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Advanced Geothermal Well Architectures: Key Issues in Upgrading Well Performance and Formation Evaluation

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ABSTRACT

Growing demand is raising among geothermal operators towards innovative wells architectures, addressing complex, tectonised, and multilayered, reservoir settings and thermochemically sensitive fluid environments, capable of sustaining high productive capacities and prolonged thermal life.

These issues, which become particularly acute when contemplating lower than anticipated reservoir performance and hostile fluids thermochemistry, are being addressed by recently implemented well designs in the areas of subhorizontal and multi radial well trajectories, anti-corrosion fibreglass lined wells and dual completions, are presented and discussed in this paper.

The subhorizontal well (SHW) concept has been field validated on a geothermal district heating (GDH) site South of Paris, France, in a stratified, carbonate platform, reservoir structure. The extended reach the SHW trajectories intercepted, over a near 90° (in fact 85 to 95°, dip dependant) inclination, the whole of the layered reservoir sequence. First of its kind in geothermal design engineering, the concept may be regarded as intermediate between the horizontal and multilateral well architectures currently practiced by the oil industry.

The paper highlights the SHW doublet outcome with respect to the directional, the RSS (Rotary Steerable System) drilling, logging while drilling (LWD), geochemically (X-Ray Fluorescence, XRF and Diffractometry, XRD) assisted geosteering and, 1.000 m long, drain stimulation, logging and testing.

Results are discussed in the light of upgraded well/reservoir performance issues, extended to a comprehensive review of a carbonate platform lithofacies, diagenetic and micro fracturing trends.

Initially designed as a fallback, the sidetracked substitute, to a SHW failure, the multi radial well (MRW) concept 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.

Fibreglass reinforced epoxy resin tubular, long regarded as a (composite) material solution to corrosion damage, a sensitive issue in the Paris Basin extensively developed carbonate reservoir and corrosive aqueous CO_2/H_2S thermochemistry, have been poorly developed in spite of its structural advantage. The design advocated in this paper, which combines both mixed steel-cased propping assembly and a non-cemented (annulus free) production liner accommodating an ESP sustained, artificial lift pumping chamber, is an extension of a former well completed in the mid-1980s, limited to self flowing (artesian lift) production. The new well architecture has been successfully completed in the fall of 2018, South of Paris.

Last but not least, two dual completion well candidates are presented, which combine either a single mixed, bi-aquifer, production, applying single drift expandable liner technology in a deep-seated reservoir or separate production of two, non-mixable fluids, medium depth sandy aquifers.

Economic aspects are analysed with a view to standardizing the process in geothermal engineering and future undertakings.

1. INTRODUCTION

Innovative well architectures recently achieved in the Paris Basin, supplying heat to GDH grids, are raising growing interest among geothermal operators.

Here, the multi doublet heat extraction scheme faces three major, often critical, concerns (i) the replacement of aging, when not damaged, well infrastructures, and productive/injective capacities, (ii) doublet densities approaching in several areas overpopulation, source of potential mining disputes, limiting well replacement opportunities, and clouding new 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 reservoir areas remaining unchallenged unless appropriate, field proofed, well architectures be made available.

Prior to this recent interest from concerned parties long committed to conservatism, several milestones before the SHW design are worth to mention. Bruel (2008) has suggested horizontal well's trajectories as an alternative to conventional directional drilling applied to GDH doublets in the Paris Basin, assuming a single layer geothermal reservoir. It is also noteworthy the first horizontal wells competed at Schlattingen in the Swiss Thurgau Canton. Not designed as such beforehand, the borehole was sidetracked as a remedial to the former vertical trajectory, which proved almost dry. Incidentally, the two-fold kick off profile described by Frieg (2014) evidenced the need for incorporating wellbore stability calculations to well design.

Of interest to our concept were the modern technological ingredients successfully implemented by several operators involved in the development of the deep-seated targets hosted by a karstified limestone of the Southern Molasse Bavarian Basin (Münich area). Here, integration of the 3D seismic, RSS (Rotary Steering Systems), and LWD (Logging While Drilling) assisted geo navigation have secured high drilling success ratios reported by Mirjolet (2014), which are becoming a standard in exploring and producing such "risky" objectives (Schubert, 2015). The present paper, further to a description of the SHW architecture and accompanying geosteering drilling/navigation technology, will focus on the wireline logging, well testing and geochemical monitoring attributes of the well and reservoir assessment strategy. Project accomplishments are discussed in the light of upgraded well/reservoir performance issues, extended to a comprehensive review of a carbonate platform lithofacies, diagenetic, cement and micro fracturing trends.

The multi radial well (MRW) architecture, inherited from the former SHW design (Ungemach et al, 2016 & 2018), should be regarded as a multilateral, radially specific, equivalence. Its benefits will be valued on a case study, hosted by a low permeability multi-layered carbonate reservoir, targeting a high, 400 m^3/hr, productive capacity from a sharp angle and three-legged drain arborescence.

The non-cemented and annular free fibreglass well-lining successfully completed recently on a severely damaged GDH site is a continuation of a former well design (Ungemach, 1995) operating since 24 years in self flowing production mode, to which it adds a mixed production column and a pumping chamber accommodating an artificial lift, ESP sustained, production facility.

Ultimately, multiple completions, currently practiced in the Oil Industry are seldom if ever, applied in geothermal production unless appropriate drilling/completion expertise be implemented. Two well architecture candidates are presented here (i) one completed to produce simultaneously, at high flowrates, two deep-seated, geochemically compatible geothermal brines, and (ii) a second one connecting separately to surface, two, medium depth, loose sandy aquifers, and non-mixable formation fluids.

Extension of the SHW and MRW architectures and related RSS and sharp angle drilling/geosteering technologies to similar low permeability, stratified and shallow, fast cooling, settings along with wireline logging/testing support, is discussed *in fine*.

2. SUBHORIZONTAL WELL (SHW) CONCEPT

2.1. Site selection

The site (Cachan) selected for the first implementation of the concept meets most of the aforementioned GDH constraints, i.e. a densely populated (sub)urban district, limited space availability, proximity of neighbouring, operating, and commissioned doublets/triplets. This includes two, 34 years old (first generation) completed wells, to which should be added locally moderate reservoir properties (15 to 10 Dm transmissivities), saturated production capacities (350 m^3/h cumulated by two existing doublets) and poor system COP (ratio of yearly produced heat over consumed pumping power close to 9). The Dogger hosts the geothermal target (Mid-Jurassic) multilayered oolitic carbonate reservoir at a ca 1 600 mTVD depth.

The previous one made this site eligible to innovative well designs, securing technically and cost-effective exploitation.

The project replaces two doublets, serviced since years 1984 and 1985, extending its productive capacities from 350 m^3/h – 45 000 MWh_{th}/yr to 450 m^3/h – 60 000 MWh_{th}/yr, ambitioning a COP of 20 instead of the former 9 MWh_{th}/MWh_{el}.

2.2. Well architecture

It conforms to the well path sketched in Figure 1, which shapes as a compromise between single horizontal and multilateral well profiles since the planned SHW trajectory intercepts the whole multilayered reservoir sequence, thus cumulating its individual layer flow contributions. Hence, given a thin layered reservoir setting and a long-legged drain, the latter would, in most instances, trend near horizontal and recover accordingly significantly larger flow amounts compared to a standard deviated well design.

Both well profiles and trajectories (Figure 2), quasi identical in design, include 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 open-hole owing to the consolidated structure of the carbonate rock mass.

Note that, would the SHW completion has failed, the provision has been made to switch, after abandoning the unsuccessful drain, to the multi radial well (MHW) design further developed in §3.

2.3. Geosteering navigation strategy

The key idea behind the geosteering workflow, 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 3, summarised hereafter (Ungemach et al., 2018; Di Tommaso et al., 2018; Ungemach et al., 2019):

- ***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 Diffractometry 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 productive drain segments;
  - Production Logging Tool (PLT) and micro-spinner flow metering providing flow and temperature profiles along the entire open-hole (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 the productive reservoir sequence accordingly.

The XRD/XRF geochemical monitoring results and expectations are depicted in Figure 4 and 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 (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 5, which evidences the many corrections implied in securing the trajectory within the two thin (metric size) bedded porous intervals.

