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Actual versus Predicted Well Cooling Kinetics: Implications on Reservoir Modelling Approaches

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ABSTRACT

Predicting production well cooling kinetics induced by (re)injection of heat depleted brines into the source reservoir is a vital segment of any geothermal district heating (GDH) doublet design and operation.

Actually the exercise is often biased by oversimplifying the reservoir structure and the heat transfer process assumed single layered and convective alone (the so called breakthrough time) respectively. It can be somewhat misleading while assessing reservoir life and designing well architectures.

The present paper favours instead an approach reflecting more closely actual multi-layered reservoir structures a distinctive attribute of the most low enthalpy sedimentary environments. It accounts for the heat stored in the confining hydraulically impervious but thermally conductive, aquitards stacked in a single heat storage volume surrounded on the top and bottom by symmetric stacked pervious layers. This configuration achieves a “3D sandwich” reservoir equivalent which not only better matched monitored temperature histories but also allowed to validate a modified convective thermal breakthrough formula.

The approach proved rewarding while modelling thin layered foliated structures, fast moving contrasted injection cycles

1. INTRODUCTION

Three dimensional modelling of geological structures is routinely applied by the oil and gas industry in integrated reservoir studies. It has proven an efficient tool in investigating complex tectonic and lithological environments. Its extension however to geothermal reservoir assessments is still constrained by the lack of adequate well density and related lithofacies control. As a result, its use is most often limited to 3D steady state temperature modelling and drill site selection, wherever backed by local 3D seismic surveys.

The present paper illustrates a geomodelling approach to the calibration of a multilayered geothermal reservoir of regional extent, long exploited, via the doublet concept of heat farming, for district heating uses. Previous reservoir simulation attempts failed in reproducing the true production well cooling kinetics induced by the injection of the heat depleted brine. The reason was attributed to an oversimplified reservoir structure, assumed in most instances single layer “equivalent”.

The exercise proved rewarding in (i) applying a GOCAD geomodelling software (Paradigm, 2009) to a multidoublet heterogeneous “*sandwich*” (Antics et al, 2005) structure - stacking interbedded, hydraulically impervious but thermally conductive, layers into one single heat storage/supply unit, squeezed between two symmetric reservoir layers, each sharing one half of stacked pervious bed thicknesses, the overall three layered equivalent system overlain/underlain by cap and bed rocks respectively - , (ii) exporting the, GOCAD issued, *sandwich* image to a, MVIEW interfaced, TOUGH2V2 simulator (Pruess, 1991), and (iii) ultimately producing relevant history matching sequences, never achieved in past simulation runs, thus securing reliable predictive heat farming scenarios. Work in progress aims at interfacing GOCAD with TOUGH 2 V2 input/output files.

2. THE SANDWICH MULTILAYERED EQUIVALENT STRUCTURE

The sandwich equivalent (fig.1), advocated by Antics et al (2005), proved to be the best candidate in matching actual multilayered cooling kinetics displayed in fig.2.

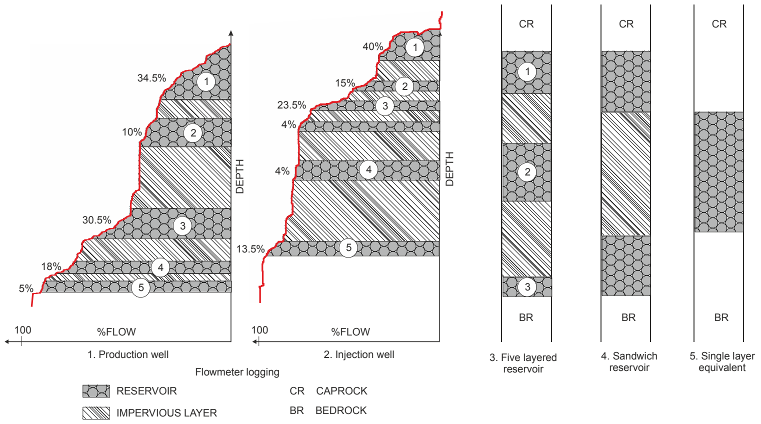


Figure 1: Multilayered reservoir. Actual and candidate equivalent structures. (Antics, 2005)

