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Assessment of Deep Seated Geothermal Reservoirs in Selected European Sedimentary Environments

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ABSTRACT

Europe features a large variety of sedimentary environments. They most common environments host dependable geothermal reservoirs thus favoring the exploitation of hot fluids within low to medium enthalpy ranges, among which geothermal district heating (GDH) and combined heat and power (CHP) undertakings hold a dominant share.

Four selected reservoir settings including carbonate and clastic deposits in the Central part of the Paris Basin, the Southern Germany Molasse Basin in the Münich area, the Netherlands Basin and the Upper Rhine Graben, respectively; will be presented and the exploratory, modeling and development strategies will be discussed accordingly.

Whereas 2D (reprocessed) and 3D seismic surveys have become standard in matching the distinctive features of a deep buried karst (reef facies, an echelon faulting, carbonate platform layering) and a key to drilling success in the Molasse Basin, and in a lesser extent in the Upper Rhine Graben, thus emphasizing a leading exploratory rationale, the Netherlands and Paris Basin instead benefit from a mature database inherited from extensive hydrocarbon exploration campaigns with concern focused on reservoir modeling and sustainable management issues.

As a result, the lessons learned from the foregoing activities have enabled to build up a nucleus of expertise in the whole chain from resource identification to reservoir assessment and market penetration.

The seismic risk, indeed a sensitive though somewhat emotional issue, which is requiring special attention and microseismic monitoring from the geothermal community, will also be commented.

1. INTRODUCTION

The geodynamics of the European Plate provide a variety of sedimentary environments eligible for geothermal uses wherever they host dependable reservoirs matching a nearby heat (or cold) or/and power demand.

Actually, Europe at large (i.e., continental, Iceland and Turkey) exhibits a number of resource settings mapped in figure 1, that feature distinctive geodynamic attributes and end uses, summarized here under.

- ***Large sedimentary units*** subdivided into:
  - Intracratonic basins (Paris-Hampshire, Aquitaine, Tajo, Castillan, Rhone-Langedoc, West Yorkshire-Netherlands, North German, Danish, Warsaw, Thracean)
  - Orogenic belt foredeeps (Pyrenean, Ebro, Caltanisetta, North Alpine, Po Valley, Apenninic, Carpathian)
  - Marginal/back arc basins (Pannonian, Transylvanian, Aegean)

    These host, generally multiple, aquifer systems with normal, low and high geothermal gradients favouring direct uses, among which geothermal district (GDH) and greenhouse heating (GHH) hold a prevailing share.
- ***Tertiary-quaternary continental rifts*** (Rhine Graben, Limagne, Rhone-Bresse, Campidano, Pantelleria) eligible for medium enthalpy/CHP prospects and, ultimately, for Enhanced Geothermal Systems (EGS) development. Two EGS plants are operating already at Soultz, FR and Landau, DE.
- ***Orogenic fold-belts and foreland platforms*** often associated with deep faults and upwelling thermal fluids circulation thus favouring medium enthalpy reservoirs, providing sound design data for closed and open systems.
- ***Crystalline massifs*** (Iberic Meseta, Armorican, Central France, Bohemian, Rhodope) with hot springs and hydrothermal fault systems.
- ***Recent "in plate" Pliocene/Quaternary volcanism*** (Catalunya, Chaine des Puys, Eifel, Campidano, Susaki), regarded as candidates for medium enthalpy, and if not EGS, projects.
- ***Active subduction zones, volcanic island arcs, active magmatic and recent or active extensional horst and graben settings***, hosting high-enthalpy volcano-tectonic structures eligible for power production from either dry steam (Central Tuscany) or liquid dominated (Iceland, Western Anatolia) sources.

The scope of this paper is focused on typical sedimentary basins, orogenic belt foredeeps and continental rifts which stand among the best candidates for direct use and combined heat and power (CHP) applications.