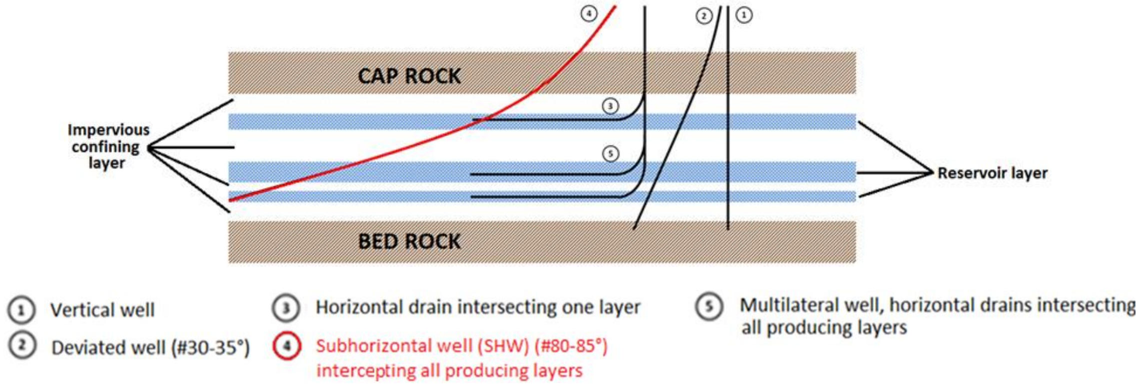
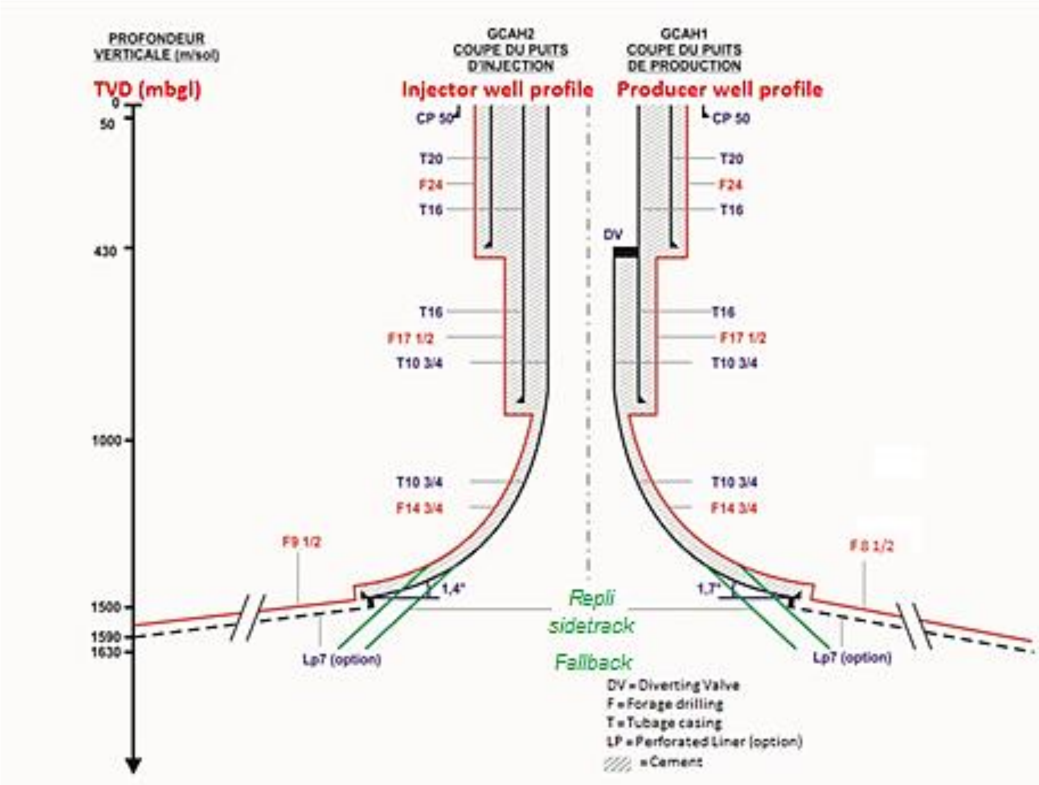
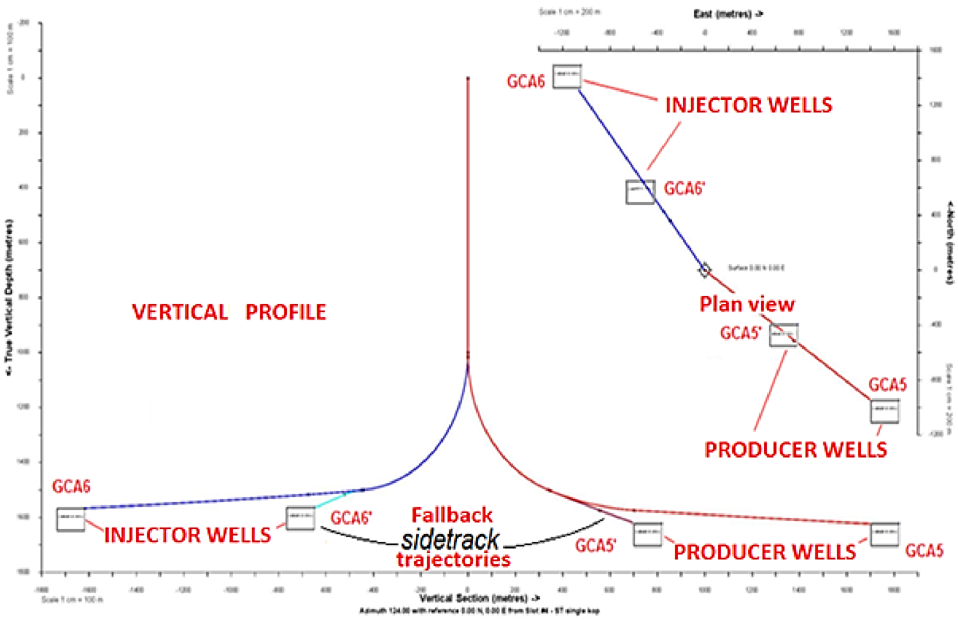


Figure 1: Subhorizontal well concept



a) Well architectures



b) Well trajectories

Figure 2: Subhorizontal well architectures and trajectories

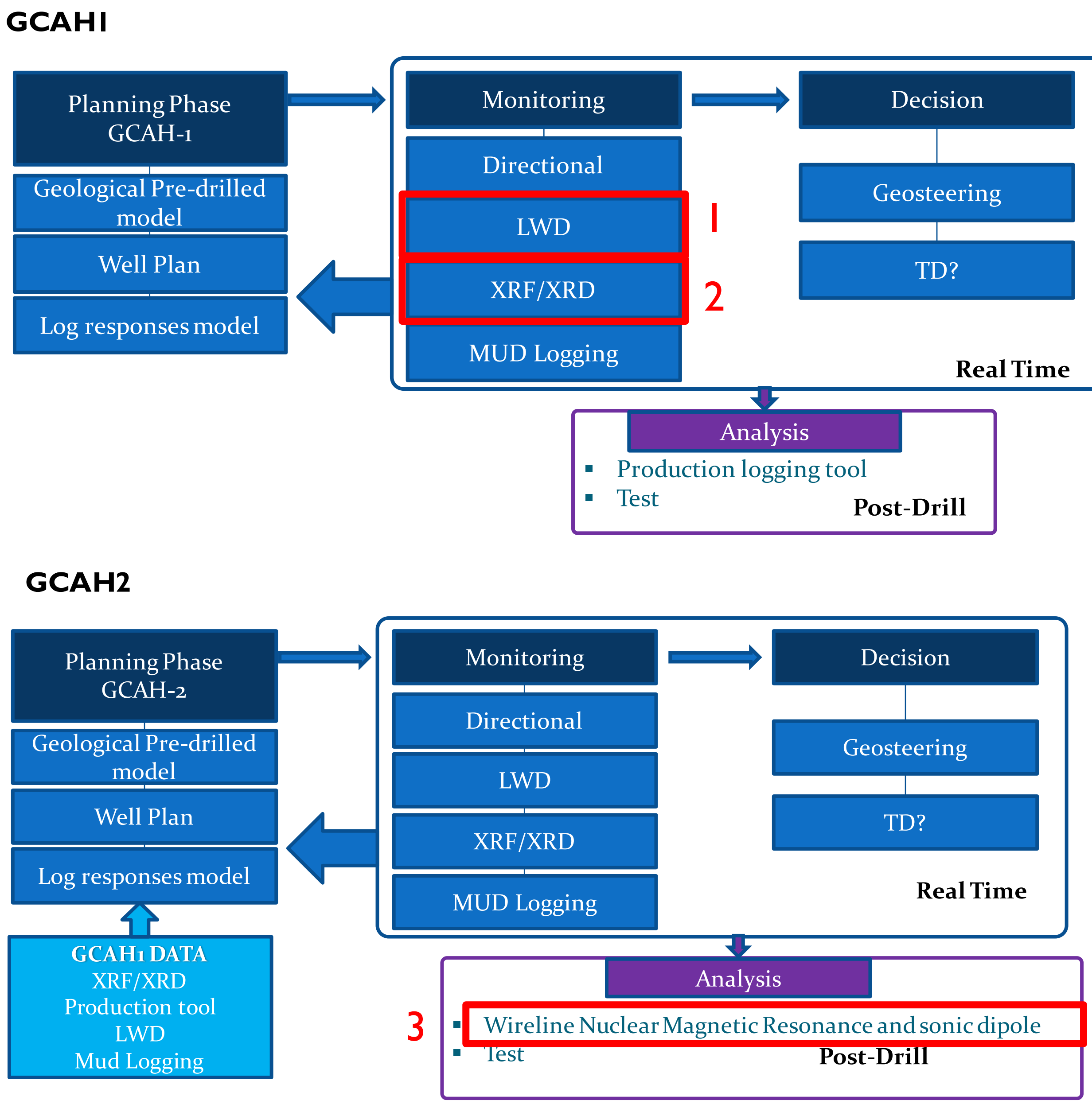
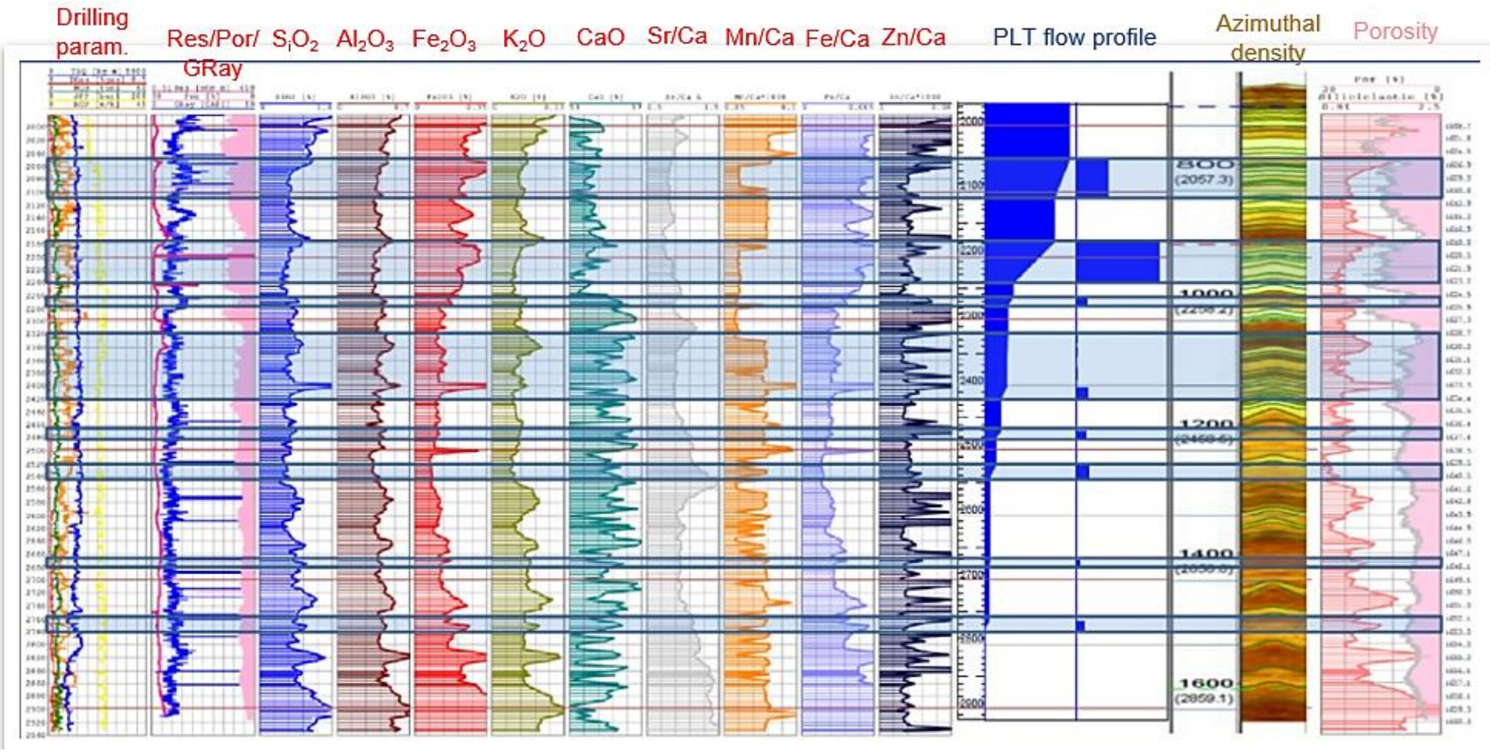
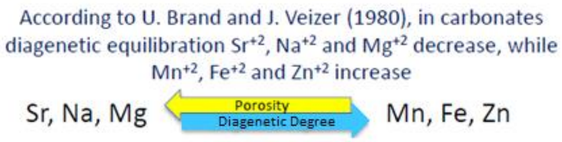


