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Multilateral wells. A key architecture in maximising geothermal exposure and multilayered reservoir performance. A review of Paris Basin well design achievements.

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ABSTRACT

The two fold increase of heat production from deep seated geothermal resources anticipated within the next decade by the French energy decarbonising policy acted as a strong stimulus among concerned designers and operators, in particular those active in the Paris Basin Dogger (mid-Jurassic) carbonate reservoir, the Word largest geothermal district heating (GDH) system developed to date.

Summing up, the ambitioned goals would result here in doubling the existing GDH farming capacity (ca 1,500 GWh_{th} supplied to the Paris suburban heating market) via the completion of thirty (30) new doublets each rated 50 000 to 60 000 MWh_{th} yearly.

Such a challenging outcome required appropriate mining schemes based on well architecture taking advantage of the prevailing multilayered reservoir structure, a distinctive attribute of a number of sedimentary settings, in order to secure both thermal longevity along larger well to reservoir exposure. Another concern addressed the reclamations of moderately to poorly productive areas, which otherwise have remained unchallenged. Several innovative candidate designs, due to replace progressively the prevailing conventional well architectures candidates among which the so-called subhorizontal (SH) well concept first initiated in 2018 on the Cachan, moderately performant (15 dm transmissivity) site south of Paris, with a view to replace two, 33 years old doublets cumulating 350 m^3/h nominal production rating. The philosophy behind the concept aimed at intersecting via a step wise, *en echelon* type, trajectory, the layering sequence inferred from either from temperature/flowmetering (PLT) logs on offset wells or straight forwardly from direct drilling assessment. This first geothermal SH well achievement, awarded as a *world premiere* in geothermal engineering recorded a 450 m^3/h nominal rating and has been operating safely, over 4,5 years after completion of two 1 000 m long drains.

The concept, replicated in 2023 on a poorly productive (10 dm transmissivity) site achieved similar performances, benefitting from a modified Ecoscope/Periscope HD™ (Schlumberger, SLB) geosteered assembly, elsewhere confirming the early pilot hole design strategy as non essential.
The multiradial (MR) well concept came second. Initially conceived as a substitute, in case of a failure, to the former SH design, its advantage lies in its limited space occupation. Its efficiency however requires a three legged 75 to 80° inclined reservoir configuration and 80 to 85° top reservoir landing angle in order to avoid excess sharp angle steering and (upwards/downwards) trajectory reversals likely to generate, either or both, navigation difficulties and/or interlayer pressure interferences and subsequent production losses.

The concept implemented in 2021 in a low permeability frontier sector South West of Paris, is operating since 2022 in spite of design and operating features deemed non fully orthodox by the authors.

Ultimately the multilateral well architecture extensively applied and documented by the Oil and Gas industry is raising increasing interest among geothermal engineers and operators, given its structural advantages among pilot hole prerequisite added to the flexibility in managing a number of laterally and multilayer distributed drains play a dominant role. On the well services side the availability of easier if not cheaper access to such facilities as drain re-entry/locator, intelligent coiled tubing units and high (up to 80°) angle tool conveyance centralisers is regarded as the most efficient response to well design architectures in stratified media.

Typical programmes and workflows along architecture modelling are documented and the figures of merits of the three candidate, SH, MR and ML, well designs addressed. Technological and economic issues are also discussed.

1. INTRODUCTION

Economy decarbonization and 2050 carbon neutrality scheduled in the French so called Economy Transition policy has targeted a 40% reduction in green house gas (GHG) emissions by year 2030 of which 38% address heat consumption proper. Within the renewable energy spectrum geothermal heat often stands as an important contributor, witnessed by the development of the Paris Basin geothermal district heating (GDH) system mapped in Figure 1. Here a deep seated dependable resource of regional extent, a hot saline brine hosted at 1 600 to 2 000 m depth in the Dogger (Mid Jurassic) carbonate platform, heats since the late 1970s, early 1980s up to 1,5 million Paris suburban inhabitants, representing a 1 500 GWh_{th} annual supply via fifty (50) well doublets/triplet mining schemes and grids. The previously mentioned goals ambitioned by the French authorities clearly means that the existing capacities will need to be doubled, rising the heat load to ca 3 000 GWh_{th}/yr, by implementing thirty (30) new doublets, each rated 50 000 MWh_{th}/yr, indeed a challenge, given space limitations, environmental/safety regulations and resource/reservoir properties inherent to densely populated urbanized areas and mining uncertainties.

In order to meet such challenges a growing demand raised among geothermal operators towards innovative well architectures addressing complex, tectonised and multilayered reservoir settings and thermochemically sensitive fluid environments capable of sustaining high productive capacities and prolonged thermal longevities.

More specifically the multiwell (doublet, triplet, quadruplet, five spot) heat extraction scheme faces three major, occasionally critical, concerns (i) the replacement of aging, eventually damaged, well infrastructures and productive/injective performance, (ii) well location densities approaching in several locations overcrowding (Figure 1 and Figure 2), a source of potential mining disputes, limiting well replacement opportunities and clouding future development issues, as a consequence of space restrictions and thermal breakthrough/reservoir cooling shortcomings and, last but not least, (iii) heat reclamation from moderately to poorly productive areas remaining unchallenged, as a result of the "best part of the cake" casual mining practice, unless appropriate, field proofed, innovative well architectures be made available.

Prior to this recent interest from concerned parties, long committed to technological conservatism, several milestones worth to mention may be found (i) in Bruel (2008) who suggested horizontal well trajectories as an alternative to conventional directional drilling practices in the Paris Basin, assuming a single layer geothermal reservoir, and (ii) in Frieg (2014) reporting the completion at Schlattingen (Switzerland) of a horizontal drain sidetracked from a geothermal well as a remedial, not known beforehand, to the former vertical trajectory which proved almost dry. Of interest to the progress and maturation of the subhorizontal well (SHW) concept was the integration to the drilling of the deep karstified Molasse Basin of Southern Bavaria, of modern technological ingredients, namely derisking 3D seismics, along RSS (Rotary Steering System), LWD (Logging While Drilling) geosteering assisted bottomhole assemblies (BHAs) securing drilling success ratios reported by Mirjolet (2014), which stand nowadays as a standards in tackling such "risky" targets (Schubert, 2015) and (Ungemach et al, 2018).

The present paper will focus on the lessons learned from the innovative drilling projects achieved since year 2018 which addressed two SHW (2018, 2023) and one Multiradial (MRW) architectures and on the benefits expected from the comissioned multilateral well (MLW) concept, presently in the advanced design stage, due to be completed on a low permeability reservoir location by late 2024.

Figures of merit of the three candidate well architectures, sketched in Figure 3, will be discussed, along their cost and environmental implications, *in fine*.

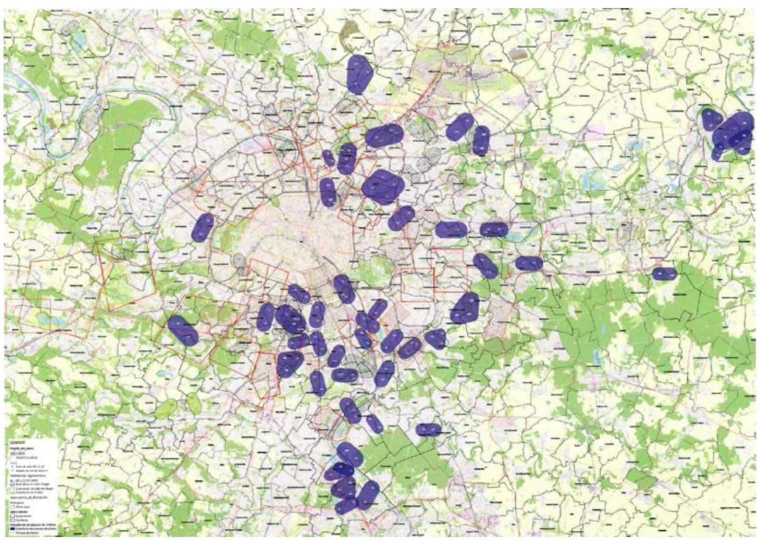


Figure 1: Locations of Paris Basin operating geothermal district heating grids

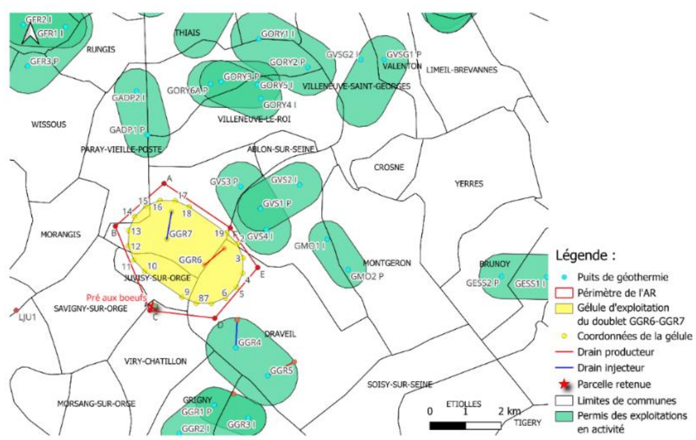
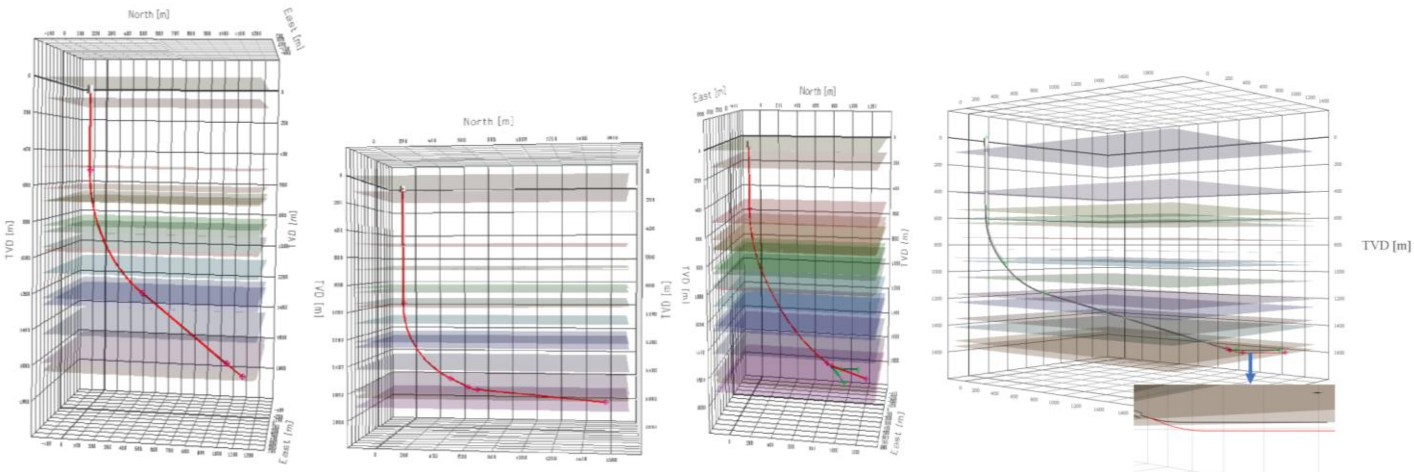


Figure 2: Location of a low permeability zone eligible to a SH doublet



a) Conventional deviated b) Subhorizontal drain c) Multiradial architecture d) Multi (planer dual) lateral well

Figure 3: 3D views of conventional and innovative well architectures

2. ACHIEVEMENTS

2.1 Subhorizontal well (SHW) concept. Site 1 (Cachan)

It was first implemented on the Cachan site, south of Paris, operated since the mid 1980s, via two doublets cumulating a 350 m^3/h nominal rating located in a moderately productive (15 dm transmissivity) densely populated area, surrounded by six nearby operating doublets, the projected SHW aiming at single doublet production targeted at 400/450 m^3/h nominal production.