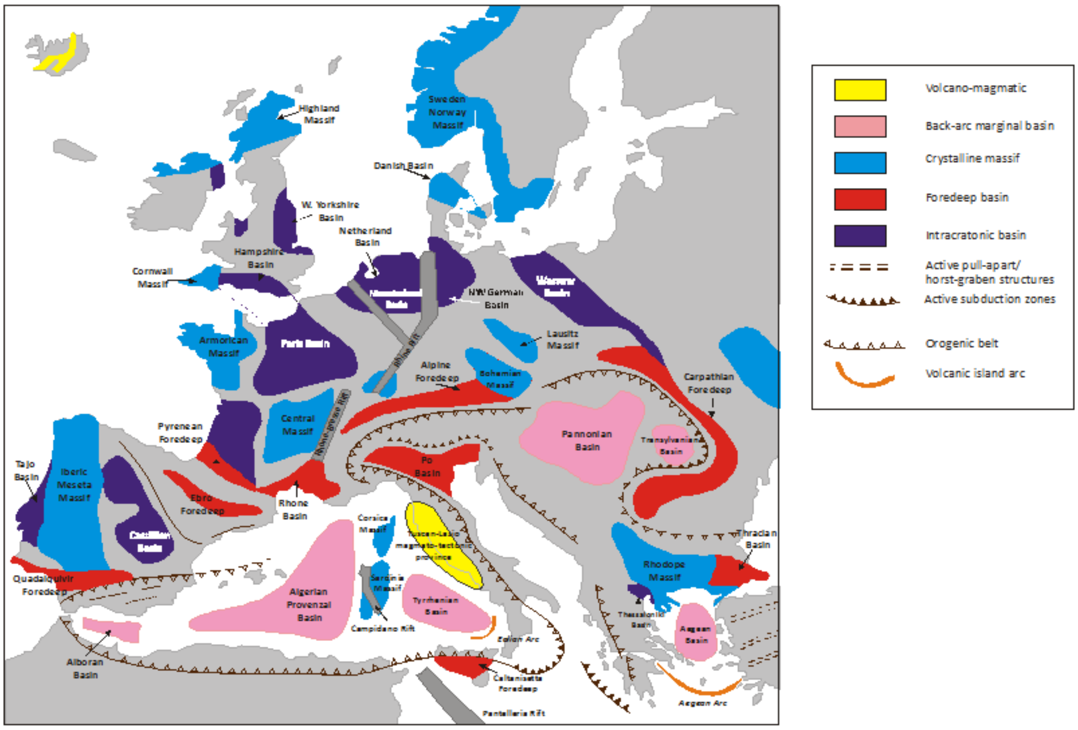

Figure 1: European geodynamic environments (after Sommaruga & Ungemach)

As a result, four typical sedimentary settings exemplifying contrasting geodynamic, depositional and tectonic features, namely (i) the southern Germany Molasse basin (Alpine foredeep, carbonate, fractured), (ii) the Paris basin (intracratonic, carbonate, micro-fissured), (iii) the Netherlands basin (folded rift, clastic, matrix), and (iv) the Upper Rhine Graben (continental rift, clastic, crystalline, fractured), will be presented and commented from the resource occurrence, identification and sustainability stand points; and the exploration, modeling and development strategies will be discussed accordingly.

The input of the foregoing into the design of a coherent, success rewarding and cost effective exploration/production methodology and sustainable resource management policies will be highlighted.

Last but not least, the sensitive, somewhat dramatized, induced seismicity issue will be discussed alongside its risk mitigation, microseismic monitoring and communication implications.

2. SELECTED SEDIMENTARY RESERVOIR ENVIRONMENTS

The salient features of the selected geothermal provinces with respect to deep seated reservoir settings are summarized in table 1.

Table 1: Selected Basin Characteristics

ITEM \ REGIONS	MOLASSE BASIN	PARIS BASIN	NETHERLANDS BASIN	UPPER RHINE GRABEN
Stratigraphy	Upper Jurassic MALM	Mid Jurassic DOGGER	Permo Triassic Rotliegend/Buntsandstein	Lower Triassic
Facies	Carbonate	Carbonate	Clastic	Clastic
Tectonics impact	High	Low	Moderate/High	Active
Flow type	Fractured	Fissured	Matrix	Fractured
Depth, TVD (m)	2 000/3 500	1 500/2 000	2 000/3 000	2 000/3 000
Temperature (°C)	70 – 150	56 – 85	70 – 100	90 – 150
Mineralization (@ TDS mg/l)	<1	20 – 30	> 100	> 100
GWR (val/vol)	ND	0.1-0.2	> 1	ND
Seismicity (Natural)	Low	Low	Low	High
Mining risk	High	Low	Moderate	High
Uses	GDH/CHP	GDH	GDH/GHH	GDH/CHP

2.1 Southern Germany Molasse reservoir

Over the past decade the Molasse Basin, in the Münich area, became a primary exploration and development objective of the German programme with 23 GDH and CHP doublets completed so far (@ early 2014) and 12 scheduled in the near future (Ühde, 2014) (see Figure 2).

