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Extended Reach Wells for Enhanced Heat Production

Pierre Ungemach, Miklos Antics and Marie-Paule Promis

GPC Instrumentation Process
(GPC IP)
165, rue de la Belle Etoile
95946 ROISSY CDG Cedex
FRANCE
pierre.ungemach@geoproduction.fr

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ABSTRACT

Complex reservoir settings encountered in various European, tectonised and multilayered, either in continental rift or sedimentary basin environments have drawn attention towards novel well architectures aimed at sustaining high productive capacities and long thermal life.

The problematic becomes more sensitive in lower than expected permeability environments which require that relevant well design strategies be substituted to the long prevailing, presumably market dictated, conventional drilling/completion practice and innovative well architectures promoted instead.

The present paper illustrates the foregoing through selected case studies exemplifying the gains achieved by subhorizontal, radial drain and multiple completion well concepts.

Risk management and mitigation issues, alongside cost impacts, are also discussed.

1. INTRODUCTION

Widening the scope of geothermal energy development, long limited in resource occurrence and uses to geodynamically favoured areas and flash power conversion cycles, has been a constant concern of the geothermal community. In the past decade it became an urgent, priority, objective as a result of the global warming issue and the leading role assigned in the future to Renewable Energy Sources (RES). Actually the European Union (EU) at large (i.e. EU member states, Iceland and Turkey) has projected a 55% supply of its whole energy demand from RESs in year 2050 (European Commission, Road Map 2011). Therefore the question arises as whether geothermal energy could significantly contribute to this ambitious share vis-à-vis other-solar, wind, biomass-competing renewable sources and, given its structural constraints, where, when and how.

The answer is straightforward: increase by at least one order of magnitude its market share whose present status stands, World and European wide, at:
(13 000 MW_{el} /74 000 GWh_{el}) / (3 400 MW_{el} /15 000 GWh_{el}) (Geopower) (Bertani, 2015) - and
(70 000 MW_{th} / 163 000 GWh_{th}) / (27 000 MW_{th}/94 000 GWh_{th}) (Geoheat) (Lund and Boyd, 2015).

In meeting this challenging objective, several development routes may be contemplated.

(i) Reclamation of, low to very low shallow seated water saturated and ground sources by means of ground water and ground source, heat pump sustained, systems; the latter, incidentally, bypassing the mining rationale as it may apply to any human populated, power or gas supplied, land location.

(ii) Extension of the geopower and combined heat and power (CHP) market segments from medium enthalpy sources and flashed steam brine recovery via Organic Rankine Cycle (ORC) turbines.

(iii) Upgraded heat extraction from poor to very low permeability, either matrix or fracture dominated, settings which, unless tackled by adequate well architectures and enhancement technologies, would remain unchallenged.

(iv) Last but not least, the ultimate EGS concept of mining heat from man engineered geothermal systems, focused on tectonically (and seismically) active environments (Baria and Baumegartner, 2016).

Seeking economic viability, items (iii) and (iv) require 300 m^3/hr and preferably 350 m^3/hr well productive capacities, a target calling on innovative, subhorizontal and multiradial well trajectories and dual completions analysed in the forthcoming sections.

Horizontal drilling technology, pioneered mainland in the early 1950s in Bashkira (Oural, Russia), (Hill et al, 2008) and off shore at Rospo Mare (Adriatic sea, Italy) in the late 1970s (Joshi, 1988) has become nowadays a routine technology, evolving, thanks to modern 3D seismic imaging, novel geosteering navigation tools and logging while drilling (LWD) to complex multilateral well architectures, an area of engineering thoroughly investigated by Hill et al (2008).

Only but recently have geothermal operators expressed interest towards innovative well designs. Worth to mention in this respect are several exceptions. Horizontal well trajectories have been suggested by Bruel (2008) as an alternative to conventional directional drilling applied to geothermal district heating (GDH) well doublets in the Paris Basin, assuming a single layer geothermal reservoir. Later, Ungemach et al (2011) and Promis et al (2013) advocated the subhorizontal well concept as the appropriate design for maximising production from a more realistic multilayered sedimentary reservoir structure, which led to an *ad hoc* project commissioning on a GDH site South of Paris (GPC IP, 2015 and 2016).

In the meantime several undertakings announced the penetration of new (imported), well siting, drilling and completion techniques among geothermal operators, long committed to conservatism.

(i) In the Molasse Basin, South of Münich over ten deep target CHP doublets could be successfully completed, and the risk of missing a buried karstified limestone reservoir reduced accordingly, by generalising the use of 3D seismic, RSS (rotary steerable systems), LWD assisted, navigation systems, securing the contrasted well trajectories displayed by Mirjolet (2014), an operating protocol trending towards a standard in such “risky” environments (Schubert, 2015).

(ii) The first horizontal wells ever achieved in geothermal drilling took place in 2012 at Schlattingen in the Swiss Canton of Thurgau. Not designed as such beforehand it was sidetracked as a remedial to the initial vertical well profile, which proved almost dry. Incidentally, the two fold kick off trajectory described by Frieg (2014) evidenced the need for structurally incorporating wellbore stability calculations to well design.

(iii) A dual completion aimed at producing/injecting simultaneously two, medium depth, poorly consolidated sandy aquifers, via two vertical, screened/gravel packed, pump sustained, wells was designed during that period (Ungemach and Antics, 2015).

2. SUBHORIZONTAL WELL DESIGN FEATURES

Well design should be regarded as an alternative to horizontal well drilling technology, known to significantly upgrade well drilling performance, aimed at meeting the requirements of geothermal district heating/cooling (GDHC) and combined heat and power (CHP) systems in farming heat from, low to medium enthalpy, stratified sedimentary reservoirs, widespread European and Worldwide.

The simplified design featured in Figure 1 assumes (i) uniform aquifer layering over the whole drain length, which is seldom the case, (ii) linear shaped reach trajectories, and (iv) ellipsoïdal drainage/flooding symmetries. Note that effective drain lengths require to be corrected from cumulated confining bed lengths and that doublet spacing corresponds to the distance between drain flow barycenters, the latter accounting for the fact flow increases/decreases from drain toe to drain heel (production drain) and *vice versa* (injection drain).