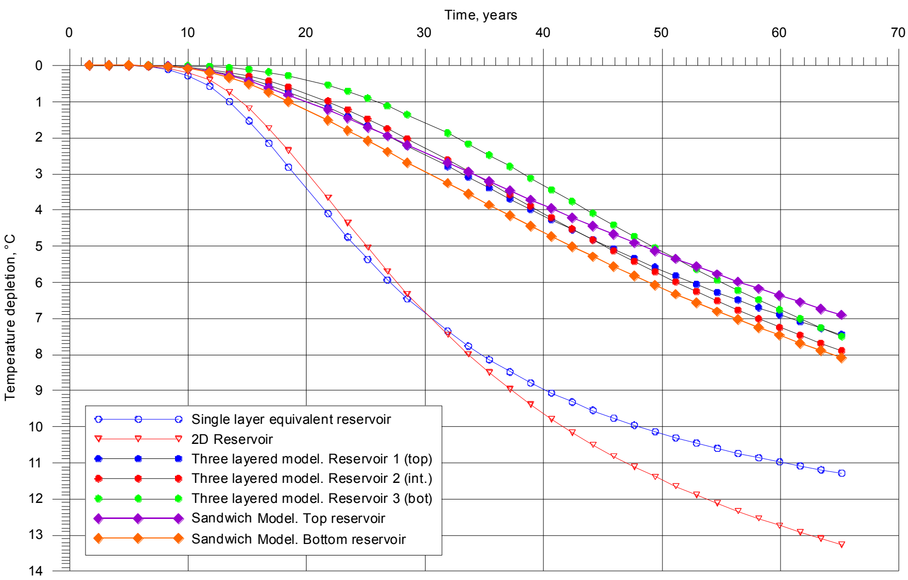


Figure 2: Candidate equivalent structure.

The stacking procedure was applied to each well flowmeter log, from which are identified both productive aquifer and interbedded aquitard layer thicknesses, thus providing the sandwich data base, which processed via GOCAD leads to the 3D image shown in fig.3, further exported to the TOUGH2V2 simulator.

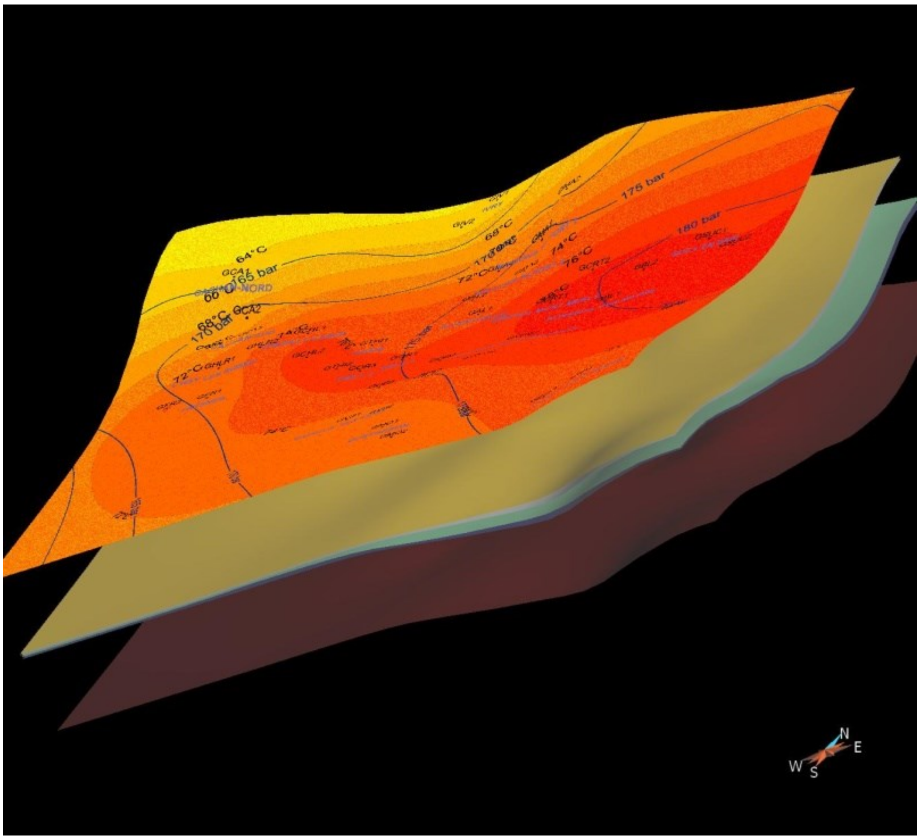


Figure 3: GOCAD 3D view of the sandwich reservoir.

