PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

GEOMODELLING AND WELL ARCHITECTURE, KEY ISSUES TO SUSTAINABLE RESERVOIR DEVELOPMENT

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ABSTRACT

Three-dimensional modelling of geologic structures is routinely applied in petroleum and, at a lesser extent though, in geothermal engineering and has proven an efficient tool in investigating complex tectonic and lithological environments. In geothermal development it is often utilised for 3D temperature modelling and well siting, the latter in conjunction with 3D seismic surveys, purposes. Well architecture, contrary to oil and gas drilling practice, has not yet passed the (slightly) deviated well design stage aimed at securing larger production vs injection well downhole spacings and intercepting productive fractures wherever they develop (sub) vertically. The present work was assigned a three fold objective (i) comprehend and properly assess a relevant multilayered structure from, log issued, well fingered data and derive reliable interpolation guidelines for further reservoir simulation studies, (ii) maximize deliverabilities of geothermal district heating production/injection well arrays, and, last but not least, (iii) minimize thermal breakthroughs thus extending reservoir life and achieving sustainable reservoir management targets. Geomodelling has been implemented on a selected Paris Basin area by integrating local geothermal and hydrocarbon lithological, logging and testing data. Horizontal and multilateral well designs have been modelled and the impact of these unconventional (geothermally speaking) architectures appraised in terms of deliverabilities, bottomhole streamline/pressure/temperature patterns and ultimately breakthrough transients. The exercise proved rewarding in (i) validating the geomodelling approach, with respect to its input to an improved conceptual model and reliable predictive hydrothermal simulations, and (ii) securing well/reservoir longevities by designing either horizontal or multilateral well paths, depending upon local reservoir layering, best assessed by combining geomodelling and logging while drilling.

Keywords: reservoir engineering, geomodelling, horizontal drilling, reservoir management, sustainability.

INTRODUCTION

Heat recovery, well deliverabilities and reservoir life are key concerns when contemplating sustainable management of geothermal resources. Such issues become particularly sensitive while engineering low enthalpy reservoirs in order to best exploit low grade sedimentary deposits for geothermal district heating (GDH) purposes.

The foregoing have been addressed while investigating and designing sustainable exploitating schemes in the Paris Basin, which apply the doublet concept of heat mining, initiated in the late 1960s South of Paris, followed later by 54 replicates of which 34 remain online to date (Rojas *et al*, 1989; Antics *et al*, 2005 and Ungemach *et al*, 2005).

Aging of these doublets, nearing 25 years, focused operators' attention towards well and reservoir longevities, bearing in mind that initial projections predicted a ca 20 to 25 year reservoir life based on the Gringarten-Sauty (1975) and Gringarten

(1979) analytical approaches. However, none of these long operating systems has yet undergone any thermal breakthrough whatsoever, if we except two, one recognized and one suspected, thermally depleted production wells.

Such discrepancies were logically attributed to over simplifying reservoir structures restricted to a single “equivalent” aquifer cumulating the thicknesses of the pervious layers identified via flowmeter logging, ignoring the heat recharge from interbedded confining aquitards. Therefore, modelling efforts concentrated on assessing relevant multilayered structures enabling to exercise more reliable simulations of actual heat transfer processes and related cooling kinetics.

Worth mentioning in this respect are the contributions of Menjoz *et al* (1996) and Antics *et al* (2005), the latter pioneering the sandwich model concept, which has proven to best simulate complex lithofacies multilayered structures of the type shown in fig.2, as later exemplified in this paper.

Impacts of such layered structures and permeability contrasts on cooling kinetics have been further investigated and quantified by Papachristou (2011).

Summing up, new tools, many of them imported from the oil industry, need to be extensively applied within the geothermal community to best assess and model actual reservoir structures and prolonge well thermal longetivities via 3D geomodelling and horizontal drilling.

After reviewing the state of the art achieved in Paris Basin geothermal modelling, this paper will illustrate a geomodelling exercise extended to a wide regional area and the thermal benefits expected from horizontal drill paths *vis-à-vis* conventional vertical or slightly deviated well doublets.

MULTILAYERED RESERVOIR MODELLING IN THE PARIS BASIN. A REVIEW.

Resource and reservoir setting

The Paris area belongs to a large intracratonic sedimentary basin, stable and poorly tectonised, whose present shape dates back to Jurassic age.

The Mid-Jurassic (Dogger) carbonate rocks were soon recognised as the most promising development target. The Dogger limestone and dolomite are typical of a warm sea environment associated to thick oolithic layers (barrier reef facies). They host a dependable reservoir, of regional extent, and display reliable reservoir properties as evidenced by the present development status.

Reservoir depths and formation temperatures range from 1400 to 2000 m and 56 to 80°C respectively.

A thorough survey of the Paris Basin geothermal reservoir can be found in a comprehensive review edited by Rojas (1989).

Development status

The location of the geothermal district heating sites is shown in fig. 1. Of the fifty five well doublets (mostly deviated from a single drilling pad), completed between 1971 and 1986, thirty four remain on line as of late 2004. They supply heating proper and sanitary hot water, via heat exchange, to ca. 120,000 equivalent dwellings. The total distributed heat amounts to 1,100 GWh_t/yr. (Ungemach et al, 2005)

Heat extraction

It was based, since exploitation start-up, on the doublet concept of heat mining pioneered by Gringarten and Sauty (1975), which provided a means for improved designs of well locations, bottomhole spacings and subsequent reservoir/well lifetimes.

The latter, assuming convective heat transfer alone, in a 2D homogeneous reservoir of constant thickness, upper and lower bounded by hydraulically impervious and thermally insulated bed and caprocks, is formalised by the thermal breakthrough time formula:

$$t_B = \frac{\pi}{3}\frac{\gamma_t}{\gamma_f}\frac{d^2 e}{q} \qquad (1)$$

where:

t_B = thermal breakthrough time (h)
d = bottomhole (top reservoir) well spacing (m)
e = reservoir thickness (m)
q = production (-)/injection (+) flowrate (m^3/h)
γ_t = reservoir heat capacity (J/m^3 K)
= $\phi\gamma_f + (1-\phi)\gamma_r$
γ_f = fluid heat capacity (J/m^3 K)
γ_r = rock heat capacity (J/m^3 K)
ϕ = porosity

The Gringarten/Sauty analytical approach accounts for conductive recharge from the confining caprock, assumed at constant temperature, thus improving from 5 to 7%, breakthrough time assessed from (1).

It can also accommodate multiple production/ injection well arrays in order to optimise heat recovery and reservoir lifetime, provided the reservoir remains homogeneous (Gringarten, 1979).