2.1.1 Well architecture

The philosophy behind the concept aimed at taking advantage of the multilayered reservoir structure, via a stepwise, en *echelon* type, well trajectory intersecting either the whole or a part of the layering sequence according to the well paths illustrated in Figure 4 and well profile and trajectories compromise between a single horizontal drain and multilateral well profiles and would structurally enable to recover significantly higher input flow amounts compared to as standard deviated well design.

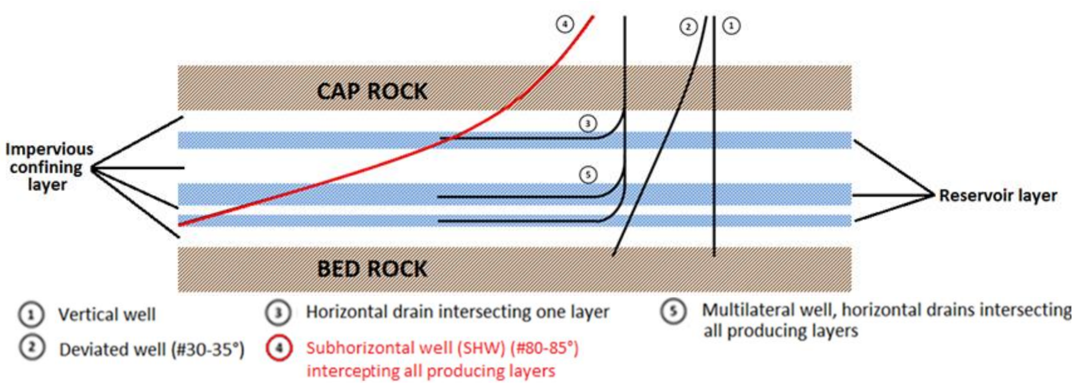
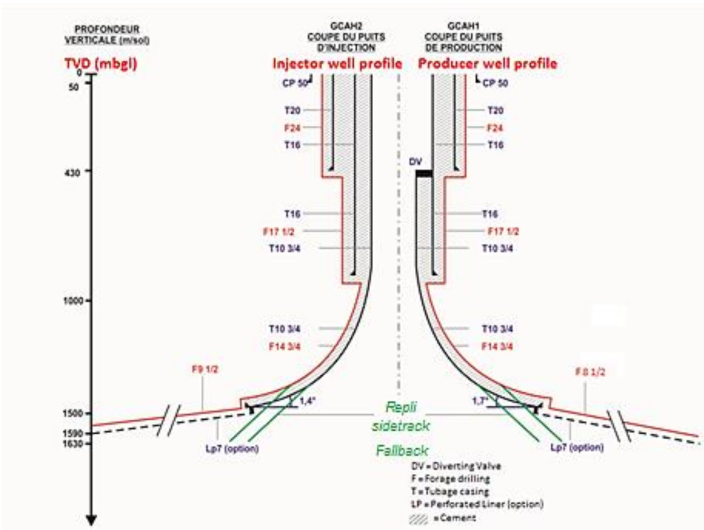


Figure 4: Subhorizontal well concept

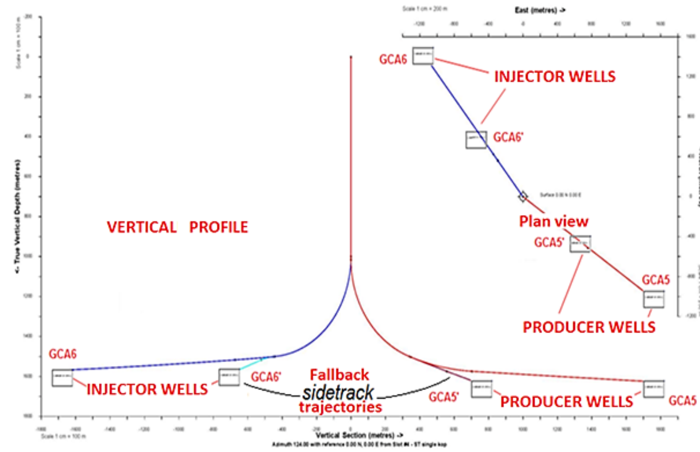
Both well profiles and trajectories, quasi identical in design, include(Figure 5) a dual drilled (18"$^{1/2}$)/cased (16") vertical section followed by a deviated section initiated by a 14"$^{3/4}$ in arc path, further 10"$^{3/4}$ cased, achieved via a standard MWD (Measurement While Drilling) x PDM (Positive Displacement Motor) assembly and finalised by a ca, 1 000 m long, 8"$^{1/2}$ subhorizontal drain drilled under a LWD (Logging While Drilling) – MWD – RSS (Rotary Steerable System) – BHA (Bottomhole Assembly) string.

SH drains were not completed and left as openhole owing to the consolidated structure of the carbonate rock mass.

Should the SHW completion have failed, provision has been made to switch, after abandoning the unsuccessful drain, to the multiradial well (MHW) design developed in §2.2.



a) *Well architectures*



b) *Well trajectories*

Figure 5: Subhorizontal well architectures and trajectories

2.1.2 Geosteering strategy

The geosteering workflow driving mechanism, while drilling the SH drains, consists of matching the productive (net pay) sequence thanks to relevant porosity indicators interacting with the navigation process, which are sourced by LWD drilling parameters (rate of penetration, ROP, torque…), offset wells and real time (0.5 hour delayed respective to bit progress) geochemical (XRF and XRD) ratios.

It involves a two stage process shown in Figure 6, summarised here after (Ungemach et al, 2018; Di Tommaso et al, 2018 ; Ungemach et al, 2019).

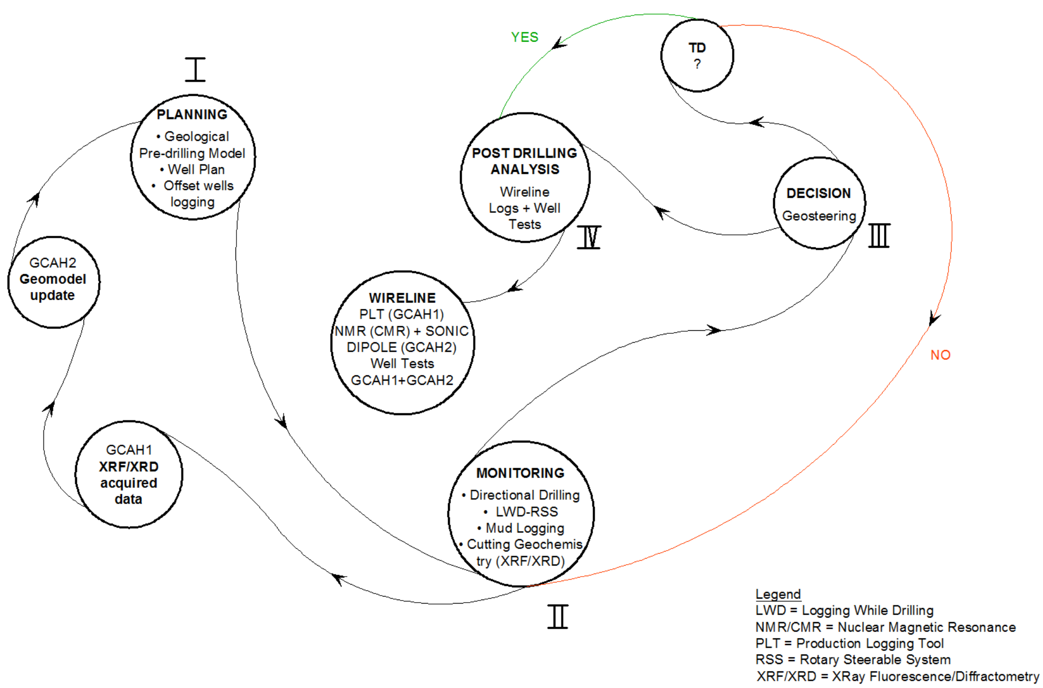


Figure 6: Geosteering workflow

- ***While drilling***

  - Integrated, real time, geosteering data acquisition;
  - Directional drilling: monitor and control RSS downhole tool performance;
  - LWD tool string: Gamma Ray, Neutron porosity, multi frequency resistivity, (imaged) azimuthal density;
  - XRD, XRF: XRay Difractometry and Fluorescence for mineralogic and elemental analysis;
  - Mud logging: cutting petrography.

- ***Post drilling analysis***

  - Integration of wireline: Nuclear Magnetic Resonance (CMR tool) and Dipole Sonic (DSI tool) for matching drain productive segments;
  - Production Logging Tool (PLT) and micro-spinner flowmeter providing flow and temperature profiles along the entire openhole (OH) drain.

The first drilled well, GCAH1, enabled, after due log (G Ray, Neutron, Density) squaring selected on the referenced offset well, to track the producing layers over the whole pay zone and identify accordingly the productive reservoir sequence.