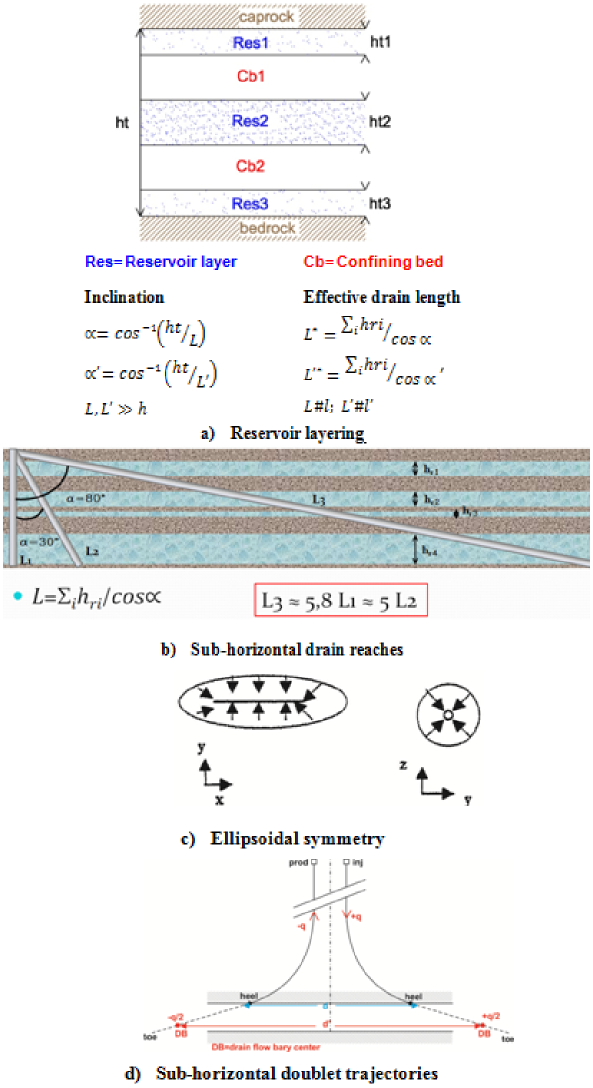


Figure 1: Summary of design features
(Source: Promis et al, 2013)

- **Productivity enhancement**

Expected productivity gains can be inferred from the following sequence, assuming a homogeneous isotropic reservoir and a steady state radial flow quantified via the Dupuit delivery equation applied to two reference configurations, a horizontal drain and a vertical well respectively.

- **Horizontal drain (Joshi, 1991)**

(1) $$q_h = \frac{C\,k\,h\,\Delta p}{\mu \log\,(4\,r_d\,h\,/\,L)} \qquad L >> h$$

(2) $$q_v = \frac{C\,k\,h\,\Delta p}{\mu \log\,(^{ro}/_{rw})}$$

(3) $$\frac{q_h}{q_v} = \frac{\log\,(^{ro}/_{rw})}{\log\,(4\,r_d\,h\,/\,L)}$$

C= System unit dependant constant
h= Net reservoir thickness (m)
k= Intrinsic permeability (darcy)
L= Drain length (m)
q= Flowrate (m^3/hr)
r_d= Drain effective (influence) radius (m)
r_o= Well effective (influence) radius (m)
r_w= Well radius (m)
Δ p= Pressure depletion/rise (bar)
μ= Dynamic viscosity (cp)

- **Numerical application**

r_w = 0.108 m, r_o = 1 000 m
q_h/q_v @ equal pressure depletion/rise

h (m) \ r_d (m)	100	200	500	1 000
5	2.4 / 3.1	3.1 / 4.4	4 / 6.7	5.7 / 13.3
10	2 / 2.5	2.5 / 3.2	3.1 / 4.4	4 / 6.6
15	1.8 / 2.3	2.3 / 2.9	2.7 / 3.7	3.4 / 5.1

L = 1 000 m / L = 500 m

It can be seen that the thinner the reservoir, the wider the drain effective radius and the lower the drain length, the higher the delivery gain. This obviously has some implications while designing a relevant alternative to conventional well architectures.

Summing up a two to three fold productivity increase respective to a vertical well can be reasonably assessed.

The exercise can be extended towards estimating the gains achieved in GDHC/CHP doublet production/injection pressures.

Assuming a 1 500 m spaced vertical doublet, a 8.5" openhole well diameter, a 10 darcy meter/zero skin/70°C reservoir environment, and a 2.5 productivity gain, production bottomhole pressures, would shape as follows:

	250 m^3/h	450 m^3/h
- Vertical well	41.8 bar	75.2 bar
- Horizontal drain	16.7 bar	30.0 bar

Would the well trajectories move from vertical to a 40° slant angle, deviated well pressures would be reduced to 32.4 (250 m^3/h) and 58.3 bar (450 m^3/h) respectively as a consequence of increased, inclination induced, reservoir net thickness (and transmissivity).

Various analytical formulations of horizontal well inflow for selected steady state models (Joshi, 1988, Babu and Odeh, 1989 and Furui et al, 2003) may be found in the thorough topical compilation of Hill et al (2008).

- **Thermal life enhancement**

Horizontal, multilateral and subhorizontal wells architectures being designed to improve reservoir drainage, as evidenced by Promis et al (2013) for typical clustered well arrays, they should logically lead to prolonged thermal longevities. The impacts on production well cooling kinetics of the candidate well trajectories displayed in Figure 2 are shown in Figure 3 temperature decline curves; the 1°C depleted temperature threshold, chosen as the thermal break through criterion, is reached after 20 years by the vertical well and after 46 years by the multilateral configuration, ranked first although the multilaterals and the 1 000 m long subhorizontal reach cooling curves stand quite close, actually merging on year 55.

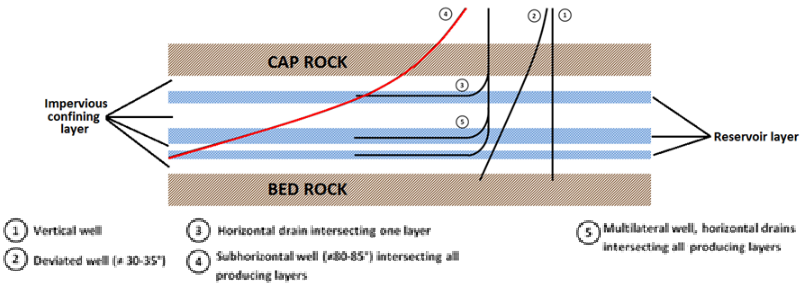


Figure 2: Subhorizontal well concept. Candidate well paths

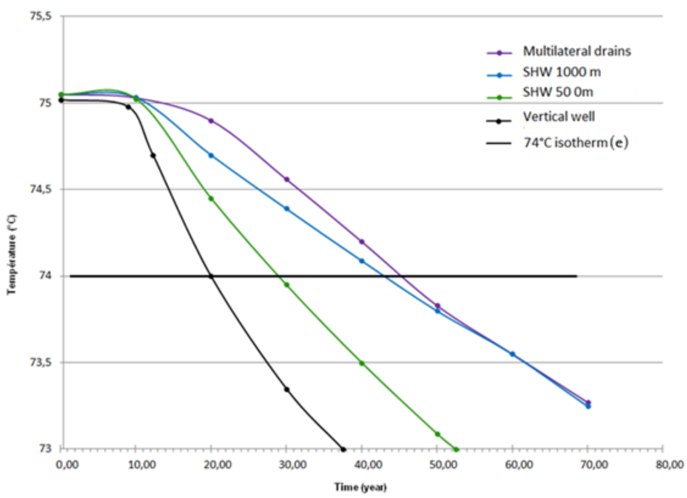


Figure 3: Well architecture cooling kinetics (200 m^3/h yearly average production rate)
(source: Promis et al, 2013)

- **Case study**

A major concern addresses the replacement of aging and declining, when not wholly damaged, well infrastructures of long operated (often over 30 year) GDHC systems, a distinctive feature of the Paris Basin geothermal development, which in several suburban districts undergoes a doublet over population trend exemplified in Figure 4 lease mapping.