3. SIMULATED DOMAIN

It addresses the area, mapped in fig.4, where exists an urgent demand for minimising the impact of interfering doublets and to accommodate new (multiplet) well arrays among other sustainable reservoir management issues.

It therefore became timely to design and implement a representative reservoir model, matching closely actual pressure/temperatures patterns and production well histories, further operated as a thorough reservoir management tool (Ungemach et al, 2011).

4. REGIONAL SIMULATION

- **Model calibration**

The history matching process can be visualised, on three selected production well localities, in fig.5 temperature decline curves and the fit appreciated on the thermal drawdowns figures – calculated vs monitored – listed hereunder:

Well	Temperature drawdown (year 2010) °C	
	calculated	monitored
A1	0.32	0.4
A2	0.1	0
A3	1.3	1.5

It is emphasized here that previous simulation runs had failed in achieving such calibration fits (thermal breakthroughs occurred after 5 years only and temperature drawdowns were in excess of 3 to 5°C !).

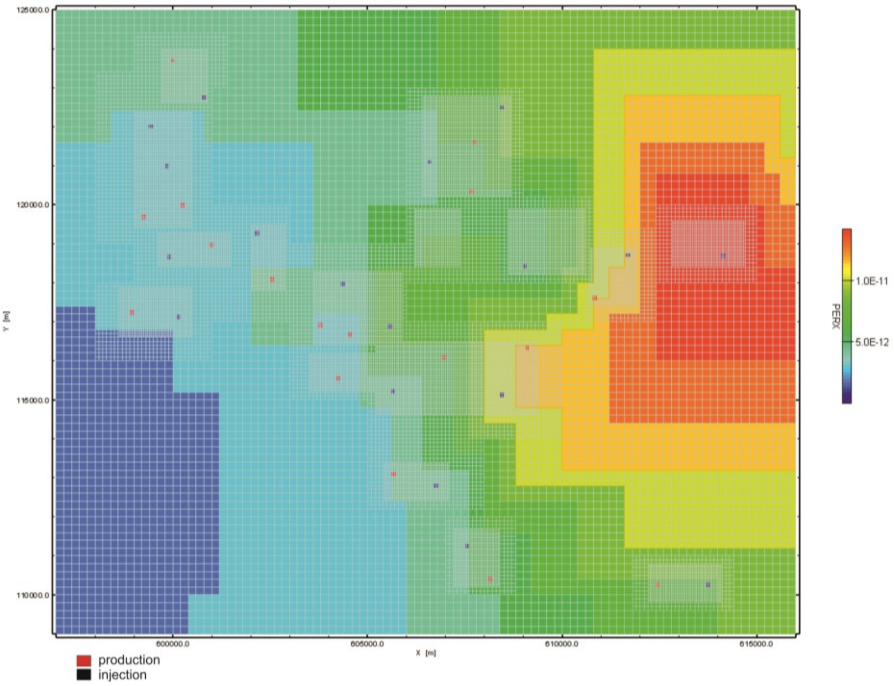


Figure 4: Model grid and discretised permeability field.