The XRD/XRF geochemical monitoring results and expectations are commented with respect to (i) the candidate alkaline (Sr, Na, Mg) and mineral (Mn, Fe, Zn) proxies as porosity and diagenetic markers respectively, and (ii) metal oxide marine littoral (carbonate barrier) lithofacies indicators according to Brand and Veizer (1980).

The data set and experience gained on well GCAH1 were integrated into the geosteering of (injector) well GCAH2, which addressed a more complex reservoir and structural setting, characterised by a poorly porous/pervious reservoir and, fast varying, up dipping trends.

The complexity of the RSS navigation process is imaged in Figure 7 which evidences the many corrections implied in securing the trajectory within the two thin (metric size) bedded porous intervals. Actually, managing 1 to 50 varying dips impacting drain effective length and reconciling tracking of thin (1 m) high porosity layers with target matching delays induced by high bit to RSS recording distance (ca 20 m) did indeed represent a tedious exercise.

2.1.3 Formation evaluation

Assessment of reservoir and well performance was carried out via (i) wireline (openhole, PLT) logging, (ii) well testing, (iii) heat and mass transfer modelling, and (iv) geochemical monitoring.

- ***Wireline Logging***

The ambitioned exhaustive wireline logging programme initially contemplated could not be wholly fulfilled owing to tractor drive limitations.

However, respective to porosity, density and lithology, logging while drilling (LWD) supplied useful clues while geosteering drain trajectories, particularly on well GCAH2 characterised by a thin, metric size, (up) dip varying, bed structure, exemplified in Figure 7**.**

On well GCAH1, the successful PLT spinner flowmeter (Figure 8) (provided unvaluable information as to flow and dynamic temperature profiles along the entire drain path. This key information enabled to assign a (flow weighted averaged) formation temperature and calibrate a wellbore heat transfer model in order to match monitored wellhead temperatures and derive accordingly a well discharge vs surface temperature function, indeed a critical issue in forecasting future doublet heat delivery, an aspect discussed later in the modelling section.

Identification of drain productive segments is imaged in the (GCAH2) composite log displayed in Figure 9.

On the other hand, the application of nuclear magnetic resonance (NMR/CMR) and dipole sonic logs proved rewarding and of great significance in correlating permeabilities to porosities and *vice versa*, along with assessing thin bed porosity layering and lateral extents from P and S wave sources, an exercise requiring advanced acoustic processing (Cavalieri and Wielmaker, 2018).

Incidentally given the significant input of the foregoing, combined NMR/CMR, dipole sonic and density wireline logs are becoming a standard in assessing well/reservoir performance, geomechanical properties and related wellbore stability issues.

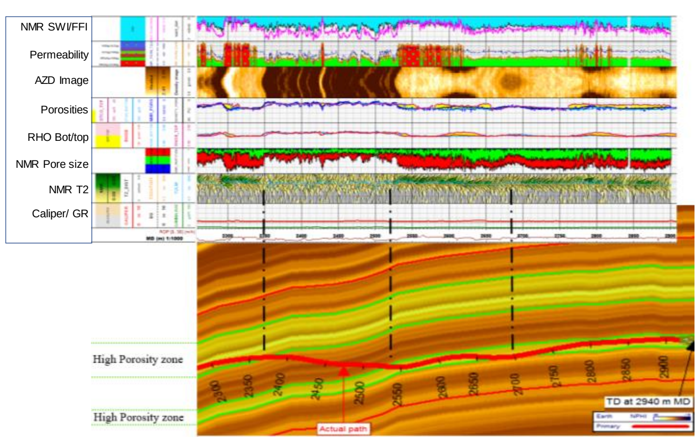


Figure 7: Composite permeability, porosity, density log imaging of a subhorizontal drain (well GACH2) (Source: Cavalleri and Wielemaker, 2018)

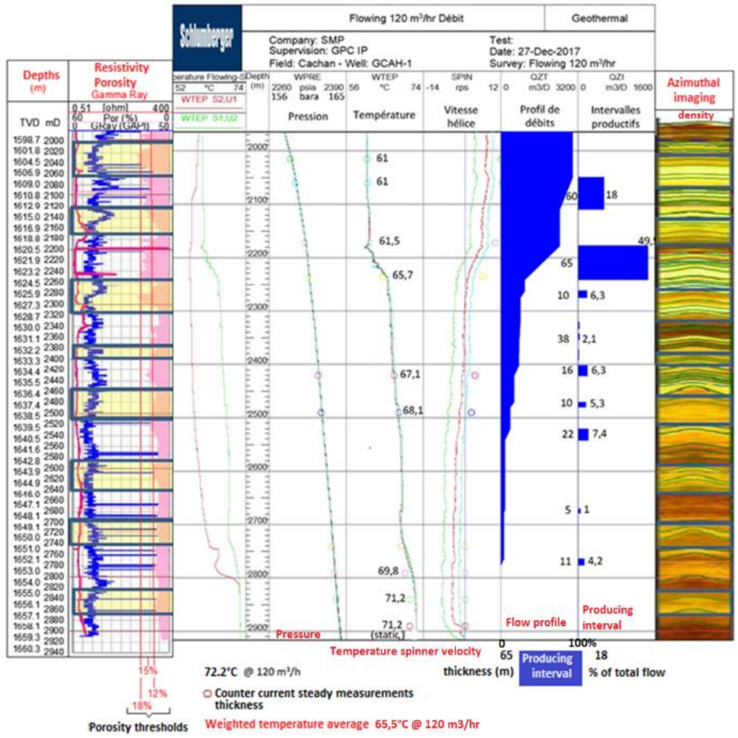


Figure 8: Subhorizontal well GCAH1. PLT logging output

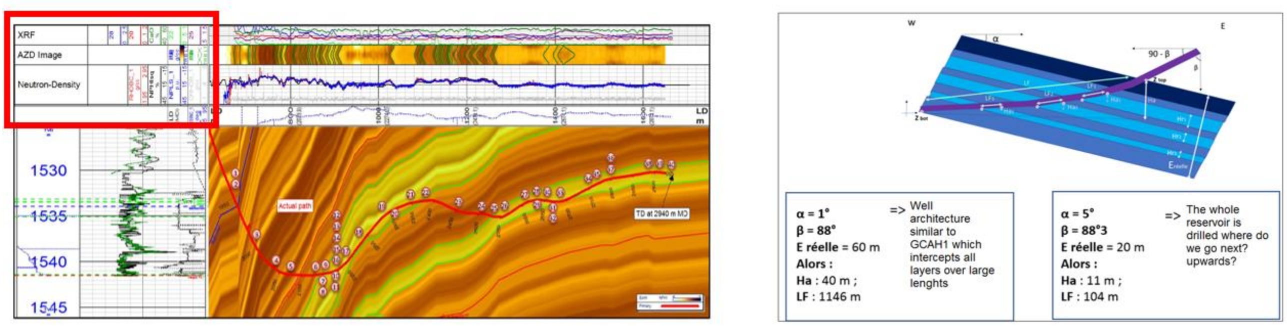


Figure 9: Subhorizontal well GCAH2. Geosteering trajectory corrections

- ***Well Testing***

It should be readily pointed out that in no way were transient well test analysis and interpretation an easy exercise as a consequence of a local reservoir environment characterised by (i) a stratified structure intercepted by a subhorizontal, occasionally tortuous, drain trajectory, (ii) a non homogeneous flow distribution along the drain, (iii) interlayer crossflow, dramatically amplified by weak (self-flowing) production capacities as a result of limited waste fluid disposal facilities, and (iv) pressure, and temperature interferences induced by neighbouring GDH doublets, operating in winter season at maximum flow ratings.

The foregoing obviously strongly impacted and complicated test operation and interpretation, the latter strongly inspired by horizontal transient well test analysis (Lee et al, 1982).

Tests were carried out after due, coiled tubing operated, acid stimulation over the, log selected, productive drain segments, whose benefits on productivity indices (PIs) stand as follows.

WELL	GCAH1	GCAH2
Pre acidising	25 (*)	21
Post acidising	41.5	38

(*) *assumed from prematurely stopped discharge*

The geometry of an idealised, laterally and vertically bound, horizontal drain and related transient flow regimes are illustrated in Figure 10 (idealised, time dependent, pressure and pressure derivative patterns), which identifies five distinctive flow regimes and their signatures on the pressure and pressure derivative plots, from early to late times, (i) wellbore storage, (ii) early radial, (iii) early linear, (iv) pseudo-radial, and (v) late linear.

However and whatever the local testing constraints, Figure 10 shows, on the pressure derivative related to production well GCAH1, a good match with the early radial and pseudo-radial drainage modes (zero slope plateau) enabling the application of conventional interpretation methods by the semi-log MDH (Miller-Dyes-Hutchinson - semi-log plot) and Horner (semi-log) plots, which clearly exhibit straight line segments in their terminal (late recovery time) sections. Transmissivities were derived accordingly, leading to a Horner value close to 30 Dm. An indirect shortcut was adopted to derive the well delivery curve, an equivalent transmissivity integrating the true calculated transmissivity (# 30 Dm) and the skin factor, the latter calculated by matching computed to measured pressures, resulting in a skin factor S = -3.5.

An alternative method was later investigated by calculating the drain productivity index PI, following the method suggested by Economides et al (1996), which addresses a horizontal drain equidistant from reservoir boundaries, an approach which leads to a PI=39m^3/h/bar, a figure which stands close to the measured value.

On well GCAH2, injection testing could be performed, contrary to well GCAH1 production tests, at higher sustained flow ratings, thanks to the availability of two on site injection well pumping facilities, diverted for the purpose to the newly completed well GCAH2 enjoying therefore a 350 m^3/h rated capacity (extendable to 450 m^3/h).

Summing up, well transmissivities, skin factors and productivity/injectivity indices shape as follows.

WELL	TRANSMISSIVITY (dm)	SKIN FACTOR	PI, II (m^3/h/bar)
GCAH1	28	-3.5	PI=41.5
GCAH2	30	-4.5	II=28

Two (GCAH1) and threefold (GCAH2) gains achieved on well transmissivities (and productivity/injectivity indices likewise) measured on existing wells clearly validate the SHW concept respective to conventional well architecture issues.

