservoir engineering. Whereas the latter addresses key issues such as heat in place, reservoir performance, well deliverabilities, heat recovery, water injection and reservoir life, reservoir management aims at optimised exploitation strategies in compliance with technical feasibility, economic viability and environmental safety requirements.

Nowadays reservoir engineers are required to construct a realistic conceptual model of the field including sub surface temperature and pressure distributions in both vertical and horizontal planes, the distribution of chemicals and gases, field boundaries, reservoir storage and transmissivity, and the flow of fluids both within the reservoir and across the boundaries. The sources of information from which the model is deduced are well test results and downhole measurements. The reliable interpretation of field measurements is therefore a major consideration for the reservoir engineer. The conceptual model of the field often provides sufficient understanding of the reservoir to enable informed and logical decisions on the field development and reservoir management [1].

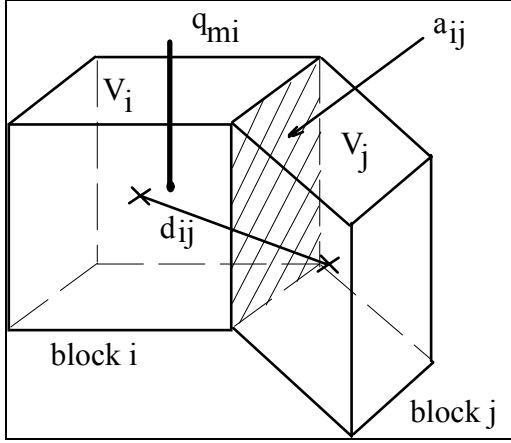## 2. NUMERICAL MODELLING

Figure 1: Block discretisation

The procedure discussed here is employed by many general purpose geothermal reservoir simulators and is based on the integrated finite difference technique developed at Lawrence Berkeley Laboratory. These simulators proved to work well in case of simulation of low temperature geothermal systems [5].

It is assumed that the region of interest is divided up into blocks or elements (Fig. 1). The i-th block has a volume V_i and is connected by an area of $a_{i,j}$ to the j-th block. This formulation allows for an irregular block structure but includes more regular block structures such as rectangular blocks or polar coordinate systems as special cases. Here p_j^n and T_i^n are used to represent pressures and temperatures in the i-th block at the end of the n-th time step. The n-th time step is of duration Δt_n.

All successful geothermal simulation techniques are based on two common ideas:

1. Difference equations are fully implicit with all mass and energy fluxes evaluated at the new time level.

2. Upstream weighting is used to calculate interface quantities.

The procedure discussed here is block-centred for pressures and temperatures while fluxes are calculated at block boundaries. The discrete mass balance equation can be written:

$$V_i\left(A_{mi}^{n+1} - A_{mi}^{n}\right) = -\sum_j a_{ij} Q_{mij}^{n+1} \Delta t_{n+1} + q_{mi}^{n+1} \Delta t_{n+1} \tag{1}$$

Here Q_{mij}^{n+1} is the mass flux from block i to block j evaluated at the end of the (n+1)th time step. Similarly q_{mi}^{n+1} is the mass production from block i evaluated at the end of the (n+1)th time step (positive for injection). The production rate q_{mi}^{n+1} use in equation (1) is a total flow rate (kg/s). Similarly the discrete energy equation is:

$$V_i\left(A_{ei}^{n+1} - A_{ei}^{n}\right) = -\sum_j a_{ij} Q_{eij}^{n+1} \Delta t_{n+1} + q_{ei}^{n+1} \Delta t_{n+1} \tag{2}$$

Here Q_{eij}^{n+1} and q_{ei}^{n+1} are defined as for the mass equation above.

For discretisation of Darcy's Law the equations below are used:

$$Q_{m\ell ij}^{n+1} = -\left(\frac{kk_{r\ell}}{v_\ell}\right)_{ij}^{n+1}\left[\frac{p_j^{n+1} - p_i^{n+1}}{d_{ij}} - \rho_{\ell ij}^{n+1} g_{ij}\right] \tag{3}$$

$$Q_{mvij}^{n+1} = -\left(\frac{kk_{rv}}{v_v}\right)_{ij}^{n+1}\left[\frac{p_j^{n+1} - p_i^{n+1}}{d_{ij}} - \rho_{vij}^{n+1} g_{ij}\right] \tag{4}$$

The total mass flow becomes

$$Q_{mij}^{n+1} = Q_{m\ell ij}^{n+1} + Q_{mvij}^{n+1} \tag{5}$$

$$Q_{eij}^{n+1} = h_{\ell ij}^{n+1} Q_{mij}^{n+1} + h_{vij}^{n+1} Q_{mvij}^{n+1} - K_{ij}^{n+1}\frac{T_j^{n+1} - T_i^{n+1}}{d_{ij}} \tag{6}$$

There are several terms in equation (3) whose calculation requires further explanation. The gravity term g_{ij} is the component of gravity acting through the interface. For example, $g_{ij}=0$ for two blocks horizontally adjacent, and $g_{ij}=g$ for two blocks with block i vertically above block j the interface densities in the "weight" terms are evaluated using:

$$\rho_{\ell ij}^{n+1} = \frac{1}{2}\left(\rho_{\ell i}^{n+1} + \rho_{\ell j}^{n+1}\right) \tag{7}$$

$$\rho_{vij}^{n+1} = \frac{1}{2}\left(\rho_{vi}^{n+1} + \rho_{vj}^{n+1}\right) \qquad (8)$$

The inter-block distance d_{ij} is the sum of the distances d_i and d_j from the centres of the ith and jth block to their connecting interface respectively. The interface permeabilities and conductivities are calculated using harmonic weighting and usually they are assumed to be independent of pressure and temperature and therefore need to be evaluated only once at the beginning of the simulation using:

$$\frac{1}{k_{ij}} = \frac{\left(\dfrac{d_i}{k_i} + \dfrac{d_j}{k_j}\right)}{d_{ij}} \qquad (9)$$

The most important aspect of the interface calculations is the upstream weighting of the mobilities and enthalpies. For example the mobilities are expressed as:

$$\left(\frac{k}{v_\ell}\right)_{ij}^{n+1} = \begin{cases} \left(\dfrac{k}{v_\ell}\right)_i^{n+1}, & for \quad G_\ell^{n+1} < 0 \\[3mm] \left(\dfrac{k}{v_\ell}\right)_j^{n+1}, & for \quad G_\ell^{n+1} > 0 \end{cases} \qquad (10)$$

where:

$$G_\ell^{n+1} = \frac{p_j^{n+1} - p_i^{n+1}}{d_{ij}} - \rho_{\ell ij}^{n+1} g_{ij} \qquad (11)$$

$$\left(\frac{k_{rv}}{v_v}\right)_{ij}^{n+1} = \begin{cases} \left(\dfrac{k_{rv}}{v_\ell}\right)_i^{n+1}, & for \ G_v^{n+1} < 0 \\[3mm] \left(\dfrac{k_{rv}}{v_v}\right)_j^{n+1}, & for \ G_v^{n+1} > 0 \end{cases} \qquad (12)$$

where:

$$G_v^{n+1} = \frac{p_j^{n+1} - p_i^{n+1}}{d_{ij}} - \rho_{vij}^{n+1} g_{ij} \qquad (13)$$