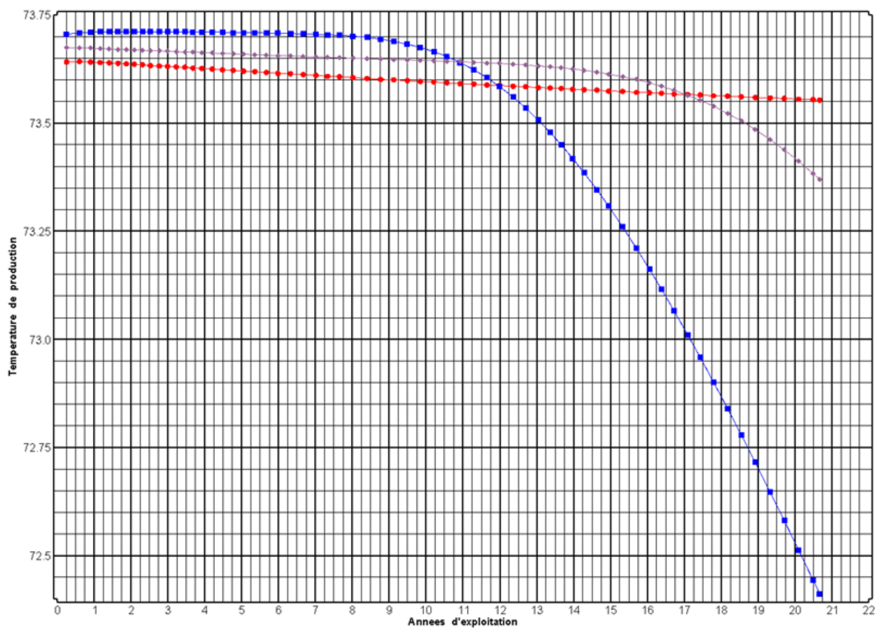


Figure 5: Model calibration. Cooling kinetics on selected production wells.

- **Model projections**

The bottomhole temperature field predicted in year 2030 (scenario perpetuating the present exploitation status) is presented in fig.6 isothermal map.

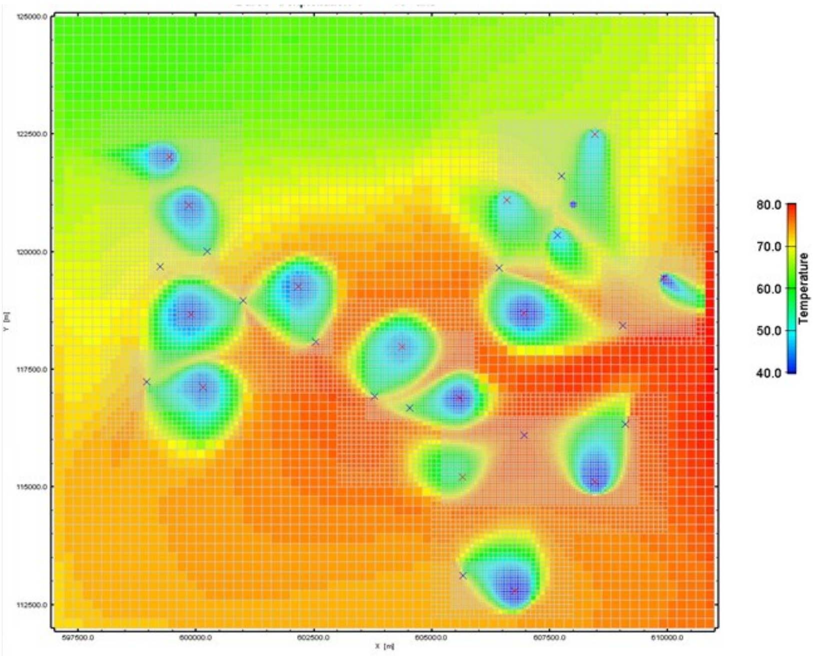


Figure 6: Model prediction. Projected reservoir temperature patterns year 2030.

5. HEAT RECOVERY IMPROVEMENT BY SUBHORIZONTAL WELL DESIGN

5.1. Design features

Simplified conceptual designs are featured in figure 7 sketches. Reservoir layering is assumed uniform (figure 7a) over the entire drain lengths (figure 7b) and drainage/flooding symmetries ellipsoidal (figure 7c). Doublet well trajectories follow with the curved (until reservoir top/drain heel)/linear (across the reservoir, total pay interval) profiles shown in figure 7d. Noteworthy is the fact (i) actual drain lengths account for effective reservoir thickness (net pay), i.e. they need to be corrected from confining beds cumulative thicknesses, and (ii) the spacing between doublet top reservoir impacts (and underlying drain heels) is equal to the spacing in conventional inclined well completions. Actual sub-horizontal drain spacings correspond to the distance separating drain (half) flowrate barycenters, which reflects the fact flowrates progressively increase from production drain toe and decrease from injection drain heel respectively. The latter feature compensates the impact of increased drain flow capacities on cooling kinetics as will be shown by further model simulations.

