Sub-Horizontal Geothermal Well Completion. A Promising Outlook

Marie-Paule PROMIS, Pierre UNGEMACH, Miklos ANTICS

GPC Instrumentation Process PARIS NORD 2 Business Park 4A, 165, rue de la Belle Etoile BP 55030

95946 Roissy CDG Cedex France

office@geoproduction.fr

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ABSTRACT

The paper investigates the performance of sub-horizontal well architectures in upgrading deliverabilities and life cycles of geothermal district heating (GDH) doublets compared to conventional completions.

The concept aims at applying horizontal drilling technology, elsewhere routinely practiced by the oil and gas industry, to intersect via long reach drains the entire productive (pay) interval of a multilayered reservoir.

Modelling of candidate conventional (vertical, inclined) and alternative (single horizontal drain, several horizontal, multilateral, legs, sub-horizontal, total pay, pathway) well trajectories highlighted the positive impact of multilaterals and sub-horizontal designs in delaying thermal breakthrough times.

The foregoing was further validated on actual (Paris Basin) reservoir settings, therefore exemplifying the benefits expected from the sub-horizontal well design from both the productive capacity, heat recovery and thermal life stand points.

Implementation of the concept and its economics are discussed *in fine*.

INTRODUCTION

Heat recovery, well deliverabilities and reservoir life are key concerns in sustainable geothermal reservoir management. Such issues become particularly sensitive while designing optimum heat farming in sedimentary reservoir environments for space and district heating uses. Current practice is based on the, mass conservative, doublet concept of heat extraction, which combines a production well and an injection well pumping the heat depleted brine in the source reservoir. Both wells are drilled directionally (30 to 35°C slant angle) from a single drilling pad in order to achieve a bottomhole spacing (1 000 to 1 500 m) securing a 20 to 25 year thermal breakthrough, assumed to match reservoir life (Gringarten and Sauty, 1975; Gringarten, 1979).

Horizontal drilling, long practiced by the Oil and Gas industry (over 150 000 wells drilled to date), should appeal to geothermal operators, given its ability to widely increase well productivities and fluid recovery, with special mention of thin pay, anisotropic and fractured reservoir settings. For instance Joshi (1991, 2010) and Hagoort (2009) report the following, horizontal vs vertical well completion, improvement ratios, (i) stabilized flow rates, 2 to 4 fold (5 to 11 for fractured reservoirs, (ii) productivity, 3 to 5, (iii) cumulative production, 2, and (iv) drainage area, 2.5 (isotropic reservoirs) up to 6 (highly anisotropic formations). The technology was thought to meet the requirements of GDH undertakings in multilayered sequences alternating pervious strata and impervious confining beds, a distinctive attribute of a number of low enthalpy resource settings (Paris and Pannonnian basins among others). The idea here consists of intersecting the whole productive (pay) interval via a highly inclined, near to horizontal, long reach well path, the so called sub-horizontal geothermal well concept.

The forthcoming sections investigate the performances of horizontal, sub-horizontal and multilateral trajectories, *a priori* rewarding in upgrading well deliverabilities, reservoir longevities and heat recovery factors, compared to conventional geothermal well completions. The impact of sub-horizontal well designs on selected case studies will be assessed and practical implementation of the concept discussed *in fine*.

DESIGN FEATURES

Simplified conceptual designs are featured in figure 1 sketches. Reservoir layering is assumed uniform (figure 1a) over the entire drain lengths (figure 1b) and drainage/flooding symmetries ellipsoidal (figure 1c). Doublet well trajectories follow with the curved (until reservoir top/drain heel)/linear (across the reservoir, total pay interval) profiles shown in figure 1d. 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.