Similarly the enthalpies can be evaluated using the following equations

$$\left(h_\ell\right)_{ij}^{n+1} = \begin{cases} \left(h_\ell\right)_i^{n+1}, & for \quad G_\ell^{n+1} < 0 \\ \left(h_\ell\right)_j^{n+1}, & for \quad G_\ell^{n+1} > 0 \end{cases} \qquad (14)$$

$$\left(h_v\right)_{ij}^{n+1} = \begin{cases} \left(h_v\right)_i^{n+1}, & for \quad G_v^{n+1} < 0 \\ \left(h_v\right)_j^{n+1}, & for \quad G_v^{n+1} > 0 \end{cases} \qquad (15)$$

The quantities A_{mi}^{n+1} and A_{ei}^{n+1} are evaluated as follows:

$$A_{mi}^{n+1} = \phi_i \left(S_\ell \rho_\ell + S_v \rho_v\right)_i^{n+1} \qquad (16)$$

$$A_{ei}^{n+1} = \left(1 - \phi_i\right)\rho_{ri} C_{ri} T_i^{n+1} + \phi_i \left(\rho_\ell S_\ell u_\ell + \rho_v S_v u_v\right)_i^{n+1} \qquad (17)$$

In these formulae variations of porosity with pressure and temperature could be included by adding the n+1 superscript to ϕ_i. The difference equations (1) and (2) together with equations (3) to (17) above are then solved for each time step.

The main aim of reservoir modelling is to set up a computer model which represents the permeability structure, heat inputs of the real reservoir with sufficient accuracy so that the simulated behaviour of the model for twenty or thirty years can be used confidently as a prediction of the real

reservoir. There are a number of minor reservoir simulation tasks that often accompany the development of a complete reservoir model. For example the results of pressure tests and interference tests can be simulated in order to help to establish the correct permeability and porosity values for different parts of the reservoir.

All modellers agree that a computer model of a geothermal reservoir must be preceded by a conceptual model; that is, a good understanding of the physical behaviour of the reservoir[1].

In summary a successful reservoir modelling program has three fundamental components:

1. The collection of meaningful and reliable geoscientific, production, and reinjection data, and the interpretation and analysis of this data.
2. The construction of a conceptual reservoir model.
3. The development of a computer model of the reservoir, to allow the simulation of behaviour patterns and response to exploitation.

The reservoir modelling studies published 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.
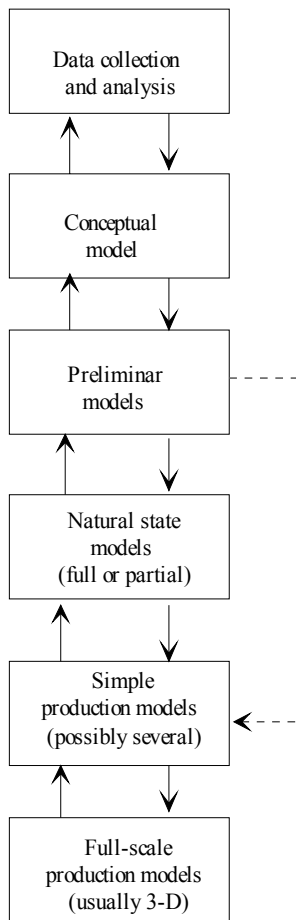
Data collection and analysis

Conceptual model

Preliminar models

Natural state models (full or partial)

Simple production models (possibly several)

Full-scale production models (usually 3-D)

Figure 2: Modelling steps

The basic steps required in setting up a computer model of a geothermal field are summarised in Fig. 2. The two-way arrows indicate that the process is an iterative one. For example, investigations of preliminary models may lead to further field studies and data collection followed by some modification of the original conceptual model and preliminary models.

4

3. CASE STUDIES

3.1 *Simulation of the Tomnatic Geothermal Reservoir, Romania [2]*

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

In the Tomnatic geothermal area the Upper Pannonian aquifers are exploited at present. The lower limit of this aquifer is the contact with the Lower Pannonian formation. The upper limit is arbitrary defined because of the intercalated permeable formations which are present up to the surface. The most important formations are located in the bottom part of the Upper Pannonian formations. The porous permeable reservoirs are multi-layered, confined, with high permeability contrasts, consisting of sandstone and siltstone inter-bedded with clays and shale, at depths of 1.4 to 2.0km. 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 to 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 mineralisation of 4 to 6 g/l, does not show variation in composition with time, proving the hydrologic unity of the whole multi-layered reservoir.

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

In the area 8 wells were drilled. From the geophysical logging and the continuous coring programs carried out during drilling there were defined 3 productive intervals which are listed below together with the wells which are opening them respectively:

- interval A:-1860m to -2000m opened by well 4633 for production and well 4637 for monitoring.
- interval B:-1690m to -1850m opened by well 1564 for production and well 1565 for monitoring.
- interval C:-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 none of the above intervals. This well initially was proposed for reinjection into the interval A.

3.1.1 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 LBL, by Karsten Pruess, 1982) was employed to carry out the simulation.

Based on the available geological data of the reservoir the first step was to set up the conceptual model. The 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. According to the assumption that the reservoir is of infinite extent and without recharge an area of 100 km^2 (10km×10km) 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 3). In vertical profile 9 layers were considered. Layers RA, RB, RC are the productive layers corresponding to intervals A, B and C. Layers CA, 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.
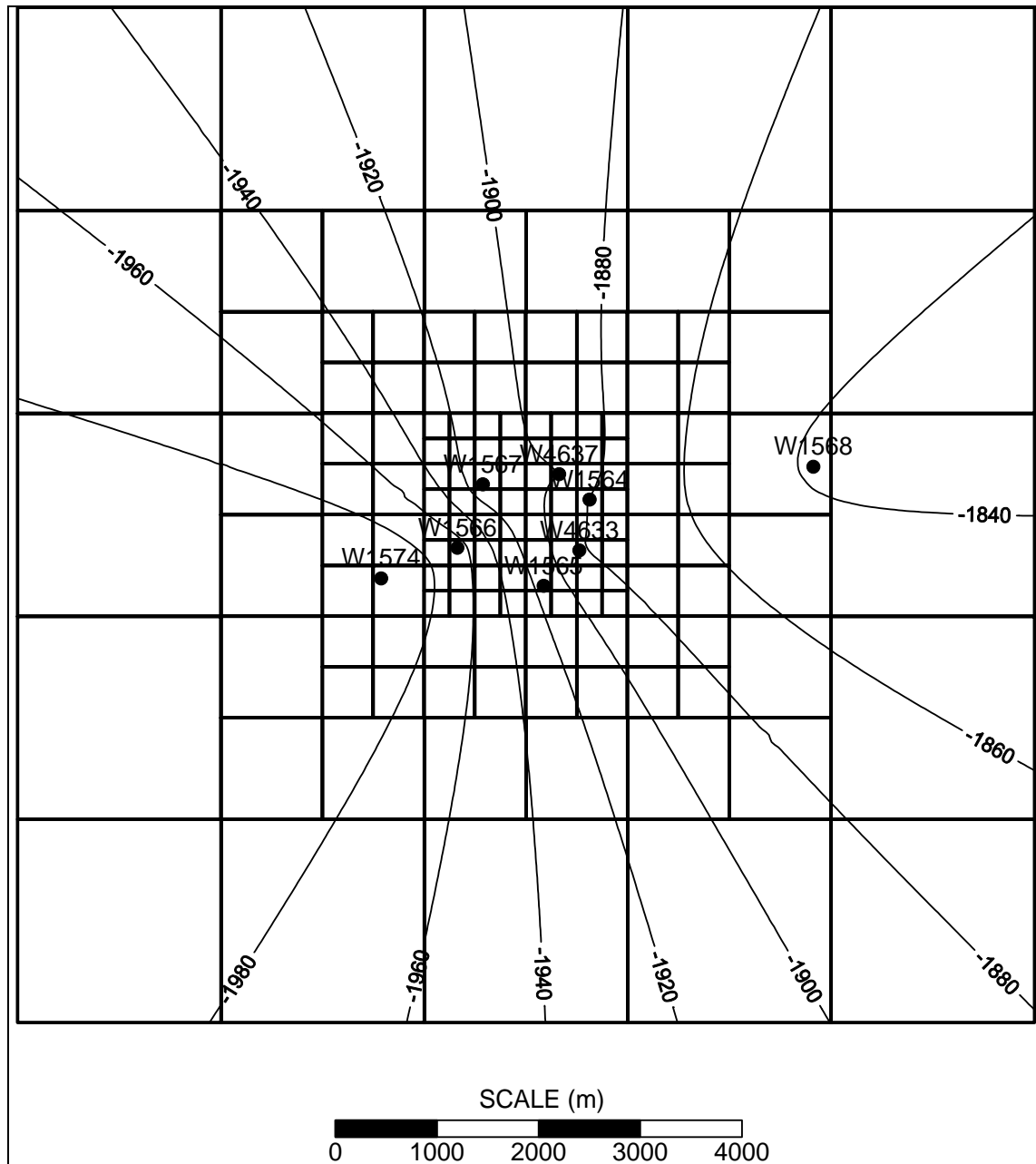
Figure 3: Simulation grid set-up and contour lines at the top of Upper Pannonian