Most, if not all, well doublet arrays were designed, as to locations and spacings, according to this procedure. Since completion (the latest in 1986), hardly two production wells have undergone (premature) cooling yet, although there has been evidence of hydrodynamic interferences between neighbouring doublets as one would normally infer from the dense well concentrations noticed in the Southern part of the reservoir (see fig. 1).

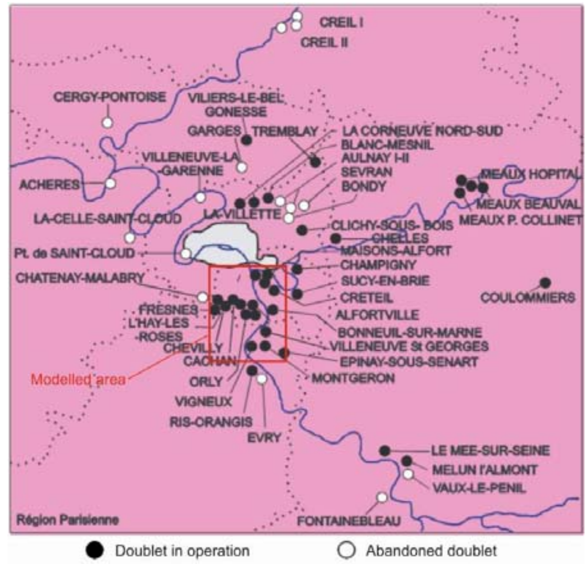

Figure 1. Location of the geothermal district heating sites in the Paris Basin

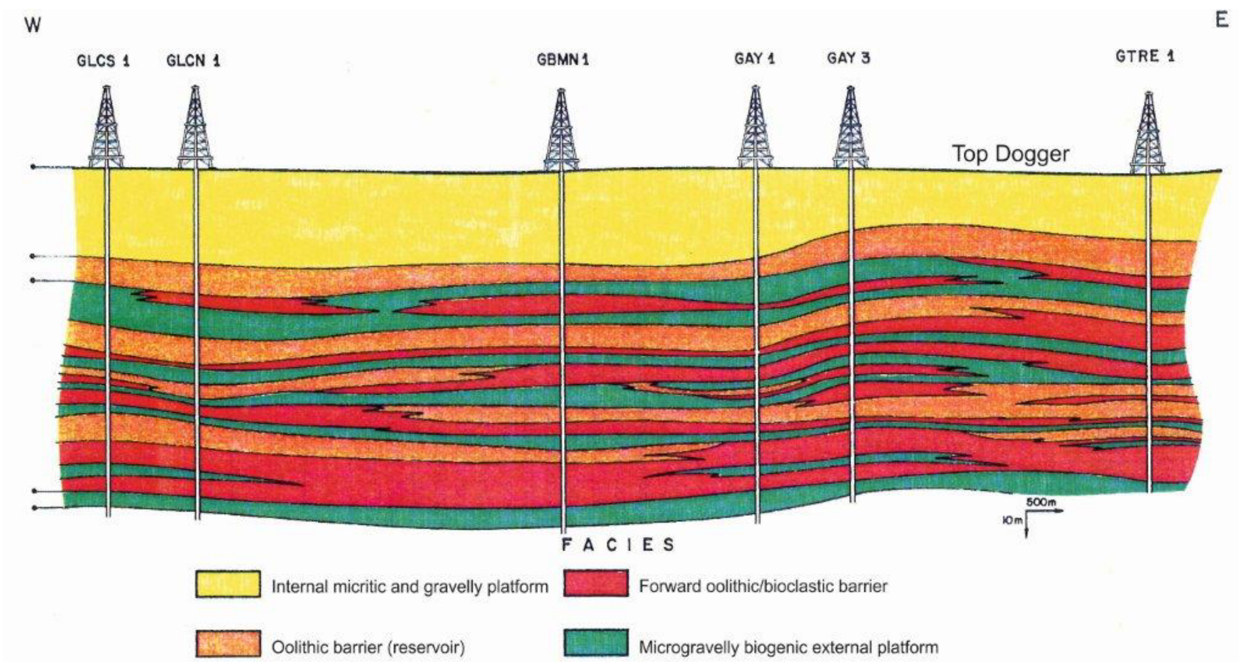

Figure 2: Tentative facies correlations. Northern area (Rojas et al, 1989)

Early works

Menjoz et al (1996) first appraised the reservoir stratification problematic and its impact on the theoretical (thermal breakthrough) and practical tolerated temperature depletion) lifetime of a GDH doublet. They concluded that its thermal behaviour in a stratified reservoir context implies two competing processes compared to the standard single layer equivalent cooling kinetics, (i) a prolonged thermal breakthrough proportionally to the number of layers, and (ii) a faster post breakthrough temperature decline inversely proportional to the average impervious strata thickness.

In summary, whereas a single layer equivalent structure requires three parameters, namely flowrates, well spacing a and cumulated "net pay" reservoir thickness to be modelled, five parameters, the three previously mentioned plus the number of productive layers and the average aquitard thickness come into play when dealing with a multilayered reservoir structure. As a result, each doublet is to be regarded as site specific and more complex simulations are required to model close to actual cooling kinetics.

The question is: Given there are two wells exhibiting different layering patterns which stratified structure should apply?

Antics *et al.* (2005), Ungemach *et al* (2005) and Papachristou (2011) elaborated on these issues in view of locally and regionally representative layering structures supporting reliable reservoir life predictions.

The investigated reservoir structures sketches in fig. 3 address candidate patterns assessed from flowmeter logging of production (fig. 3.1) and injection (fig 3.2) structure combining three reservoirs and two wells. The first (fig 3.3) conforms to a five layer (hydraulically impervious but thermally conductive) interbedded aquitard units and two confining layers, upper (cap rock) and lower (bedrock) respectively. The second, a sandwich structure, includes two symmetric reservoir units (each equal to half the five layered cumulated reservoir thickness) and an intermediate single layer aquitard (cumulating the two individual intermediate aquitard thicknesses of the five layer model). The third represents the single layer equivalent reservoir cumulating the (five layered model) net pay thickness but discarding the interbedded aquitards. Vertical boundary conditions consist of a constant heat flow (0.09 W m^{-2}) and temperature (caprock mid point figure) for the bed and caprock respectively. In one instance (labelled 2D reservoir configuration in fig. 4) the upper and lower boundaries were kept adiabatic.

Simulated temperature decline curves are quite explicit regarding the impact of the interbedded aquitards, which dramatically delay the production well cooling kinetics.