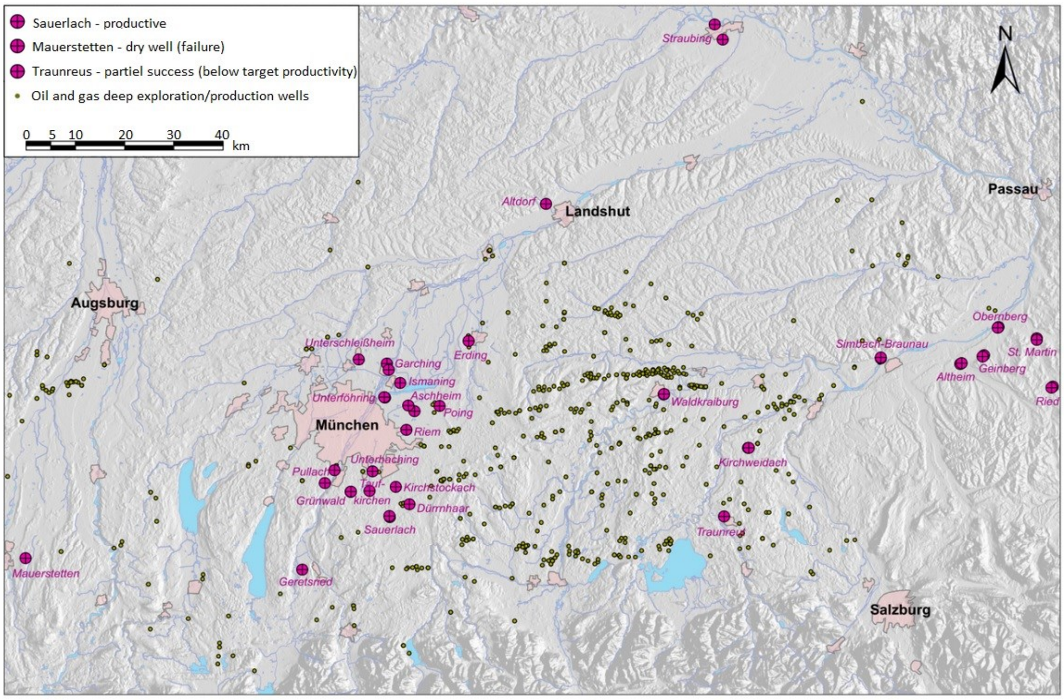

Figure 2: Location of deep geothermal projects. Münich area (source : Erdwerk, 2014)

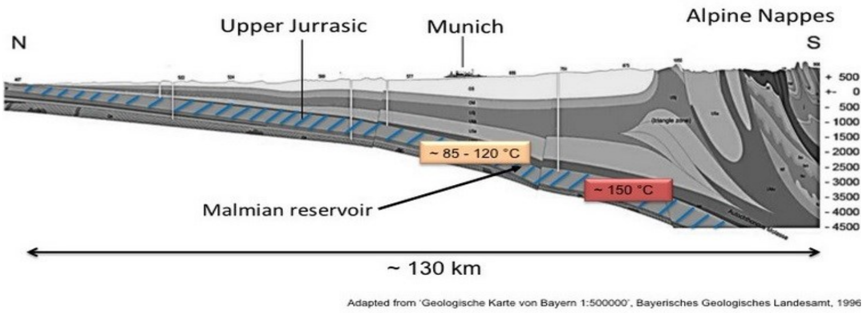

Figure 3a: N-S Thematic Cross Section (source : Mirjolet, 2014)

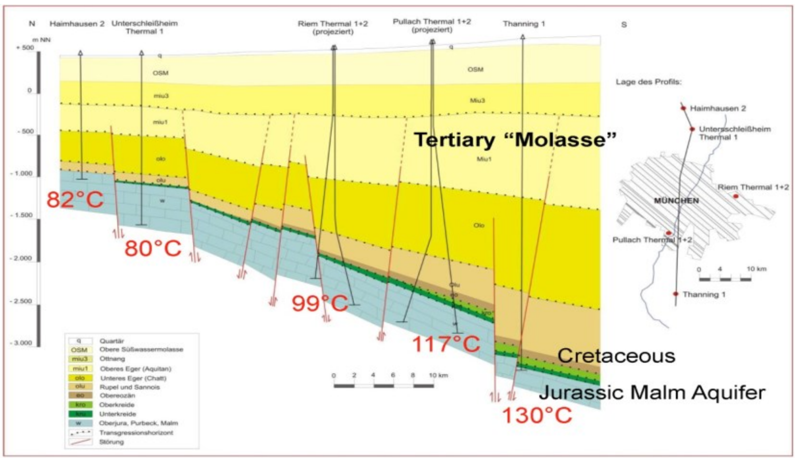

Figure 3b: N-S Cross Section evidencing the Malm *en echelon* fault block strcture (source: Erdwerk, 2011)

