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Geothermal De-risking: How to Learn and Succeed from Failure Stories

Mélanie DAVAUX[2], Pierre UNGEMACH[1,2], Miklos ANTICS[1] and Charles NAVILLE[3]

[1]GPC Instrumentation Process (GPC IP)

[2]GEOFLUID

[3]Institut Français du Pétrole et des Energies Nouvelles (IFPEN)

165, rue de la Belle Etoile - Bât. 4A - BP 57072

95947 ROISSY CDG Cedex, France

m.antics@geoproduction.fr

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ABSTRACT

Geologic de-risking and mining sustainability are two inseparable concepts while contemplating geothermal resource exploration and field development issues.

But, contrary to the mining and petroleum industries, the geothermal community shares no global vision of risk assessment and mitigation prior to resource reclamation. Moreover, it lacks a risk evaluation methodology related to resource classification and standardized reporting codes and templates, which incidentally would act as a strong stimulus among potential investors/operators and energy/environmental planners and stake holders.

Whereas a risk analysis of an oil and gas play would currently integrate a number of geologic, tectonic and reservoir features, a geothermal exploratory drilling application would in most instances reduce to the sole temperature and flow performance predictions, regardless of any normalized, multi-attribute, reservoir assessment. Neither is a *post mortem* screening systematically exercised further to well completion and testing.

Recent failures, particularly in the widely developed Paris Basin, Dogger carbonate resource, have shed some light on the mining risk problematic in geothermal exploration of a reservoir; long regarded as a proven reserve of low geologic risk. Here sustainable exploitation of the 48 operated district heating sites raises major issues addressing thermal life and well integrity expectations, which added to injection, induced seismicity in tectonically active areas requires adequate monitoring remedial/preventing procedures and policies.

It became obvious here retrospectively that the oil and gas mining rationale would have thoroughly modified the former exploration/production strategy.

The foregoing is exemplified by several case studies borrowed in most instances from the Paris Basin geothermal development. Lessons learned leads us to share a vision in which the exploration problematic would be revised, and the extensively drilled area revisited as a single development field (equivalent to an oil/gas field development) and not as a multiplicity of "exploration" (according to the mining law) doublets.

Hence, the present paper aims at statistically quantifying the history of geothermal wells and field development on two reservoir case studies via a type of prior to *post mortem* well/campaign review.

Not restricting to the exploration/resource/reserve segment, the assessment exercise advocates the need for a standard geothermal reporting code/template as already practiced or suggested by the Australian and Canadian national organization respectively. Summing up, these guidelines should provide guidance to geothermal explorers and operators by bridging the gap between the less mature geothermal and demonstrated oil and gas know how.

1. INTRODUCTION

Many countries could contemplate harnessing their geothermal potential, thus achieving a significant share of their domestic energy demand either as geopower, geoheat or combined heat and power. However, it has become a common place to lament that geothermal development worldwide does not progress at the expected pace. As a matter of fact, projected (2050) vs present (#2020) installed capacities of geopower and CO_2 emission savings speak for themselves.

	2020	2050
Geopower (GW_{el})	15 (IGA)	200 (IEA)
CO_2 savings (M_{io} tons/yr)	#55	760 (World Bank)

Clearly, the risk inherent to geothermal, as to any mining, exploration venture and related early capital investment in costly drilling works, have slowed down a number of candidate and eligible development targets.

In order to widen the scope of geothermal operators and attract potential investors and stakeholders, risk mitigation policies and financial mechanisms have been implemented by International Institutions (UN, WB, EBRD, Interamerican & Asian Development Banks…) and concessional funding awarded to developing countries. As regards the EU, it is worth mentioning the specific incentives in the form of geopower feed in tariffs (FITs), coverage of wildcat drilling failure costs, support to geoheat exploitation, fiscal advantages (VAT deductions) set up by various national environmental supporting schemes (France, Germany, The Netherlands).

In fact, these mitigation policies and incentives aim basically at an insurance coverage of the geologic risk and at securing (FITs, fiscal exemptions) downstream exploitation economics.

In no way do they question exploration strategies, neither do they provide direct financial and technical support to complementary field investigations prior to drilling.

In addition to the foregoing, resource assessment methodologies and reporting codes are being promoted at European scale (EGEC, EC) and worldwide (IGA). An international template meeting the petroleum and mineral industry standards (Van Vees et al., 2013), is already recommended when not practiced by the Australian (AGCC, 2010) and Canadian Geothermal Associations. Such normalized reporting codes and templates aim at attracting potential investors on reliably identified geothermal plays.

Summing up, ahead of the mining geologic risk, mitigation/insurance and reporting code issues remain the key prerequisite of reconciling on specific targets, predrilling exploration, well design and reservoir conceptual models with upgraded drilling success expectations; which, in many instances, would substitute for the conventional probabilistic (Monte Carlo uncertainty analysis) approach to reservoir performance.

As a result, the forthcoming sections focus (i) on the geological requirements on either reservoir or single well/doublet scales, and (ii) exploratory/development strategies of selected, deep sedimentary Paris Basin settings, according to the petroleum assessment rationale.

2. EXPLORATION RISK: AN OVERVIEW

Risk addresses uncertainty, which encompasses the whole range of possible issues would it imply successes and gains or failures and losses.

Risks and uncertainties fall into four main rewarding, attractive or dissuasive classes, namely:

(i) high economic reward/low geologic risk = frontier exploration,

(ii) high economic reward/high geologic risk = classical exploration,

(iii) poor economic reward/low geologic risk = mature production basin and nearby field,

(iv) poor economic reward/high geologic risk = no interest,

(v) classes (ii) and (iii) are the most frequently encountered.

Risk evaluation in hydrocarbon and geothermal exploration maybe summarized in the Table 1 matrix.

Table 1: Petroleum vs geothermal exploration matrix

Objective	Petroleum	Geothermal
Prospect volume	×	-
Play, system, basin potential	×	No system
Regional, national, worldwide scale	×	×
Economic value & strategy	×	×

In petroleum exploration the recoverable volume is regarded as the dominant geologic risk. Its evaluation, at prospect scale, addresses the following structural, reservoir and fluid characteristics featuring the system potential:

- the source (source rock, maturation, expulsion, migration),
- the reservoir (gross, net, porosity-permeability, saturation, recovery factor),
- the trap (structural, stratigraphic…),
- the cover (vertical, lithology, thickness, stratigraphy, tectonics),

which lead to a success ratio appraisal.