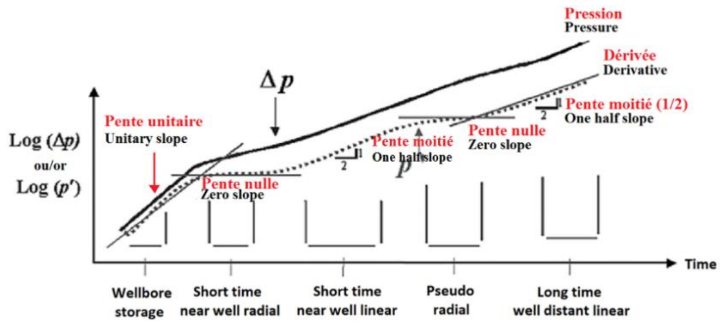


Figure a: (Sub)horizontal drain (idealised) flow regime identification (after Lee et al, 1982)

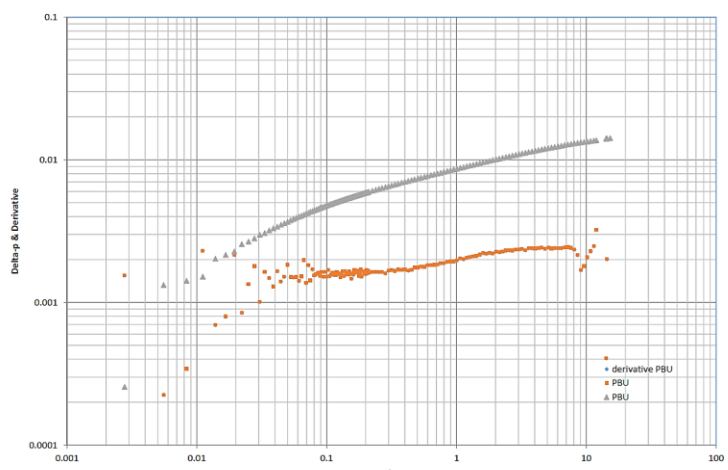


Figure b: Well GCAH1. Self flowing production test. Build up pressure and derivative log-log plots

Figure 10: Production testing pressure transients. Theory vs practice

- ***Modelling***

Three modelling issues were addressed (i) well test modelling, (ii) wellbore heat transfer modelling, and (iii) reservoir simulation of present status and future predicted pressure and temperature patterns respectively.

A satisfactory fit was achieved in reproducing the recorded bottomhole pressures in response to a busy local (Cachan and neighbouring GDH doublets) production/injection history, adding to a varying GCAH1/GCAH2 production testing schedule proper. Hence, the simulation exercise, based on TOUGH2 (Pruess et al, 1999), m-View interfaced, heat and mass transfer software, and on the multilayered sandwich equivalent reservoir structure (Antics et al,2005, Ungemach et al, 2011) illustrated in Figure 11, validated the, test issued, input reservoir hydrodynamic parameters.

Furthermore, an inhouse wellbore heat transfer model was able to match the monitored wellhead temperatures from the, PLT derived, bottomhole temperature (BHT) and therefore anticipate their evolution as a function of BHTs and production ratings.

Based on the foregoing, predictive reservoir simulation runs could (i) infer the pressure interferences induced by the future GCAH1/GCAH2 SHW doublet operating at maximum flowrate on the neighbouring GDH systems, and (ii) forecast reservoir cooling and pressure depletion/rising trends, both exercises, mapped in Figure 12, exhibiting minimum impacts, therefore justifying the future, boosted, exploitation schedule.

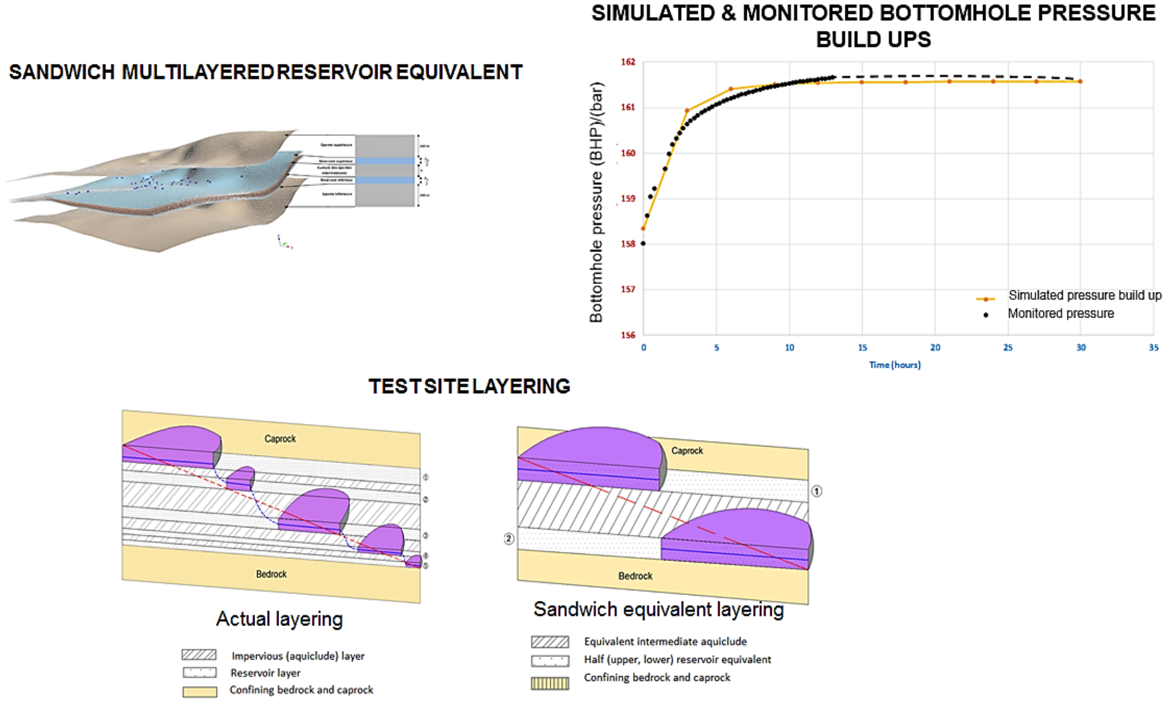


Figure 11: Subhorizontal drain modelling. *Sandwich* flow model (pseudo radial stationary, regime)

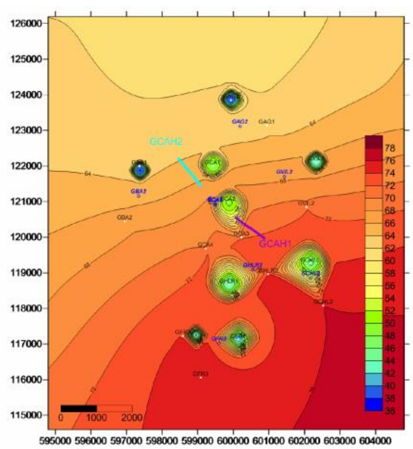


Figure 12.a: Cold bubble and pressure depletion map

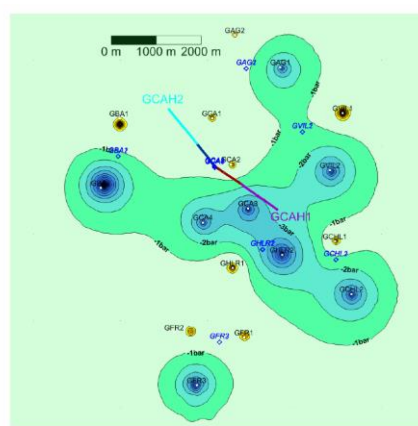


Figure 12.b: Maximum winter pressure drawdowns

Figure 12: Simulated pressure and temperature patterns (year 2048)

2.2. Subhorizontal well (SHW) concept. Site 2 (Grigny)

Major drilling features recorded on both Cachan (site 1) and Grigny (site 2) wells, trajectories are sketched in Figure 13, stand as follows.

Local reservoir performance:	Site 1	Site 2
Drain characteristics • **Transmissivities (D m)** • **landing angle (°)** • **length (m)** • **diameter (")** • **number of exploited levels**	15-20 ≥ 85 1010m (GCAH1)/ 1030(GCAH2) 8"1/2 2	6-15 800 (GGR5)/630 (GGR4) 9"1/2 2
Pilot hole	None	One
Drain drilling	RSS	RSS
Geosteering criterion	Azimuthal density	Resistivity x Azimuthal density
PLT	1 (GCAH1)	2 (GGR4, GGR5)
Target flowrating (m^3/h)	450	400

Salient differences, which are worth mentioning address (i) the absence of any pilot hole whatsoever on the Cachan site and the second Grigny well, (ii) the geosteering criteria and tooling, and (iii) *last but not least*, on the contrasted top reservoir landing angles, calling for the following comments.

The pilot hole, which aims at delivering a flow profile of the entire pay zone (in our case the Bathonien multilayered sequence), shapes as a mandatory prerequisite, while selecting the drain entry layer and predicting its optimum trajectory according to layer performance inferred from PLT flowmeter, especially in areas lacking nearby offset holes. Nevertheless, its impact ought to be mitigated as a consequence of mostly discontinuous horizontal and lateral layering sequences, a distinctive attribute of the Bathonian reservoir structure, which has been evidenced on the GGR5 drain, whose geosteered trajectory parameters are imaged in Figure 14.

The geosteering process has been proved thanks to the Periscope HD navigation logging tool based on the azimuthal resistivity acquisition which via an inversion algorithm enables to qualify the reservoir and its inhibition fluid impact through its (resistivity inversed) conductivity. Its capacity to guide the trajectory at the centre of a 4 mTVD thick layer via a 2 m apart vision makes its a reliable tool in anticipating proactively the progress of the trajectory ahead from the bit. Note that resistivity measurements are complemented by density and neutron porosities measured by the Ecoscope behind of the Periscope. Tool positioning in the centre of the identified productive layer can be significantly optimised via an upgraded inversion process handled by the Periscope Edge navigator whose simulated trajectory is imaged in Figure 14 and in the whole 3D view of the GGR4 x GGR5 SH doublet depicted in Figure 15.

Most important is the inclination of the trajectory at target reservoir inflow (here the top of the Bathonian mid-Jurassic formation), which is a matter of debate among geothermal operators and engineers focusing on the (wrong, in our opinion) 80/85 against 60/65 landing angle dilemma, arguing on whether or not excessive inclinations would condemn the use of wireline casing inspection, top reservoir located pressure/temperature monitoring while testing logging tools or/and the RIH/ROH of downhole resident chemical inhibition lines. High angles favour safe BHA landing and easy, low DLS, progress while drilling the SH drain. Instead low angles generate sharp increases and up to 8-10 DLS figures prior to initiating the (close to 90°) target SH trajectory, likely to increase costs and BHA integrity risks if not missing the projected layer entry. The argument against wireline logging and bottomhole line operation and costly substitution of tractor tool conveying does not stand neither since modern centralising outfits allow to operate sensitive acoustic logging tools and downhole control and inhibition lines at 80° slant trajectories (Adam Donald et al, 2020).