Figure 3: N-S Cross Sections. Molass basin

The drilling objective is the Malm (Upper Jurassic) fractured carbonate whose structural and temperature patterns are illustrated in the fault block *en echelon* trend, dipping southwards towards the Alpine Nappes, depicted in Figure 3.

The ability to differentiate lithofacies in a carbonate platform, overlain by fault lineaments and karst systems (Schubert et al, 2008), is a prerequisite to drilling success, which may prove a delicate exercise when contemplating Figure 4 well trajectories (Mirjolet, 2014).

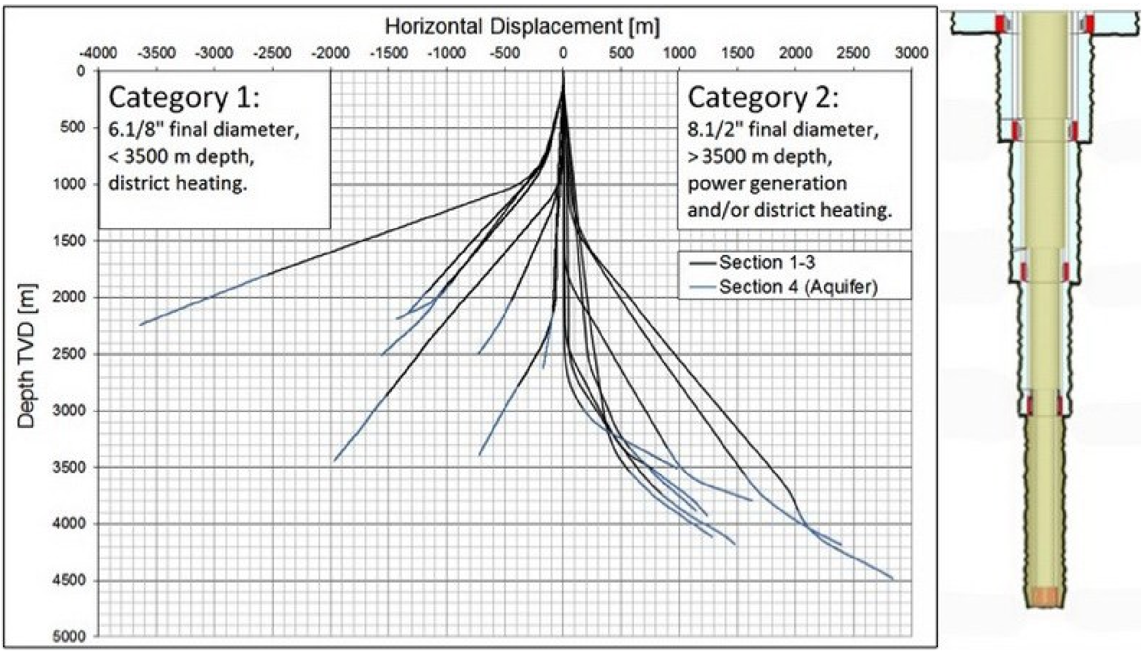

Figure 4: Malm targeted well trajectories (source : Mirjolet, 2014)

Fault matching, facies identification and karst occurrence are key factors while spotting productive reservoir zones, since it depends on facies and diagenesis bearing in mind that coarse, crystalline and dolomitized, reef facies enhance connected porosity, i.e., permeability. To simplify, faults ease access to permeable areas, i.e., karst systems and reef edifices capping massive and thin bedded reef limestones, a path imaged in Figure 5 cross section, which incidentally shows the impact of seismic processing.