Approaches, depending on available background knowledge and data sets (offset wells…), would currently call for (i) experts (subjective) advice mitigated by a *Delphi Technique* back-up, (ii) comparison of geologic analogs [for instance of conjugate basins as exemplified by the Angola/Brazil pre-salt structures (Hart energy, 2017; Davaux et al., 2019)], (iii) production histories from a large number of well records, and (iv) prospects, plays, system, basin geologic attributes analyzed statistically either via deterministic, probabilistic (PDF/Monte Carlo analysis), geostatistics (3D seismics) methods or/and body mapping, the foregoing occasionally mitigated by various subjective, environmental when not emotional noise sources.

As far as geothermal exploration is concerned, the geologic risk addresses reservoir performance, formation temperature, fluid thermochemistry and well discharge (recharge) rate which represents the major economic risk contributor. Volume appraisals would most often address regional and national resource assessments of heat in place and (technically, economically) recoverable reserves (§3 and Figure 2).

It should be noted that in the sedimentary environments addressed by this paper, most geothermal reservoir structural, lithostratigraphic, hydrochemical and occasionally, hydrodynamic background information originates from previous hydrocarbon exploration/development campaigns under the form of seismic surveys (when released to the Public) and drilling/logging/testing records.

Risk mitigation policies and incentives should be regarded as an insurance covering the mining risk and securing (FITs, fiscal incentives) downstream exploitation economics and benefits.

Simultaneously to the foregoing, resource assessment methodologies and reporting codes are being promoted with a view to set up, European and worldwide, an international template according to petroleum and mineral industry standards (Van Vees et al., 2013) and already either practiced by the Australian (in force) or projected by the Canadian project Geothermal Energy Associations.

Such an initiative, in addition to normalizing geothermal resource/reserve evaluation and classification, is aimed at attracting investments on clearly identified geothermal plays.

The probabilistic (Monte Carlo uncertainty analysis) approach to the geothermal (reservoir/wellhead thermal energies and power generation output, both Log normal distributed) potential associated to the assessment exercise and related P90, P50, P10 probability thresholds is illustrated in Figure 1 assessment chain (Williams et al., 2008). Note incidentally that probabilistic estimates may reduce drastically with time as exemplified by the assessments of the US geothermal potential (in GW_{el}) display in Table 2.

Table 2: Estimates of US geothermal potential (GW_{el})

Installed capacity	Identified		Undiscovered	EGS
(2010)	USGS	1978		
# 3 500	23		100	
	USGS	2008		
	9		30	517 5 (mean)
	MIT	2006		
				#100

However, upstream from the mining risk mitigation/insurance and reporting code issues remains the key prerequisite in reconciling on specific targets, predrilling exploration, design and reservoir conceptual model with upgraded drilling success expectations.

Hence, the present paper focuses on the **geological** requirements on either a reservoir or single well doublet scales and exploratory/development strategies of two deep sedimentary Paris Basin settings according to the petroleum assessment rationale, an example borrowed to a pre-drilled Angola play of which will be commented.

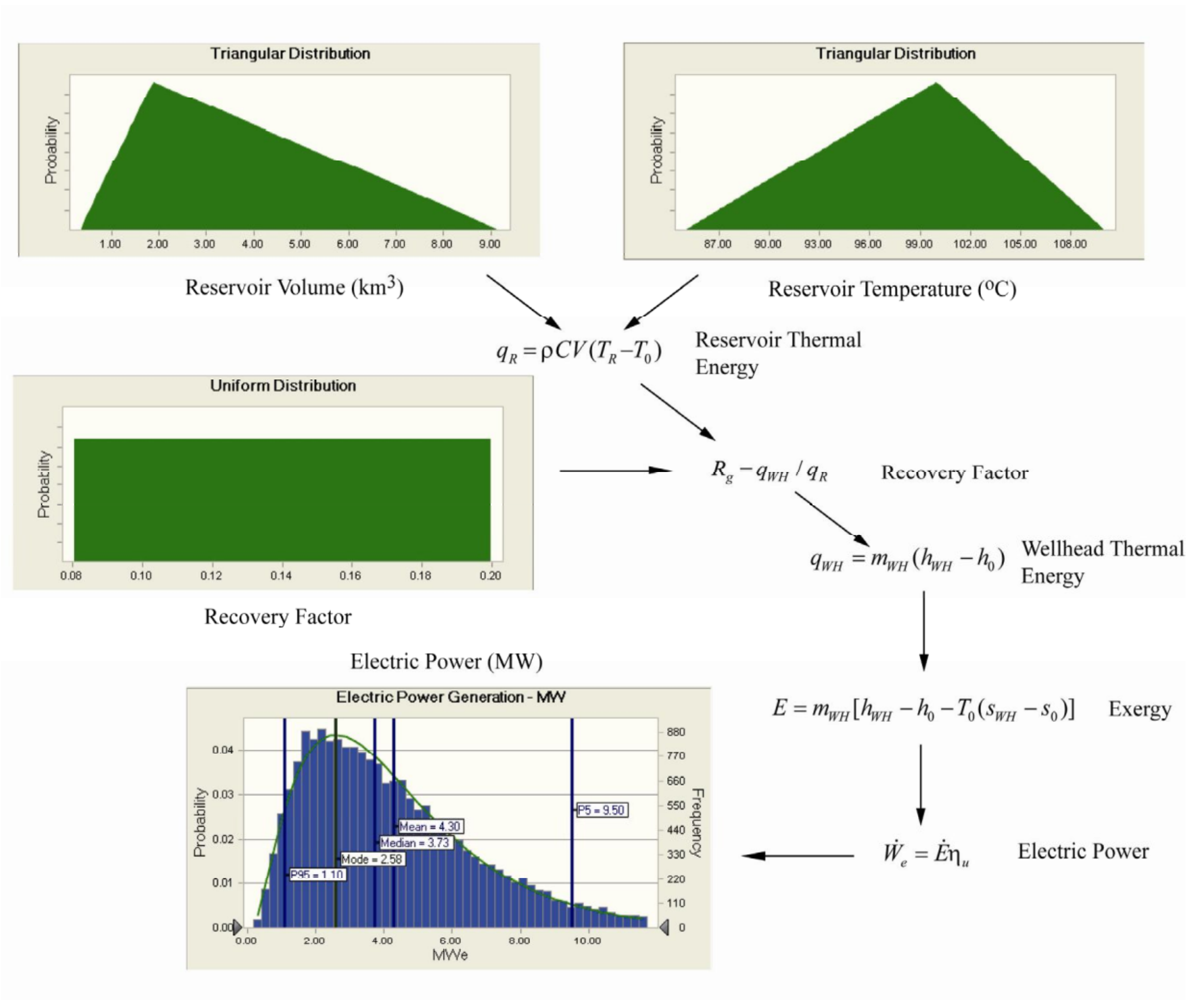


Figure 1: Geoheat and Geopower potential.
Probabilistic assessment chain.
(source: C.F. Williams et al., 2008)