Assuming a homogeneous and isotropic reservoir, steady state and axi symmetrical radial flow, the Dupuit equation for a horizontal wellbore is expressed as follows (Joshi, 1991):

$$q_h = \frac{Ckh\Delta p}{\mu_0 log\left(\frac{4r_d h}{L}\right)} \quad L>>h \qquad \textbf{(1)}$$

Where:

k	=	permeability (Darcy)
h	=	layer thickness (m)
L	=	drain length (m)
r_d	=	drainage area radius (m)
Δp	=	pressure (bar)
q_h	=	flowrate (m^3/hr)
μ_0	=	fluid dynamic viscosity (CP)
C	=	a system unit dependant constant

Similarly the Dupuit equation for a vertical well may be written:

$$q_v = \frac{Ckh\Delta p}{\mu_0 log\left(\frac{R_0}{R_w}\right)} \qquad \textbf{(2)}$$

With:

q_v	=	flowrate (m^3/hr)
R_0	=	influence radius(i.e. where $\Delta p = 0$) (m)
R_w	=	vertical well radius (m)

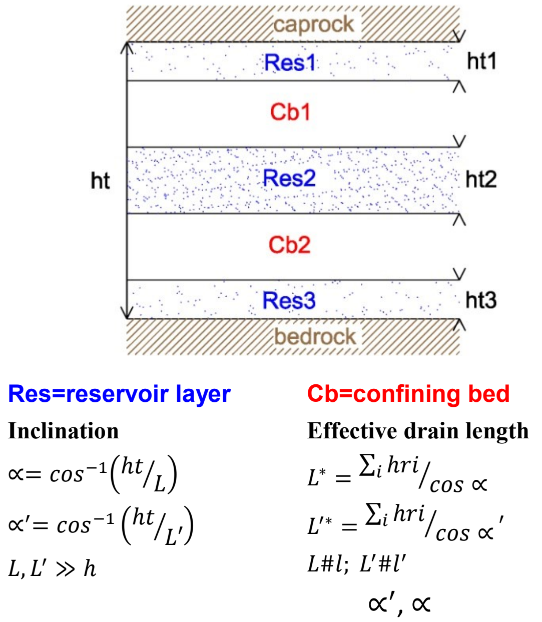
Hence:

$$\frac{q_h}{q_v} = \frac{\log(\frac{R_w}{R_0})}{\log(4r_d\frac{h}{L})} \qquad \textbf{(3)}$$

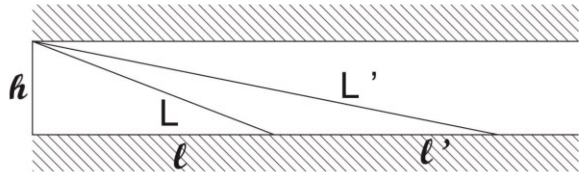
Numerical application:

H	=	20 m
L	=	1 000 m
R_0	=	1 000 m
r_w	=	0.1 m
r_d	=	500 m
$\frac{q_h}{q_v}$	=	2.5

Practically one should regard a two fold improvement a realistic figure.