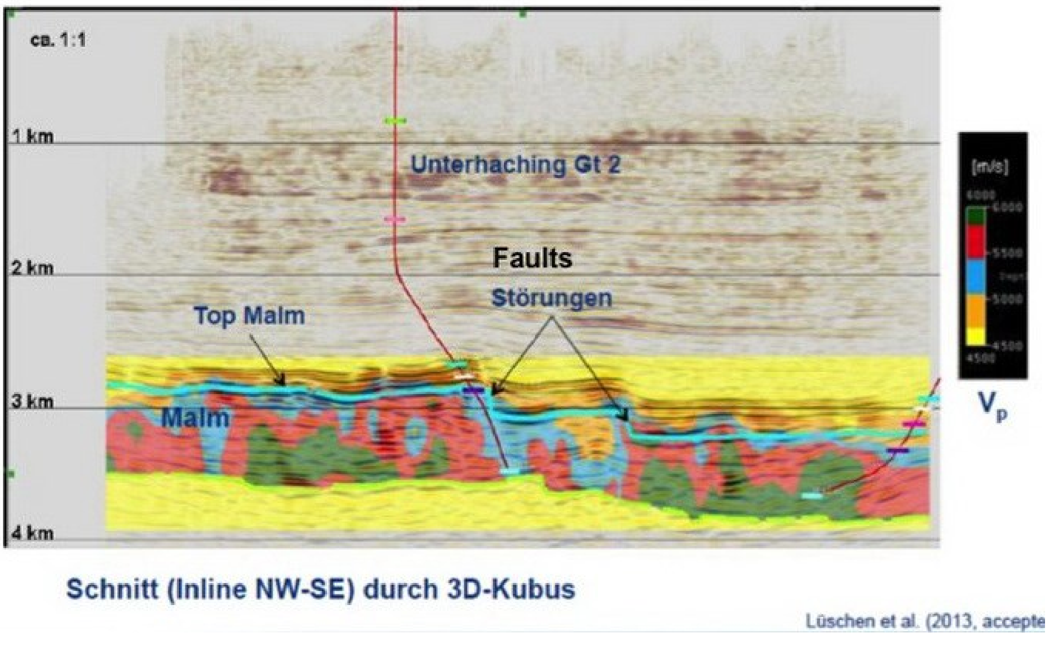

Figure 5: Selected seismic attributes (source: Luschen et al, 2013, quoted by Knapek, 2014)

As a matter of fact, the aforementioned problematic definitely required extensive application of reflection seismic that is routinely practiced by geothermal operators. Nowadays, reprocessing of existing 2D lines, implementation of 3D seismic and VSP surveys have become a standard (almost twenty 3D surveys completed to date) and a request from investors and insurance companies.

Processing requires thoroughly exercising seismic facies and stratigraphy analyses, seismic (velocity) inversion, and attributing analysis (Buness et al, 2010; Von Hartmann, 2012). It proves rewarding a methodology as shown in Figure 5 which enabled to spot the second well of a doublet further to a VSP assisted, reprocessing of the former 3D seismic survey (Knapek, 2014). In other circumstances, a formerly dry well could be retargeted/sidetracked (sub-horizontally) towards a productive zone with the use of seismic reprocessing (Erdwerk, 2012).

In spite of the fracture dominated exploration rationale, it is reported that in most instances well tests exhibit a quasi-radial porous matrix flow signature (Dorsch, 2012), a fact noticed in other similar, presumably fractured/fissured, carbonate reservoirs (Paris Basin).

Summing up, the sedimentary investigations backed by 3D seismic and well seismic profiles systematically implemented secured rewarding (over 80%) drilling success ratios, not expected beforehand, in areas of high mining risk.

2.2 Paris Basin

Within the aquifer sequence shown in Figure 6 the Dogger (mid-Jurassic) carbonates host a dependable reservoir of regional extent, exploited since the late 1970s with a total of 61 GDH doublets drilled of which 36 (including six triplet recompleted doublets) remain online (early 2014 status) a figure likely to dramatically increase with 15 doublets commissioned until 2008 (Ungemach, 2014) (Figure 7).

The Dogger reservoir belongs to a stable, poorly tectonised, intracratonic meso-cenozoic basin and to a thermo-subsidence process initiated during the Permo-Triassic. Its structure is the result of the geodynamics of the Western Eurasian Plate, i.e., (i) opening and closing of the Thetys Sea, and (ii) opening of the Atlantic Ocean.

Lithofacies and subsidence evolution from the Triassic to Cretaceous, along with the geochemistry of clay minerals, suggest a geodynamic model resulting from (i) a long lasting subsidence, (ii) successively accelerating/decelerating, transgressive/regressive cycles, and (iii) diagenetic events occurring at 190 MY (200 – 250°C), 150MY and 80MY.