Table 1 Parameters used for the reservoir model

Layer	Middle of layer (m)	Rock name	Porosity ϕ	Density ρ (kg/m^3)	Permeability k_x (mD)	Permeability k_y (mD)	Permeability k_z (mD)	Thermal conductivity (W/mK)	Heat capacity (kJ/kgK)
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

6

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.
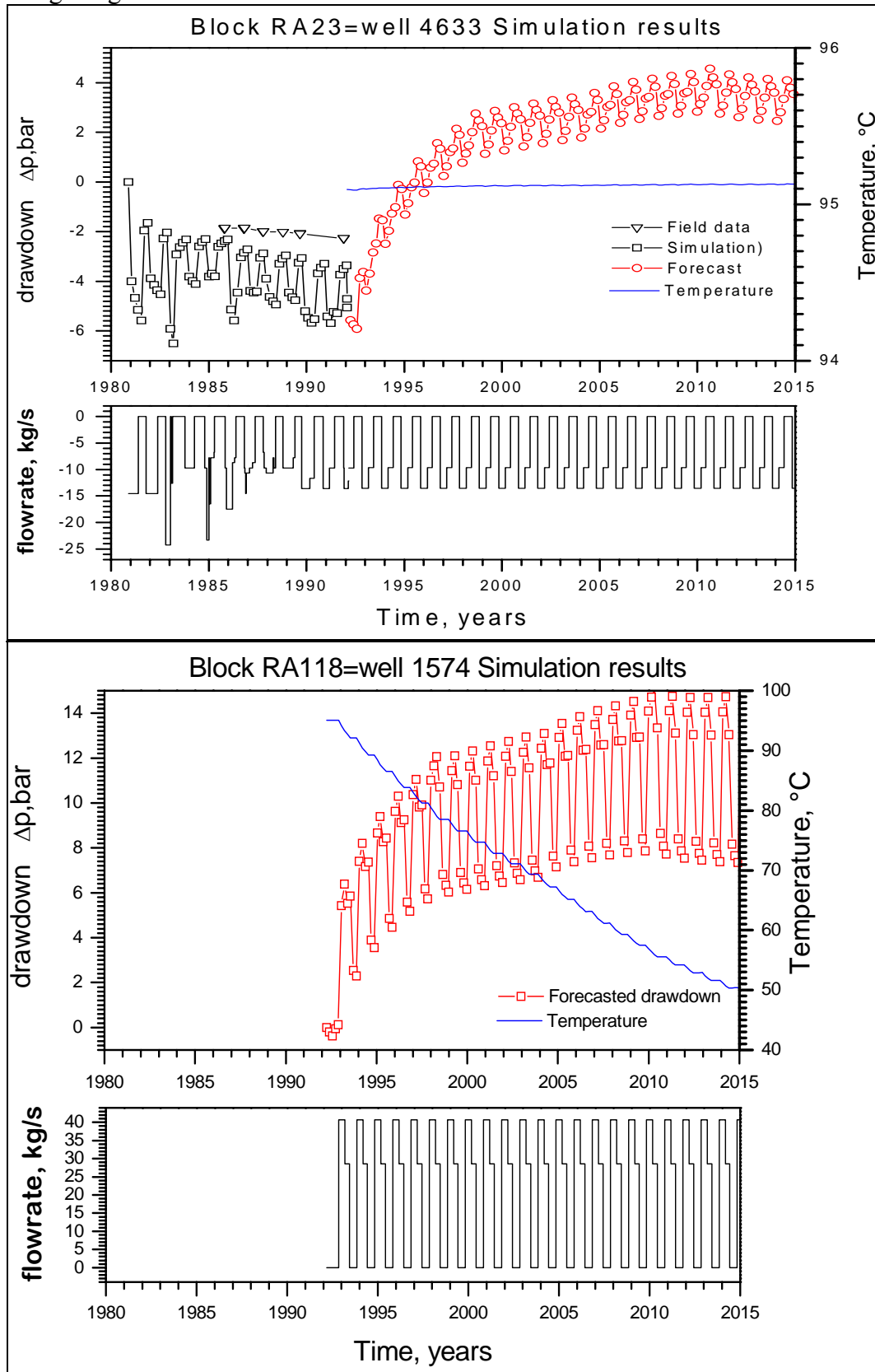

Figure 4: Tomnatic reservoir simulation results

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 step would have increased computer time. The time step of 2 months can cover in good conditions both of the production period (7 month) and the recovery period (5 month). 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 produced from the actual producer 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 assumed that the injection flowrate is changing at the same time with the production flowrate and 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 A (Figure 4), by 4.2 bar in interval B and by 2.2 bar in interval C. 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 and the present simulation of this situation should be considered as a pure theoretical one.

3.2   Simulation of the Oradea Geothermal Reservoir, Romania [3]

The Oradea aquifer is located in Triassic limestone and dolomites, at depths of 2,200÷3,400 m, on 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 the mineralisation 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 5). The internal faults do not produce discontinuities in the circulation of the water in the reservoir The main circulation is from the north-eastern 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.

3.2.1   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, developed by Karsten Pruess at the Earth Science Division, L. Berkeley Laboratory, University of California.