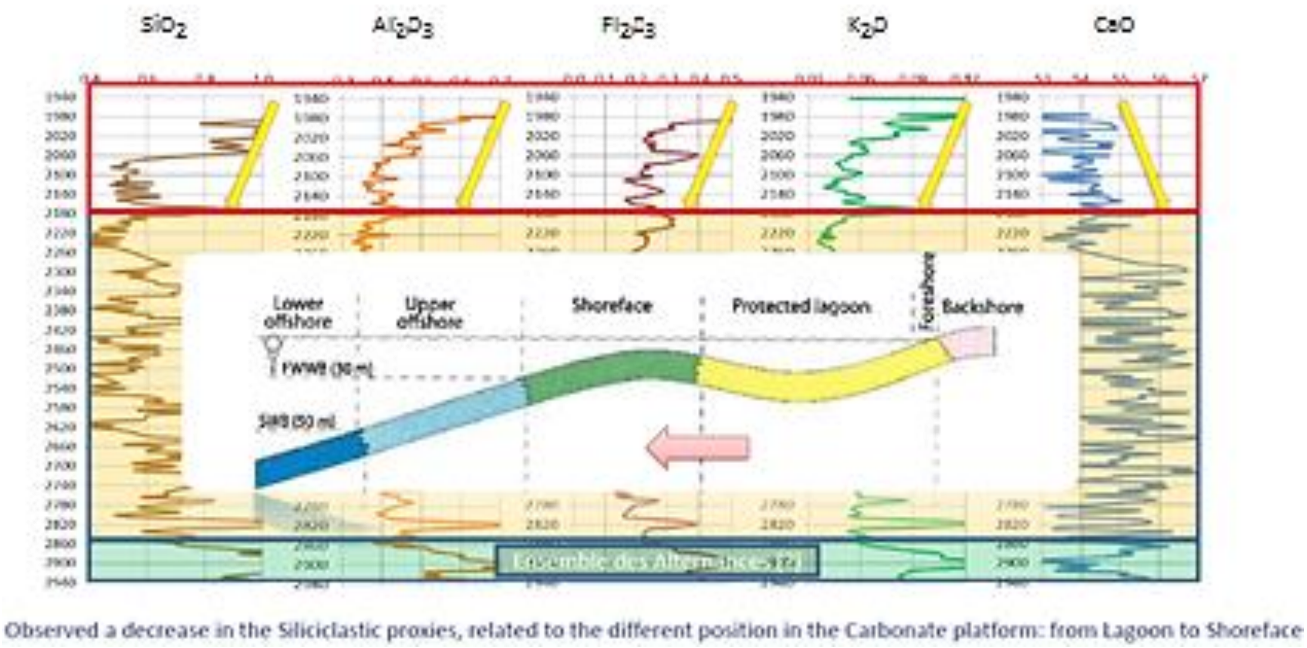
Figure 3: Geosteering workflow



Candidate proxies

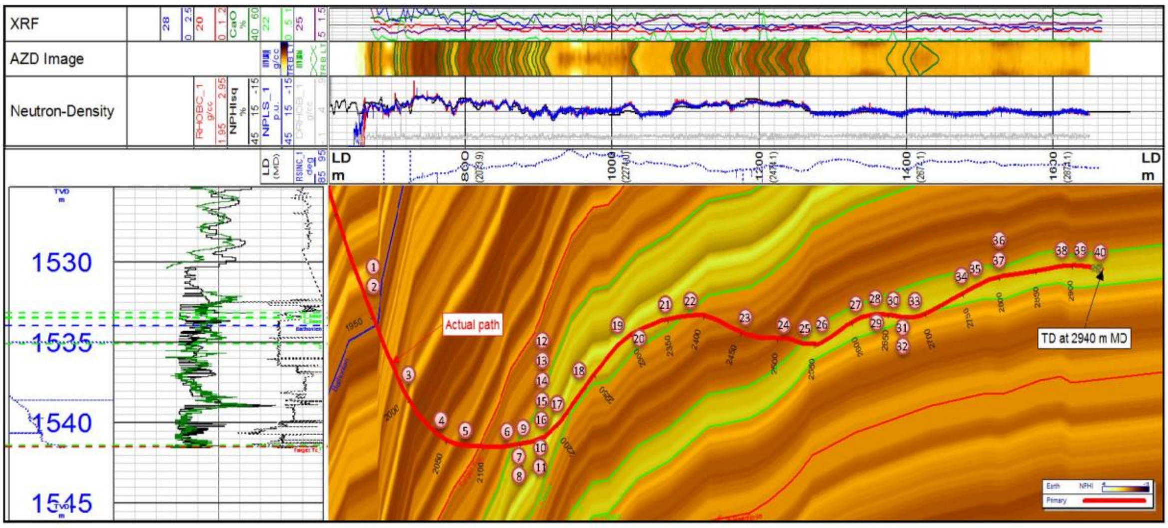


- Objective: Correlate, geochemical traced, lateral carbonate variations with LWD data to optimise GCAH2 geosteering.
- Identify diagenetic, cement. Micro fracturing shows impacting porosity.
- Put these figures in perspective with PLT flow metering while designing GCAH2 trajectory.

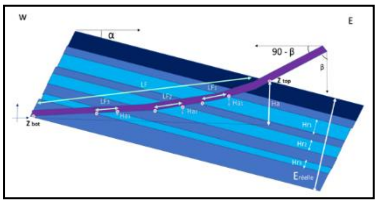


Siliciclastic proxies. Carbonate platform environment

Figure 4: Well GCAH1. Geochemical (XRF, XRD) monitoring



CRITICAL CASES



α=1° ß=88° Actual E=60m Then:	Well architecture similar to GCAH1 which has intersected the whole payzone	α=5° ß=88°3 Actual E=20m Then:	After crossing the entire pay interval will drilling progress upwards?

- Challenge: Real-time trajectory corrections
  - 1 to 5° varying dips, impacting drain effective length
  - Reconcile tracking of thin (#1 m) high porosity layers with target matching delays induced by high bit to RSS recording distance (#20 m)

Figure 5: Well GCAH2. Geosteering. Trajectory corrections

2.4. Formation evaluation

Assessment of reservoir and well performance was carried out via (i) wireline (open-hole, 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.

On well GCAH1, the successful PLT spinner flow metering provided invaluable information as to flow and dynamic temperature profiles along the entire drain path (Figure 6). 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 productive drain segments is imaged in (GCAH2) composite log displayed in Figure 7.

On the other hand, the first application on French geothermal projects of nuclear magnetic resonance (NMR/CMR) and dipole sonic logs (Figure 8) 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).

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

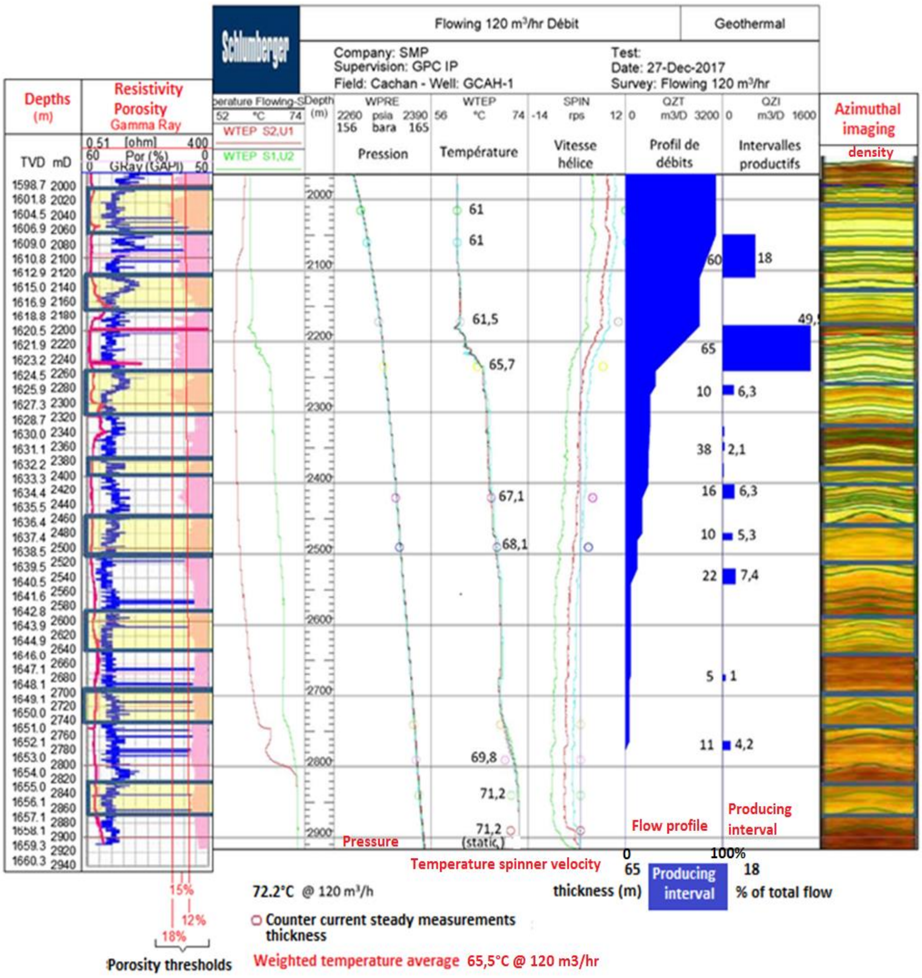


Figure 6: Well GCAH1. PLT logging. Flow metering, temperature and pressure logging of the open-hole subhorizontal drain (27/12/2017). Co-current dynamic measurements.