Summing up Figure 6 stratigraphy is determined by three governing factors namely (i) subsidence (tectonic component), (ii) sea level changes (eustasy), and (iii) influx/production of sediments, leading to distinctive paleogeographic attributes of Dogger carbonates, i.e., (i) marine transgression and subsidence (sedimentary mass and crustal stretching), and (ii) reef carbonated sedimentation.

The Dogger Bathonian member takes place in the carbonate platform where it occupies the upper part in the platform complex that corresponds to the maximum calcarenitic deposition associated to oolithic limestones, exhibiting high connected porosity and subsequent permeability.

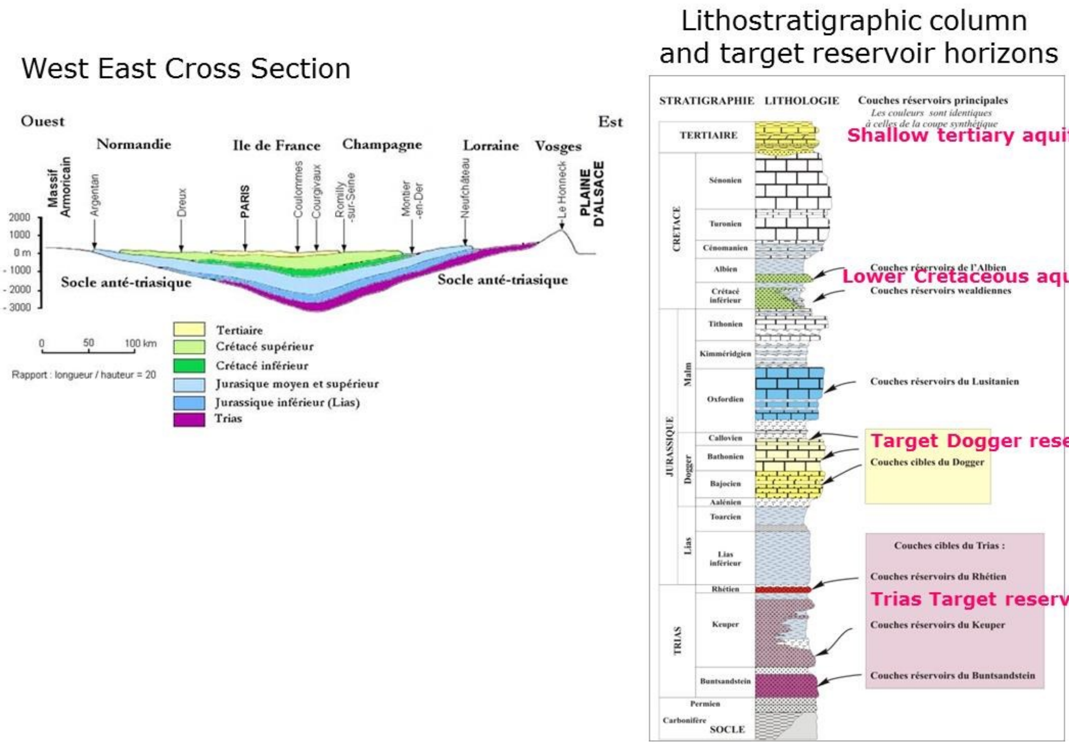

Figure 6: Paris Basin. Geological overview

Well to well correlations of pervious layers identified via flowmeter logs (Figure 8) may prove a tedious exercise as they are in most instances biased by layer discontinuities induced by post depositional diagenetic processes (dissolution, compaction, fracturing and recrystallization) adding complexity to the porosity typology.