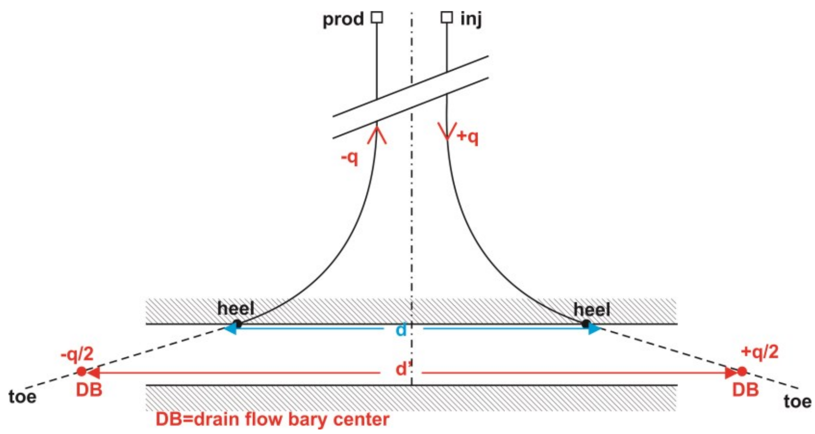


a) Reservoir layering



b) Sub-horizontal drain reaches

c) Ellipsoidal symmetry



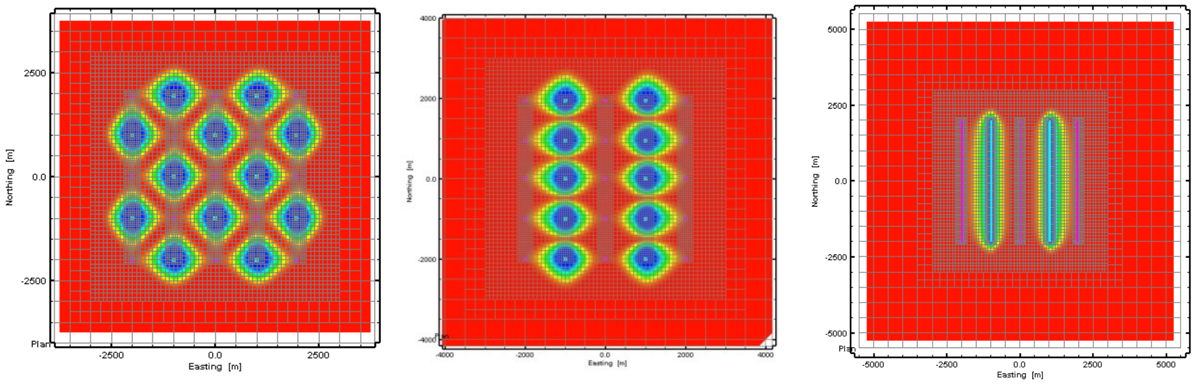
d) Sub-horizontal doublet trajectories

Figure 7: Summary of design features

5.2 Modelling

5.2.1 Heat recovery. Single layer reservoir

Cooling kinetics induced by the three production/injection well/drain arrays exploiting a 5 x 5 km square single layer reservoir, namely (i) vertical five spot, (ii) vertical stripe, and (iii) horizontal drains (figure 8) are displayed in figure 9. Clearly, scheme (iii) exhibits the best thermal performance by minimizing the extent of the cooled area, thus maximizing heat recovery from the reservoir.



Vertical five spot | Vertical stripe | Horizontal drain stripe

Figure 8: Production/injection well/drain arrays

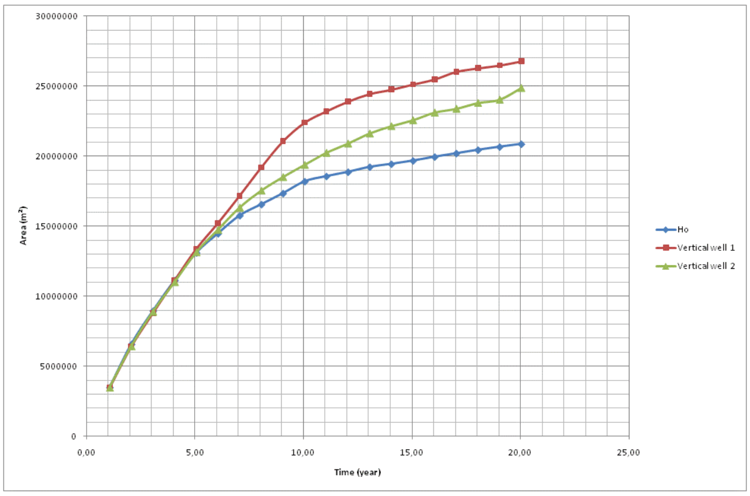


Figure 9: Cooling kinetics. Cold areal extents

5.2.2. Cooling kinetics. Multilayered reservoir. Sub-horizontal wells.

The multilayered reservoir structure sketched in figure 10 has been reduced to its, three layer stacked *sandwich* equivalent (figure 11), formalised by Antics et al (2005), in order to assess the sensitivity of thermal breakthrough times to layered wise, productivity patterns. The sandwich model shortcut has been selected owing to its physical reliability and its ability to (drastically) cut down computer time without significantly distorting actual cooling kinetics (Antics et al, 2005).

Results displayed in table 1 evidence the wide scattering of thermal breakthrough times, which vary in a fourfold ratio in response to the five contemplated flow distributions.