Based on the available data, it was considered a 2D computer model for the Oradea geothermal reservoir. The assumptions used for modelling are the 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 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 5) was set up in the production area and in the outer part of the production area 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 an unit volume of rock and the fractures have 100 m 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 obtained from well test data (Figure 6).
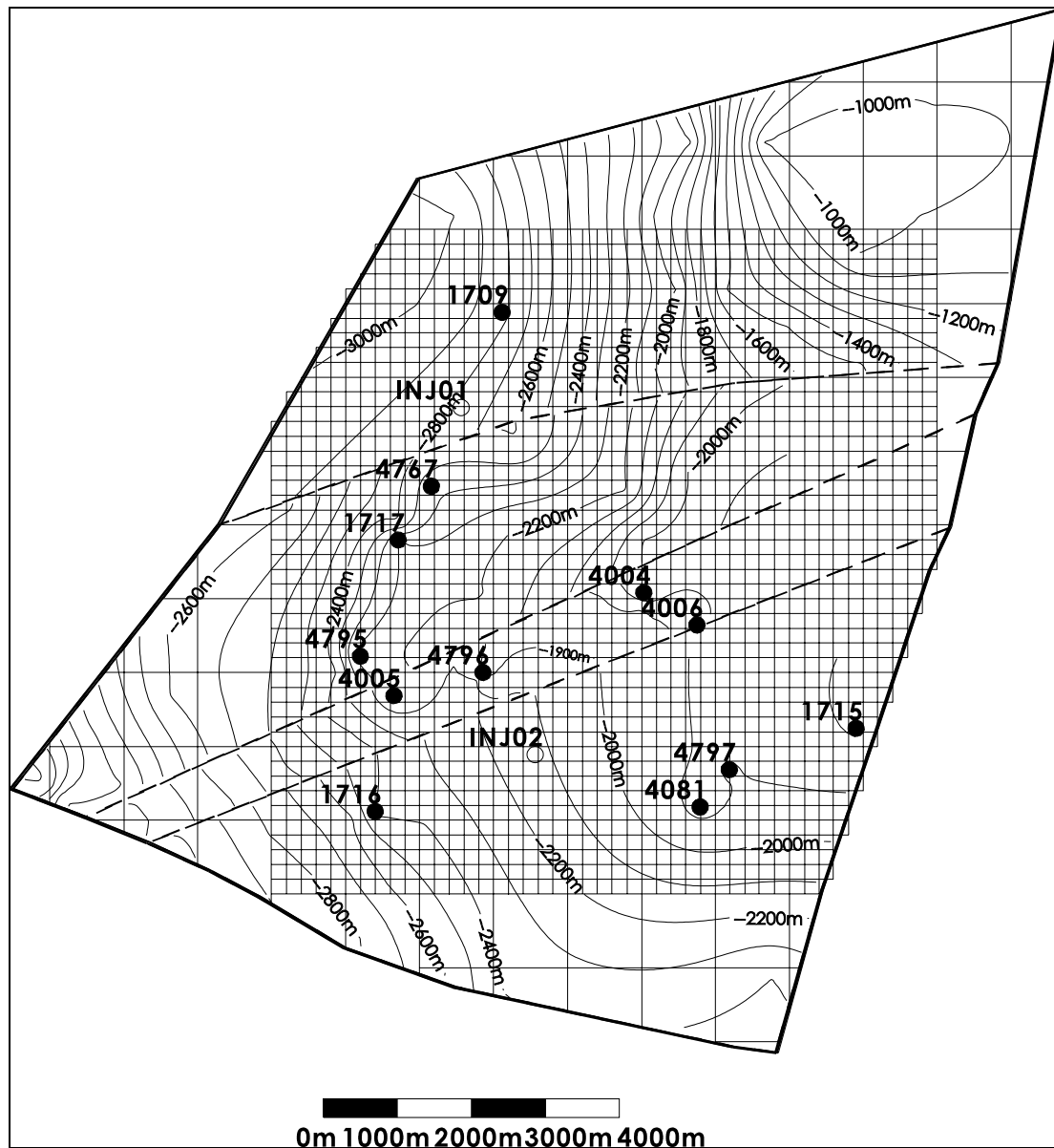

Figure 5: Oradea reservoir simulation. Grid set-up and contour map at the top of the reservoir

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

Site	Uses [l/s]			Production		Injection		Injection temperature[°C]
	SHW	Other	Total	Well	Q [l/s]	Well	Q [l/s]	
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			
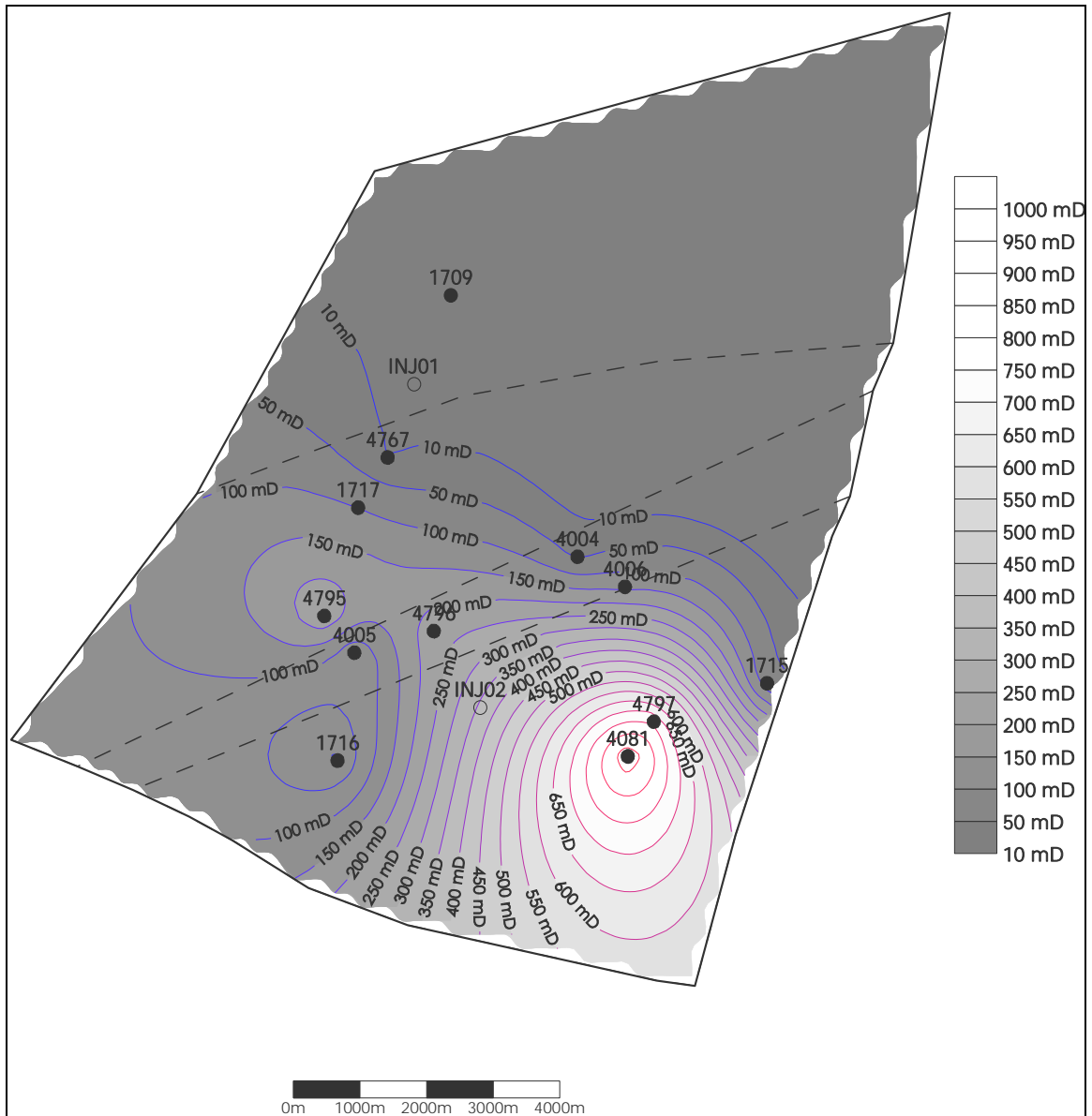
Figure 6: Permeability distribution of the Oradea reservoir model

3.2.2   Simulation runs

The computer model has been calibrated on the measurements carried out during the interference test in 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 (Figures 7 and 8). 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 very stable during the past 11 years of exploitation.