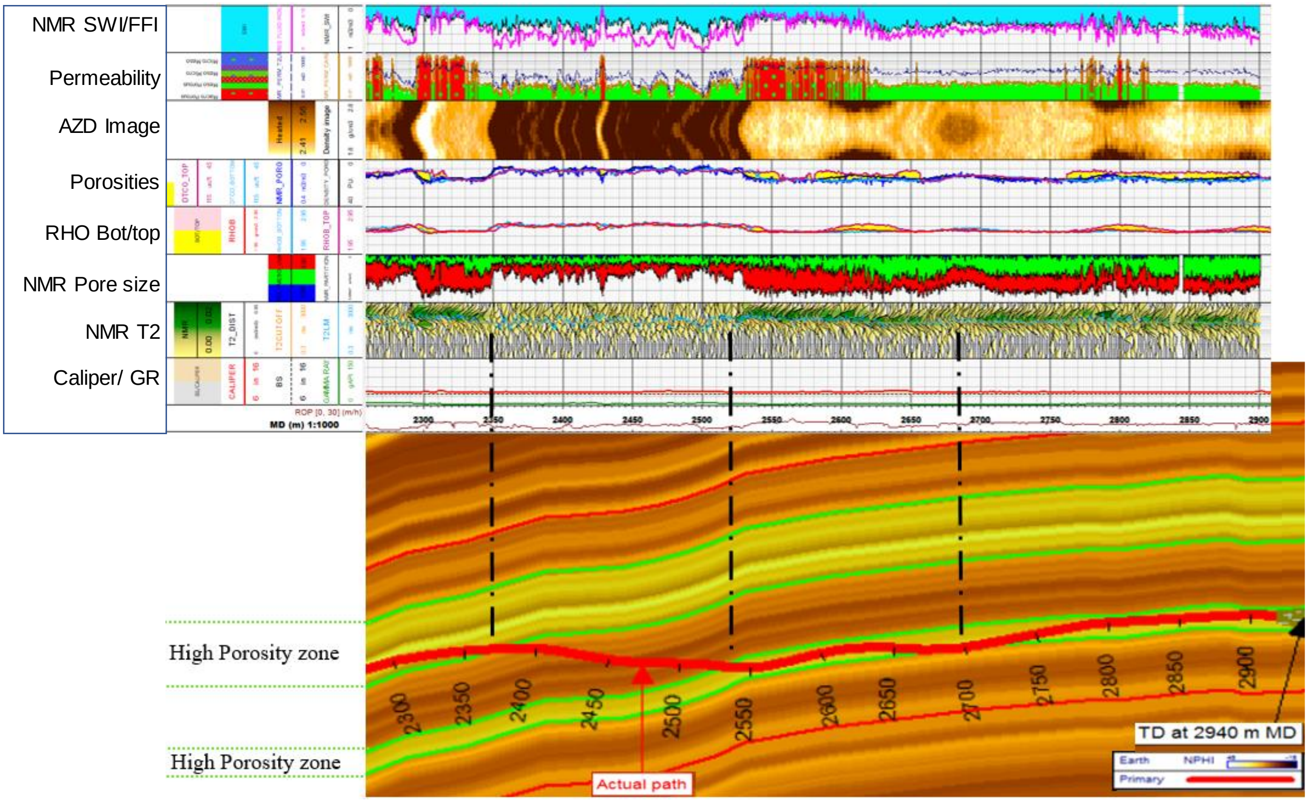


Figure 7: Composite permeability, porosity, density log imaging of a subhorizontal drain (well GACH2)

(source: Cavalleri and Wielemaker, 2018)

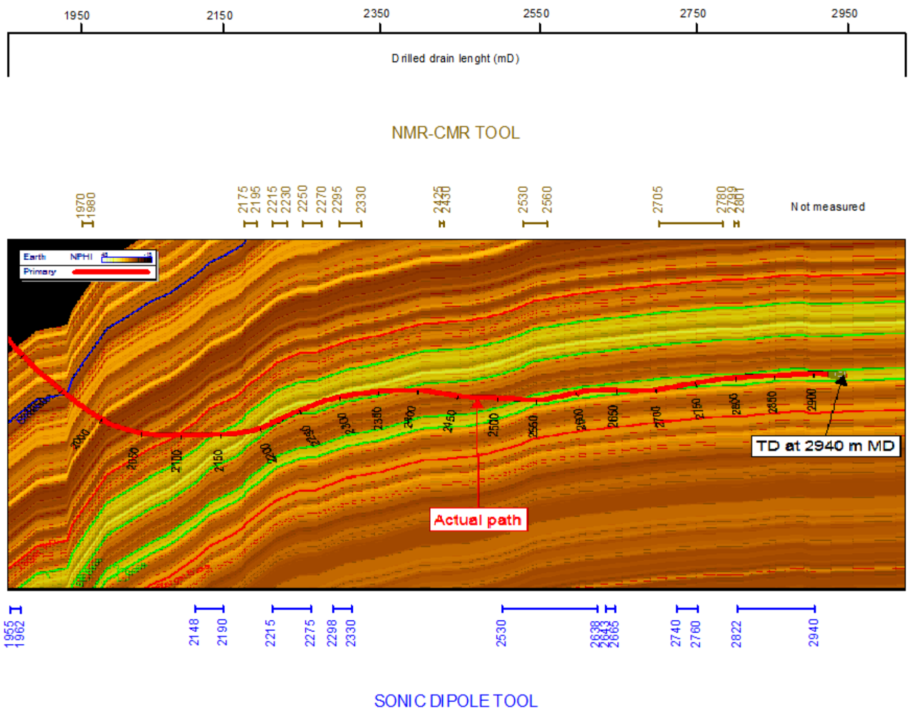


Figure 8: Well GCAH2. Wireline log (NMR-CMC and Sonic Dipole porosity, permeability tools) correlation with drain productive segments

<u>Well Testing</u>

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 9 (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 and Horner 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 truly 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 flow metering injection well-pumping facilities, diverted for the purpose to the newly completed well GCAH2 enjoying, therefore, a 350 m^3/hr rated capacity (extendable to 450 m^3/hr).

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

WELL	TRANSMISSIVITY (dm)	SKIN FACTOR	PI, II (m^3/hr/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.

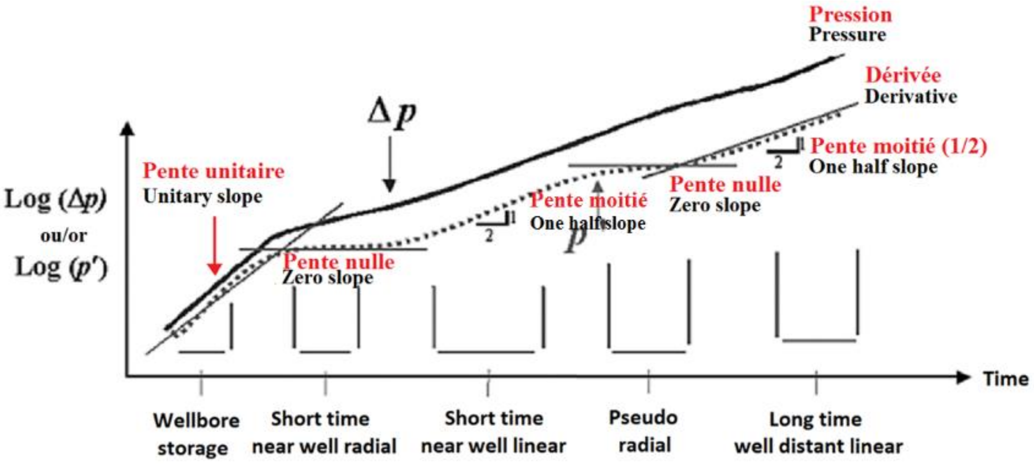


Figure 9: (Sub)horizontal drain (idealised) flow regime identification (after Lee et al., 1982)

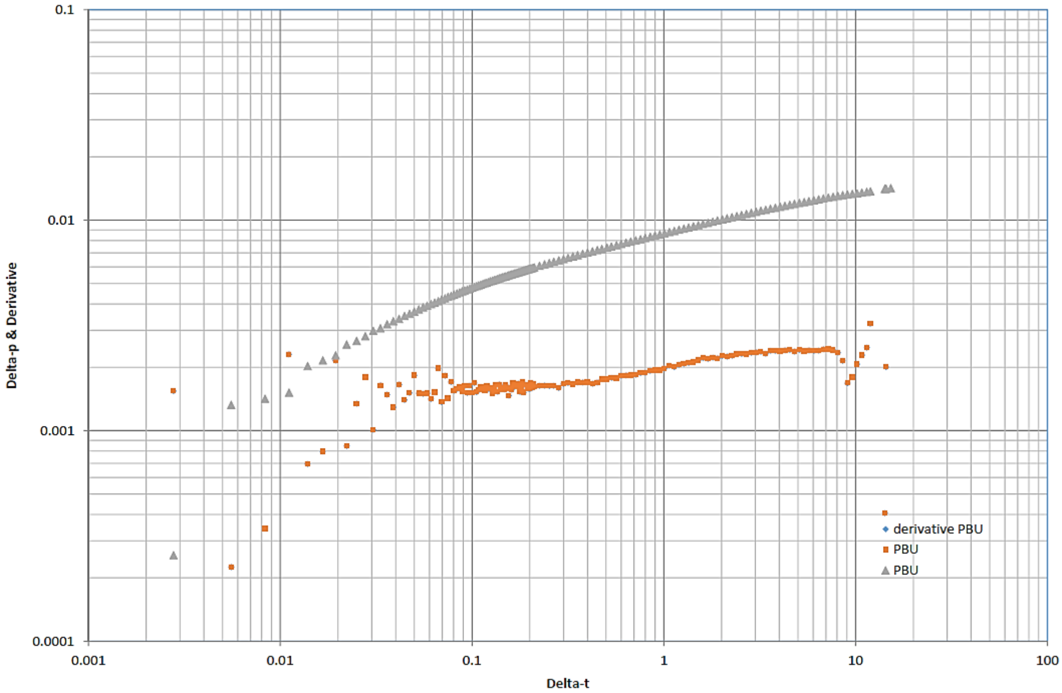


Figure 10: Well GCAH1. Self flowing production test. Build-up pressure and derivative log-log plots

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 bottom-hole 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) illustrated in Figure 11, validated the test issued, input reservoir hydrodynamic parameters.