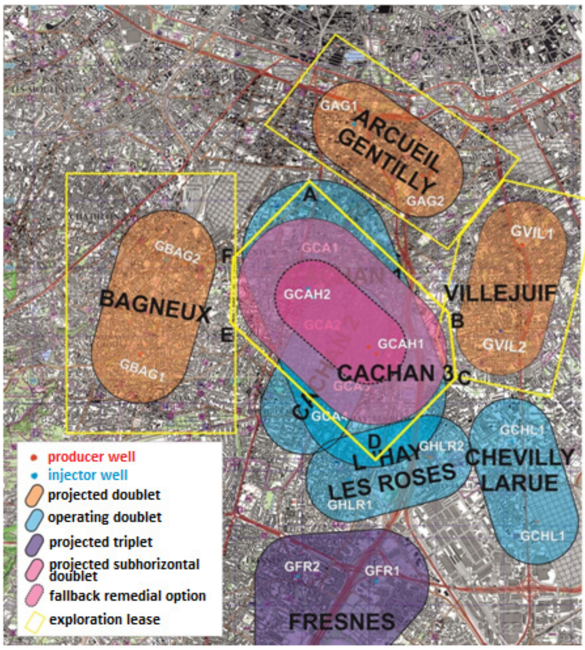


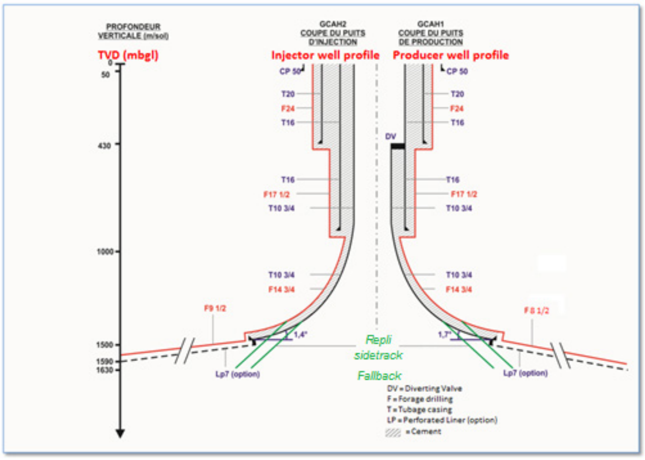
Figure 4 : Paris Basin geothermal district heating (GDH). Locations (June 2016 status)

The site selected for the first implementation of the Subhorizontal Well (SHW) concept meets most afore mentioned GDHC attributes, in particular a densely populated location, limited space availability, proximity of neighbouring, operating and commissioned doublets including two, 30 years old first generation completed wells, to which should be added locally moderate reservoir properties, saturated production capacities and poor system COP (ratio of produced heat over consumed pumping power).

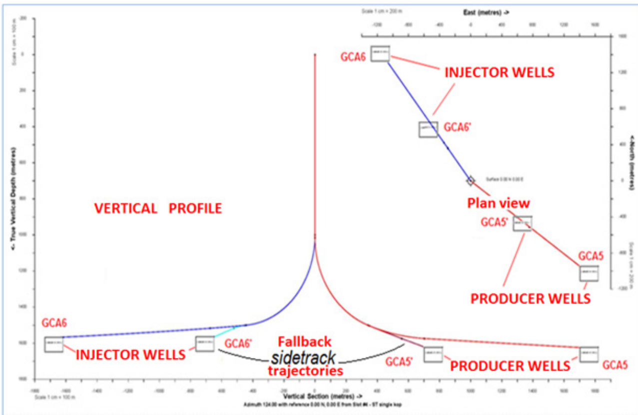
The foregoing made this site a representative background eligible to innovative well designs, securing technically and cost effective exploitation objectives.

The SHW project replaces the existing two doublet mining schemes, serviced since years 1984 and 1985, and extend its productive capacities from 350 m^3/h – 45 000 MWh_t/yr to 450 m^3/h – 60 000 MWh_{th}/yr, ambitioning a COP of 20 instead of the former 10 MWh_{th}/MWh_{el}.

Well design features are portrayed in Figure 5 (well architecture), and Figure 6 (3D well profile).



a. Well architectures



b. Well trajectories

Figure 5: Subhorizontal well architectures and trajectories

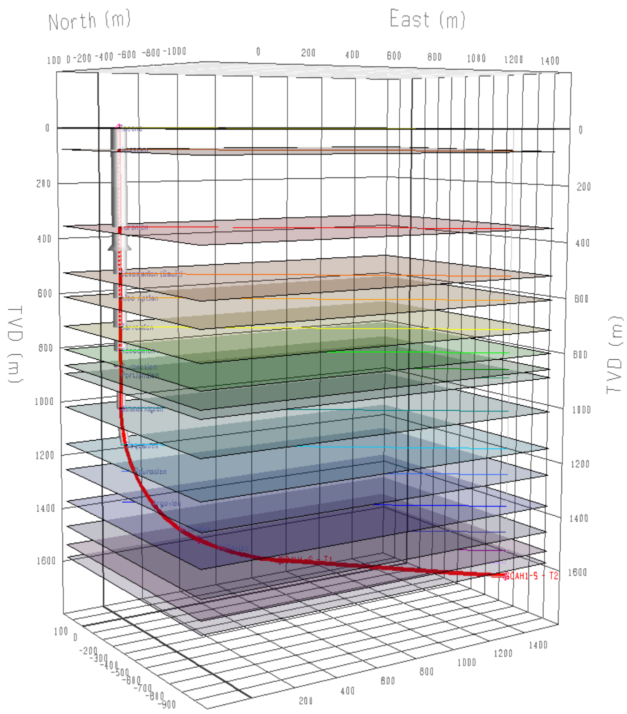


Figure 6: Subhorizontal well 3D profile

Note that, would the implementation of the planned trajectory fail, a sidetracked fallback remedial trajectory, complying with the design sketched in Figure 7 and further developed in section 3, is foreseen.