Summing up, lessons learned lead to the following recommendations (i) the pilot hole is not mandatory, (ii) BHA landing angles should remain close to 80-85°, and (iii) the last cased hole ($10"^{3/4}$ diameter) phase be drilled via a RSS equipped BHA.

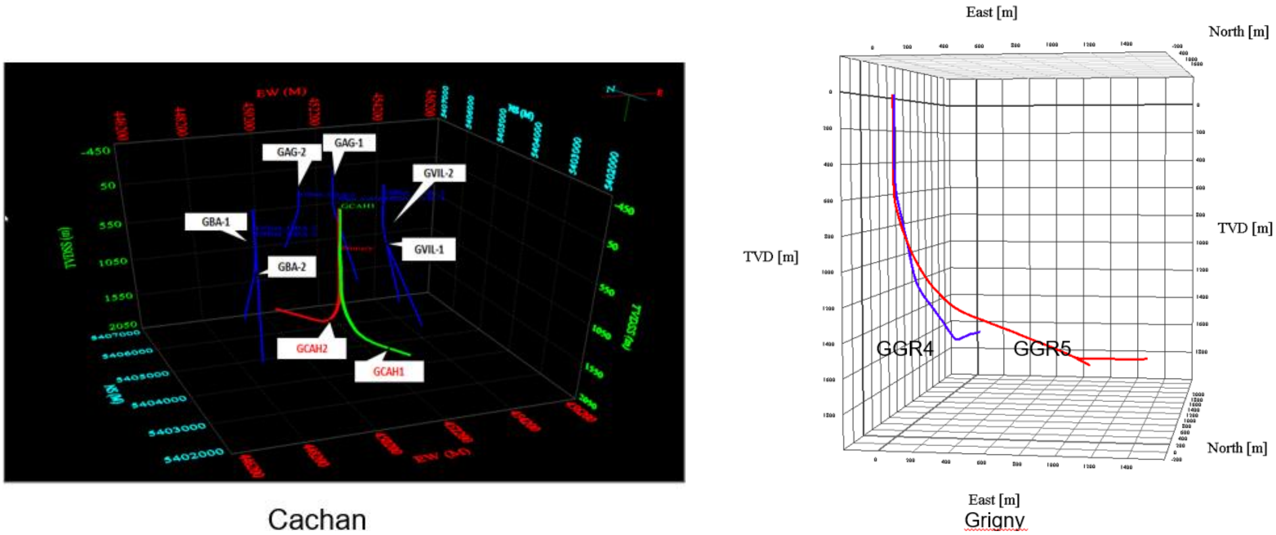


Figure 13: Cachan and Grigny sites. Compared SH well trajectories

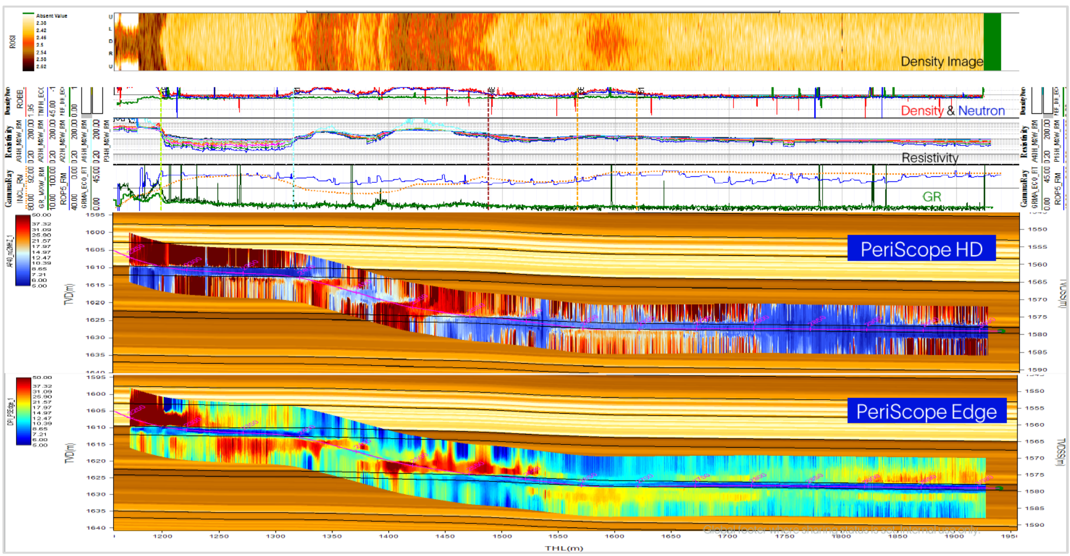


Figure 14: Grigny site. SH well GGR5. Twin layered Periscope geosteered imaging

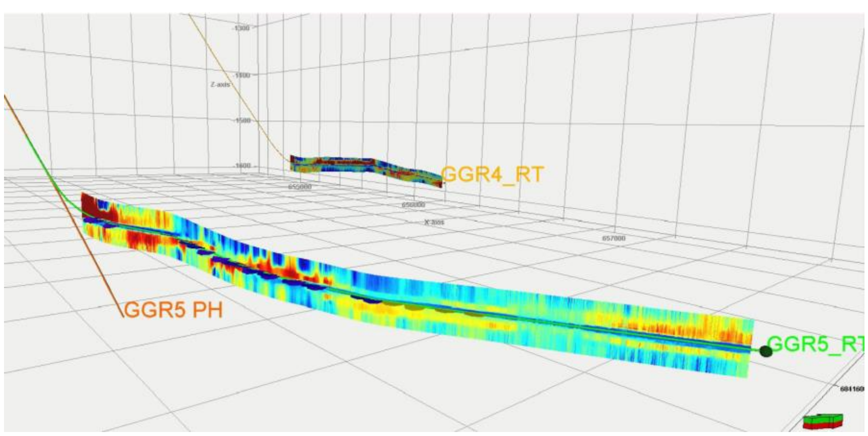


Figure 15: Grigny site SH doublet periscope geosteered trajectories (Source: SLB and GPC IP, 2023)

2.3. Multiradial well architecture

Initially designed as a fall back, sidetracked, substitute to a subhorizontal well failure (Ungemach et al, 2016 and 2018) it was further developed as a candidate architecture in areas where space restrictions would constrain the implementation of extended reach (sub)horizontal drains. As a result it should be regarded, in the well architecture typology, as the multilateral equivalent of (sub)horizontal wells. Actually both subhorizontal and multilateral drains may coexist in a single well scheme as exemplified in section §2.3.

The design, here after described, addresses multilayered reservoirs where the dominant productive interval(s) stand(s) in the upper part of the structure, which implies a sharp landing angle into the target objective in order to maximize well exposure and productive performance.

Hence the reservoir approach has been sequenced as follows:

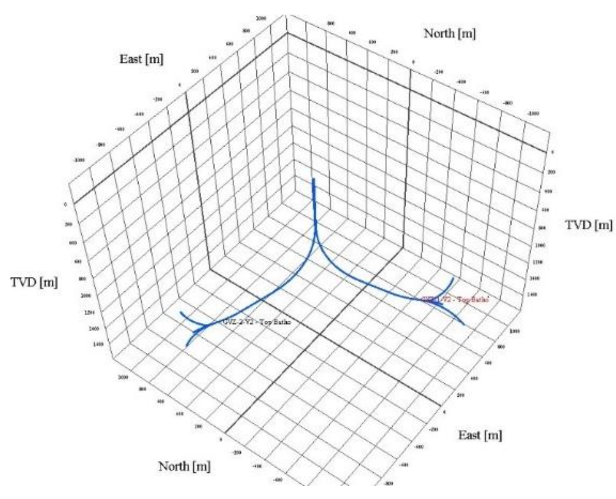
- (i) drilling of a 45° inclined pilot hole aimed at assessing the local reservoir layering and performance, eventually complemented by a VSP survey and related reprocessing of seismic lines and facies,
- (ii) design accordingly radial drain profiles, moving from two to three legs in the present application,
- (iii) optimise drainage volumes respective to drain lengths and inclinations,
- (iv) increase slant angle, up to 80°, to achieve maximum drain spacings therefore minimizing inter-drain pressure interferences, as evidenced in Figure 16.

Benefits expected from the multiradial well concept have been investigated on a case study addressing a poorly productive carbonate reservoir environment by geothermal district heating (GDH) standards (Geofluid, 2019). Here, GDH objectives require a maximum 400 m^3/h discharge rate whereas from several, reliably documented, offset wells and seismic processing, transmissivity would stand close to 10 Darcy meters (Dm), net (layer cumulated) and gross reservoir thicknesses to 10.5 and 49 m respectively (N/G # 0.2).

Prior to drilling, direct assessments reservoir simulation runs, based on the well trajectories depicted in Figure 16 and on the previously mentioned *sandwich* equivalent multilayered structure, proved the validity of the concept displayed in the attached records (compared performances of selected well architectures), Figure 17 (conventional vs multiradial well delivery curves) and imaged in Figure 18 bottomhole induced temperature and Figure 19 pressure changes.

The foregoing suggest the following comments: (i) the initially contemplated 70° slant angle option was no longer considered since, owing to the local reservoir layering, it did not provide any significant pressure drawdown improvement respective to the conventional single legged architecture (Figure 16), a conclusion which emphasises the input of the pilot hole strategy (whenever required), (ii) the 80° inclined three legged radial well design achieves a 45° single legged architecture for the 400 m^3/h targeted production, and (iii) Figure 18 and Figure 19 clearly illustrate the wider well exposures and related energy savings and thermal longevity to be credited to the recommended, tri-radial/80°, scheme (EGEC, 2021).

An alternative scheme has been implemented according to the design and completion illustrated in Figure 20. Here the trajectories land at top reservoir at a 60 to 62° thus requiring within the reservoir to rise the drain inclination up to 90° leading to DLS (dog leg severity) values of 7, requiring a sharp angle BHA enabling to intercept downwards the entire reservoir section before inverting the trajectory upwards, the so called crow feet path, a curiosity likely to generate occasionally severe interleg pressure interferences at exploitation stage. The operator claims a fairly successful 320 m^3/h new doublet nominal rating, chiefly due to a massive acid stimulation operated globally and not selectively leg wise.