3. PETROLEUM VS GEOTHERMAL DE-RISKING

Despite their distinctive attributes, both sectors (should) display similar pre-drilling exploration strategies owing to the coherent and well-established petroleum body of doctrine. In doing so, respective to geothermal operators, a clear distinction should be made between exploration and development policies and regulatory frameworks.

Petroleum exploration derived risk factors address five headings: source rocks reservoir, trap, seal and timing/migration. Geothermal exploration deals with five leading indicators: reservoir, temperature, productive (injective) capacity, geochemistry and thermal life (sustainability); the latter being strongly connected to the exploitation de-risking issue.

Both sectors differ markedly from the resource volume standpoint by several orders of magnitude from oil (gas) to heat in place (OIP vs HIP), whereas the recoverable marketed heat share reduces drastically, contrary to oil and gas, from heat in place to distributed heat as evidenced by Figure 2 pyramidal sketch applied to the Dutch resource case (Van Vees et al., 2008).

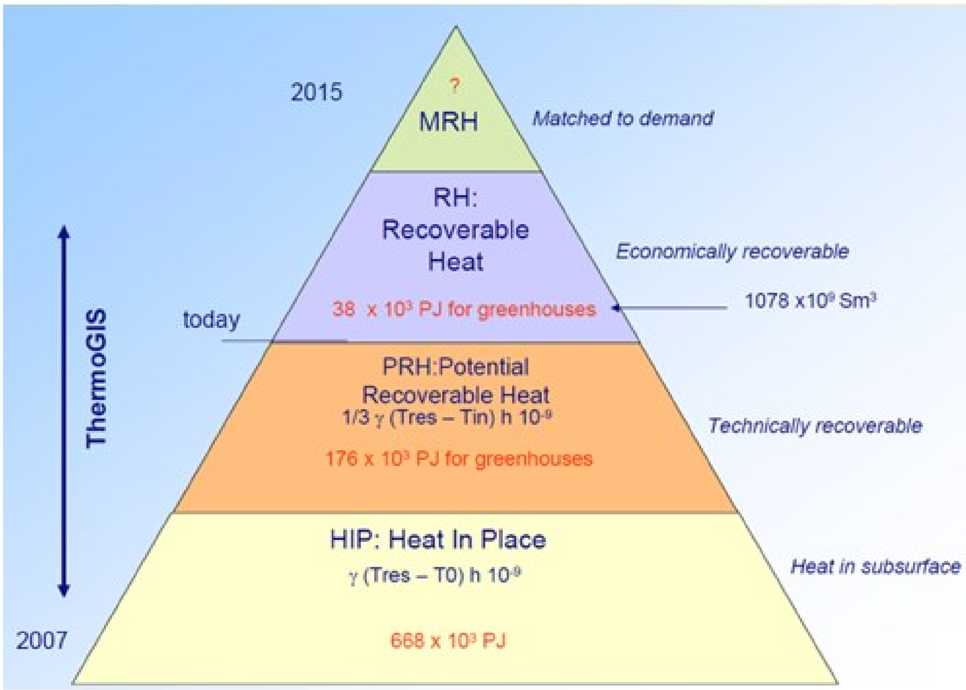


Figure 2: From heat in place to market heat. The Ditch case.
(source: Van Wees et al., 2008)

3.1. A petroleum de-risking case study [Southern Angola (De-Risking the Frontier, Hartenergy, 2019)].

The non-drilled yet Namibe basin (off shore Angola) belongs to a pre-salt Jurassic structure, which stands as the Eastern Atlantic margin of Western Africa and as a marginal conjugate, somewhat asymmetric though, of the dependable and hydrocarbon rich Brazilian Santos and Campos basins *vis-à-vis*. A dual sensor broadband seismic campaign allowed to image the pre-salt/post-salt structures, which, combined with a geoscience marginal conjugate analysis of structural, lithofacies and hydrocarbon feed, led to a comprehensive featuring of a frontier unexplored/unexploited basin.

Pre-salt plays in the Angola province proved rewarding elsewhere as to commercial discoveries, raising due interest among concerned operators.

Summing up, 2D regional dual broadband seismic data processed and migrated to 15 km depths enabled to de-risk basin architecture and pre-salt plays. The latter could be further illuminated thanks to promising premises by a 3D dual sensor survey securing imaging of the pre-salt section and delineation of reservoir facies.

The foregoing issued the following assessments regarding the reservoir system, source rock history, lithofacies distribution, traps, pre-salt structures and CO_2 contamination risks.

- <u>Petroleum system</u>

Undrilled geological and hydrocarbon features were issued from comparison with neighbouring Angola and distant Brazilian conjugate basins, which are amended via sequential stratigraphic analysis. They ultimately complemented inputs from Western Angola Cretaceous outcrops.

- *Source rock history*

Regional thermal and geochemical information in Angola/Namibia were input to source rock modelling, leading to promising maturation profiles.

- *Lithofacies*

Comparison to similar Angolan and Brazilian conjugate replicates and 3D seismic findings, enabled to delineate pre-salt facies, which were further compared to drilled analogs in Angolan and Brazilian fields.

- *Traps*

Aptian salt diapirs appear to act as the main seals

- *Pre-salt structures*

Those could be successfully imaged and a basin structural framework reliably derived.

- *CO_2 contamination*

Thanks to additional gravity and magnetic offshore surveys, CO_2 contamination could be derisked due to the unlikelyhood of mantle sourced CO_2.