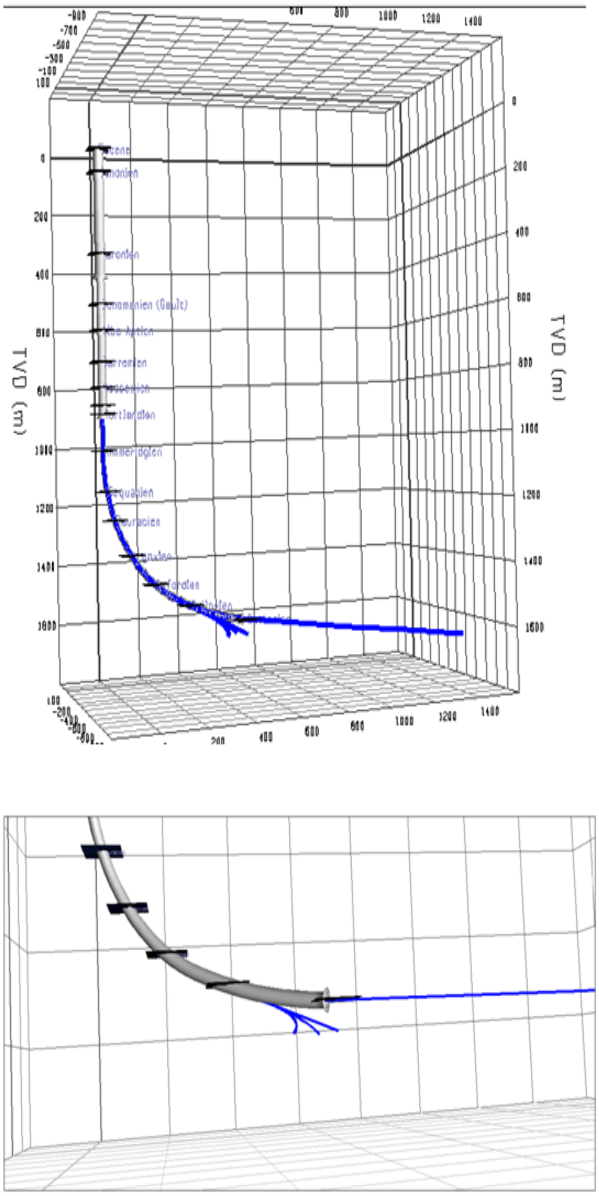


Figure 7: Subhorizontal well and sidetrack fallback trajectories

Given site limitations, the urban environment and well architecture specifications a compact, silent and heavy duty rig force should be hired and comply to the following prerequesites.

Rig type: Hydraulic
Hook load: 300-350 mt
Top drive: TDS (350 t, 50 000 ft.lbs)
Pumps capacity: 3 Triplex VSD, 2 500 l/min rated units
Miscellaneous facilities:
·Skidding
·Drill pipe & tubular side racking
·Push/rotate/reciprocate in hole casing running
·Drilling fluids: water based mud formulations (bentonitic, bipolymer/cellulosic/ lubricated, brine/biopolymer/lubricated)
·Directional drilling: Geosteering, RSS/LWD navigation system
·Logging:
-OH/LWD (GR, density/LDL, porosity/CNL, cesistivity/MFR, Caliper)
- CH (CBL/VDL-SBL, USI/URS imagers, MFC CAL)
- PLT (P/T quartz gauge, fluid sampler, flowmeter)
- Tractor/coiled tubing driven modes

- **Wellbore stability**

Whenever stress concentration at well face exceeds rock mechanical strength it will develop either cavities filled with debris removed from the bulk rock, known as breakout or shear stress induced fractures. As a result, wellbore stability will be achieved provided mud pressure while drilling remains within the limits of a (mud) window higher and lower than the collapse and frac pressure respectively.

Mud window calculations exercised, assuming geomechanical properties close to the following figures (carbonate rocks, central Paris Basin, 1 500 mTVD):
- Compressive strength .... 25 MPa
- Internal friction angle .... 30°
- Mechanical cohesion factor 7
- Main vertical stress .... 32 MPa
- Main minimum horizontal stress .... 22 MPa
- Pore pressure .... 15 MPa

confirm that a [1.08-1.12] density range i.e. a ca (16-17) MPa pressure meet the foregoing stability criteria, for the targeted trajectories, a prognosis evidenced by the normalised Torque and Drag diagrammes shown in Figure 8.

- **Openhole drain erosion**

Fluid velocity within the 8"$^{1/2}$ diameter, drain assuming a 350 to 450 m^3/h rated well discharge (recharge), stands between 2.6 and 3.4 m/s i.e. a drain inlet velocity varying from 1 to 5 mm/s, depending on its active length and flow. The latter is unlikely to cause any wall damage given the precedent of two, existing doublets operated since thirty years at a max 300 m^3/h rate, over a 8.5 to 10 m effective reservoir thickness, without any evidence of sandface spalling whatsoever

- **More about Drag and Torque**

No acting force nor torque during tripping, rotation with /without weight, back reaming, single tension buckling with/without rotation would exceed tubulars' breakage thresholds, according to the torque and (drill string, annular) mud pressures applied to BHAs, illustrated in Figure 8 diagrammes. With respect to mud pressure, which integrates the (high) losses incurred in 5" drill pipes and, 9"$^{5/8}$x5" and 8"$^{1/2}$ annular spaces, it is worth to mention it remains within the limits stated in the wellbore stability section.