Furthermore, the inhouse wellbore heat transfer model was able to match the monitored wellhead temperatures from the PLT derived, bottom-hole 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 neighboring 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.

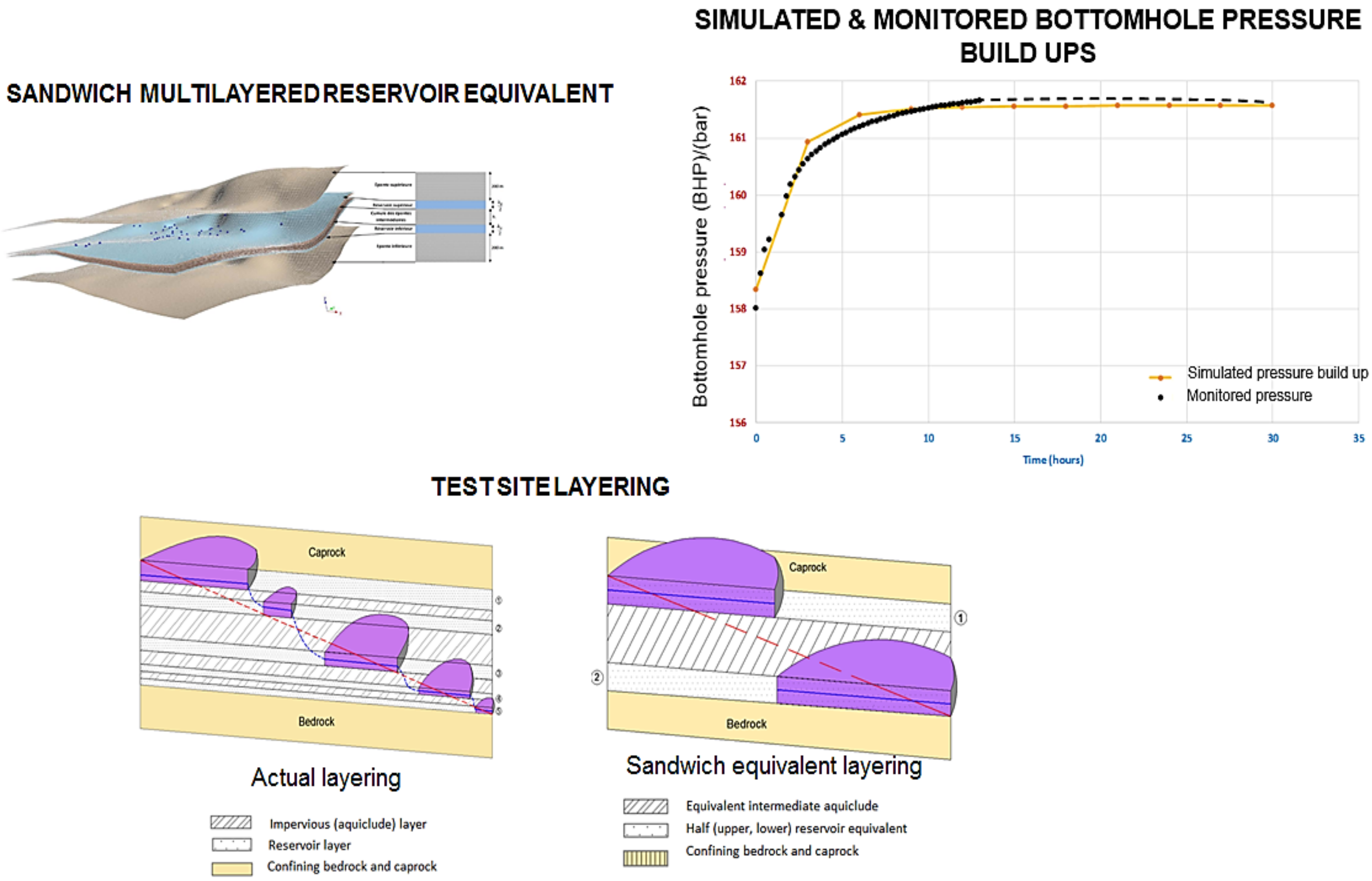


Figure 11: Subhorizontal drain modelling. Flow model (pseudo radial stationary, regime)

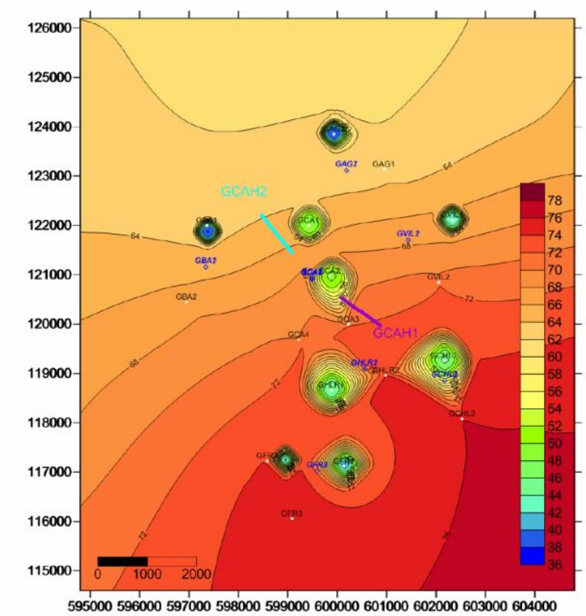


Figure 12.a: Cold bubble and pressure depletion map

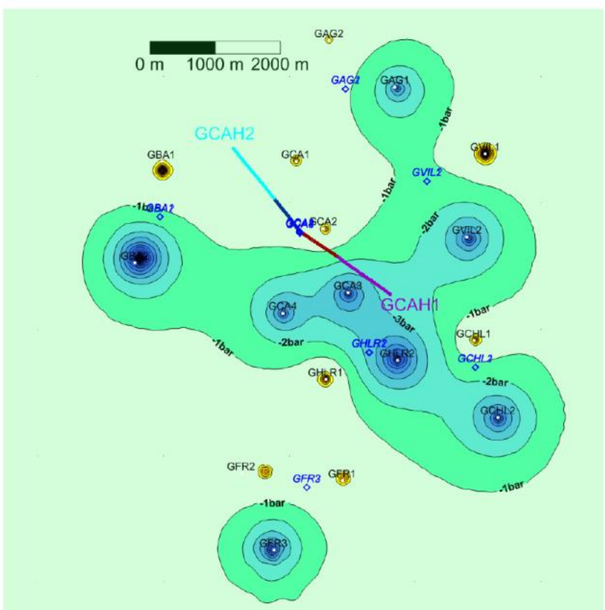


Figure 12.b: Maximum winter pressure drawdowns

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

Geochemical monitoring

Alongside real time assistance to geosteering while drilling, XRF, elemental, and XRD, mineralogic monitoring was expected to contribute to formation evaluation in relation to facies changes and diagenesis impacts on porosity/permeability trends within the carbonate platform.

As a result, it targeted three main objectives.

(i) Carbonate vertical and lateral reservoir zonation and depositional environments by correlating LWD (neutron and azimuthal density, AZD) with XRF issued elements, and XRD derived mineralogies, which, once characterized on well GCAH1, would serve as markers for optimizing well GCAH2 trajectory;
(ii) Evaluation of rock petrography from porosity assessments, inferred from diagenesis and cement occurrence (Moore and Drucksman, 1981), (Brand and Veizer, 1980);
(iii) Microfracturing detection by tracking filling minerals through minor and trace element concentrations regarded as indicators of microfracture aperture (open) and sealing (closed) (Moore and Drucksman, 1981), elsewhere supported by LWD (and mud logging) evidence.

- *Depositional environments*

Two lithostratigraphic units, a fissured, almost pure $CaCO_3$, limestone and an Oolithic level demonstrate reservoir properties (LWD neutron porosities above 15%); the first depositional setting relates to the internal part of the lagoon (i.e. the shallower platform level) and the Oolithic limestones to a barrier (infralittoral) type (i.e. the transition from the internal, lagoon part to the external – barrier – part of the carbonate platform).

- *Selected markers*

With respect to sedimentary unit characterization, carbonate, diagenesis and porosity markers are portrayed as XRF oxides ($Si\,O_2$, $Al_2\,O_3$, $Fe_2\,O_3$, $K_2\,O$ and $Ca\,O$), plots, [Sr/Ca] and [Mn, Fe, Zn, Ca normed] ratios and summed siliciclastic [$\sum$ ($Si\,O_2$ + $Al_2\,O_3$ + $Fe_2\,O_3$ + $K_2\,O$)] proxies (Figure 13).

Attention is drawn to a remarkable correlation, in Figure 13, between the Sr/Ca ratio and LWD neutron porosity showed within the (0.9-1.1%) range.

- *Microfracturing indicators*

Worth to mention is the distinctive positive anomaly of Ni, Pb and S concentrations, limited to the (2360-2530 mMD) interval, noticed on Figure 13 (well GCAH2), which happens to match precisely the non-productive section of the drain, thus confirming their contribution as a micro-fracture (in this instance cemented) indicator.

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.