This case study illustrated how assisted modern 2D/3D seismic and geoscientific analysis applied to an undrilled and unexploited play could be thoroughly assessed and further successfully drilled.

3.2. A geothermal mining risk assessment

Antics and Ungemach (2010) quantified the geothermal risk related to high and low enthalpy well productivities, by defining critical success/failure criteria.

- **The high enthalpy case**

The single flash conversion cycle and entropy diagram are represented in Figure 3. From the well output parameters and Figure 4 delivery curve, namely:

Formation temperature: 250°C
Cold source (condenser) temperature: 50°C
Condenser pressure: 0,120 bar
Separator pressure (single stage flash): 10 bar
Separator temp. (single stage flash): 180°C
Mass flowrate @ 10 bar: 110 kg/s
Power output @ 10 bar turbine inlet: #10 MW_{el}

the full success and total failure figures stand at 10 MW_{el} and 5 MW_{el} respectively.

- **The low enthalpy case**

Production success/failure criteria relating to the geothermal district heating scenario listed below and imaged in Figure 5 stand as follows (2010 economy standards):

INV=12 10^6 €
OMC=5 10^5 €
n=20 years
nh=8256 hr/yr
r=5% (total failure)
r=10% (total success)
Full equity (zero debt)
Subsidies=25% INV
C=35.45 MWt
T=45.4°C

Full success
Q=299 m^3/h; no subsidy, c=35 €/MWh_{th}
T_{wh}=70°C T_i=45°C
T_{wh}=65°C T_i=40°C
Q=200 m^3/h; 25% subsidy, c=45 €/MWh_{th}
T_{wh} unchanged

Full failure
Q=246 m^3/h; no subsidy, c=35 €/MWh_{th}
T_{wh}=70°C T_i=45°C
T_{wh}=65°C T_i=40°C
Q=155 m^3/h; 25% subsidy, c=45 €/MWh_{th}
T_{wh} unchanged

In this instance, the success/failure criteria produced by associating well productivity and exploitation economics were adopted by the French Environmental Agency Risk Mitigation Fund.

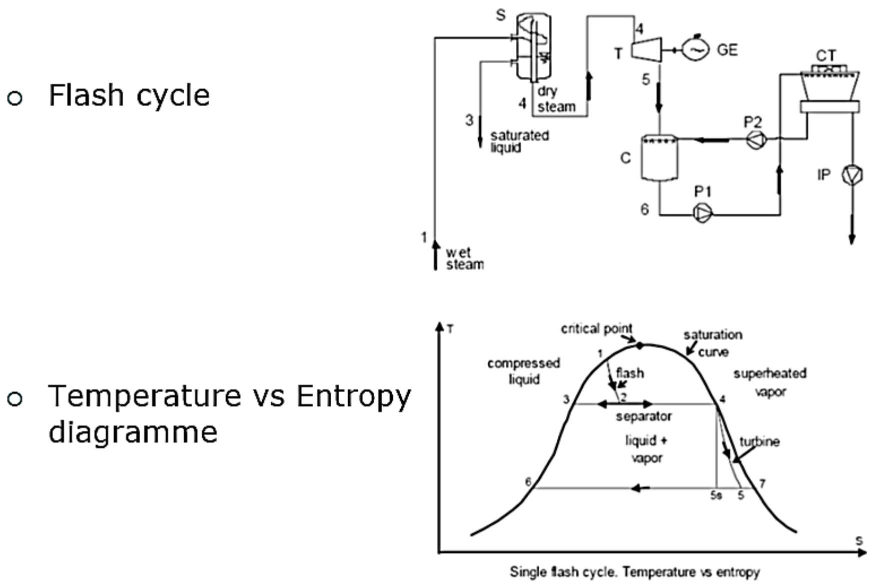


Figure 3: The high enthalpy power scheme

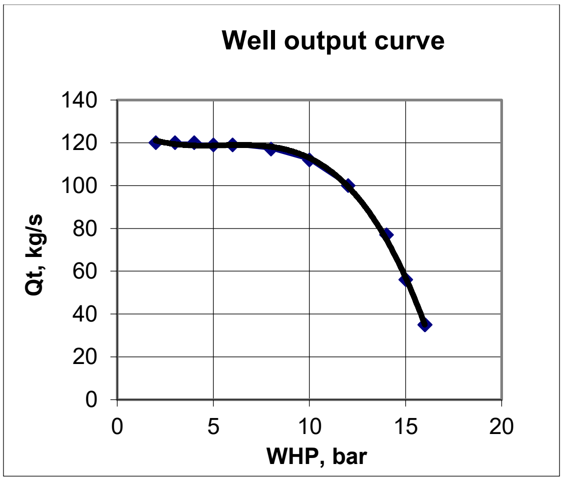
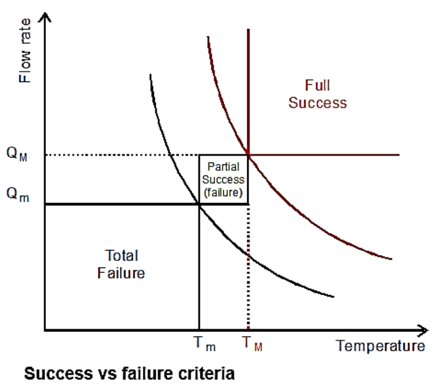


Figure 4: The high enthalpy well delivery curve



Full success:

$$Q\left(T_{wh}-T_i\right)=\frac{1}{1.161\cdot nh\cdot c}\left[A\cdot INV+OMC+\frac{INV}{n}\right]$$

Total failure:

$$Q'\left(T_{wh}-T_i\right)=\frac{1}{1.161\cdot nh\cdot c}\left[A'\cdot INV+OMC+\frac{INV}{n}\right]$$

Where:
Q, Q' = flowrate (yearly average) (m^3/h)
T_{wh} = production wellhead temperature (°C)
T_i = injection temperature (yearly average) (°C)

$$A=\frac{r(1+r)^n}{(1+r)^n-1}$$

$$A'=\frac{r'(1+r')^n}{(1+r')^n-1}$$

INV = capital investment (€)
OMC = operation and maintenance costs (€/yr)
c=heat selling price (€/MWh_t)
n = project lifetime (years)
nh = number of operating hours per year
r, r' = discount rates

Figure 5: The low enthalpy success/failure diagramme

4. TOWARDS A RELEVANT EXPLORATION VS EXPLOITATION RISK MANAGEMENT. A PARIS BASIN PROBLEMATIC

4.1. Exploration de-risking

Geothermal development of the central part of the Paris Basin was initiated in the late 1970s in Bathonian Oolithic limestones of Mid Jurassic (Dogger) age via the doublet concept of heat farming, combining a production well and an injection well pumping back the heat depleted brine into the source reservoir. The 54 to 84°C resource, at depths ranging from 1400 to 200 mTVD, extends over ca 6000 km².