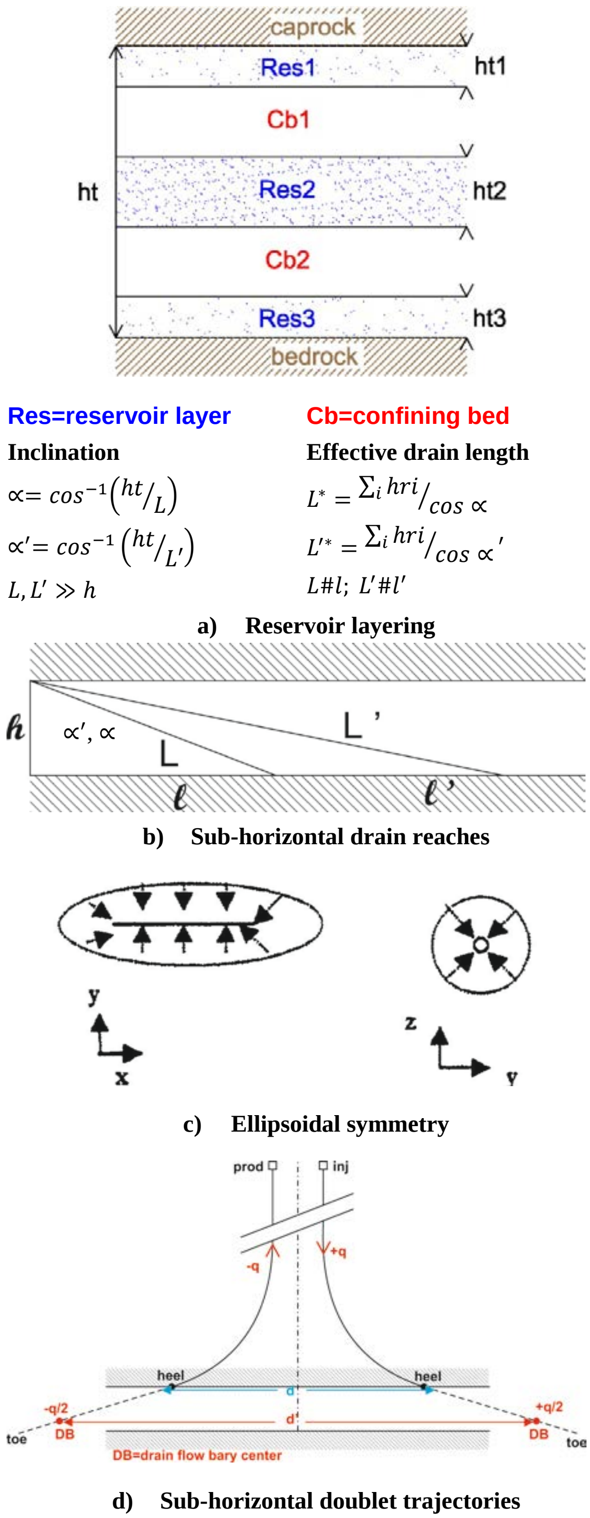


Figure 1: Summary of design features

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):

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

(1)

Where:

k	=	permeability (Darcy)
h	=	layer thickness (m)
L	=	drain length (m)
	(2)	
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:

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

(3)

With:

q_v	=	flowrate (m^3/hr)
	(4)	
R_0	=	influence radius(i.e. where $\Delta p = 0$) (m)
R_w	=	vertical well radius (m)

Hence:

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

(5)

Numerical application:

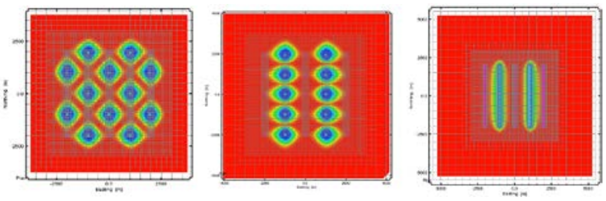
H	=	20 m
L	=	1 000 m
R_0	=	1 000 m
r_w	=	0.1 m
r_d	=	500 m
$\frac{q_h}{q_v}$	=	2.5

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

MODELLING

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 2) are displayed in figure 3. 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 2: Production/injection well/drain arrays

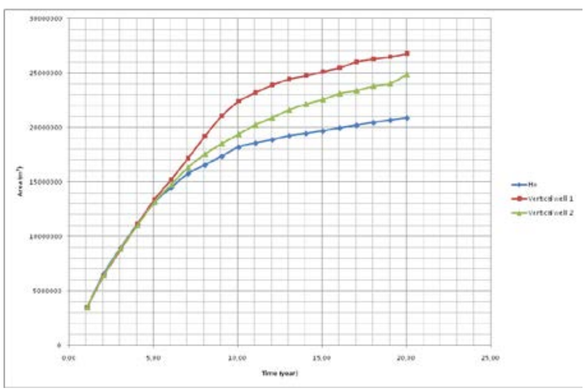


Figure 3: Cooling kinetics. Cold areal extents

Cooling kinetics. Multilayered reservoir. Sub-horizontal wells.

The multilayered reservoir structure sketched in figure 4 has been reduced to its, three layer stacked *sandwich* equivalent (figure 5), 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.