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

Hence the reservoir approach has been sequenced as follows:

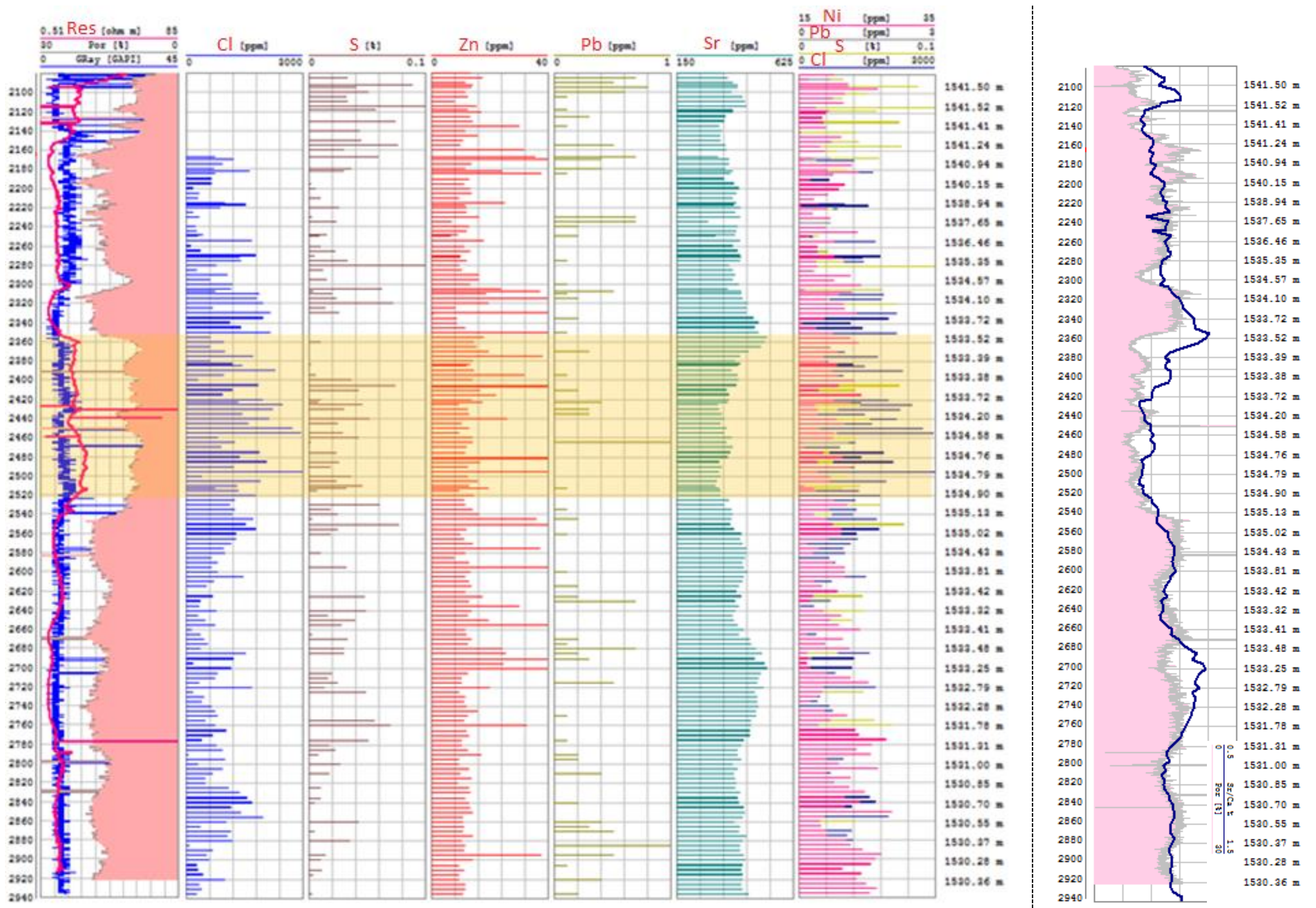
(i) drilling of a 45° inclined pilot hole aimed at assessing the local reservoir layering and performance, eventually complemented by a VSP survey and related reprocessing of seismic lines and seismic faciès,

(ii) design accordingly radial drain profiles, limited to two 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.

Benefits expected from the multiradial well concept have been investigated on a case study addressing a carbonate reservoir environment regarded poorly productive by geothermal district heating (GDH) standards (Geofluid, 2019). Here, GDH objectives require a maximum 400 m^3/hr 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 at 10.5 and 49 m respectively (N/G # 0.2).



a) Positive anomalies in micro-fracture markers. Colored band corresponds to the [2360-2530 mD] low porosity cemented interval

b) Correlation between raw Porosity log and Sr/Ca

Figure 13: Well GCAH-2. Geochemical monitoring display

Prior to drilling, direct assessments reservoir simulation runs based on the well trajectories depicted in Figure 14 and on the *sandwich* equivalent multilayered structure (Antics et al., 2005; Ungemach et al., 2011) proved the validity of the concept displayed in Table 1 (compared performances of selected well architectures), Figure 15 (conventional vs multi radial well delivery curves) and imaged in Figure 16 bottom hole induced temperature and Figure 17 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 (Table 1), a conclusion which emphasings the input of the pilot hole strategy, (ii) the 80° inclined three-legged radial well design achieves a 45° single-legged architecture for the 400 m^3/hr targeted production, and (iii) Figure 16 and Figure 17 clearly illustrate the wider well exposures and related energy savings and thermal longevity to be credited to the recommended, tri-radial/80°, scheme.

WELL ARCHITECTURE	CUMULATED DRAIN LENGTH (m)	MAXIMUM PRESSURE DEPLETION @ 400 m^3/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

Table 1: Impacts of drain architecture on well performance

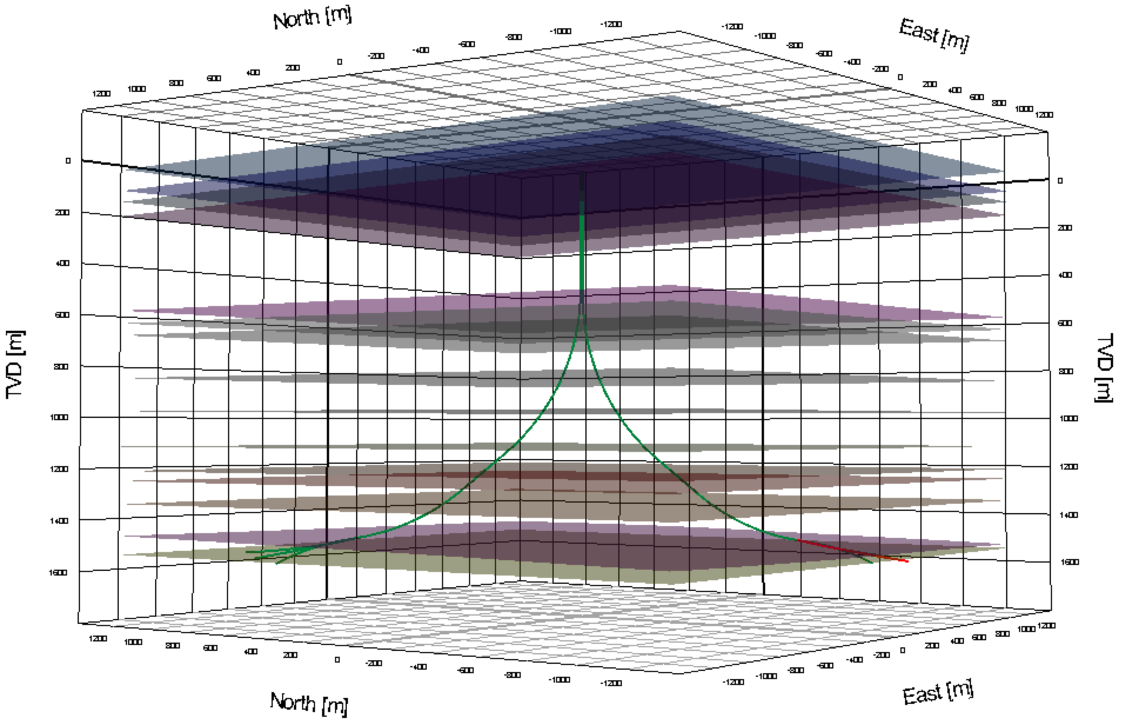


Figure 14: Three, inclined 80°, radial drain well trajectories

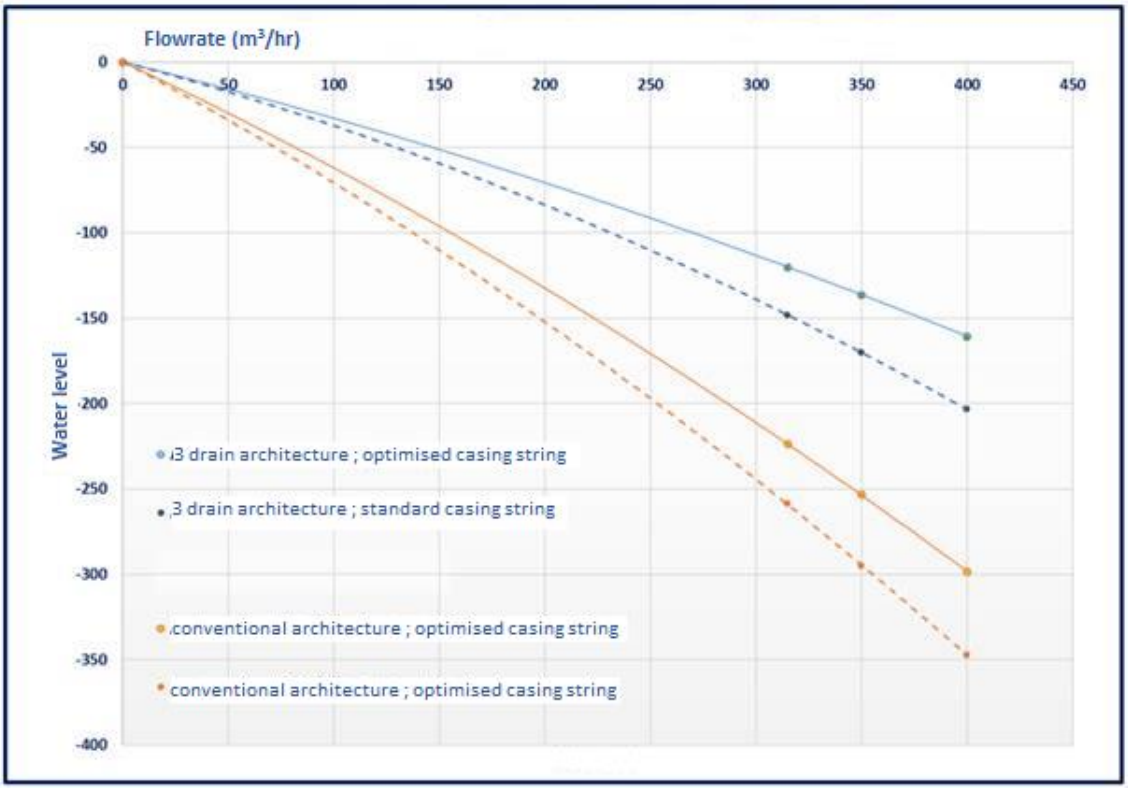


Figure 15: Conventional vs three radials, 80° inclined, drain well delivery curves