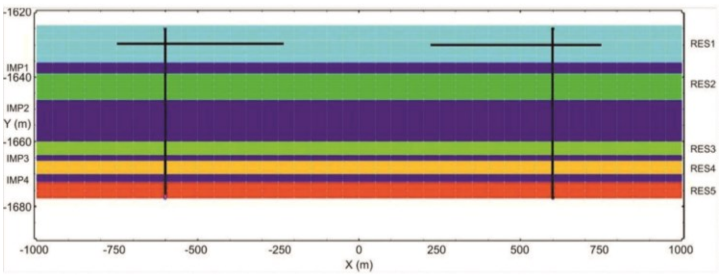
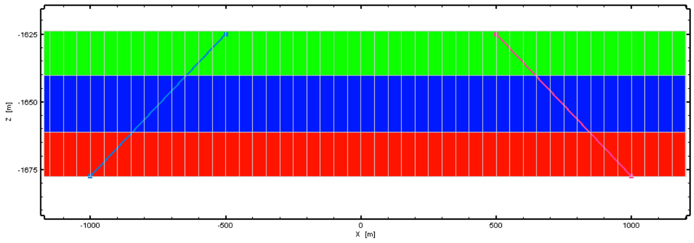


Figure 10: Three layer equivalent



$T_{initial}$ = 75 C°	K_1 = 1.5 darcy	$Q_{tot} = Q_1 + Q_2$ = 200 m^3 /h
$T_{injection}$ = 30 C°	$K_2 = 1^{-20}$ darcy	$P_{initial}$ = 179 bar

Figure 11: Multilayered sandwich equivalent reservoir. Porosity, permeability, temperature and pressure patterns.

Table 1: Flow pattern and thermal breakthroughs

LAYER PRODUCTIVITY % TOTAL FLOW		THERMAL BREAKTHROUGH (YEARS)
Q1	Q2	
0.75 X QTOT	0.25 X QTOT	21.5
0.25 X QTOT	0.75 X QTOT	77
0.65 X QTOT	0.35 X QTOT	29
0.35 X QTOT	0.65 X QTOT	71.5
0.50 X QTOT	0.50 X QTOT	49.5

5.2.3 Cooling impacts of candidate well/drain trajectories. Multilayered reservoir.

Three well/drain architectures, namely vertical, multilateral and sub-horizontal (500 and 1 000 m long) among the five candidates illustrated in figure 12, were modelled in order to investigate their impact on cooling kinetics and pressure depletions. The multilayered reservoir structure is approximated through its sandwich equivalent subject to constant temperature (upward caprock) and heat flow (downward bedrock) vertical boundary conditions respectively.

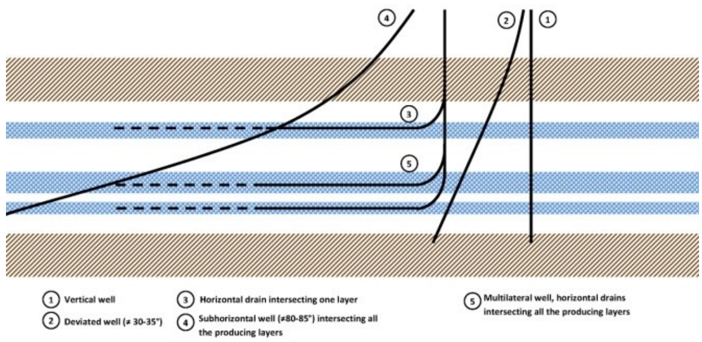


Figure 12: Candidate well/drain trajectories. Multilayered reservoir

Results, summarized in figure 13 (cooling kinetics) and table 2, emphasize the benefits of the multilateral and sub-horizontal drain strategy. The advantages over the conventional completion are manifest on both cooling kinetics and vertical well pressure depletion trends. The multilateral configuration shapes the most attractive as one could have inferred intuitively from four, each 1 000 m long, horizontal drains. Its costs and completion complexity are however dissuasive. As a result, the 1 000 m long sub-horizontal architecture may be regarded a reasonable compromise.