They also bring into evidence the fact that the five layered and sandwich cooling patterns trend very similar.

However, it should be noted that they do not match exactly the actual situation since no cooling has yet been observed on this bench test doublet after 25 years of exploitation.

The five layer model strategy was further successively applied to the simulation on a subregional, heterogeneous reservoir setting, located in the North-West of the Basin (Antics *et al*, 2005; Ungemach *et al* 2005; and Papachristou 2011). Whether it could be reliably applied to other parts, or even to the whole, of the Dogger reservoir or would the sandwich alternative be a satisfactory substitute instead, remained unanswered questions at this stage.

The conclusions of a sensitivity analysis of the cooling kinetics to contrasted reservoir features, carried out by Papachristou (2011) are highlighted hereinafter and illustrated in fig. 5.

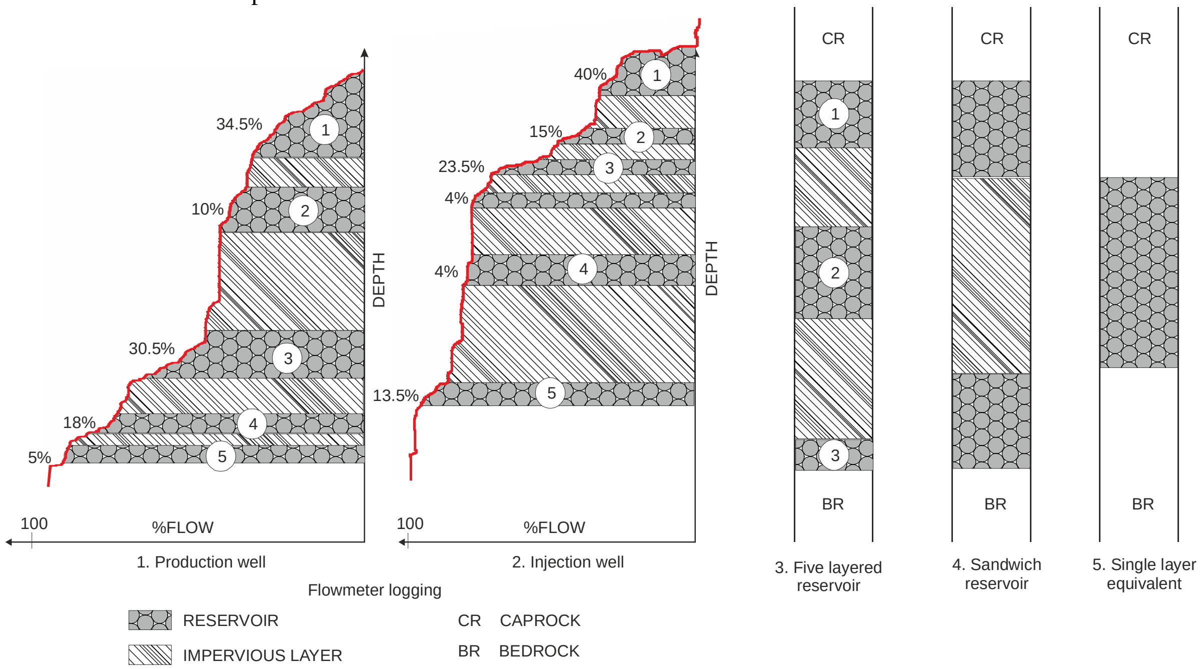

Figure 3: Candidate reservoir structures

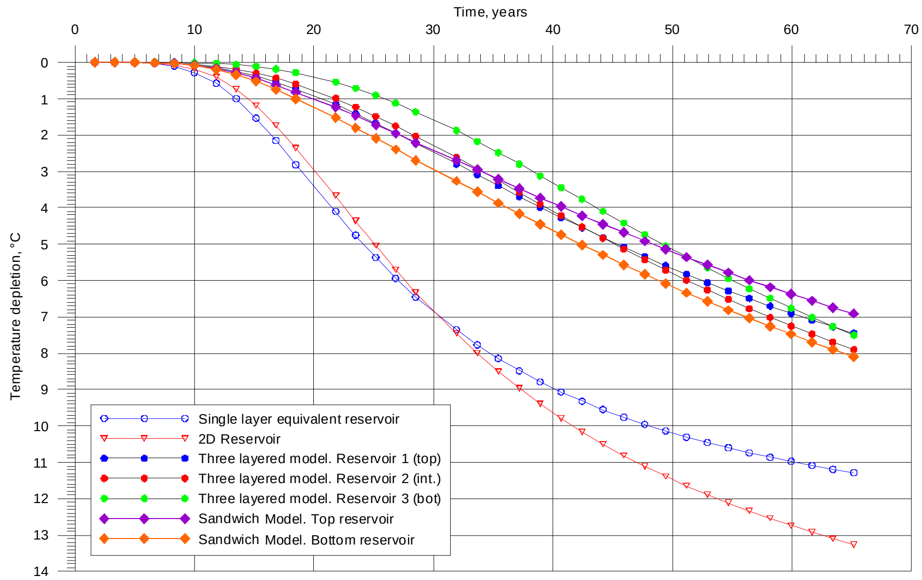

Figure 4: Production well cooling kinetics

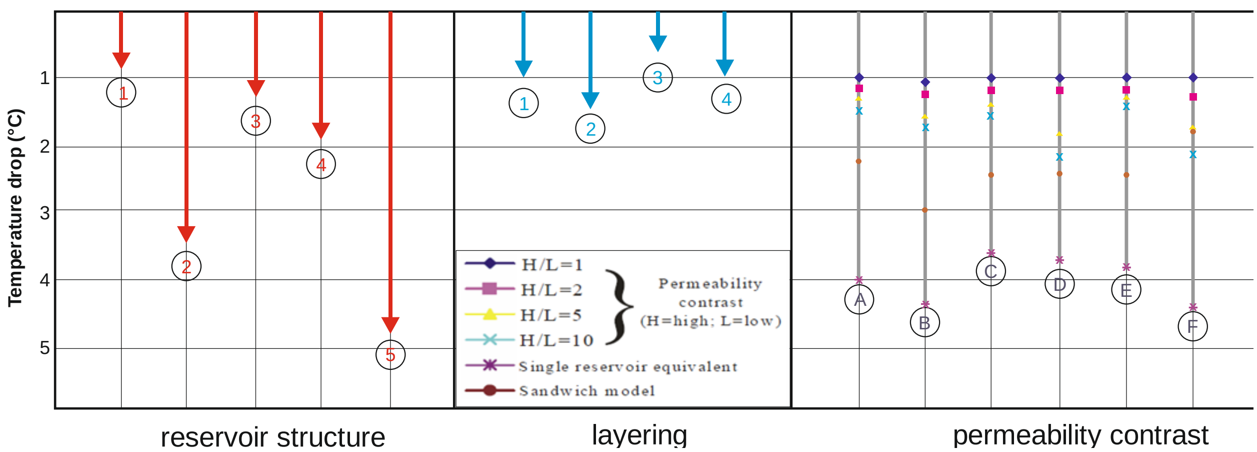

Figure 5: Impacts on cooling kinetics of reservoir structure, layering and permeability contrasts

Investigated contrasts:

- structure
- geometry
- permeability

Performance criteria: Thermal breakthrough, i.e. the later the breakthrough the best and, *vice-versa*, the faster the worse.