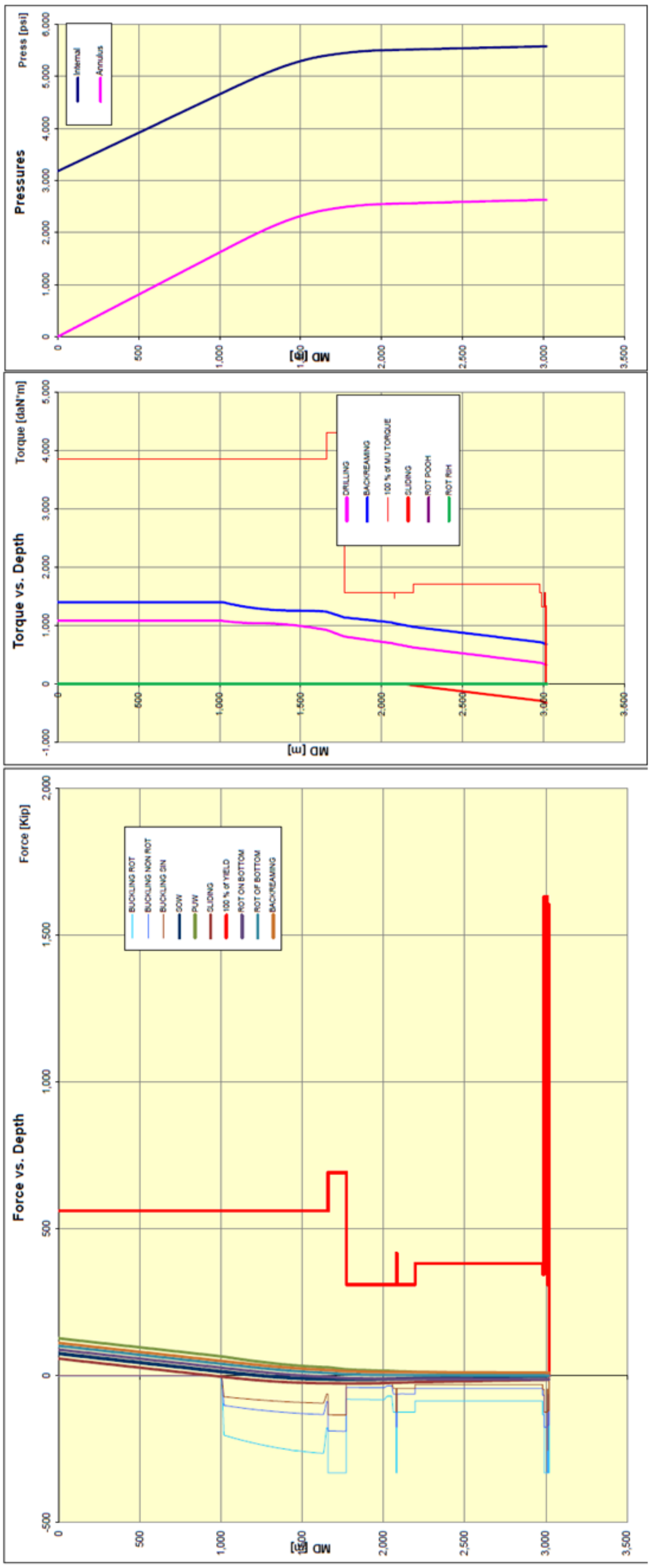


Figure 8: Drag and Torque. 14"$^{3/4}$ and 8"$^{1/2}$ subhorizontal drilling phases

- **Modelling strategy**

The multilayered reservoir structure sequenced in Figure 9 has been reduced to its, GOCAD (Paradigm, 2009) derived, three layered stacked, sandwich equivalent formalised by Antics and al (2005), in order to assess the hydrothermal impacts of the planned SHW doublet in terms of pressure and temperature patterns, interferences with neighbouring GDH systems (Figure 10) and production well cooling kinetics.

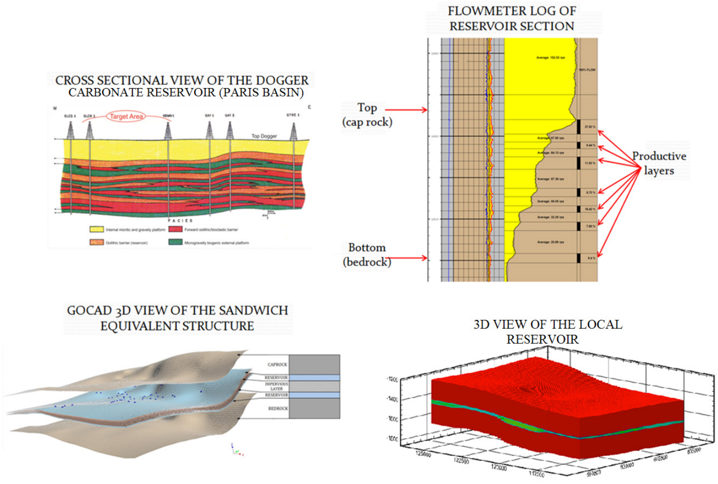


Figure 9: Multilayered reservoir assessment

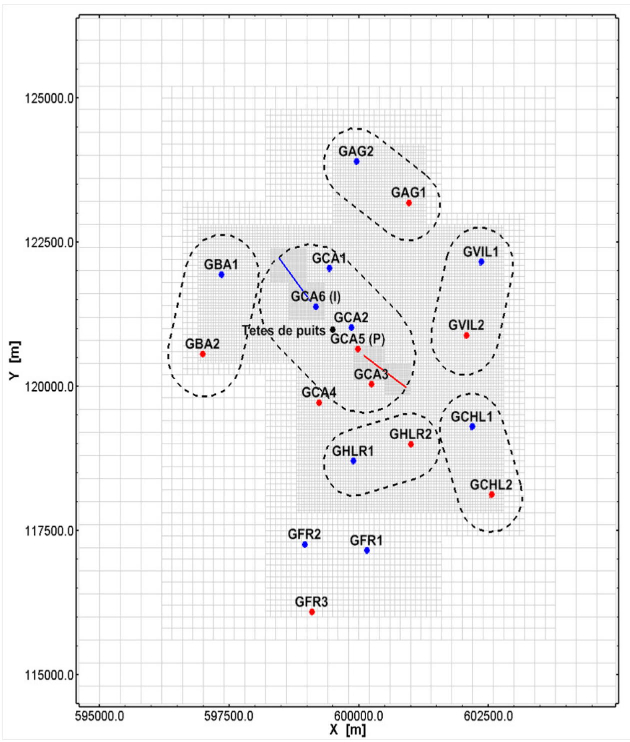
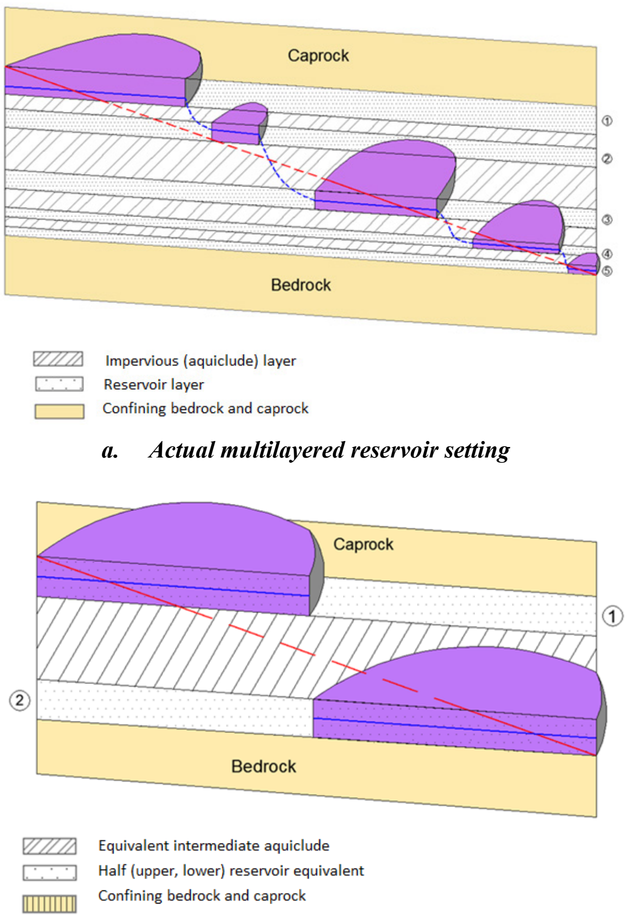