Three legged multiradial drain doublet. 3D view

WELL ARCHITECTURE	CUMULATED DRAIN LENGTH (m)	MAXIMUM PRESSURE DEPLETION @400 m³/hr (bar)	COMMENTS
Conventional Single (45° incl.) drain	15	38	
Multiradial Three (1x45° + 2x70° incl.) drains	190	37	High drain Interference Impact
Multiradial Three (1x45° + 2x80° incl.) drains	240	25	Limited drain Interference Impact

Performance

Figure 16: Impacts of drain architectures on well performance

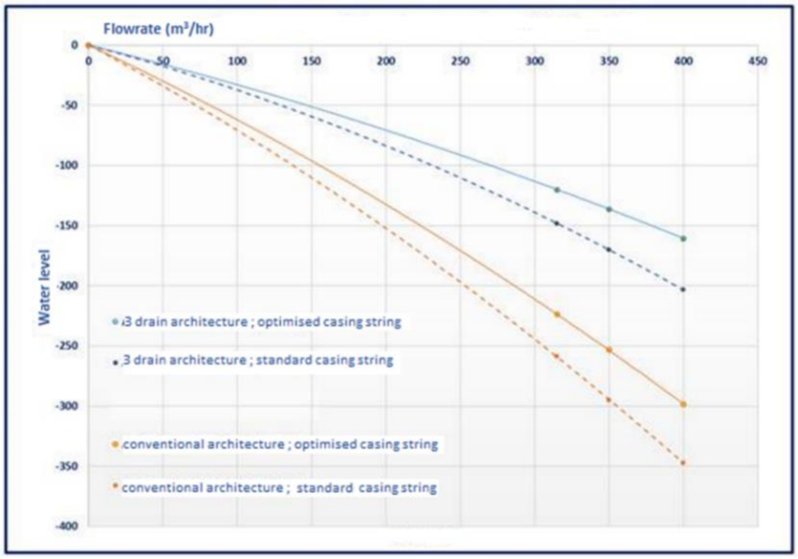


Figure 17: Conventional vs three radial, 80° inclined, drain well delivery curves

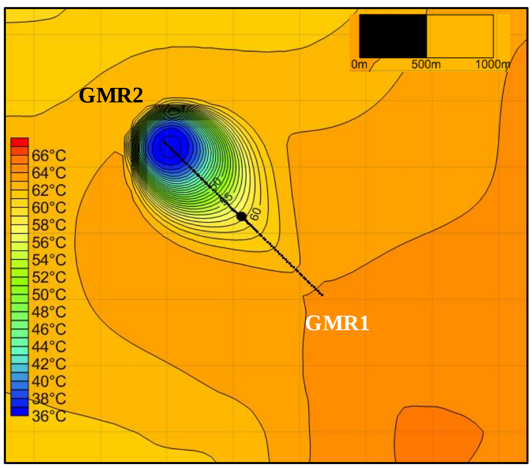


Figure 18.a: Conventional (single, inclined 45°, leg) well architecture

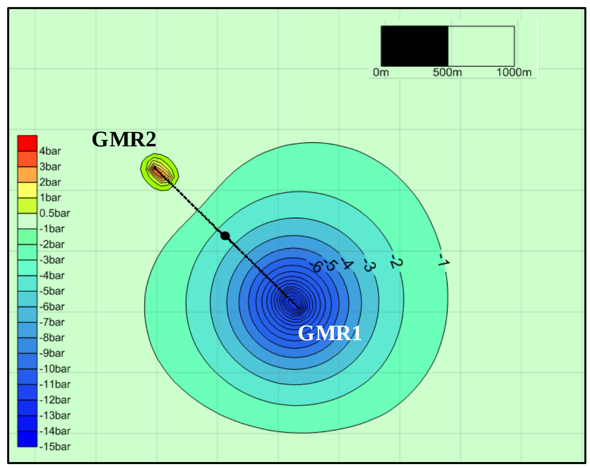


Figure 19.a: Conventional (single, inclined 45°, leg) well architecture

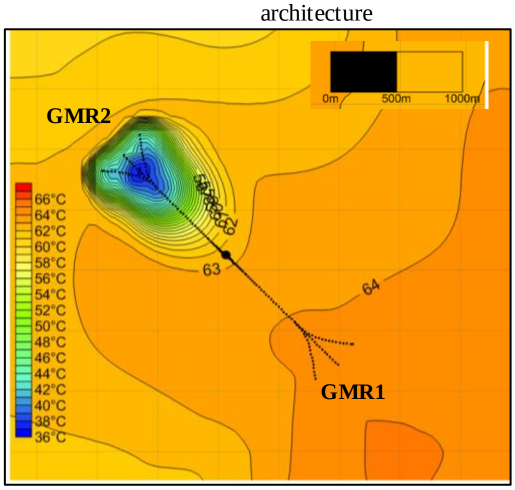


Figure 18.b: Innovative (three, inclined 80°, radial drain) well architecture

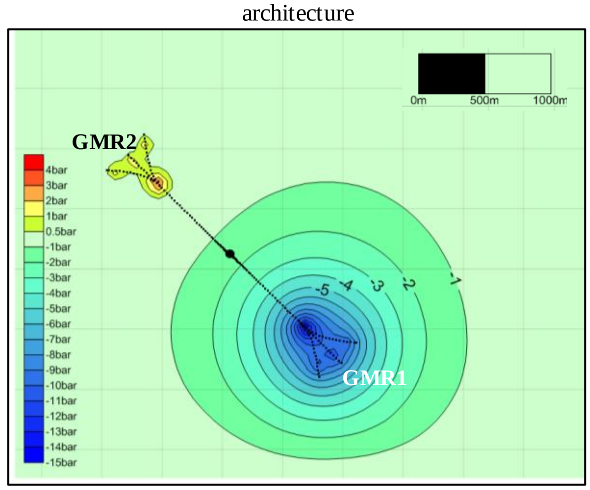
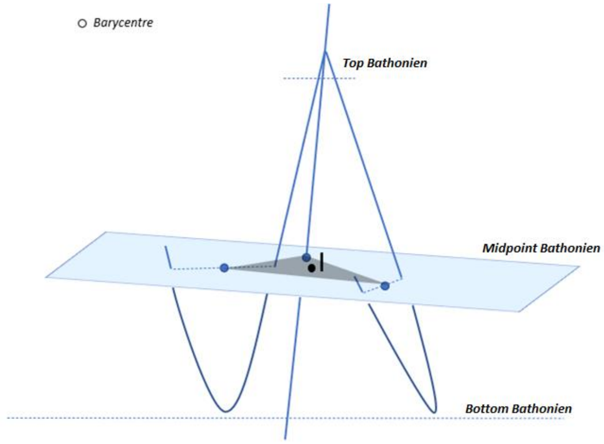


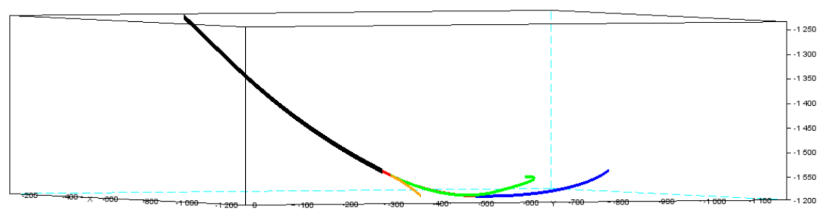
Figure 19.b: Innovative (three, inclined 80°, radial drain) well architecture

Figure 18: Temperature patterns year 30

Figure 19: Maximum pressure drawdowns



a) Projected



b) Achieved

Figure 20 : Alternative low landing and sharp radial build up angle MR well design (Source: Geofluid, Engie Solutions, 2019)

3. MULTILATERAL WELL ARCHITECTURE

The foregoing achievements in innovative well architectures were likely to move towards the trendy multilateral (multi)well design, which becomes increasingly attractive to geothermal operators given the fast development of the technology and its growing share of the oil and gas drilling market.

As a matter of fact the concept widened the scope of horizontal and extended reach wells to an architecture connecting the (most often vertical) mother bore to either vertically or horizontally stacked, fork wise, dual opposed, multibranched laterals according to the configurations described in (Schlumberger, 2021) and (Bosworth et al, 2000), whose completions are formalized in the TAML (Technology Advancement of Multilaterals) classification, which individualizes six levels according to mechanical complexity, connectivity and hydraulic isolation (Hill et al, 2008; Schlumberger, 2021).

Most of the obstacles inherent to oil and gas production including high pressures, gas cap invasion/water inflow, cross flow (thief zones), commingled production, junction re-entry shortcomings do not apply to, mostly single phase, low grade heat geothermal sources, which benefit from multilayered reservoir settings and, in the case of the Paris Basin, self consolidated Dogger carbonates eligible to the simplest open hole TAML level completions. However, the geothermal doublet concept of heat mining, which implies to accommodate sufficient spacing between the reservoir impacts of production and injection well trajectories, in order to avoid premature cooling of the production well and related thermal breakthrough, is likely to oppose the trunk function of the mother bore.

The candidate multilateral design shown in Figure 21 addresses a drill site located (Figure 22) within a poorly productive area (transmissivity below 10 dm) close to the Western boundary of the Paris Basin, geothermally dependable, carbonate platform. The area elsewhere is facing a high demand requirement, a 450 m^3/h nominal rating and a 30°C minimum grid rejection temperature i.e. a ca 20 MW_{th} installed capacity, given a 70°C wellhead temperature. As a result, the mining strategy got assigned a threefold objective aiming at (i) targeting a distant upgraded, North East sited, transmissivity area (Figure 22), (ii) securing a 30 year, breakthrough free, thermal longevity, and (iii) minimizing pumping energy consumption and costs. It therefore dictated the selection of an architecture combining (i) an extended reach (ER) subhorizontally (SH), either single or double layered, trajectories drilled according to two azimuths, ending in (ii) a multilateral, likewise structured either as a single (planar) or dual (stacked) branched laterals according to two similar azimuthal pathways, leading ultimately to the four candidate configurations displayed in Figure 24. Actually, one could regard the twin SH architecture as a hybrid multilateral. Note also that this, somewhat exotic, mining scheme shapes as a natural extension of the ER/SH architecture pioneered in 2018 on the Cachan site (§2.1). Field implementation of the planned architecture would follow the geosteering rationale developed previously on the late site 2 subhorizontal doublet, starting from the generic geomodel integrating the regional petrophysical and hydrothermal environment. From this starting point the work flow would stick to the back and forth geonavigating process (i) interpreting the LWD issued data and the trajectory mapping algorithm, (ii) updating the local curtain section corrected from the derived dip, and (iii) plan the forwards geosteered pathway and adjust the trajectory accordingly.