Almost one half of the 48 geothermal district heating (GDH) doublets serviced to date are located in the Val de Marne (94) district south of Paris, a 250 km² area where the resource is regarded as well-known and recognized of high potential.

This area undergoes a paradoxical setting. The dependable nature of the reservoir in terms of pressures, temperatures and transmissivities is based on geostatistical (kriging) interpolation methods regardless of any complementary investigation of the sedimentological body and associated depositional, diagenetic and micro-fracturing attributes whatsoever.

Nevertheless, it can be noticed (Figure 6) that the transmissivity distribution within the 10 to 90 Dm range remained unchanged during the two 1983-1987 and 2007-2018 key development periods (i.e. 40% of the wells stand below 20 Dm). More surprising, the most favourable zone stretching eastwards is widely untapped, which reflects land occupation and market-oriented concerns instead of reservoir performance as such. The same rationale is applied by the Mining Code; regulating geothermal exploration/production where each new doublet settlement requires to an exploration lease application, in an area of proven reserve!

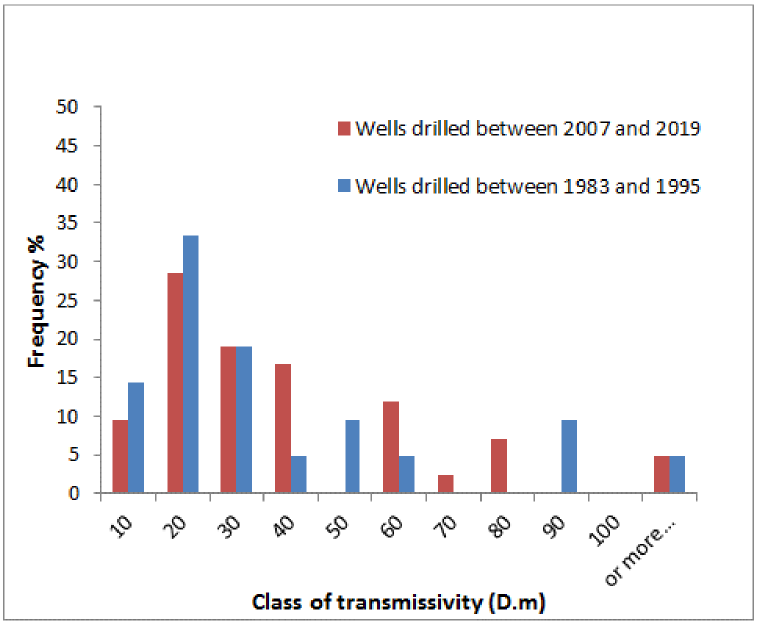


Figure 6: Transmissivity of wells drilled in the Val de Marne and the Hauts-de-Seine Districts

As a result, the new Cachan subhorizontal well achievement (Ungemach et al., 2019) ought to be regarded as a compensatory means, enhancing well performance along prolonged thermal life in a reservoir area, mapped in Figure 7, dominated by low transmissivities, high GDH doublet densities and locally depleted formation temperatures.

This paradox leads us to share a vision in which the exploration problematic would be revised, and the extensively mined area revisited as a single development field (equivalent to an oil field development) and not as a multiplicity of "exploration" doublets. Therefore, modern reservoir evaluation and management would prevail, calling on (i) permanent downhole sensors and Fiber Optics technology to investigate lateral variations in reservoir characteristics, (ii) thorough evaluation of 2D, 3D and occasionally 4D surface seismics whose implementation may be questioned in sensitive, densely populated areas, and (iii) the latest drilling/navigation/completion/logging technologies such as Measurement (MWD) and Logging (LWD) while drilling, Rotary Steering Sytem (RSS) Geosteering and advanced formation evaluation Nuclear Magnetic Resonance – (NMR) and Full Wave Sonic – (FWS) logging tools whose cost would amount to that of a lost/dry well, a risk covered by the *ad hoc* mutualised insurance mechanism.