The development schedule assumes that the utilisation will be developed to maximum by installing electrical down hole pumps in 8 wells and reinjecting in 6 wells. Reinjection will be carried out in 4 selected production wells and in 2 future 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 in 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 north-western part of the reservoir, which have lower permeability. The temperature in the injection blocks will decrease during 30 years of exploitation from their initial value close to the injection temperature (Figures 9 and 10). However, there will be no thermal breakthrough between the injection and the production blocks.
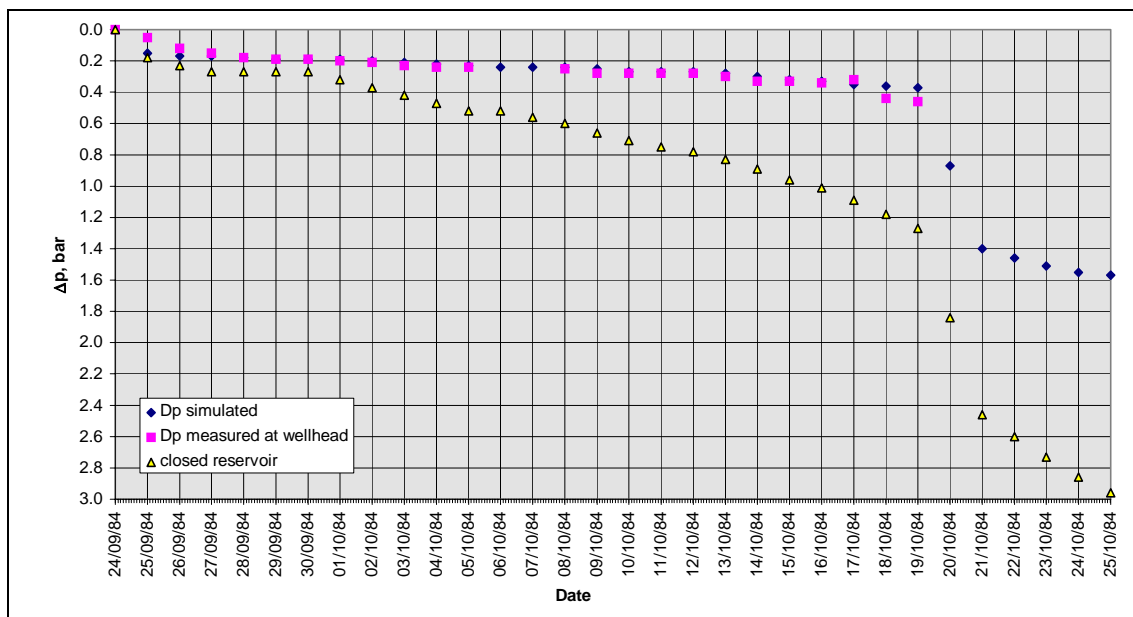

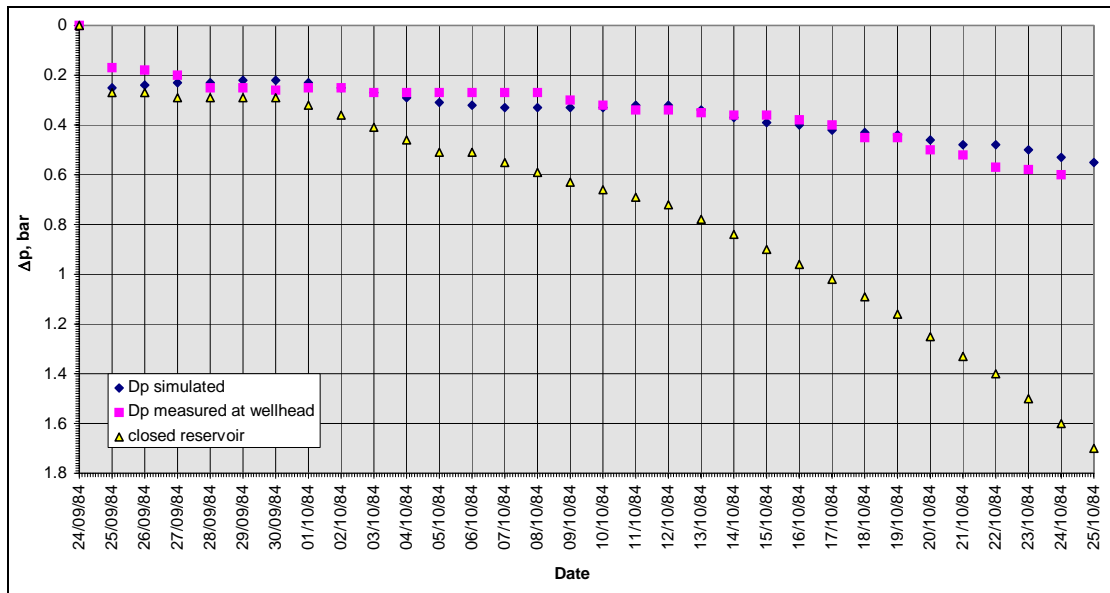
Figure 7: Calibration results, Well 4004 Oradea