Further to the geomodelling phase, the four candidate SH and ML architectures were simulated via the TOUGH2-V2, mView interfaced, software (K. Pruess et al, 1999) applied to the sandwich multilayered equivalent structure (Antics et al, 2005; Ungemach et al, 2011). Simulation outputs projected, further to due history matching calibration, to a thirty (30) year prediction assuming a constant flowrate (450 m^3/h)/30°C (injection temperature) exploitation scenario, are illustrated and listed, respective to pressure patterns and cooling kinetics, in Figure 23 (graphic pressure and temperature displays) and Table 1.

Summing up, Figure 24 exhibits (i) contrasted predictive pressure patterns within the "bubbles" localized around concerned single and multiple drains and branches associated to production well GGR6 and injection well GGR7, but (ii) no evidence whatsoever of pressure interferences with neighbouring GDH doublets, and minimum, if any, significant cooling of production wells after a 30 year intensive exploitation; only does well GGR6 undergo a hardly one degree (1°C) temperature depletion relevant to the most intensive, twin branched, multilateral array.

The foregoing are confirmed by the results listed in Table 1, which emphasize (i) the dominant thermal impact of the twin multilateral scenario, and (ii) the minimum production pressure drawdown exhibited by the same twin multilateral scheme along a quasi identical injection pressure rise, slightly more favourable as regards the pressure average on the twin subhorizontal well GGR7.

It may be concluded that the attractive performance displayed by the twin options of both SH and ML architectures secures moderate pumping pressures (and related energy costs) and prevents significantly the advent of premature temperature breakthrough shortcomings. Note that, modelling issued, well pressures ought to be corrected, after due correction of radial truncating bias, from skin and well friction losses.

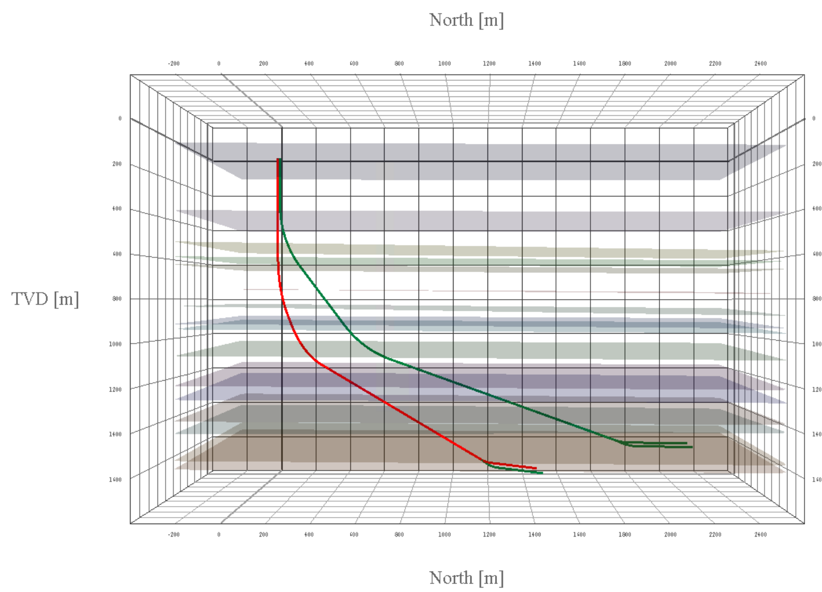
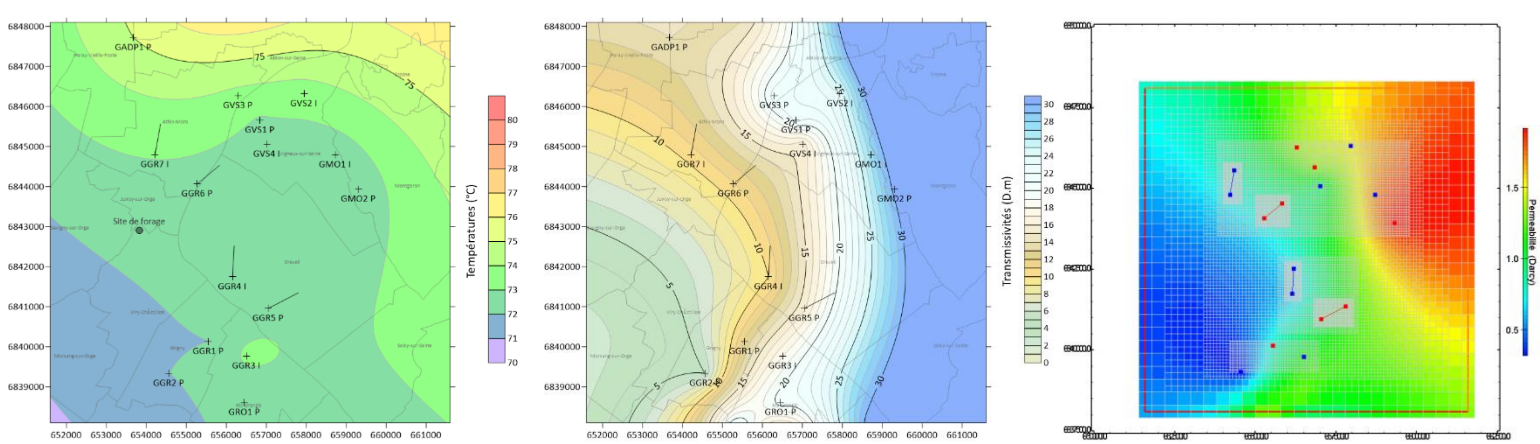
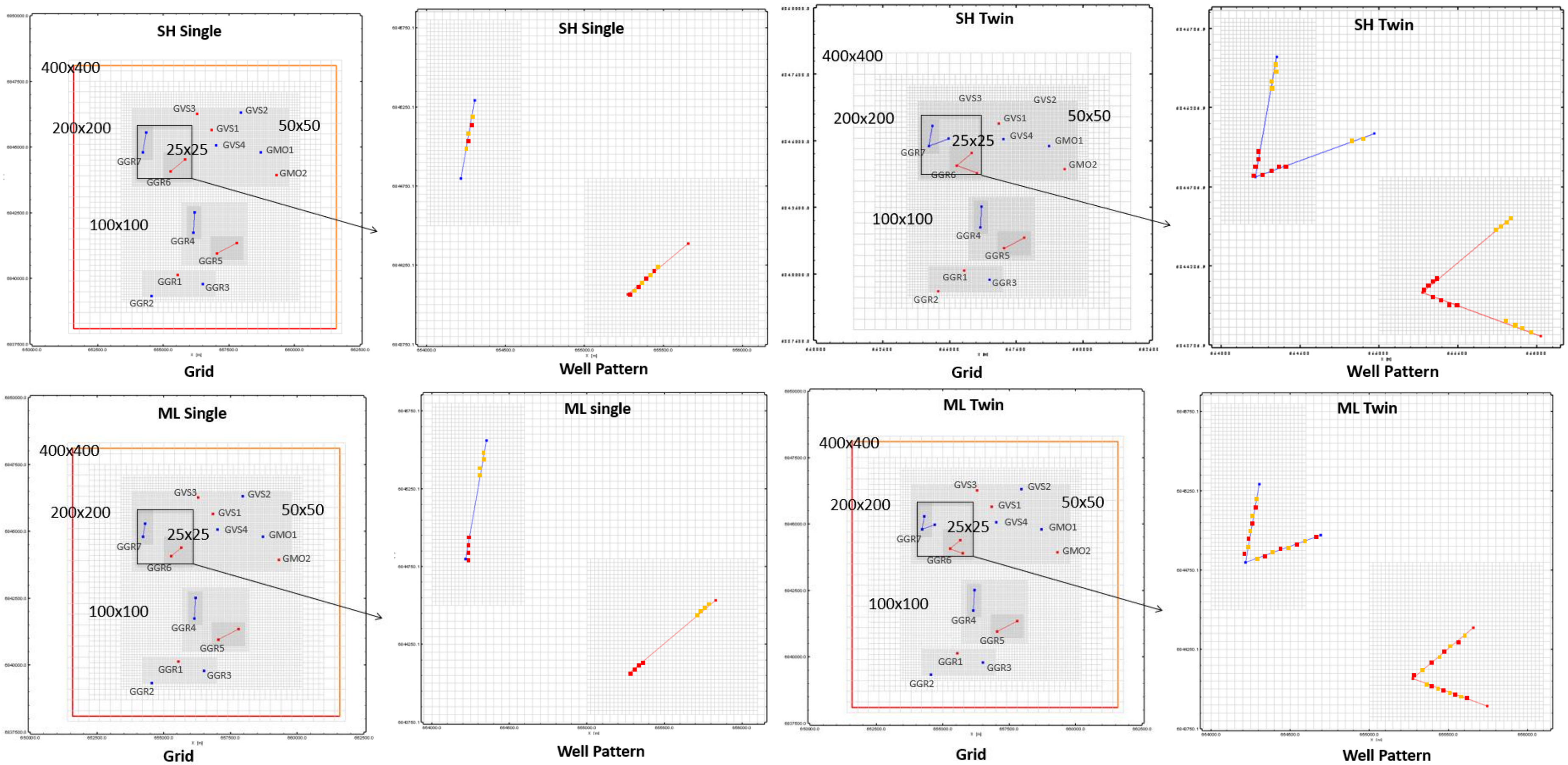


Figure 21: Candidate Multilateral architecture



Well locations — Transmissivities (dm) — Isotherms

Figure 22: Project exploitation, productive and thermal environments



Legend

- Injection
- Production
- Sandwich upper reservoir
- Sandwich lower reservoir
- GGR4 } Existing SH doublet
- GGR5

Figure 23: Extended Reach (ER) subhorizontal (SH) and Multilateral (ML) single and twin azimuthal drain configurations (according to sandwich model)