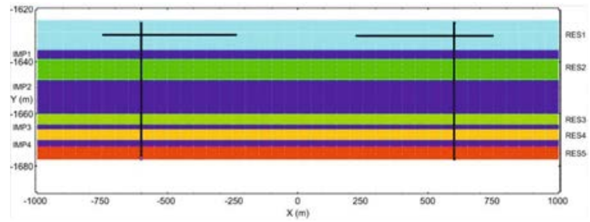
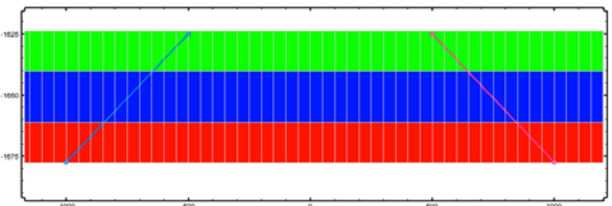


Figure 4:



$T_{initial}$ = 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 5: Multilayered sandwich equivalent reservoir. Porosity, permeability, temperature and pressure patterns.

Table 1: Flow pattern and thermal breakthroughs

LAYER PRODUCTIVITY % TOTAL FLOW		THERMAL BREAKTHROUGH
Q1	Q2	(YEARS)
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

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 6, 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.

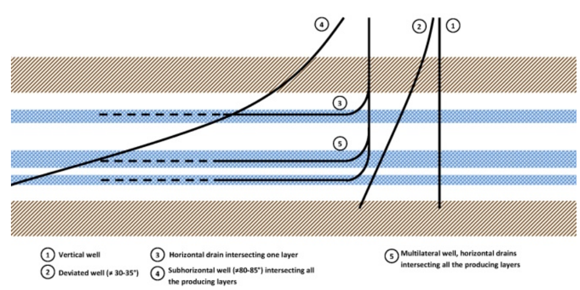


Figure 6: Candidate well/drain trajectories. Multilayered reservoir

Results, summarized in figure 7 (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.

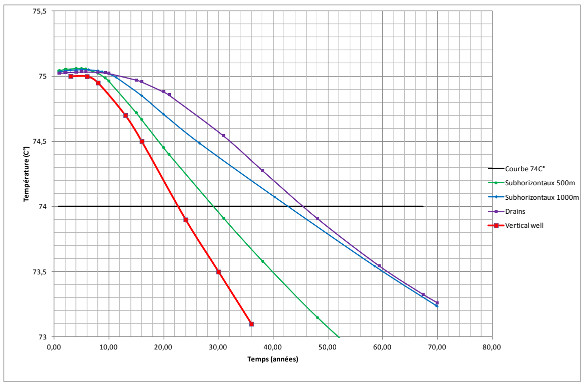


Figure 7: Impacts on cooling kinetics. A selected well/drain designs

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*

CASE STUDIES

Sustainable development. Scenario 1.

The dense GDH doublet/triplet population projected over the next decades, depicted in figure 8, requires due care with respect to reservoir thermal life and well hydrodynamic interferences. The target area, circled in figure 8, addresses presently a dual doublet [GCA3(P) x GCA3(I) and GCA4(P) x GCA2(I)] exploitation, rated 350 m^3/h, operating since 28 years. It cannot be sustained any longer without the completion of new mining infrastructures aimed at maintaining at least, and possibly increasing, the present rating. Two development strategies and three mining schemes were comtemplated, either (i) drill a new doublet [GCA5(P) x GCA6(I)], rated 250 m^3/h, followed later by the completion of a triplet [GCA7(P) x GCA1(I) x GCA2(I)] rated 200 m^3/h, or (ii) switch to an innovative sub-horizontal well design, portrayed in figure 9, rated 400 m^3/h. The later shaped promising in consideration of its (CAPEX, OPEX) cost savings and its reservoir management outlook highlighted in figure 10 outputs. It can be seen that (i) there are now significant pressure interferences with neignbouring doublets and triplets, and (ii) the sub-horizontal mining scheme concentrates (re)injected cold fluid invasion in the northern [GCA1, GCA2, GCAH2] area.