Figure 10: Simulated domain

Accordingly, the transfer from the actual multilayered reservoir setting to its sandwich equivalent, with regard to the prevailing pseudo steady state radial flow typology suggested by Hill et al (2008), is reflected in Figure 11. The heterogeneous sandwich simulation, applied over the domain depicted in Figure 10, leads to the thirty year predicted interfered pressure impacts, at maximum (450 m^3/h) SHW discharge, mapped in Figure 12, which prove minimum. Temperature cooling kinetics trended negligible (less than 0.2°C/30 yr depletion), therefore validating the concept at design stage.



a. Actual multilayered reservoir setting

b. Multilayered sandwich equivalence

Figure 11: Pseudo stationary radial flow typologies

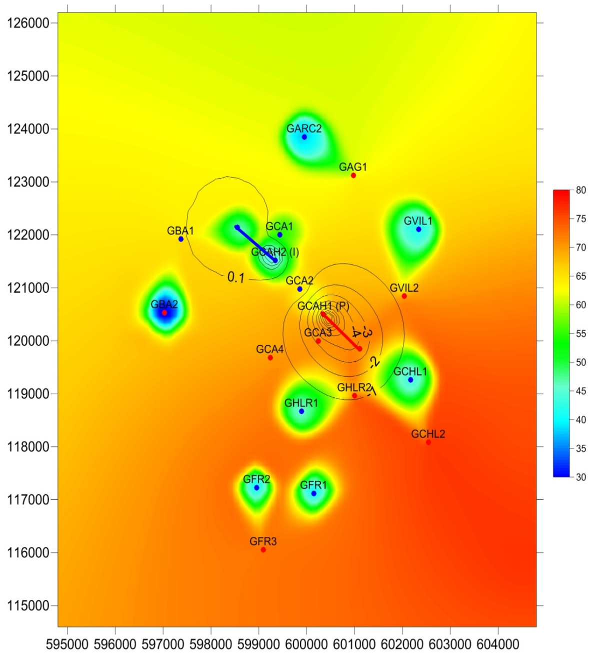


Figure 12: Simulated pressure interference impacts ($450\ m^3/h$ maximum production rate)

3. MULTIRADIAL WELL CONCEPT

Designed previously as a fall back option in case of a subhorizontal well failure, it may well be regarded as an architecture of its own, applicable to low permeability or radially heterogeneous reservoir settings. As a matter of fact the latter was mentioned by Lemesnager (2015) as an attempt by a major oil operator to select optimum, radially oriented, multilayered oil drainage pathways.

The concept, illustrated in Figure 13, addresses two candidate trajectories departing symmetrically from a conventional slant well design, (i) a twin legged, and (ii) a threefold star legged radial paths respectively, displayed in Figure 14 3D well profiles.

Reservoir simulation trials, based on a sandwich modelling strategy, were implemented to compare the performances of the five scenarios related to single (1) twin (2) and three (2) legged trajectories portrayed in Figure 15, operated in a high flowrate ($350\ m^3/h$) and low reservoir transmissivity (10 Dm) context.

Results of bottomhole pressure variations exclusively (i.e. regardless of skin pressure, well losses and radial discretisation truncated correction) proved rewarding, respective to the multi-legged, particularly the threefold, radial path architecture, in spite of the mutually interfering downhole impacts. On the other hand, cooling kinetics shaped satisfactory with a maximum 0.35° depletion after 30 years operation, noticed for scenario 4 (Figure 15).

Torque and drag calculations validated wellbore stability issues as one could have expected from the geomechanical modelling of the openhole SHW drain depicted in Figure 8.