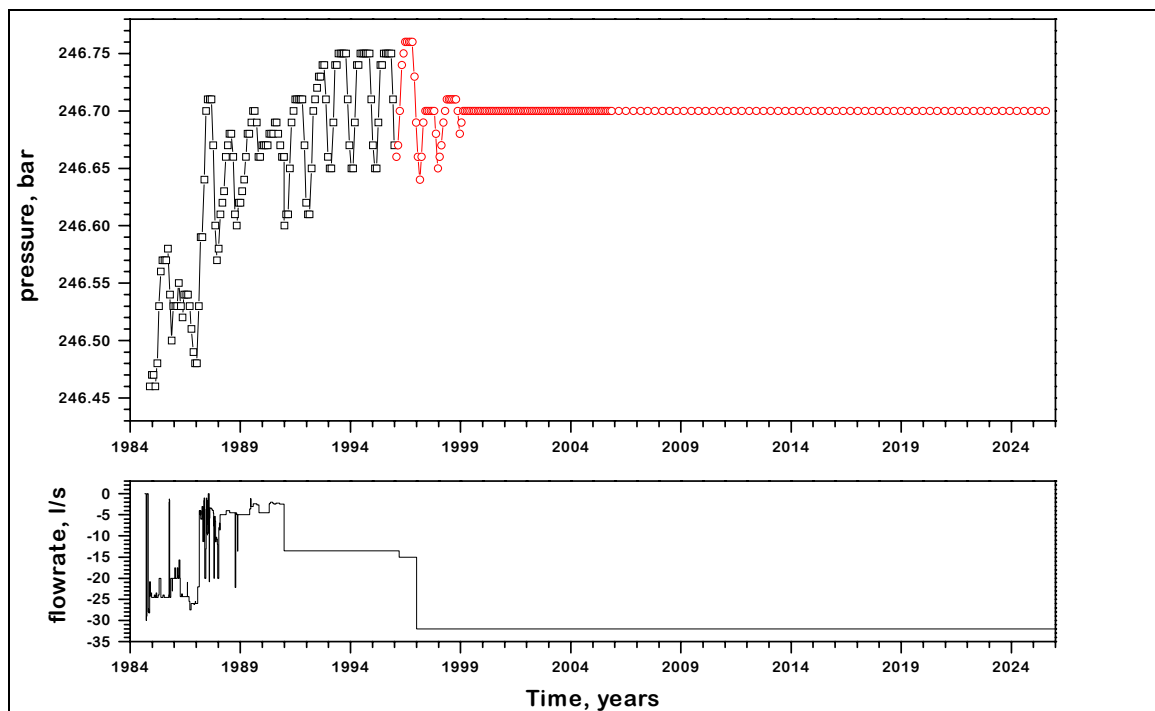**Figure 8: Calibration results, Well 4005 Oradea**

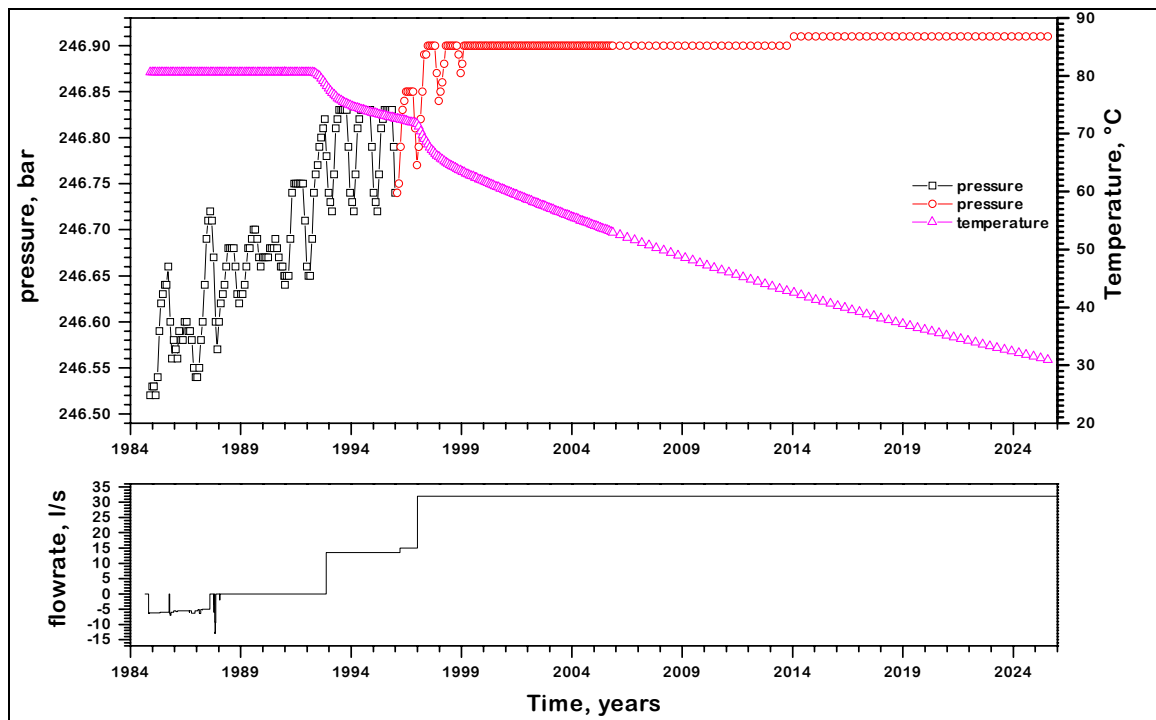**Figure 9: Simulated pressure / flowrate history for the producer block, Iosia doublet**

Figure 10: Simulated pressure / temperature / flowrate history for the injector block, Iosia doublet

3.3 *Simulation of the Overpressured Geothermal Reservoir, Nagyszénás, Hungary [4]*

The Nagyszénás area belongs to the southern belt of the Békés Basin i.e. to the Battonya-Pusztaföldvár Mesozoic Through. 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 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 nestled in fractured Mesozoic formations which may be suitable for power generation exist in the area (se cross section in Figure 11).

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 clayey marl and marl.

3.3.1 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, 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 developed by Dr. Karsten Pruess at Lawrence Berkeley Laboratories.

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 that has a rectangular shape with the dimensions of 15x2km and thickness of 950m. The grid set-up is shown in Figure 12. 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 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.
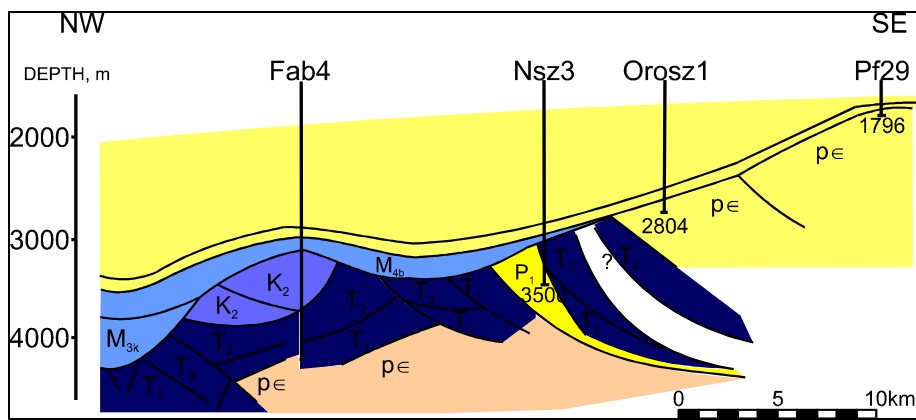

Figure 11: NW-SE Cross section through the Nagyszénás-Fabiánsebestyén area (source MOL Geothermal)
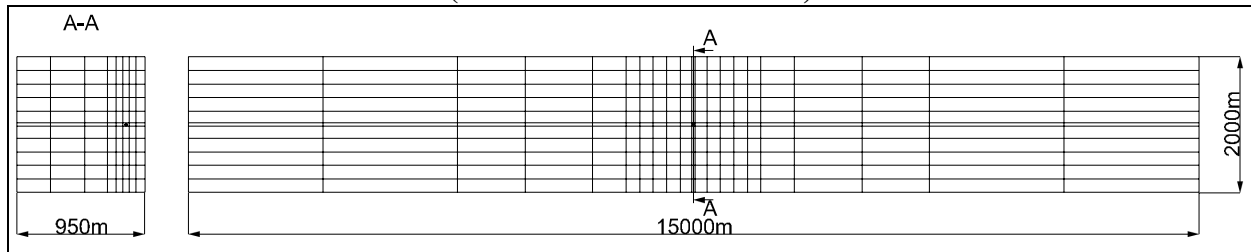

Figure 12: Grid set-up

Table 3: Rock properties for the Nagyszénás reservoir model

Parameter / Model	Uni1	Uni2	Fra1	Fra2
Rock density, kg/m³	2650	2650	2650	2650
Matrix porosity	0.03	0.03	0.03	0.03
Fracture porosity	-	-	0.1	0.03
Matrixpermeability, 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, m²/N	10^{-9}	10^{-9}	10^{-9}	10^{-9}

3.3.2 Simulation runs

The initial temperature was considered 190°C. All models were run first under no flow conditions until hydrostatic equilibrium 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 (figure 13). Another conclusion that could be drawn was that the reservoir's aerial extent was correctly estimated from the geological data therefore no further sensitivity studies regarding the aerial 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 ideal duration for a long term flow test (Figures 14 and 15).