Performance ranking:

- Structure contrasts (fig. 3)
- Investigated structures and equivalents
  1. Production well layering (from flowmeter logs)
  2. Injection well layering (from flowmeter logs)
  3. Averaged three layer equivalent
  4. Sandwich reservoir equivalent
  5. Single layer equivalent
- Ranking: 1, 2, 3, 4, 5
- Geometry contrasts (fig. 5)
- Ranking: 3, 1-4, 2
- Permeability contrasts (fig 6)

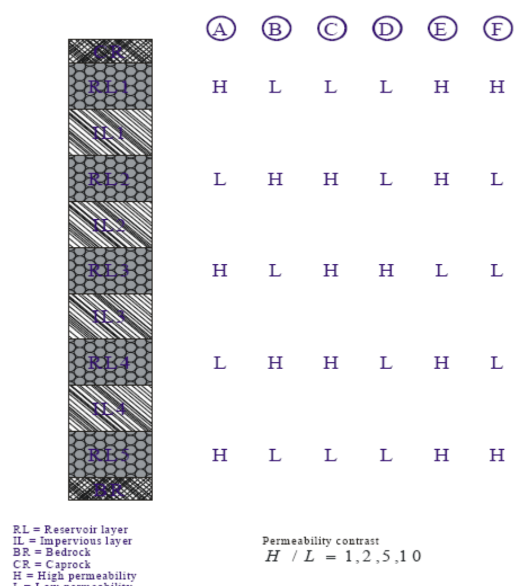

Figure 6: Layering stack and permeability contrast

Candidate settings (H=High; L=Low)

1. H/L=1 (no contrast)
2. H/L=2
3. H/L=5
4. H/L=10
5. Sandwich equivalent
6. Single layer equivalent

- Ranking: 1, 2, 3, 4, 5, 6

In the framework of a bench test exercise, aimed at comparing various simulation codes and modelling strategies, reported by Le Brun *et al* (2011) several clues deserve a comment.

In particular, the improved thermal efficiency demonstrated by the sandwich model *vis-à-vis* its three layered reservoir counterpart, in the constant production schedule, is interpreted as a consequence of a thicker (single) aquitard, sustaining more heat than the two slimmer ones acting separately.

Noteworthy is that this trend gets reversed after 18 years in the seasonally variable exploitation case.

This variability, displayed in fig. 7, may be summarised as follows (GPC IP, 2010):

(i) *Sandwich model.* Initially, the production temperature declines more rapidly, in the constant case, until year 18, then matches the variable case trend until year 30 (2.5 °C depletion)

(ii) *Three reservoir model.* The production temperature, contrary to the sandwich model behaviour, drops faster for the variable case, then slower after year 18. The temperature depletion (year 30) amounts to 0.95°C in favour of the variable case. On the contrary, in the constant case, the cooling curve trends more sharply, starting from year 15 achieving a 2.7°C temperature loss in year 30.

(iii) 30 years temperature drawdowns (°C) are summarized hereunder.

Model	Constant production	Variable production
Sandwich	2.5	2.5
Three reservoir	2.7	1.8

It seems that the combination of a multilayered stratified reservoir and a (seasonally) variable production/injection schedule tends to significantly slow down cooling kinetics. This trend has been somewhat dramatically amplified in the case of a thin layered structure (over twenty individual strata) modelled by one of the workgroup member contribution (ARMINES, Le Brun *et al* 2011).

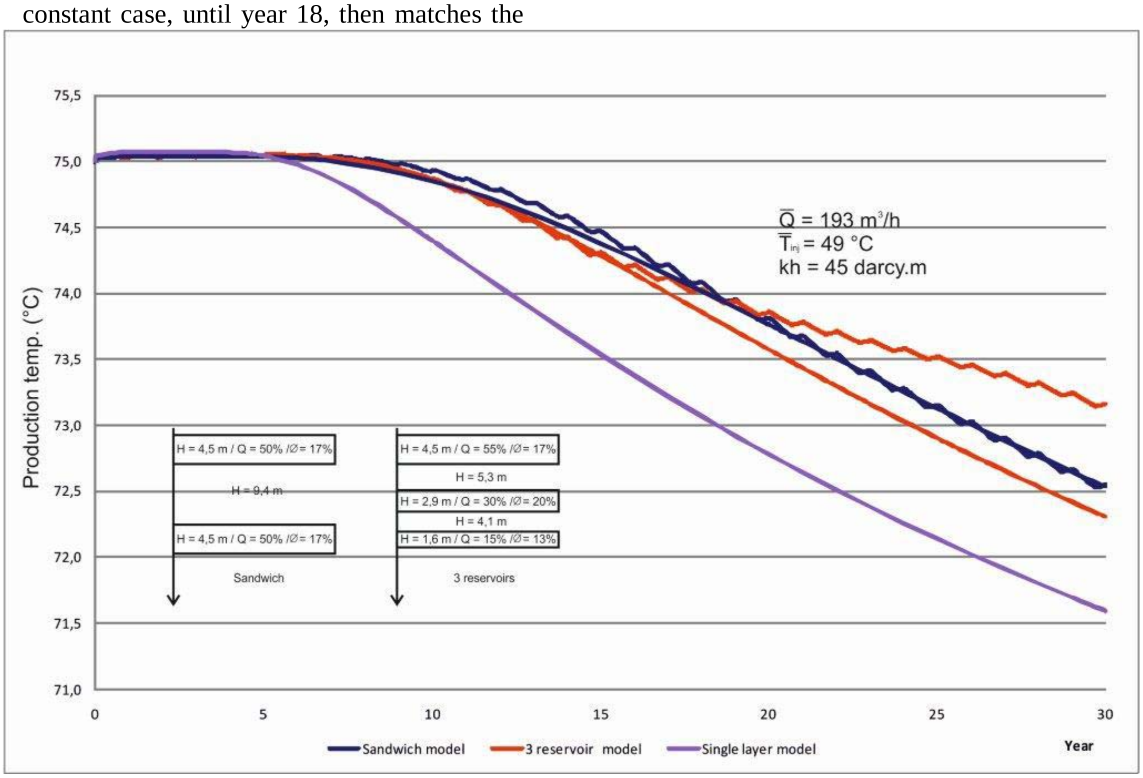

Figure 7: Modelled cooling kinetics for various reservoirs structures and production/injection schedules constant vs. variable (input data in Le Brun et al, 2011)

GEOMODELLING

As shown in fig. 1, a major segment of the Paris basin GDH market is located south of the capital city. Here exists therefore urgent needs for minimising the impact of interfering doublets and accomodate new well doublet/triplet targets among other sustainable reservoir management issues.