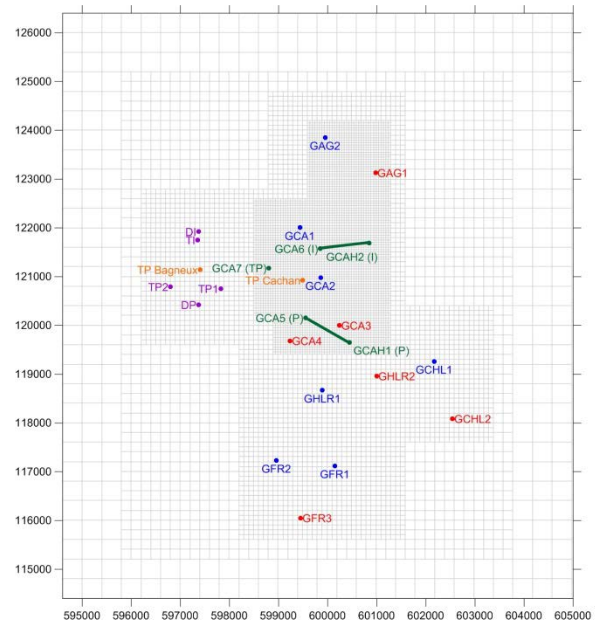


Figure 8: Reservoir simulation grid and well (existing, projected) locations (top reservoir impacts)

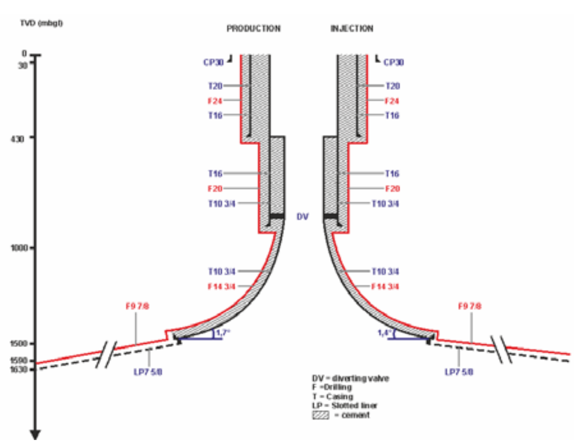
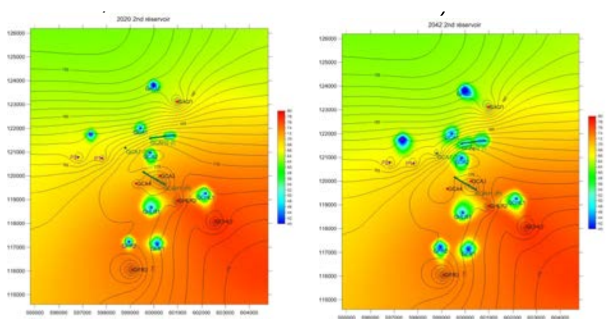


Figure 9: GDH doublet (sub) horizontal well profiles



a) Year 2020 b) Year 2042

Figure 10: Reservoir simulation. Case history 2. Completed pressure and temperature fields. Sub-horizontal well scenario

Sustainable development. Scenario 2.

Another advantage expected from the sub-horizontal doublet design is the limitation of the number of doublets required to meet the GDH production objective, an exercise exemplified in figures 11 and 12. Here one such doublet, rated 400 m^3/h, substitutes for two, each rated 200 m^3/h, conventional doublet completions. The pressure influenced area, though more depleted in the sub-horizontal drain array owing to its higher rating, is less scattered and the cooled zone (one against two) likewise, than its twin doublet replicae. Cooling kinetics trend also more favourably, a trend evidenced in figure 12 and 13.

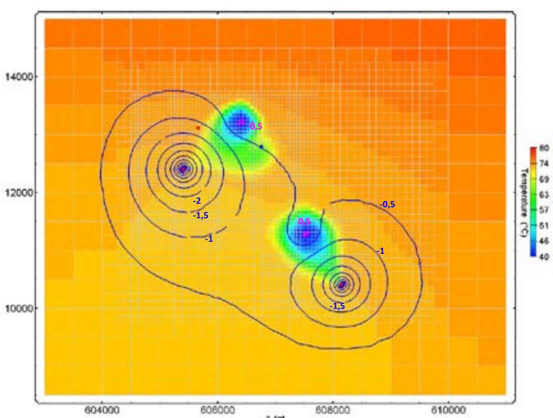


Figure 11 : Temperature and pressure drawdown fields. Year 2044. 1st reservoir layer. Conventional doublets scenario