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 runs results 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 models studied would be able sustain a production of 5MW for 25years (figure 16). This suggests that the reservoir in question is a small sealed compartment of Lower Triassic formations.
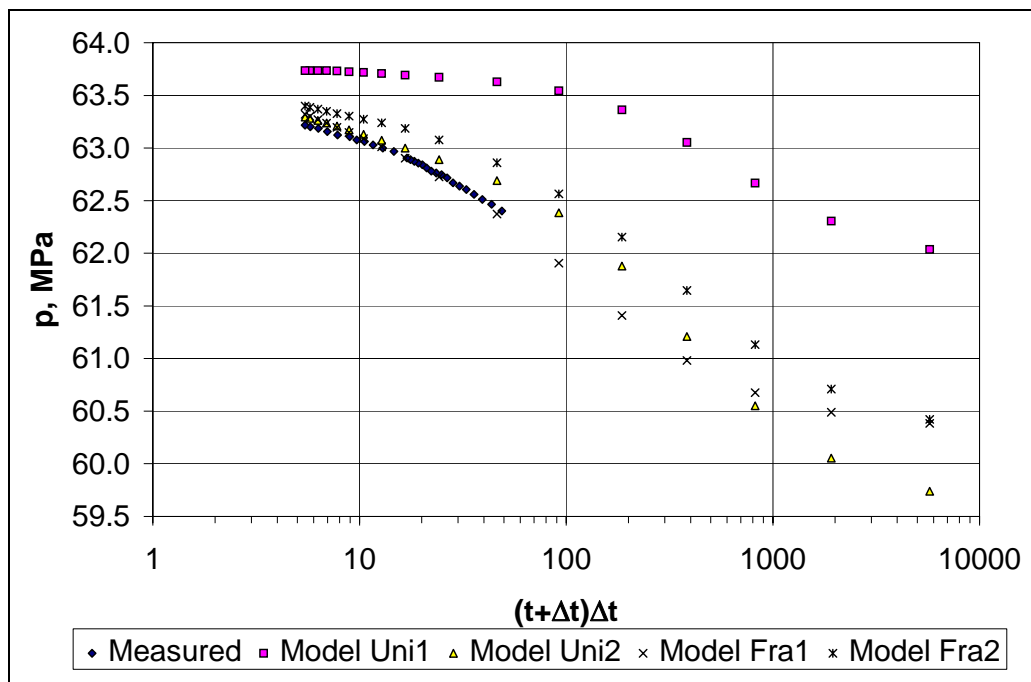

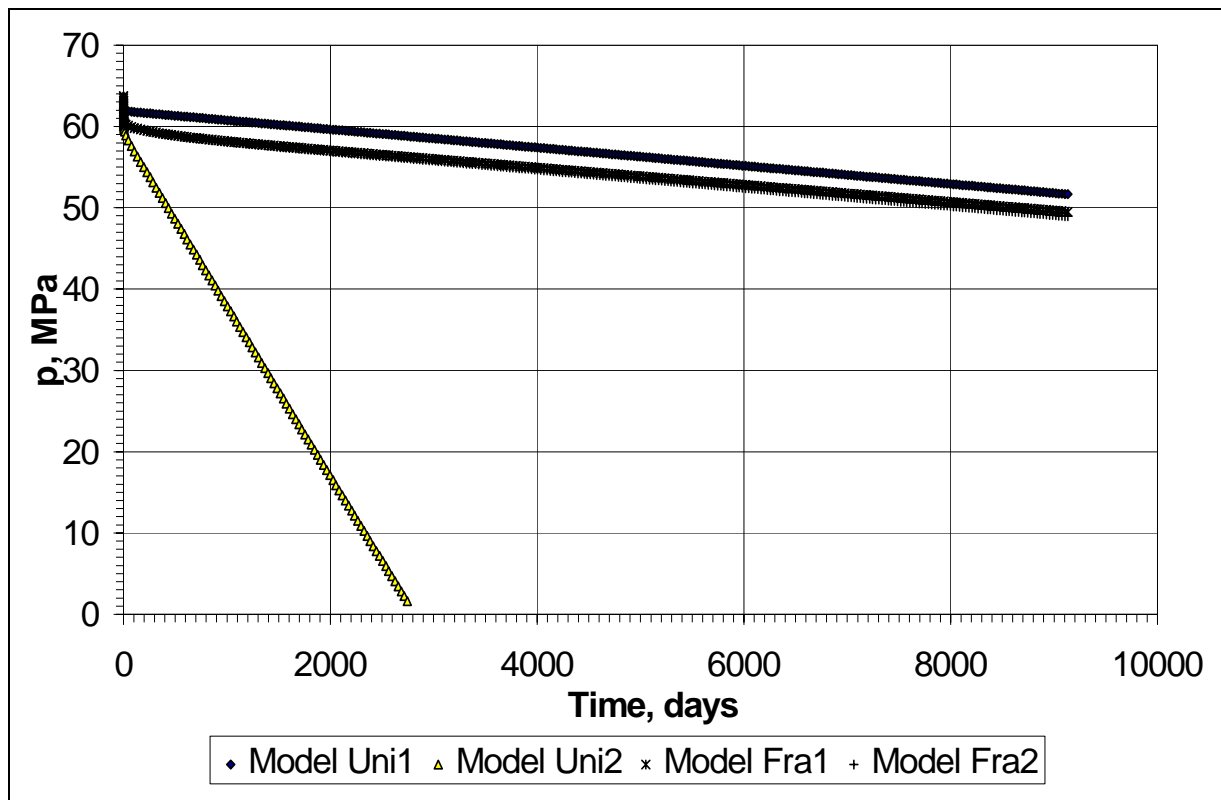**Figure 13: Horner plot of measured and simulated build-up**
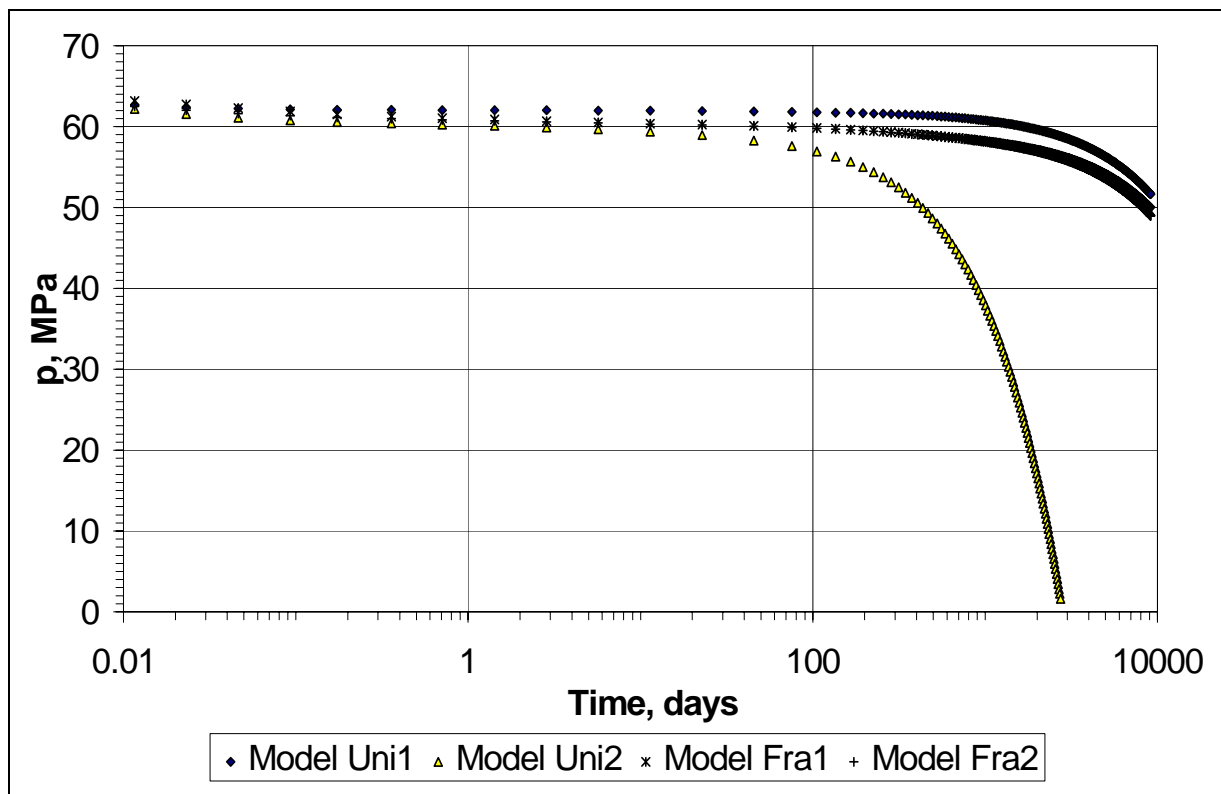
Figure 14: 1MW production simulation