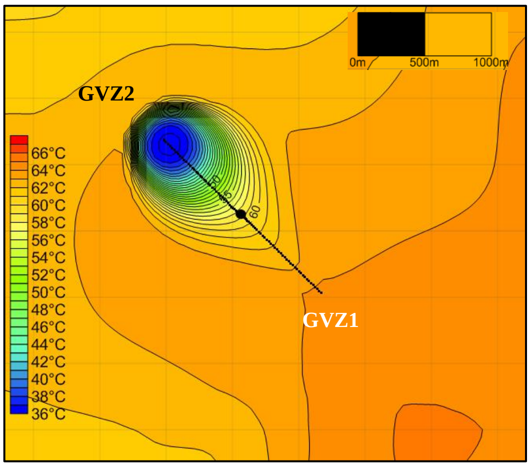


Figure 16.a: Conventional (single, inclined 45°, leg) well architecture

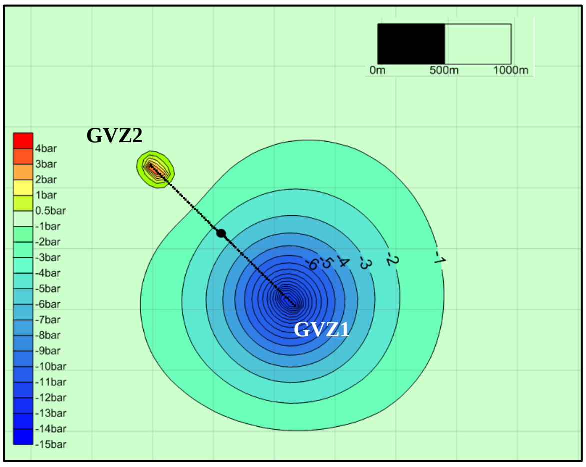


Figure 17.a: Conventional (single, inclined 45°, leg) well architecture

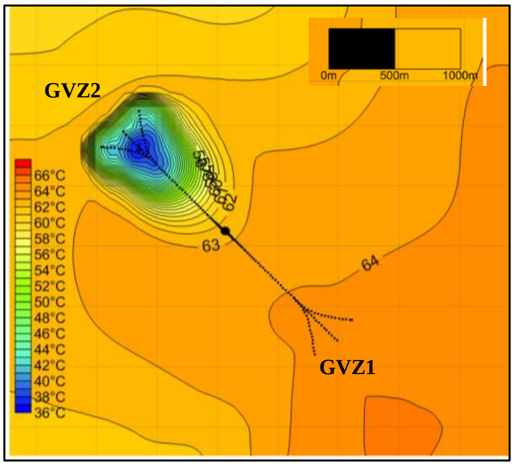


Figure 16.b: Innovative (three, inclined 80°, radial drain) well architecture

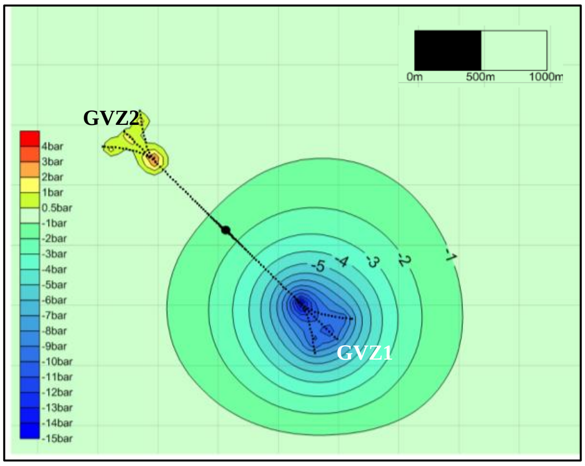


Figure 17.b: Innovative (three, inclined 80°, radial drain) well architecture

Figure 16: Temperature patterns year 30

Figure 17: Maximum pressure drawdowns

4. FIBERGLASS LINED ANTI-CORROSION WELL

Fiberglass-reinforced epoxy resin tubulars have long been regarded as a (composite) material response to corrosion damage, a sensitive issue in the Paris Basin extensively developed mid-Jurassic (Dogger) carbonate reservoir subject to a hostile aqueous-CO_2+H_2S-thermochemical environment.

In spite of this structural advantage, field applications to geothermal wells have been markedly limited. However, it is worth to mention that (i) the cemented fiberglass casing/liner first completed geothermal GDH doublet South West of Paris reported by Anglès (1979), followed (ii) by a geothermal production well (US Patent Office, 1986) combining a 13"$^{3/8}$ steel-cased propping column and a single 9"$^{5/8}$ fiberglass liner, the casing x liner annulus being **kept free** (i.e. not cemented), a well design pioneered in 1985 on the emblematic Melun l'Almont site (Ungemach, 1985).

This former experience validated the fiberglass lining concept with respect to material aging (no fiberglass wheep nor destructuring), well integrity (no heavy-duty workover and no acidizing so far), reduced maintenance (only one master valve change since operation start-up), well productive performance (artesian, non-sustained, 300 m^3/h flowing rate under 2 bar wellhead pressure), in spite of below bubble point self-flowing production and related fluid degassing.

Well architecture, imaged in Figure 18, addresses an artificial lift, pump sustained, production, which implied significant design modifications (Antics et al., 2019), chiefly:

(i) an upper, wider (13"$^{3/8}$ OD-11.97" ID) liner section acting as a pumping chamber, sized to accommodate a 500 HP rated ESP, placed under compression between the wellhead and the lower section;

(ii) a lower and slimmer (9"$^{5/8}$ OD-7.74" ID), freely suspended production liner;

(iii) a (13"$^{3/8}$x9"$^{5/8}$) liner connecting system, placed at the (20"x13"$^{3/8}$) casing interface, allowing for a free annular fluid (a make-up corrosion inhibitor agent) passage, indeed a key issue, and,

(iv) a wellhead expansion spool.

The additional capital investment costs (ca 20% compared to a conventional 13""$^{3/8}$x9""$^{5/8}$ steel cased well architecture) would get paid back in less than eight years thanks to yearly OM (OPEX) cost savings.

Persuing previous uphill climbing innovation trends, a novel well architecture has been designed which ambitions to reconcile both advanced well trajectories with a corrosion-resistant material definition in poorly productive reservoirs and thermochemically hostile fluid settings. The latter resulted in an anti-corrosion subhorizontal well architecture, which aims at producing 300 m^3/hr in a 15 Dm, highly corrosive, reservoir environment. This design benefits from the fibreglass, 5 (5°/30 m), DLS tolerance, compared to the 2.5 maximum sub-horizontal threshold of the SHW profile shown in Figure 2.

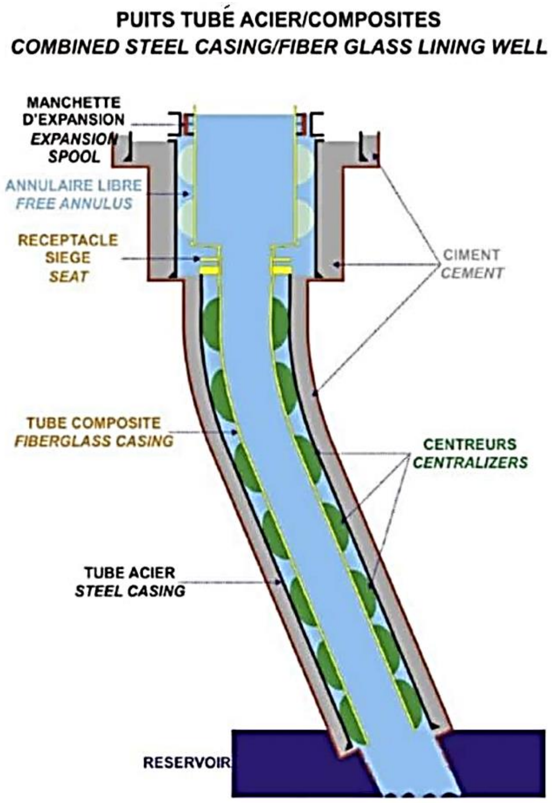


Figure 18: Anticorrosion well architecture

5. DUAL WELL COMPLETIONS

Currently practiced by the Oil and Gas industry, those deserve due consideration while designing production/injection well architectures in areas where exist two dependable reservoirs hosting either geochemically compatible or incompatible source fluids.

Hence, two candidate completions, depending upon reservoir lithologies and fluid compatibilities, have been derived, (i) case 1 which addresses two deep-seated geothermal reservoirs with compatible saline brines, the upper, a consolidated, prolific carbonate aquifer, the lower moderately permeable but hotter, which aggregates less consolidated alternating sand, clay, and sandstone sequences, and (ii) case 2 consisting of two, medium depth, loose sands aquifers and incompatible (unmixable) soaking fluids, respectively.

Figure 19 well profile exemplifies a design which (i) secures the same drift between the top of reservoirs A and B, achieved thanks to the expendable liner (EL) technology, and (ii) a combined ESP sustained production of both reservoirs via a wire wrapped screen/gravel packed assembly (reservoir B) and perforations of the upper (uncemented) EL section *vis-à-vis* reservoir A.

The table below illustrates the gains achieved in productivity and temperature.

Reservoir(s)	Temperature (C°)	Discharge rate (m^3/hr)
A	64	250
B	75	150
A + B	68	400

Poorly consolidated sediments, such as loose sands, and, flow-dependent, suspended solids entrainment arise the problematic, known as sand control, of external vs internal particle-induced damage and subsequent permeability impairment and pore bridging shortcomings (Ungemach, 2003). It may, therefore, be suggested that surface particle filtering is the answer. Actually, several operators have implemented filtering facilities, including chains of the bag to cartridge and millipore units and solid separation thresholds cut down to 1 µm as practiced on the Copenhagen and several Netherland GDH doublet locations.

Limiting the impacts of external particle cake build-up and internal particle invasion would suggest instead to design and operate improved well completions and architectures achieving both downhole filtering and sand face velocity reduction. In this respect, an example of dual completion aimed at producing simultaneously (and separately) two superimposed sandy aquifers (Albian and Neocomian respectively), according to the surface managed geothermal loop, is developed in Figure 20 completion and Figure 21 surface loop schematics (Ungemach et al, 2015). Note incidentally that this well architecture improved by 35% the energy output anticipated from a single well completion.