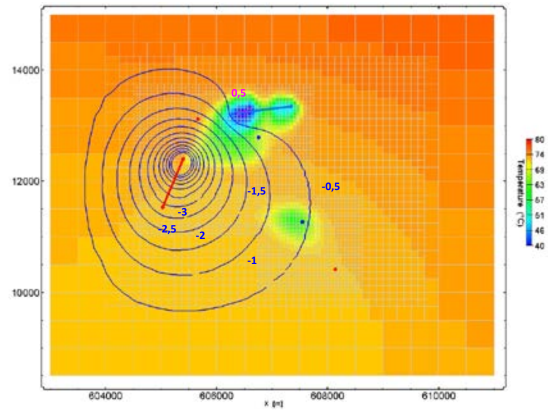


Figure 12 : Temperature and pressure drawdown fields. Year 2044. 1st reservoir layer. Sub-horizontal drain scenario

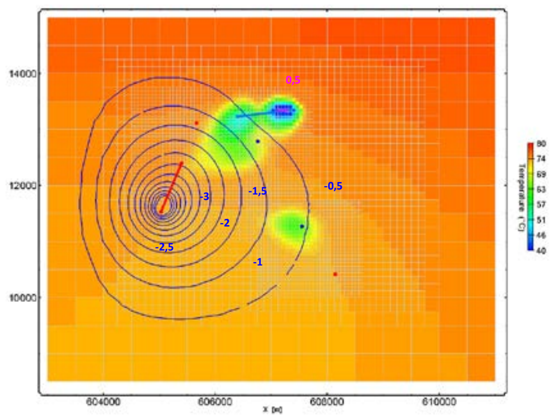


Figure 13 : Temperature and pressure drawdown fields. Year 2044. 2nd reservoir layer. Sub-horizontal drain scenario

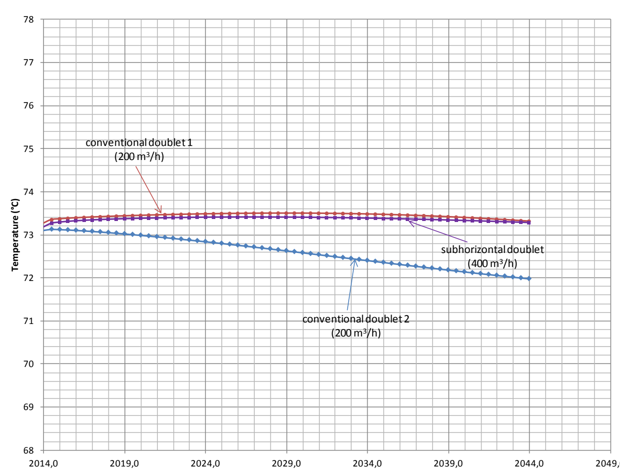


Figure 14: Cooling kinetics. Case study 2.

DISCUSSION

In spite of its attractive productive and thermal performance the sub-horizontal geothermal well concept arises several questions regarding practical implementation, costs and risks.

- **Field implementation**

The first and prioritary requirement addresses drilling rig capacities which, given the well design outlined in figure 9 i.e. 1 600 to 2 000 m vertical depth, 3 000 to 3 500 m drilled depth, 1 000 m long horizontal drains and 9’’7/8 terminal diameter (7’’5/8 completion), should not be lower than 250 t (dyn.) hook load.

Drain trajectories rely on modern steering capabilities which in turn need to account for reliable identification of reservoir layers best achieved via logging while drilling (LWD) technology including at least a Gamma Ray and Litho-Density tool assembly.

Openhole, the easiest though risky, production/injection mode is restricted to consolidated carbonate rock settings. Hence, slotted liner completions are recommended seeking conduit propping and well longevity. As regards poorly consolidated, loose even, clastic sediments, gravel packed screen completions should be implemented, an issue advocated by Martins and Calderon (2009).

Last but not least, proper material definition is required at completion level to defeat corrosion damage in hostile thermochemical fluid environments as those encountered in the Paris Basin Jurassic (Dogger) reservoir.

Downhole chemical inhibition being difficult to operate in (sub)horizontal profiles, the use of composite, casing designed pressure ratings, corrosion resistant fibreglass liners (Ungemach et al, 2010; Ungemach, 2012) appear a relevant option

- **Costs**

The extra expenditure (mining CAPEX) incurred by the afore mentioned designs has been estimated at 20% compared to the cost of a conventional (30 to 35°) deviated doublet.

- **Risks**

No historical record, enabling to assess the longevity of the concept, being available, the analysis is restricted to the drilling/completion risk. In this respect the well profile described in figure 9 makes it possible to bypass a drilling or completion failure within the reservoir section, via side tracking from reservoir top, thus leading to a conventional deviated well design.

CONCLUSION

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.

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