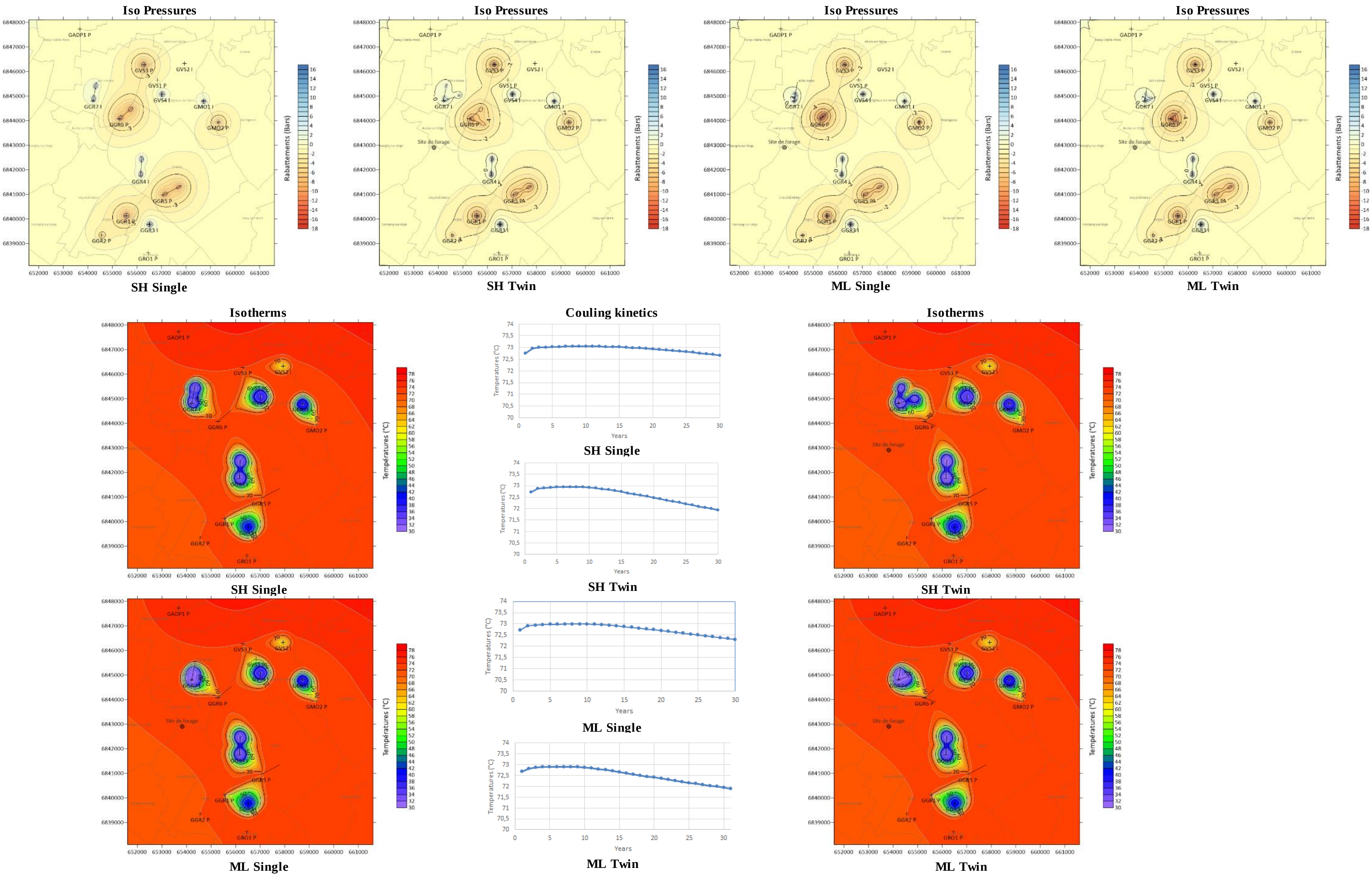


Figure 24: Thirty year predictive hydraulic and thermal patterns respective to pressure drawdowns/uprises and cooling kinetics related to two single/twin subhorizontal and multilateral ML well architectures

Table 1: Subhorizontal vs multilateral simulation results

Well architecture	Type	30 yrs average vs maximum pressure drawdowns & rises (bar)		30 yrs Temperature cooling (°C)
		Production	Injection	
Subhorizontal (SH)	Single	-11,3/-12,3	+16,7/+17,5	-0,2
	Twin	-6,5/-8,4	+11,7/+13,7	-0,55
Multilateral (ML)	Single	-9/-9,4	+15,6/+18	-0,65
	Twin	-5,5/-7	+12,4/+13,6	-1

4. DISCUSSION

Prior to exercising the figures of merit and tentative ranking of the achieved (SH, MR) and commissioned (MR) candidate novel geothermal well architectures it should be kept in mind that they are located in a somewhat "easy" reservoir setting. Actually they take place in a dependable, poorly tectonised, multilayered aquifer system hosted by consolidated carbonate rocks avoiding the implementation of any well completion whatsoever, replaced by open hole production instead.

Selected merits and pros vs cons appraisals are summarised in Table 2 in the light of four criteria, flow performance, technological maturity, economics (as of CAPEX) and pilot hole back up respectively. The exercise is commented hereinafter.

Table 2: Well architecture comparative figures

Well Architecture	Flow Performance (m3/h)	Technological Maturity	CAPEX (k€)	Pilot Hole back up	Remarks
SH	450	High	13 600	No	80° landing angle recommended VSP impedance inversion suggested
MR	350	Medium	14 300	Yes	80° landing angle recommended Delicate leg evaluation/stimulation
ML	450	High	18 000	Optional	500 m^3/h eligible (sub)vertical mother bore recommended

- ***Flow performance***

Target 450 m^3/h flow rate has been achieved at the first SH site, which is currently operating since 2021 at a maximum 435 m^3/h as a consequence of undue pressure interferences induced during the winter heating period by a neighbouring GDH doublet. On the second SH site, 400 m^3/h are confidently anticipated from earlier testing results.

The unique MR doublet completed to date claims, a 350 m^3/h peak production with no indication so far of the injection pressure deemed to stand below the 40 bar threshold. Here it is felt that well performance could have been significantly upgraded thanks to higher landing angles and modified geosteered leg trajectories among others.

Regarding the ML architecture, predictive reservoir simulation at a 450 m^3/h – 30°C constant production schedule speaks for itself.

- ***Technological maturity***

Reviewed well architectures benefit since the 2020s of an outstanding technological support since the move to high resolution, real time, multilayered geosteering mapping tools such as the Periscope, first used worldwide in geothermal drilling at SH site 2, for optimising detection of thin bed boundaries, which usefully complemented the single Ecoscope multilayer navigator implemented at the Cachan site five years earlier.

As a matter of fact geothermal drillers and well designers benefit from a tool box dedicated to Rotary Steerable Systems (RSS), Logging While Drilling (LWD) strings, XRD-XRF real time geochemical monitoring, real time boundary bed mapping/trajectory geosteering, intelligent multipurpose Coiled Tubing Units (ICTU), interbed re-entry locators, performant line/string/logging tool centralisers facilitating operation of near horizontal (80°) wireline and downhole resident lines, readily available for innovative well architecture undertakings.

- ***Economy (CAPEX costs)***

Listed figures, which do not include drill site preparation/restoration and rig move in/move out costs, have been exposed in the past two years to important price increases, particularly in the areas of tubular supplies, directional drilling, chemicals, waste management which impacted the ML cost estimate compared to the earlier SH and MR CAPEX evaluations. Nevertheless, CAPEX amounts ought to be balanced against OPEX costs, which actually benefit to the ML alternative, which exhibits significant pumping cost savings owing to their markedly lower productive/injective pressures.

- ***Pilot hole backup***

Among the three competing designs, only does the SH option evidences a structural obstacle opposing the pilot hole inherent to its near horizontal landing angle. On the contrary the MR scheme offers, via the drilling of the first leg, a (pilot hole) opportunity for investigating and evaluating (via PLT) the whole pay interval which, given the limited space extent of the concept, proves relevant in representing the true layering of the area and guiding accordingly the inclination of the two remaining legs. The ML well architecture could structurally include a pilot hole provided its mother bore be drilled (sub)vertically and PLT applied successively for layering identification and flow quantifying purposes.

However, the pilot hole within the Dogger carbonate layering context should not be regarded at face value and questioned given its marked layering discontinuity, forbidding any reliable incremental extrapolation over a hectometre. In conclusion the pilot hole impact ought to be mitigated and limited to an initial interlayering assessment.

Note to be overlooked are the following advantages to be added to the aforementioned attributes

(i) **SH architecture.** Tracking of a distant targeted impact via a maximum two kilometer long subhorizontal drain;

(ii) **MR design.** In spite of its structural complexity in complementing and further operating the concept, it may reconcile the production target with locally drastic space limitations, and

(iii) **ML well scheme.** Given the doublet spacing requirements to defeat premature production cooling kinetics, it associates a preliminary (eventually contributing) (sub)horizontal drain with a multilateral mother bore to the adjacent branches tree structure, securing both system thermal longevity, low pressure variations and high productivities. The self propping properties of the reservoir host rocks, which allow to exploit the resource in openhole, simplifies dramatically the implementing process thus allowing to validate the system as level 1 in the TAML six degrees ladder. The extra CAPEX costs should be significantly compensated by the larger productive capacity and lower consequently the electricity intensive OPEX running costs.

5. CONCLUSIONS

Innovative subhorizontal, multiradial and multilateral geothermal well architectures, achieved and commissioned in the initially poorly productive margins hosted by the, otherwise geothermally dependable, Dogger (Mid Jurassic) carbonate platform of the Paris Basin have been reviewed.

The technologies involved, inherited from the long practiced oil industry know-how, have been analysed from the flow performance, technical maturity, cost and pilot hole back up standpoints, leading to the following conclusions.

(i) All three reviewed candidates achieve nominal 350 to 450 m^3/h flow ratings taking advantage of the latest issued drilling, logging and above all geosteering/well placement technologies.

(ii) Candidate architectures exhibit capital intensive (CAPEX) mining investments balanced by the benefits expected from important OPEX savings, the latter pleading in favour of the combined subhorizontal x multilateral extended reach mining scheme, which appears to best suite the production sustainability, thermal longevity and environmental safety standards required by the geothermal community at large.

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