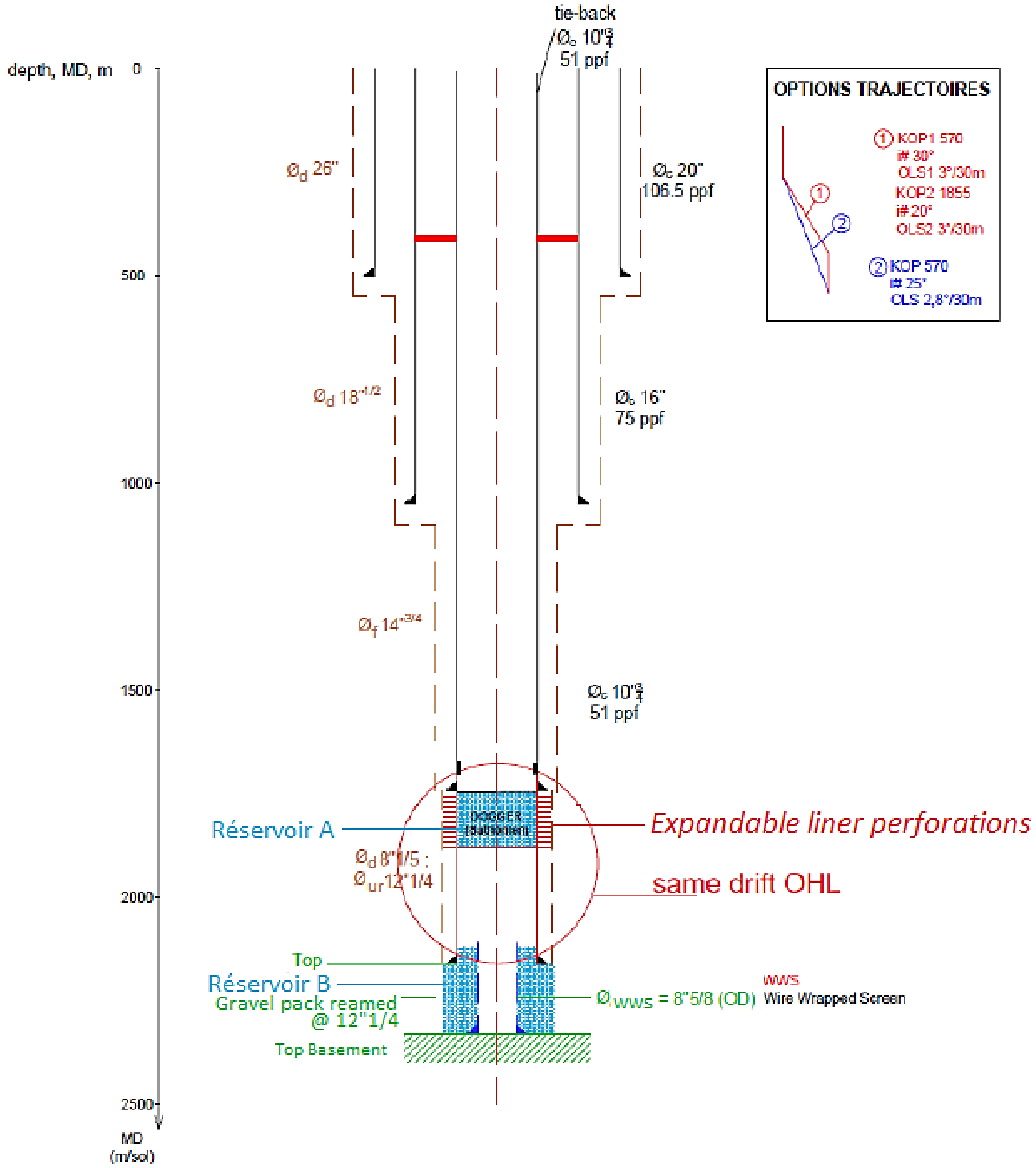
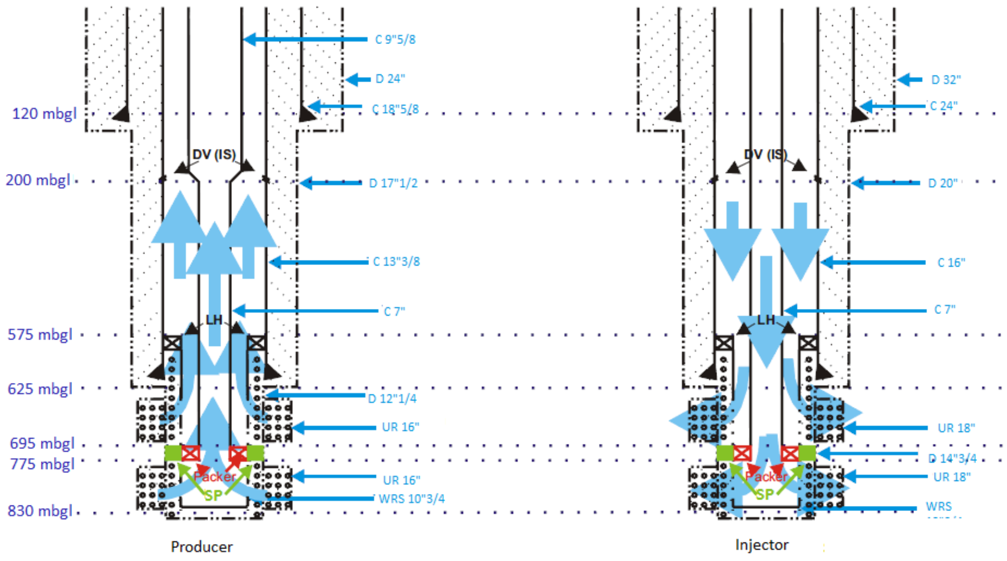


Figure 19: Well profile designed to accommodate a deepening from bottom reservoir A to top of reservoir B via an Expandable Liner (EL) and a dual miscible reservoir production thanks to wire wrapped screens (reservoir B) and EL perforations (reservoir A)

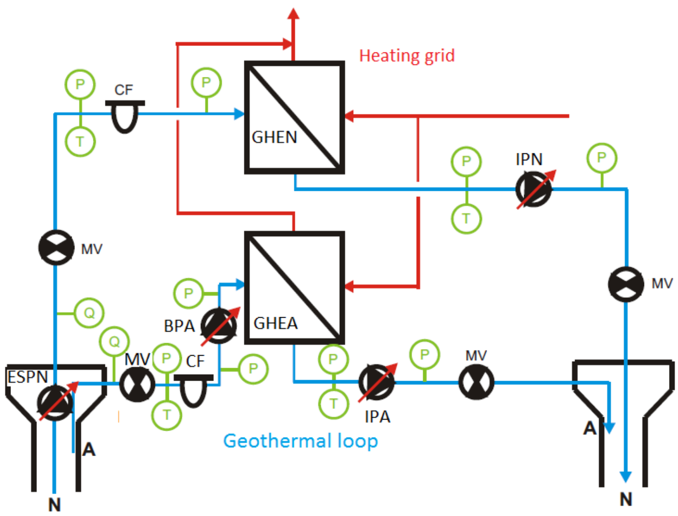


Key:

C : Casing
D : Drilling
DV (IS): Stage Cementing Collar (inner string)
LH: Liner Hanger

SP : Sealing Plug
UR : Under reaming
WRS: Wire wrapped screen

Figure 20: Candidate dual Albian/Neocomian completion



Key:

A: Albian
BPA : Boost Pump Albian
CF: Cartridge Filter
ESPN: Electrosubmersible Pump Neocomian
GHEA : Geothermal Heat Exchanger Albian

GHEN : Geothermal Heat Exchanger Neocomian
IPA : Injection Pump Albian
IPN : Injection Pump Neocomian
N: Neocomian
P/Q/T : Pressure/Flowrate/Temperature

Figure 21: Combined Albian/Neocomian geothermal loop

6. CONCLUSIONS

General and design specific conclusions may be drawn from reviewed well architectures.

There is clear evidence that, in many instances, oil industry practice and know-how can be reliably transferred to advanced geothermal drilling, navigation, and completion undertakings in sedimentary, thermochemically sensitive and densely populated environments, requiring high well deliverability, thermal longevities and meeting safe exploitation standards.

Proposed, innovative compared to prevailing conventional designs, mining schemes seek optimization in the sense they ambition reclaiming low permeability, geochemically hostile, space limited reservoir and fluid settings, which would otherwise remain unchallenged.

Regarding techno-economic concerns, the following existing vs future performances achieved on a recently completed SHW GDH doublet speak for themselves.

STATUS	DOUBLETS	FLOW & ENERGY RATINGS	COP	MINING CAPEX
Existing	2	350 m^3/hr; 40 GWh_{th}/yr	9	14-15 Mio €
Future	1	450-500 m^3/hr; 60-65 GWh_{th}/yr	20-28	12-13 Mio €

Similar conclusions could be derived from the operating fiberglass lined anti-corrosion wells whose long life expectations and OPEX savings secure sustainable exploitation along with economic viability.

More specifically, lessons learned have highlighted

(i) The RSS/PDC bit directional drilling prerequisite, securing fast penetration rates, improved trajectory control and hole calibration, among others. The availability of an RSS designed BHA for the SHW 14"3/4 phase would have significantly impacted drilling and trajectory monitoring performance;

(ii) The benefit, exemplified on SHW well GCAH2, of a multidisciplinary, geosteering team approach, combining drilling, logging, geological, reservoir engineering, geochemical skills and expertise;

(iii) The significant input of the combined NMR/CMR, dipole sonic and density wireline logging segment suggests they become a standard in assessing well/reservoir performance, geomechanical properties and wellbore stability issues;

(iv) Well testing sequences, although limited in time (maximum 45 hrs), which matched satisfactorily horizontal transient well test theory and related time-dependent phases exhibited by pressure derivative plots, and

(v) Last but not least, real-time geochemical monitoring, via XRF and XRD elemental and mineralogic analyses on sampled cuttings, provided rewarding clues with respect to selected (oxides, elemental ratios, proxies) porosity markers and related diagenetic and micro-fracture indicators.

In future designs of subhorizontal and multi radial well architectures, due attention should be paid to (i) cementing procedures and protocols favouring stage cementing of the $10''^{3/4}$ and 16" sections, (ii) accommodate hole transition from the $10''^{3/4}$ cased/cemented to the $8''^{1/2}$ OH drain sections in order to ease the passage of long, tractor driven, OH/PLT wireline, logging strings, (iii) elaborate relevant geosteering strategies, based on either (or both) careful screening of candidate documented offset wells and descending (reconnaissance)/ascending (optimizing) drain trajectories within the identified pay interval, and (iv) longer (up to 120 hrs) well-testing sequences so as to best appraise long term drain hydraulic behaviour in relation to lateral/vertical boundary and anisotropy effects and interlayer cross flow artefacts.

Regarding the anti-corrosion well concept, it should be born in mind that the candidate design is compatible with the in-arch transition of the SHW trajectory thanks to the fiberglass liner DLS specification.

7. ACKNOWLEDGEMENTS

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