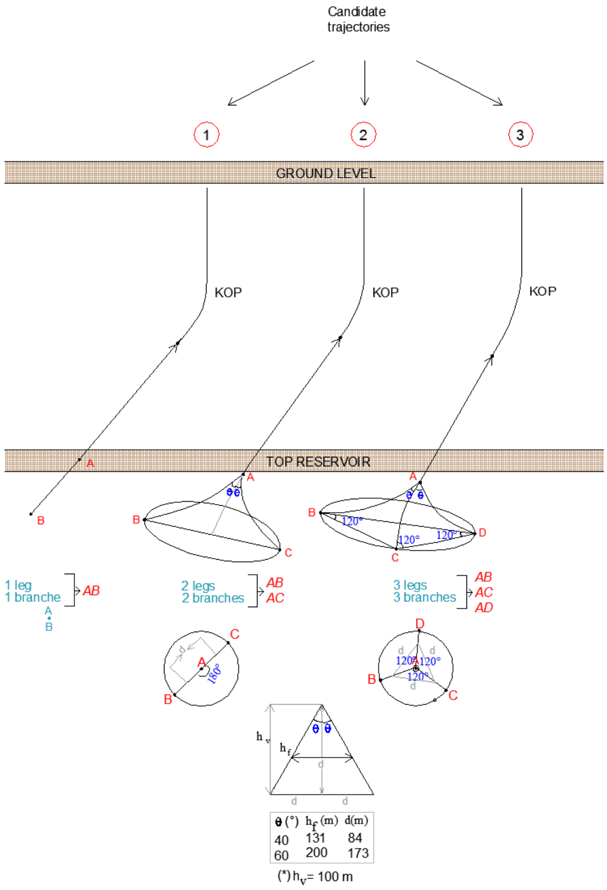
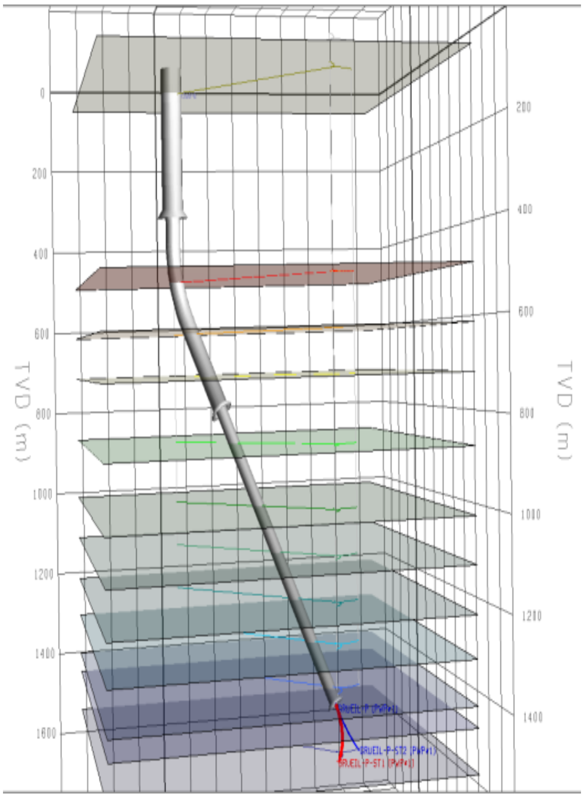
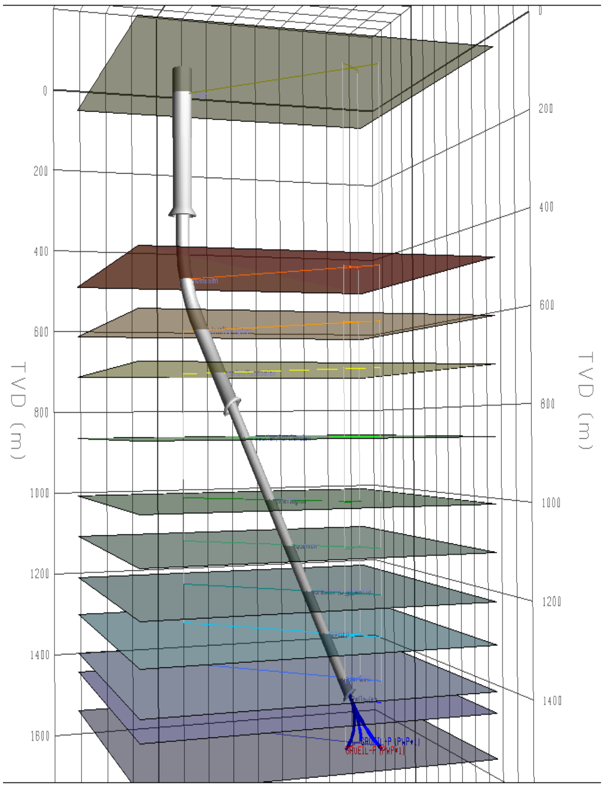


Figure 13: Multilateral radial well path trajectories



a. Twin legged



b. Three fold star legged

Figure 14: Symmetric multi-legged radial well paths. 3D production well profile

4. DISCUSSION

Design and implementation of the subhorizontal and multiradial well concepts arise three major areas of concern, trajectory build up/monitoring/steering, well completion and costs respectively.

- **Trajectory concerns**

The sharp attack angle (85 to 88°) may cause problems while placing the (10"$^{3/4}$) casing shoe, would reservoir depth not be precisely assessed, especially if its very upper part happens to prove productive. In such circumstances drilling of a sidewall pilot hole could be envisaged to secure both casing shoe cementing and reservoir entry. This option was deemed irrelevant owing to locally accurate lithostratigraphic well control (Figure 15) and the versatility of the RSS/LWD navigation system including continuous rotation (no sliding) and logging control, enhanced simultaneous steering correction attributes, as compared to conventional MWD/DD practice.

Design of an optimum multilayer intercepting trajectory may elsewhere prove a delicate exercise, as highlighted by Figure 15 correlations of locally monitored total pay/net pay thickness zones and, within the net pay zone, the discontinuities affecting the pervious layers sketched in Figure 9a, merely unpredictable beforehand. Hence, two strategies can be contemplated, either (i) a quasi straight line, inclined at ca 87.5°, assuming a 1 000 m long reach and given that most wells logged nearby exhibit a 50 m effective reservoir thickness (measured from formation top to last reservoir layer bottom), or (ii) a stepwise approach, illustrated in Figure 11a, which consists of following each tracked productive interval until the reach assigned (1 000 m/50 m) target.

The latter has been selected and will be applied unless otherwise dictated. Such indicators as penetration rate, cuttings examination, porosity (density, neutron) and multifrequency resistivity LWD real time information and lost circulation records should definitely help in assisting the dedicated geological and reservoir engineering team.

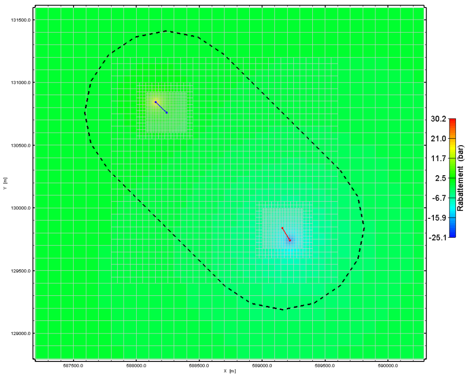
Note incidentally that the stepwise strategy should contribute to mitigating the paradox of the optimum multilateral drain configuration i.e. a thin reservoir, a wide effective radius, a low drain length, by combining thin interbedded layers, limited layer drained lengths and supposingly large effective drain radii.

- **Drain completion issues**

Initially, a perforated 7" perforated liner completion was foreseen. This choice largely influenced by drillers, known to love completions, was further deemed inadequate in consideration of a limited if not inexistent exploitation risk. Actually the Dogger, Mid Jurassic aged, reservoir is a consolidated carbonate rock alternating highly pervious oolithic limestones and compact interbedded, impervious limey strata, developed in a barrier/reef, hot sea, sedimentary environment. Several geothermal wells are exploited over 10 to 15 m thick, 40 to 50° slant openhole sections, at often high flow velocities, since 30 years or more, without any wall collapse nor spalling damage evidence. To our knowledge, local oil operators exploit via horizontal drains and multilaterals (up to 800 m reaches) exploit the Dogger hosted oil deposits in openhole. Ultimately, wellbore stability modelling validated the foregoing factual evidence.

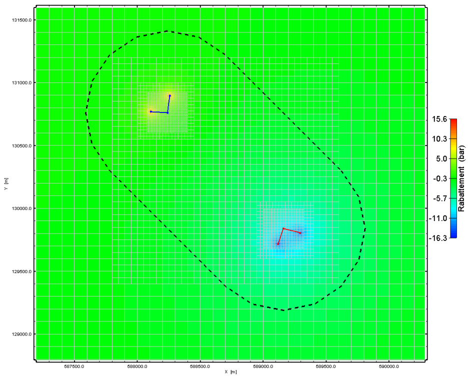
However, this openhole, no completion, option remains site specific. In most sedimentary reservoirs, in particular those addressing clastic dominated, continental detrital, fluvio-deltaic depositional environments as encountered in most European exploited and candidate plays, completions, preferably of the wire wrapped/gravel packed screen type stand as a prerequisite to feasible commercial exploitation. Here again a transfer from oil and gas multilateral completion technology is required.