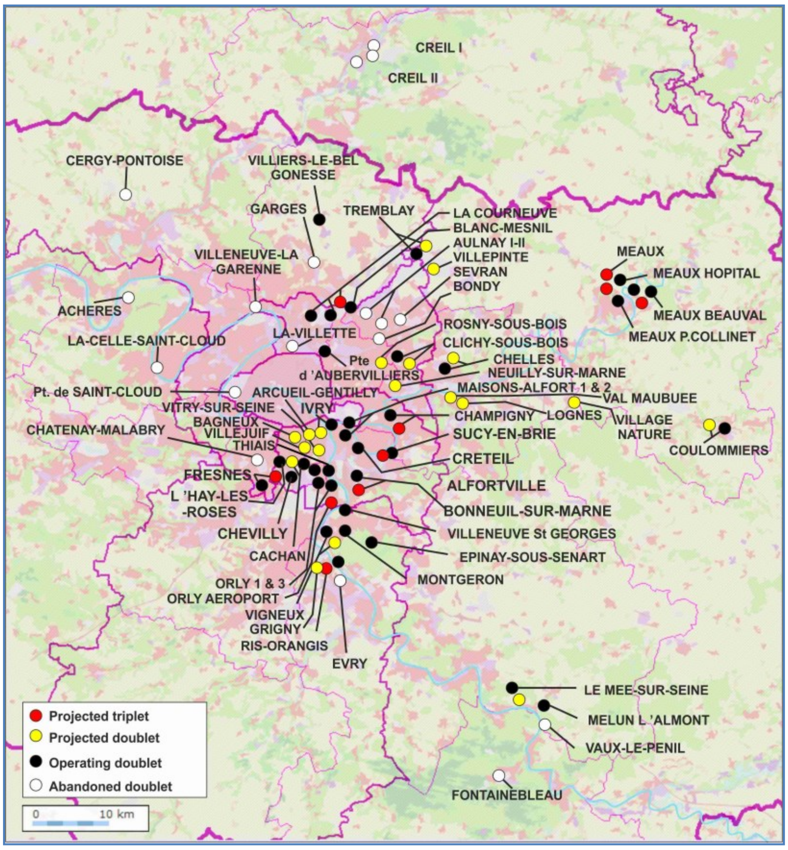

Figure 7: Paris Basin Dogger reservoir. GDH status (@ 2013)

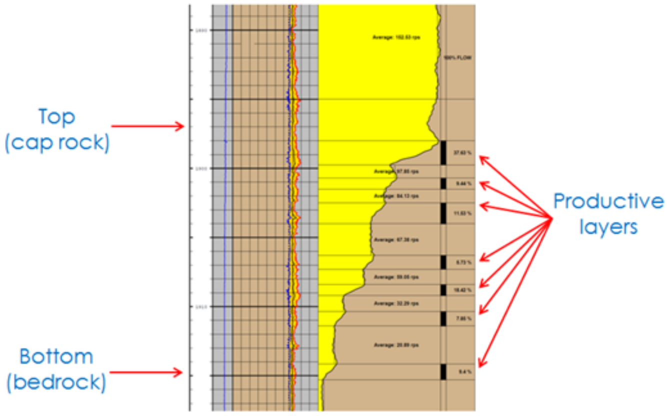

Figure 8: Dogger reservoir. Flowmeter log of reservoir section

Here, as noticed in the Molasse Basin, well test transient pressure draw down/build up responses conform to the (non-fractured) infinite acting line source model leading us to advocate a micro fissured porosity/permeability mechanism reacting at macroscopic scale as a matrix porosity medium.

Whatever its complexity, in no way should reservoir multilayering be neither ignored nor reduced to an oversimplifying single (stacked) reservoir equivalence. In fact the latter has proved misleading while simulating reservoir cooling kinetics and estimating production well thermal breakthroughs (Antics et al, Ungemach et al, 2011).

Hence the symmetric, so called *sandwich*, equivalence sketched in Figure 9 has been proposed by Antics et al (2005) and Ungemach et al (2005, 2011), to reliably model heat and mass transfers in such quasi 3D multilayered reservoir settings.

2.3 The Netherlands Basin

Most of the Dutch territory, often characterized as a folded rift province (see cross section documented in Figure 10), holds an important geothermal potential (Lokhorst & Wong, 2007). Deep sedimentary reservoir targets are hosted by Permo-Triassic (Rotliegend, Buntsandstein) and Lower Cretaceous sand and sandstones (Slochteren formation).

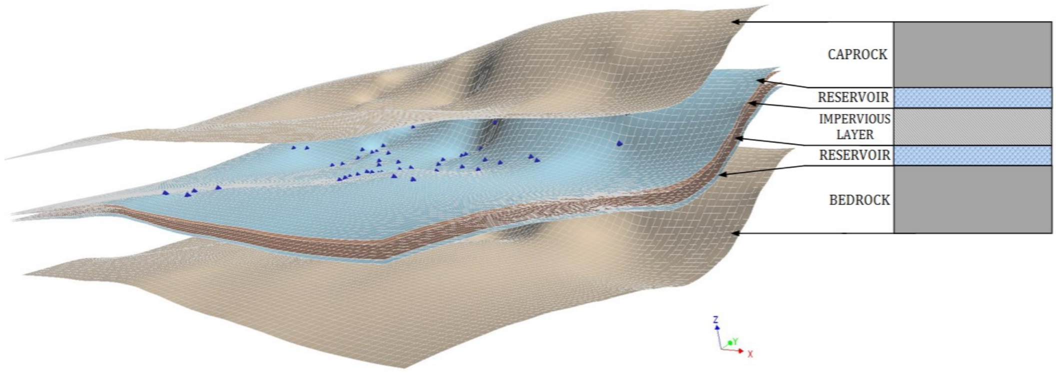

Figure 9: Dogger reservoir. 3D geomodelling view of the sandwich multilayered reservoir equivalence