It becomes timely to design and implement a representative reservoir model matching closely actual pressure/temperature patterns. This offers an opportunity to check whether the five layer model successfully operated North of Paris (Antics *et al.* 2005) would stand valid when extended over the much wider southern area mapped in fig. 8. This, bearing in mind that estimating the distributions of the Dogger characteristics troughout the whole reservoir remains a delicate excercise as stressed by Martin and Menjoz (1988) in conclusion of a geostatistical survey of the Dogger geothermal reservoir. As a matter of fact, the authors insist on the difficulties encountered in adjusting theoretical variogram models, due in particular to a severe random component and strong estimation variances. Hence, a significant amount of experience and intuitive skills need to be exercised at reservoir assessment stages, seeking reliable simulation predictions.

For this purpose a GOCAD software marketed by Paradigm (2009) was utilised to produce a reservoir image integrating the five layer slicing, when effective, on each well. Unfortunately it failed as a consequence of facies discontinuities, sparse sampling localities and poorly documented well logs. This led to a sandwich reservoir model instead, sampled on a single well basis, applying the rationale earlier advocated by Antics *et al.* (2005) in which case the GOCAD code demonstrated its capabilities imaged in fig. 9. These GOCAD issued sandwich grids were further exported to the, MView interfaced, TOUGH2V2 simulator (Pruess, 1991) processed via the canonical natural state, calibration and prediction sequence.

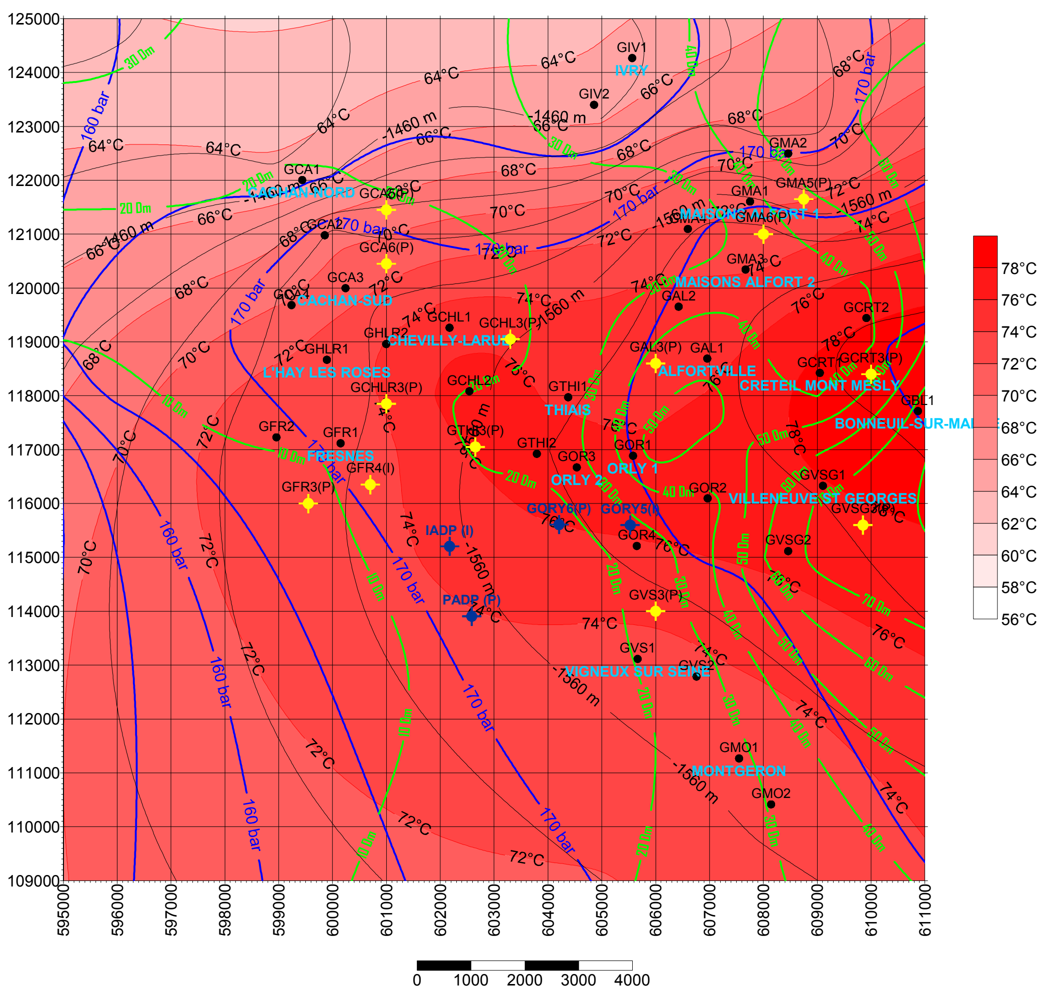

Figure 8: Southern Paris Basin modelled area. Well location map and top reservoir, formation temperature and transmissivity contour line.