SCENARIO 1



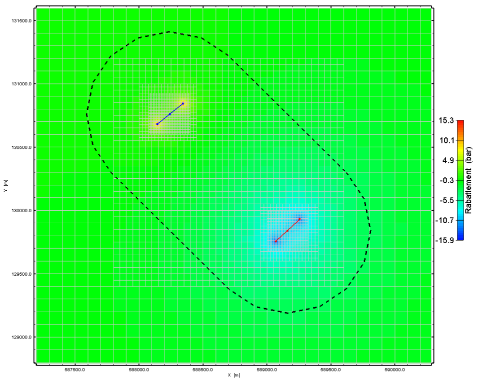
PRO	INJ
-24.8	+30.1

SCENARIO 2



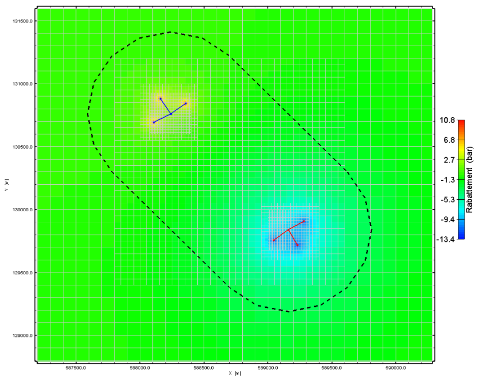
PRO		INJ	
-16.1	-16.1	+15.6	+15.6

SCENARIO 3



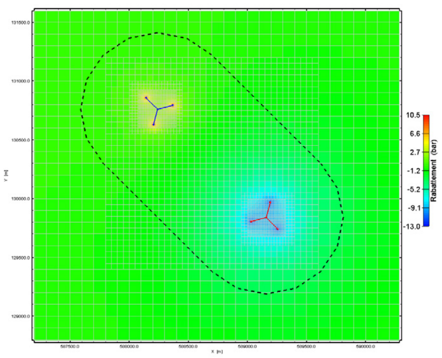
PRO		INJ	
-15.7	-15.7	+15.2	+15.2

SCENARIO 4



PRO			INJ		
-12.3	-13.25	-12.75	+10.45	+10.75	+10.45

SCENARIO 5



PRO			INJ		
-12.9	-12.75	-12.85	+10.45	+10.45	+10.45

Figure 15: Multiradial leg well architectures. Production and injection bottomhole pressure variations (barg) (10 Dm reservoir transmissivity; 350 m^3/hr nominal flowrate)

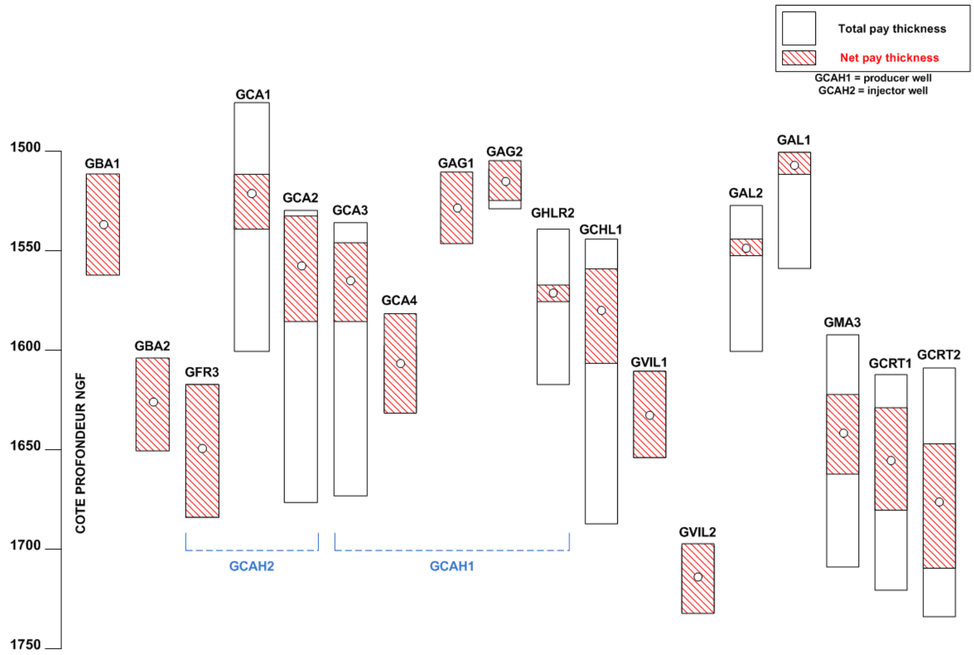


Figure 16: Correlation of reservoir producing layers. Paris South Suburban area

- **Economic viability**

Additional capital investment (CAPEX) costs incurred by the two investigated well architectures, compared to conventional slant hole doublet designs, amount to:

Subhorizontal doublet: 4 M€

Multiradial doublet

  twin legged: 1.15 M€

  tri legged:1.6 M€

These additional costs are compensated by savings on (i) mining infrastructures (one SHW doublet, rated 450 m^3/h, instead of two conventional designs, one multiradial doublet instead of one triplet), and (ii) yearly running (OPEX) costs achieved by increased revenues and lower pumping power expenditure.

5. CONCLUSIONS

The extended reach subhorizontal well concept, aimed at intersecting the entire productive sequence of a multilayered geothermal reservoir, has been reviewed and its benefits and risks *vis-à-vis* conventional slant well architectures assessed accordingly.

This innovative well design achieves substantial (up to three fold) gains in productivity along improved heat recovery and reservoir thermal longevity. Moreover, it makes it possible to reclame poor to very low permeability reservoir settings, which otherwise would remain unchallenged. Implementation of the concept requires modern and versatile directional drilling, technology, based on logging while drilling assisted rotary steerable navigation systems, securing well trajectory and borehole integrity.

The multiradial well design, initially conceived as a sidetracked fallback remedial to the subhorizontal well, stands as an intermediate architecture applicable to moderately transmissive (10 Dm) and tepid temperature environments requiring high flow ratings.

Actually, a combination of both schemes, leading to a multilateral subhorizontal well architecture could postulate to enhanced production from hot, thin layered, tight rock environments of the type encountered in deep seated Triassic formations in the Paris Basin.

Benefits expected from both concepts widely compensate incurred additional drilling/completion costs as exemplified by two typical case studies.

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