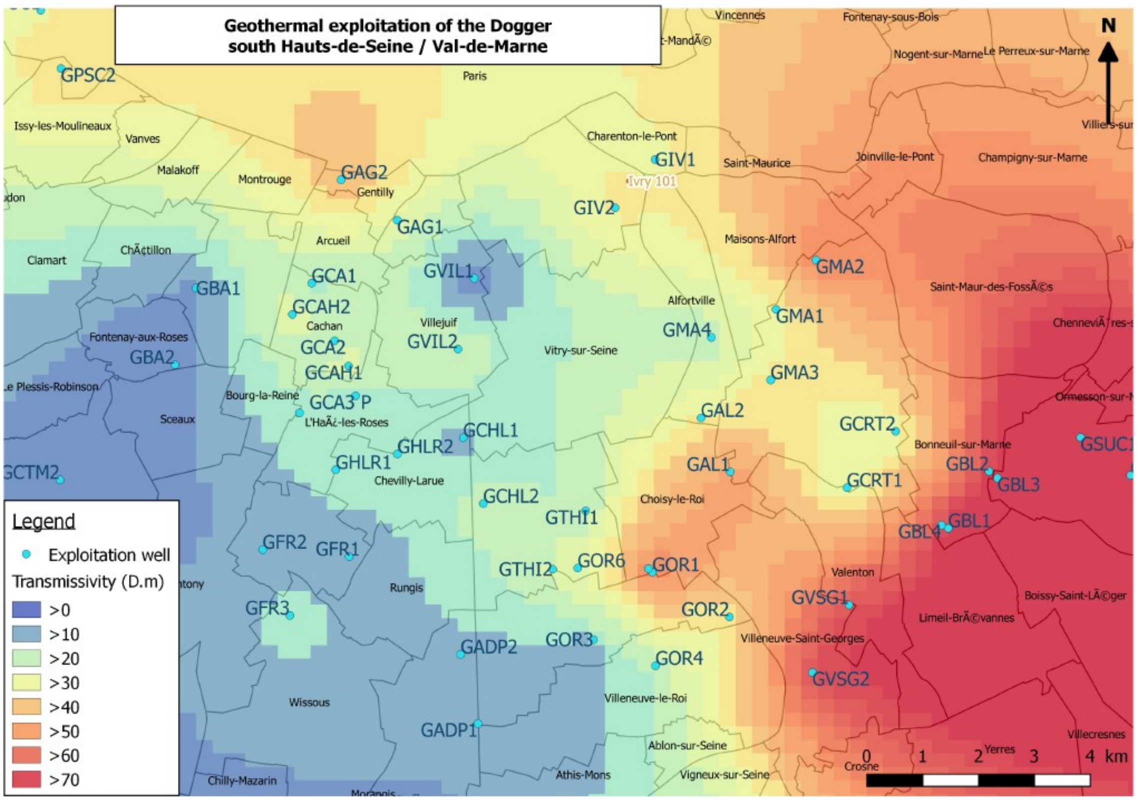


Figure 7: Location of GDH doublets South of Paris (Val de Marne and Hauts-de-Seine districts)

4.2. Sustainable exploitation de-risking

Long term, far sighted, production of a renewable, though exhaustible, geothermal source requires well integrity, thermal longevity, sustained well deliverability and low, non-damaging, induced seismicity. This is what sustainable geothermal exploitation is all about. Note that induced seismicity whose impact is negligible in the stable, poorly tectonized and non-gas depleted sedimentary Paris Basin context will be mentioned allusively *in fine*.

Well integrity

It implies (i) wellbore stability in a given, preferably known, *in situ* stress field, (ii) corrosion, resistant materials or/and efficient corrosion/scaling inhibitor systems, and (iii) efficient cementing procedures and cement slurries.

As a result, geomechanical modelling including torque & drag and stress check calculations documented via appropriate logging (density, dipole sonic) tools and leak off/formation integrity tests while drilling should be the rule during drilling and further exploitation phases, especially when dealing with complex well trajectories requiring stress resistant casing/liner design.

Corrosion is currently defeated by (i) anticorrosion well designs combining steel propped casings and fiberglass lined wells with a free annulus of the type described by Antics & Ungemach (2019), which can cope with horizontal/subhorizontal non tortuous (DLS ≤ 5) well trajectories, and (ii) inhibitor formulations aimed at abating corrosion/scaling shortcomings by means of downhole chemical injection lines of the AIT (auxiliary injection tubing) type which are currently operating in Paris Basin wells (Ungemach & Antics, 2018).

State of the art cementing protocols and appropriate cement slurries and additives, generally class C (including Puzzolan lightening agents), replacing conventional stage cementing practice in the case of long range cased sections are a prerequisite to prevent micro-annulus (debonding) and channeling casing/liner damage.

Nevertheless, operation at high flowrates in thermochemically hostile fluid environments limits well physical life at nominal ratings thus requiring appropriate mining schemes and well completion discussed later.

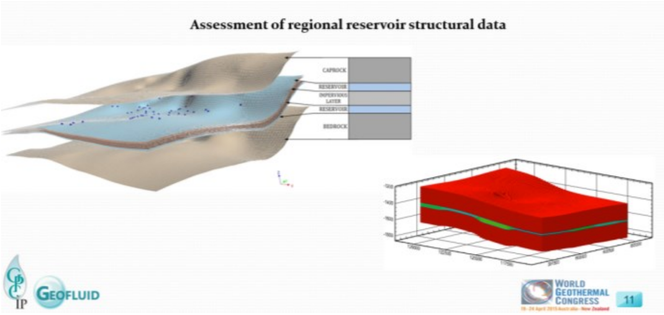
Thermal longevity

Since cooling has already occurred on several Paris Basin GDH production wells, reliable prediction of cooling kinetics and thermal breakthrough times is a key reservoir management issue based on a dependable conceptual model.

Hence, whatever its complexity, in no way should reservoir multilayering be neither ignored nor reduced to an over simplifying (stacked) single layer equivalence. The latter proved misleading while simulating, either numerically or analytically, reservoir cooling kinetics and production well thermal breakthrough.

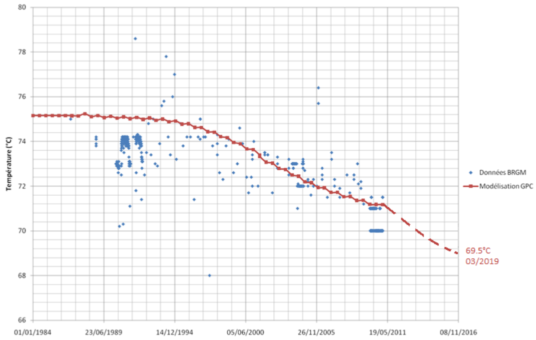
Thus, the symmetric so called *sandwich* equivalence, proposed by Antics et al (2005) and Ungemach et al (2011), to reliable model heat mass transfers in such quasi 3D multilayered reservoir settings, sketched in Figure 8 a, enabled to accurately match the observed cooling history (Figure 8 b); its extension to the initially single layer assessed resource/reserve and breakthrough analytical calculations is summarized in Figure 8 c, and the *sandwich* conductive heat resupply concept validated in Figure 8 d case study. It has been since then systematically applied in prefeasibility design engineering surveys.