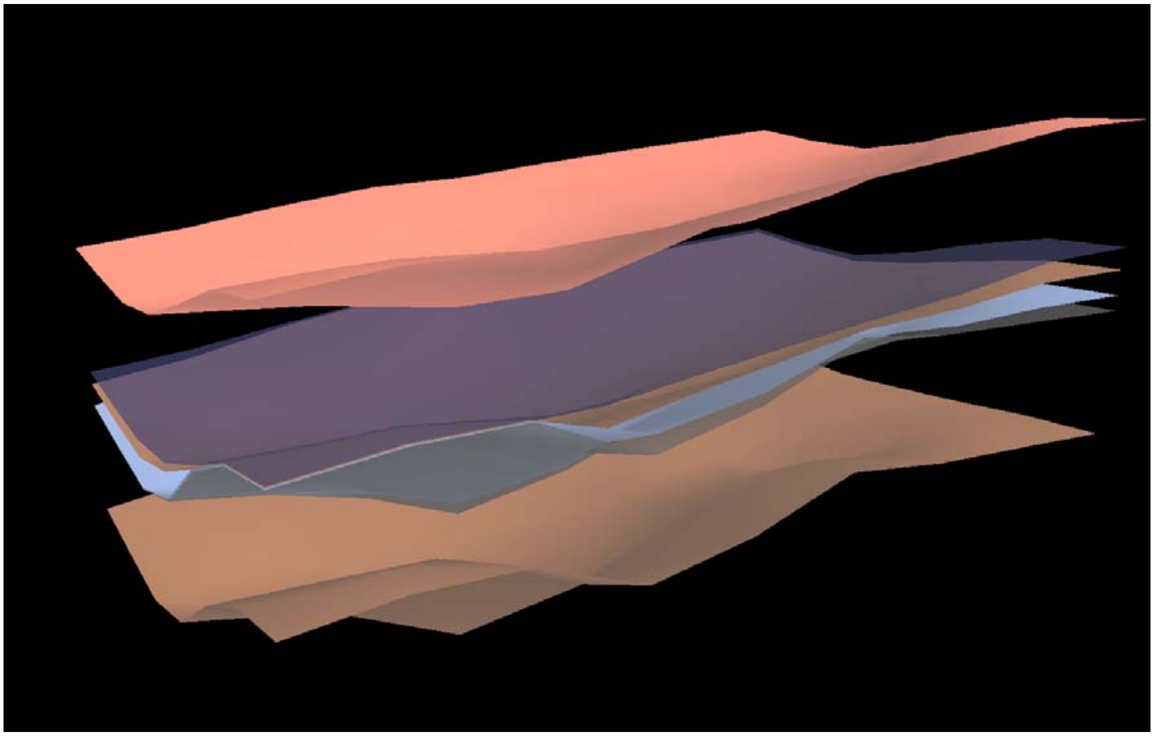

Figure 9: GOCAD 3D view of the sandwich reservoir

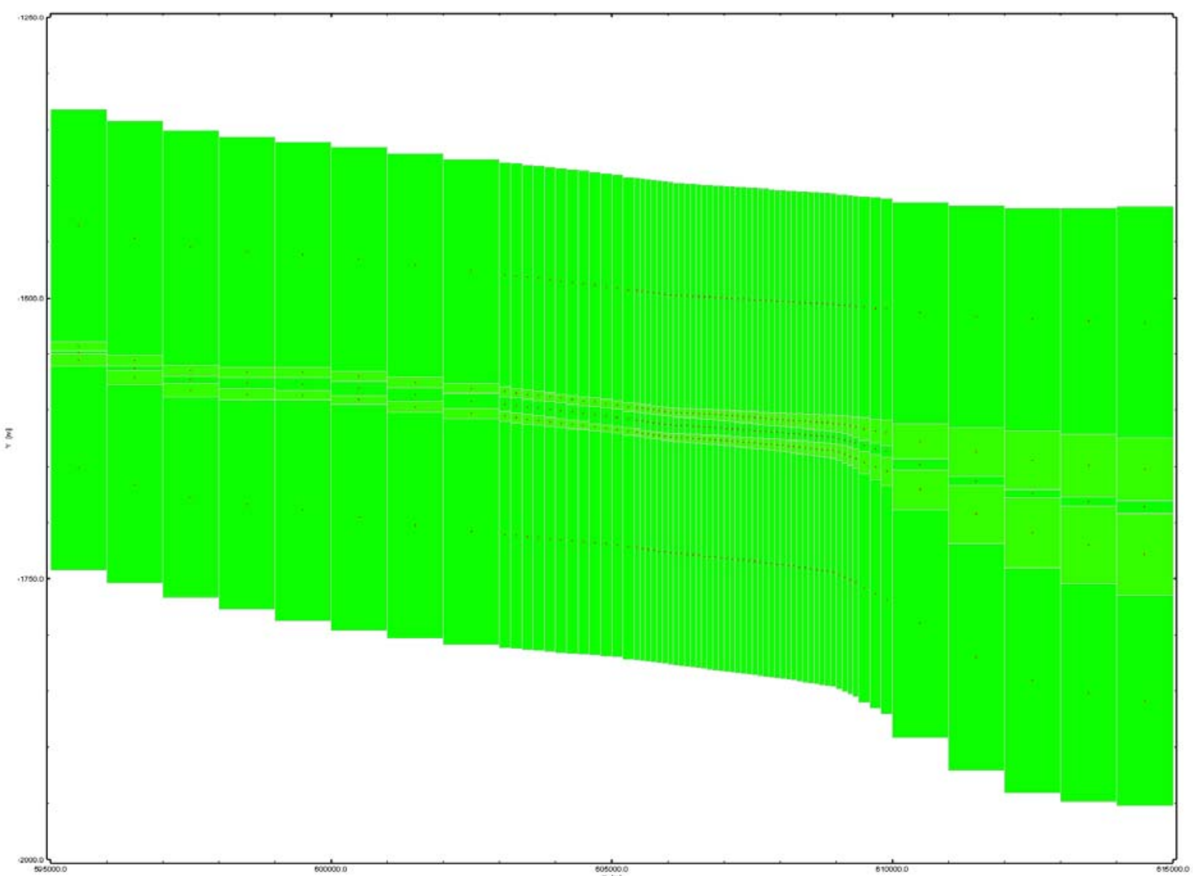

Figure 10: Vertical discretisation

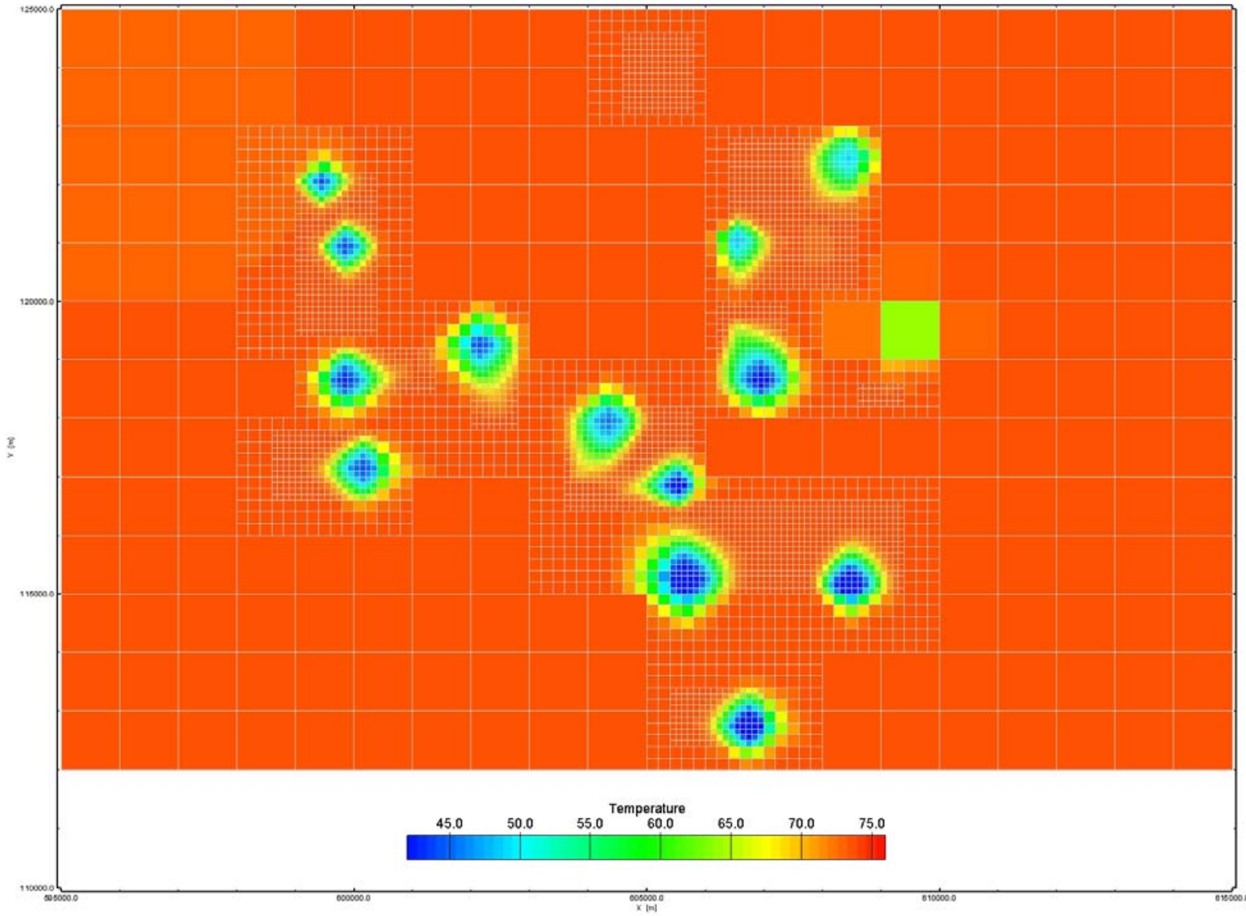

Figure 11: Horizontal gridding and simulation results, layer 2, after 20 years of exploitation

Fig. 10 illustrates the vertical discretisation of the sandwich layering and fig. 11 the variable horizontal gridding along doublet thermal (cooling) fingerprints after twenty years exploitation. The latter confirms that no breakthrough had yet occurred, thus confirming wellhead monitoring records.

WELL ARCHITECTURE

In the Paris Basin GDH the production and injection wells are routinely drilled directionally with an average 30 to 35° slant angle securing a well spacing, at top reservoir depth, varying from 900 to 1200 m depending upon locations.

In order to upgrade both well deliverabilities and system thermal life, the horizontal drilling design shapes quite attractive. While balancing technical and economical pros and cons one may contemplate in the Paris Basin geothermal environment four drilling/completion alternative designs (i) two vertical wells, (ii) two slightly deviated wells (the present status), (iii) two horizontal wells draining one preferential layer, and (iv) two horizontal wells intersecting the entire pay interval (i.e. a slant angle nearing to 80 to 85°)