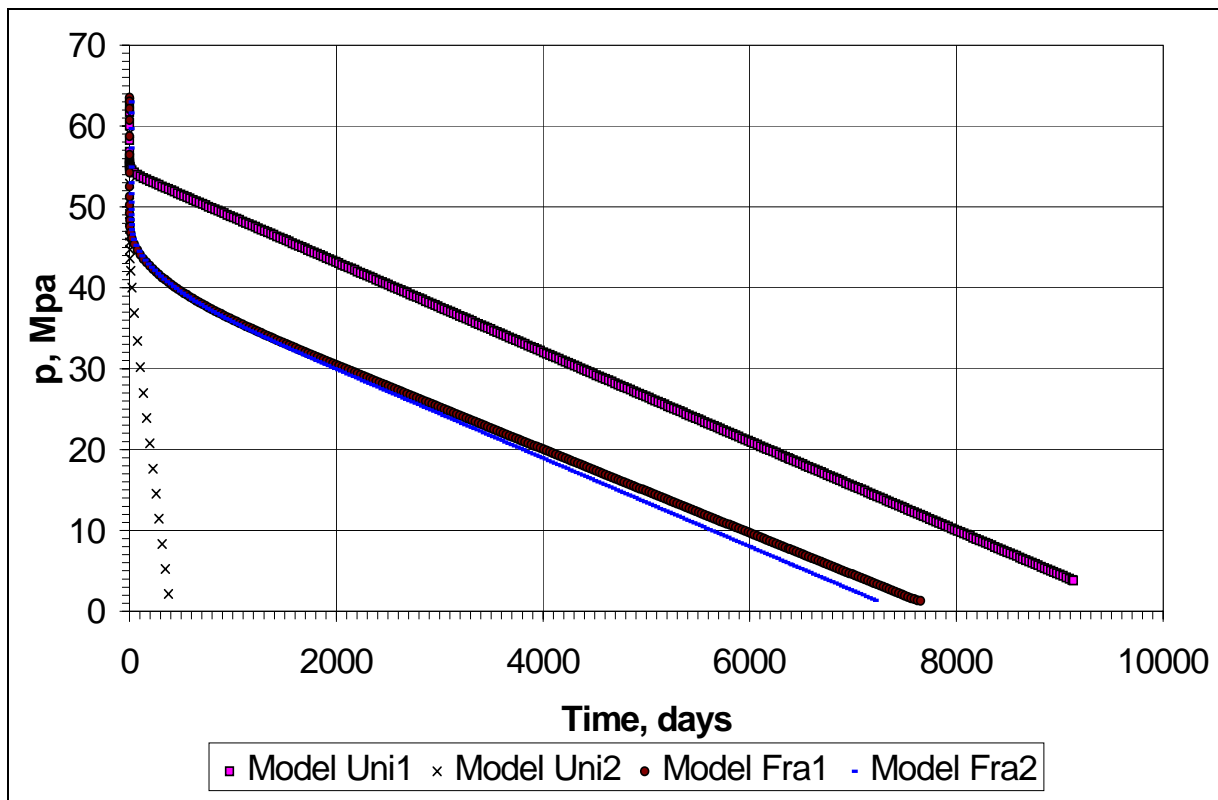**Figure 15: 1MW production simulation semilog plot**

Figure 16: 5MW production simulation

4.   CONCLUDING REMARKS

Reservoir simulation contributes to the design and implementation of relevant exploitation strategies aimed at reconciling users' demands with reservoir longevity concerns.

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 reservoir, nestled 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.

Summing up, the general modelling philosophy consists of using a calibrated model as a thorough reservoir management tool.

REFERENCES

1. Economides, E. and Ungemach, P. (editors) (1987): *Applied Geothermics*, John Wiley and Sons, 238 pp.
2. Antics, M.A. (1992): *Reservoir Simulation of the Tomnatic Geothermal Area, Romania.* Geothermal Diploma Project Report No. 92.02. Geothermal Institute, University of Auckland, 59 pp.
3. Antics, M.A. (1997): Computer Simulation of the Oradea Geothermal Reservoir, *Proceedings of the 22nd Workshop on Geothermal Reservoir Engineering,* Stanford, CA., pp. 491-496.
4. Antics, M.A. (1998): Computer Modelling of an Over-Pressured Medium Enthalpy Geothermal Reservoir Located in Deep Sedimentary Basin, *Proceedings of the 23rd Workshop on Geothermal Reservoir Engineering,* Stanford, CA., pp. 362-367.
5. Antics, M. (2001). *Computer simulation of low enthalpy geothermal reservois.* European Summer School on Geothermal Energy Applications.. Oradea, Romania, April 26-May 5, 2001. Text Book (Rosca, M. ed.), pp. 77-92.