CASE STUDY, RESERVOIR SIMULATION OF HEAT AND MASS TRANSFER



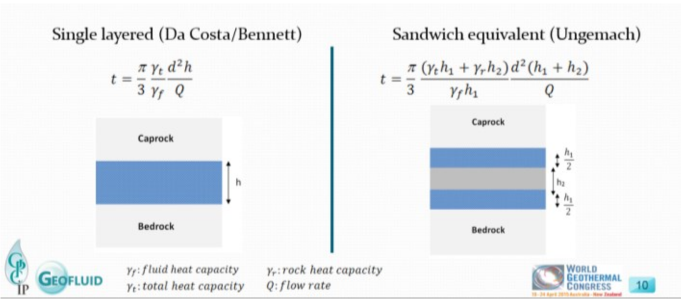
a) Multilayered equivalent sandwich reservoir

CASE STUDY, ACTUAL VERSUS SIMULATED WELL COOLING KINETICS HISTORY MATCHING



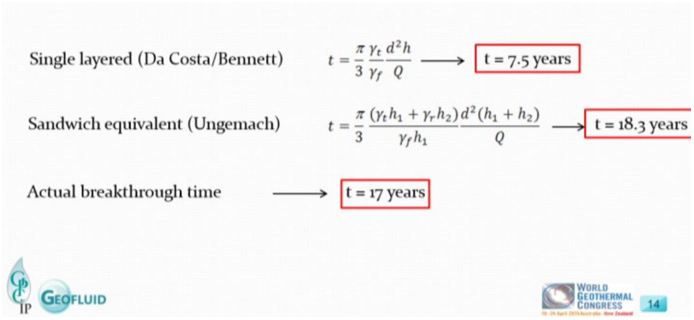
b) Model calculated cooling kinetics

RESERVOIR LAYERING
ANALYTICAL FORMULA THERMAL BREAKTHROUGH



c) Thermal breakthrough formula

CASE STUDY
COMPUTED AND MODELLED/MEASURED THERMAL BREATHROUGH



d) Comparataive thermal breakthrough results

Figure 8: Doublet thermal life expectations. A case study

A sustainable heat farming scheme

Exploitation records dating back to the mid-1980s have shown that, with the exception of a 1985 fiberglass lined production well, almost all GDH wells have hardly exceeded 10 to 15 years without undergoing a heavy duty casing lining workover reducing either (or both) 13"3/8 pumping chamber and 9"$^{5/8}$ production/injection casing diameters to 10"$^{3/4}$ and 7", 7"$^{5/8}$ lining diameters respectively.

In order to prolong the physical and thermal life and generate added value to a mining asset that's often patrimonial, the three 25 year staged well doublet (initial), triplet (intermediate), doublet (final) arrays described in Figure 9 has been advocated. Figure 10 simulation suite images the three successive end stage pressure/temperature patterns and injected water aerial extents. No thermal breakthroughs expressed as a maximum 1°C temperature depletion have been evidenced so far in simulation runs.

4.3. More about sustainable doublet performance

In areas subject to high GDH doublet/triplet densities and occasionally to low transmissivities and depleted formation temperatures, the subhorizontal well architecture, recently completed at the Cachan site (Paris South Eastern suburbs), provides high well performance (up 450-500 m^3/hr) along prolonged thermal life (Ungemach et al., 2019).

4.4. Induced seismicity

Contrary to the somewhat dramatic events reported in Basel (Fabbri, 2013) and Pohang, South Korea (Grigoli et al., 2018) further to massive hydrofracturing of faulted basement rock masses and the seismic activity recorded as a consequence of the Groningen depleted gas fields (Van Thienen & Breunese, 2015), the Paris Basin, being a poorly tectonized and seismically quiet region with no significant gas field exploitation, is not concerned by this issue.

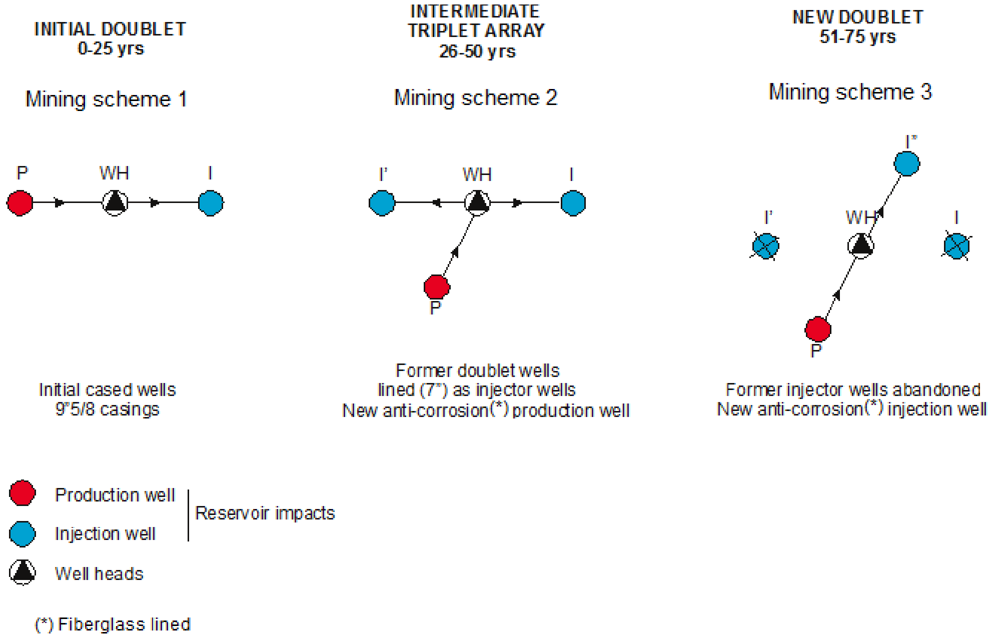
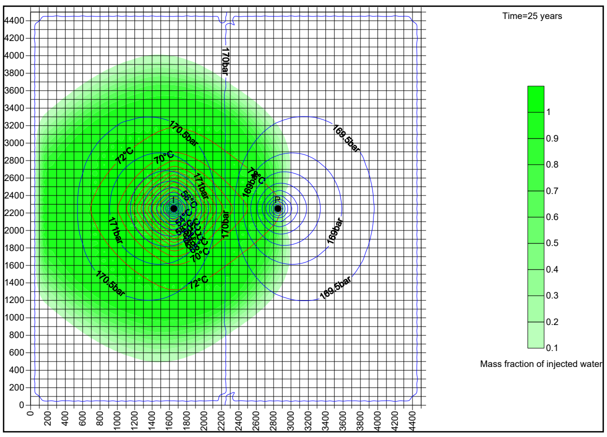
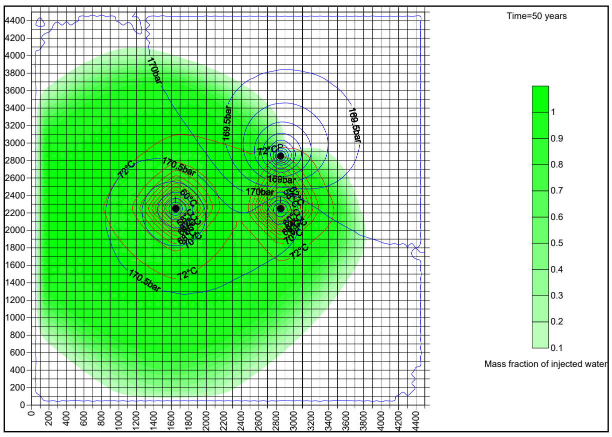