The paper investigates schemes (i) and (iii), definitely the most contrasted trajectories (fig. 12).

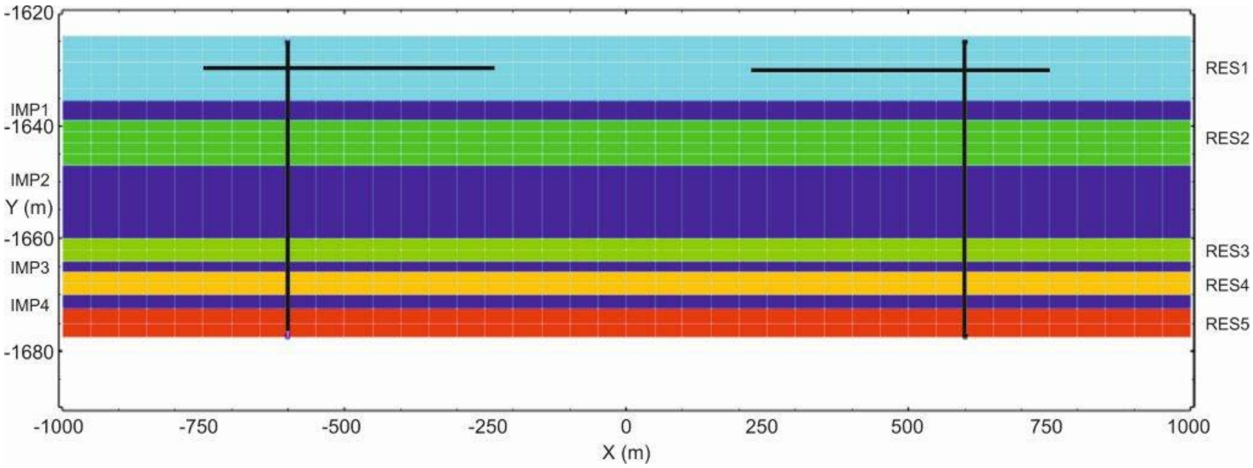

Figure 12: Well traces (vertical vs horizontal) at reservoir depths.

Table 1: Local model input parameters

ITEM \ LAYERING	CAP ROCK	RES1	IMP1	RES2	IMP2	RES3	IMP3	RES4	IMP4	RES5
Depth (m)	1424	1624	1635.5	1639	1647	1660	1664	1666	1670	1672.5
Mid point depth (m)	1524	1629.75	1637.25	1643	1653.5	1662	1665	1668	1671.25	1675
Thickness (m)	200	11.5	3.5	8	13	4	2	4	2.5	5
Temperature (°C)	71.4	75	75	75	75	75	75	75	75	75
Pressure (bar)	166.7	177.15	178.05	178.48	179.55	180.28	180.55	180.78	181.02	181.39
Permeability (darcy)	10^{-20}	1.74	10^{-20}	0.78	10^{-20}	3.63	10^{-20}	1.44	10^{-20}	1.4
Porosity	0	0.16	0.001	0.16	0.001	0.16	0.001	0.16	0.001	0.16
Thermal Conductivity (W/mK)	2	2.5	2.1	2.5	2.1	2.5	2.1	2.5	2.1	2.5
Thermal Capacity (MJ/m^{3}K)	3	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
% total flowrate	-	40	-	12.5	-	29	-	11.5	-	7

The candidate site, actually the one modelled by Antics *et al.* (2005) and Papachristou (2011), characteristics are listed in table 1 summary sheet.