Table 2: Cooling kinetics and pressure drawdown

Well architecture	Thermal breakthrough time (years)(*)	Pressure drawdown @70 years (*) (**) (bar)
Two multilaterals, 1 000 m long, well	45.5	0.15
One (sub)horizontal drain, 500 m long, well	29	0.45
One (sub)horizontal drain, 1 000 m long, well	42.5	0.30
One vertical well	23	1.5

(*) 1°C thermal depletion (**) not accounting for skin and well losses

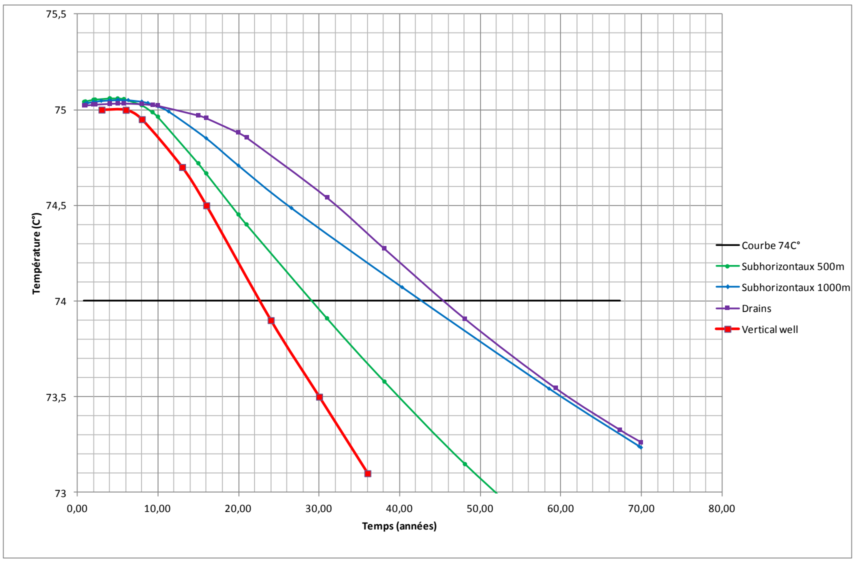


Figure 13: Impacts on cooling kinetics. A selected well/drain designs

5. CONCLUSIONS

Simulation of multilayered reservoirs has long been constrained by inadequate modelling of complex fingered lithofacies structures alternating pervious vs non pervious properties until the implementation of reliable geomodelling software and physically meaningful equivalent structures.

Although geomodelling failed in generating a multilayered structure closely fitted to the actual reservoir stratification derived from flowmeter logging, it succeeded in imaging a relevant overall sandwich grid further exported to the, MView interfaced, TOUGH2V2 simulator. It therefore proved a valuable substitute, later validated by relevant simulation runs.

The sub-horizontal long reach well concept, aimed at intersecting the entire productive interval of a multilayered geothermal reservoir, shows promising premises. Modelling of actual sedimentary settings confirmed the important gains achieved in well productivity, heat recovery and reservoir longevity by the innovative well design, indeed a challenging contribution to sustainable resource management. Advantages expected from the concept widely compensate the incurred extra drilling/completion costs provided reliable directional steering, completion drain completion and material definition be implemented.

Work in progress focuses on (i) reservoir assessment via upgraded well logging and lithofacies control, (ii) interfacing the Geomodeller (GOCAD) with the simulator (TOUGH2V2) input/output files and (iii) improvement of heat recovery by subhorizontal well concept

REFERENCES

Pruess, K. (1991): TOUGH 2. “A General Purpose Numerical Simulator for Multiphase Fluid and Heat Flow”. Lawrence Berkeley Laboratory. Berkeley, CA.

Antics, M., Papachristou, M., and Ungemach, P. (2005): “Sustainable Heat Mining. A Reservoir Engineering Approach”. Proc. Thirty. Sixth Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA, January 31-February 2, 2005

Ungemach, P., Antics, M., Lalos, P., Borozdina, O., Foulquier, L., and Papachristou, M. (2011):“Geomodelling and Well Architecture, Key Issues to Sustainable Reservoir Development”, Proc. Thirty. Sixth Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA, January 31-February 2, 2011

Promis, M-P. Ungemach P., Antics M. (2013) Sub-Horizontal Geothermal Well Completion. A Promising Outlook. Proceedings of the European Geothermal Congress, Pisa, Italy