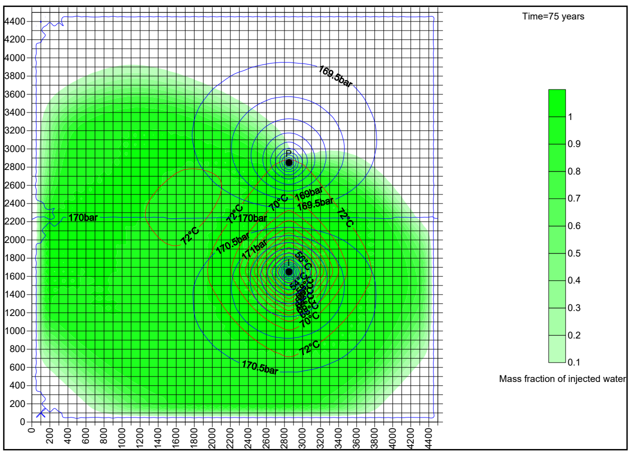
Figure 9 : A 75 year sustainable farming scheme. Candidate well arrays



a) Scheme 1. Year 2010



b) Scheme 2. Year 2035



c) Scheme 3. Year 2060.

Figure 10 : A 75 year life sustainable heat farming scheme. Simulated pressure/temperature patterns and mass fractions of injected brine

5. CONCLUSIONS

The reviewed, exploratory pre (and post) drilling back up strategies, practiced by the petroleum and geothermal sectors, lead to the following conclusions. In spite of their sectorial specificities, it is strongly recommended that the upstream geothermal exploration methodologies in similar sedimentology environments seek guidance from the oil industry know how and stand more closely to the geological background knowledge, the essence of any reservoir occurrence and assessment, a statement supported by both a typical petroleum case history and the paradoxical mining strategy applied to the Paris Basin heat farming outlook.

It is important not to be overlook the post exploration reservoir development issues, which require sustainable resource exploitation strategies securing prolonged well/reservoir life, bearing in mind that, although renewable, geothermal energy sources are exhaustible. In order to defeat premature reservoir cooling kinetics and extend well physical lives, appropriate multiplet GDH mining schemes and advanced well completions and architectures have been designed and field proofed.

REFERENCES

AGEA-AGEG (2010). Australian Code for Reporting of Exploration Results. Geothermal Resources and Geothermal Reserves. The Geothermal Reporting Code, Second Edition, 28 p., Canberra, Australia.

Antics,M., Papachristou,M., Ungemach,P. (2005). Sustainable Heat Mining. A Reservoir Engineering Approach. Proc. Thirtieth Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, Californie, January 31-February 2, 2005.

Antics,M., Ungemach,P. (2019). The Bonneuil fiberglass lined anti-corrosion production well. Paper accepted for poster presentation. European Geothermal Congress, EGC 2019. Den Haag, The Netherlands, 11-14 June 2019.

C.F. Williams, M.J. Reed, R.H Mariner (2008). A Review of Methods Applied by the U.S. Geological Survey in the Assessment of Identified Geothermal Resources, U.S. Dep. of the Interior, U.S. Geological Survey, Open-File Report 2008-1296, 27p.

Davaux,M., Ungemach,P., Antics,M., Naville,C. (2019). Geothermal De-risking. How to Learn from Failure Stories. Paper accepted for oral presentation. European Geothermal Congress, EGC 2019. Den Haag, The Netherlands, 11-14 June, 2019.

Fabbri,S. (2010). Correlation of Stress Variations and Natural Fractures in the Basel Geothermal Borehole (Switzerland). B. SC. Thesis, ETH Zürich, Switzerland, 2010.

Grigoli,F. et al (2018). The November 2017 M_w 5.5 Pohang Earthquake: A Possible case of Induced Seismicity in South Korea. Science June 2018 Issue, Vol.360, Issue 6392, pp.1003-1006.

HARTENERGY (2017). De-Risking the Frontier. A New Study Provides a Clearer Image of the Namibe Salt Basin, 3 April, 2017.

J.D. Van Vees, T. Boxem, P. Castagno, C.Desayes, C. Lacasse, A. Manzella (2013). A Methodology for Resource Assessment and Application to Core Countries. GEOLEC. Deliverable n°21, March 2013, Brussels, Belgium.

M. Antics, P. Ungemach (2010). Quantifying Risk in Geothermal Development. The High Enthalpy and Low Enthalpy Cases. Proc. GRC Annual Meeting, 24-27 Oct. 2010, Sacramento, CA.

Ungemach,P., Antics,M., Lalos,P. (2009). Sustainable Geothermal Reservoir Management Practice. Transactions Geothermal Resource Council. Annual Meeting, Reno, Nevada, 4-7 October, 2009.

Ungemach,P., Promis,M.P., Antics,M. (2015). Actual Versus Predicted Well Cooling Kinetics. Implications on Reservoir Modelling Approaches. Proc. World Geothermal Congress, WGC 2015, Melbourne, Australia, 19-25 April 2015.

Ungemach,P., Antics,M., Davaux,M. (2019). Subhorizontal Well Architecture and Geosteering Navigation Enhance Well Performance and Reservoir Evaluation. A Field Validation. Proc. 44th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, February 11-13, 2019.

P. Ungemach, M. Antics, M. Davaux (2019). Subhorizontal Well Architecture Enhances Heat Production. The Cachan Milestone European Geothermal Congress, EGC 2019, 11-14 June, 2019, The Hague, The Netherlands.

Van Thienen, K., Breunese, J.N. (2015). Induced Seismicity of the Groningen Gas Field: History and Recent Developments. The Leading Edge, **34** (6), 664-671, June 2015.

World Bank (2018). Feature Story, Geothermal Energy is on a Hot Path, May 3, 2018.