In modelling the horizontal drains the following steady state flowrate/pressure relationship, quoted in Joshi (1991), has been considered assuming a homogeneous and isotropic reservoir and a drain length widely exceeding reservoir thickness:

$$q_h = \frac{C\,k\,h\,\Delta p}{\mu_0 \log\left(\frac{4r_d\,h}{L}\right)} \qquad (2)$$

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

Simulation results are summarised in the cooling transients depicted in fig. 13 which reflect a positive impact of the horizontal well on cooling kinetics. Both thermal and productivity/injectivity improvements could be sought from a longer drain penetration and wider spacing at reservoir level. Not to mention the benefits likely to be expected from design option (iv) which drains the whole payzone against 40% of total productivity for option (iii).

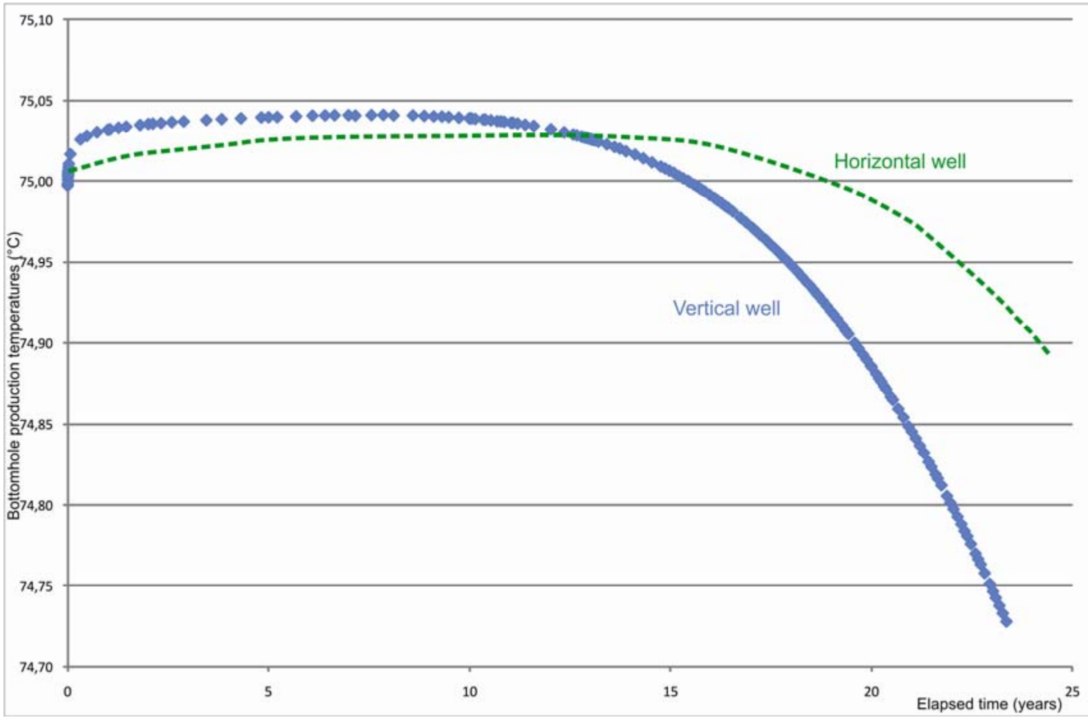

Figure 13: Vertical and horizontal well thermal profiles.

DISCUSSION

It addresses two key issues, reservoir description and well architecture respectively.

Reservoir description

Though somewhat idealised, the equation (1) thermal breakthrough appraisal, assuming a purely convective heat transfer and a single equivalent homogeneous reservoir remains a reasonable engineering shortcut in doublet well spacing design, thanks to its structurally pessimistic lifetime estimate.

However doublet and reservoir structures reflecting lateral and vertical facies changes reservoir heterogeneities make a multilayered and structure a reservoir modelling prerequisite. Neither can reservoir simulation substitute "smooth" yearly averaged flowrates and injection temperature input files to actual daily and seasonally outdoor temperature dependant, variable sequences. The latter suggests that the heat transfer process is more sensitive, than its pressure counterpart to thin multilayered, structures, likely complicated by facies changes.

Although a minimum three layer structure is recommended, it has been shown practically inaccessible to geomodelling software when dealing with widespread reservoir areas as a result of insufficient lithological and structural back up and sparse well locations.

Nevertheless, the sandwich model approach, based on doublet instead of single well geostatistic interpolation, has proven a reliable compromise validated on the previously described simulation exercise.

Well architecture

Although in its infancy application to geothermal reservoir environments of the horizontal well technology seems promising as suggested by the simple case study presented herein. It needs to be optimised at design stage and, needless to say, field validated and its economics thoroughly assessed before becoming a standard well completion.

CONCLUSIONS

The exhaustible nature of geothermal resources requires sustainable heat mining strategies reconciling market heat demand with reservoir longevity concerns, a statement evidenced by 30 years GDH experience in the Paris Basin.

The multilayered structure of the Dogger carbonate reservoir can no longer be ignored while assessing the reservoir hydrothermal behaviour and predicting its, doublet exploitation induced, cooling kinetics. Neither can the definitely time varying nature of the production/injection sequences be overlooked. Summing up, combining both attributes in reservoir simulation protocols is a key issue in assessing reservoir and well longevities.

Geomodelling software failed in generating a multilayered structure closely fitted to the actual reservoir stratification derived from flowmeter logging, but succeeded in imaging a relevant overall sandwich grid exported to the, MView interfaced, TOUGH2V2 (Pruess, 1991) simulator. It proved a valuable substitute, later validated via relevant simulation runs.

Further efforts should focus on improving well logging and lithofacies support alongside integrating variable production/injection schedules to reliably simulate actual reservoir thermal behaviour.

From the drilling/completion standpoint, horizontal drilling technology would achieve a breakthrough in geothermal well architecture. It should upgrade both well productivities and thermal longevities. However, these routes need to be thoroughly explored at design and field validation stages and their economics assessed before becoming a standard in geothermal drilling/completion practice.

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