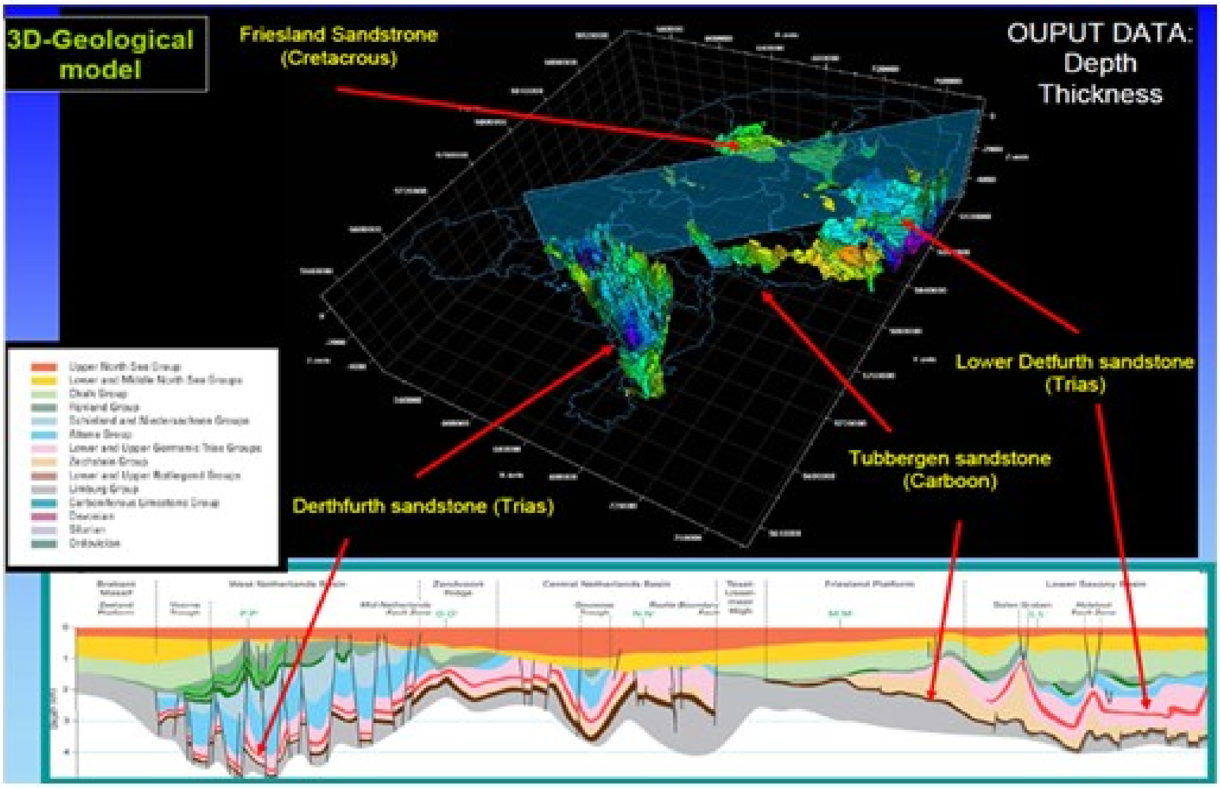

Figure 10: Netherlands Basin. EW Cross section and 3D structural model (source : TNO)

Triassic sandstones (Main Buntsandstein subgroup) in the southern and north eastern parts of the country and Lower Cretaceous sands and sandstones on its west central façade (Figure 11).

In 2006, greenhouse farmers completed the first deep seated space heating doublet in Bleijwjik, initiating a developing trend illustrated by the ca. one hundred concessions, mapped in Figure 12, awarded by the Ministry of Economic Affairs. As of early 2014 16 doublets have been completed (Figure 12) and 50 or so more should add to the list to meet the 800 MW_t objective targeted by the State (Van Heekeren, 2013).

The Netherlands are a known petroleum province, extensively drilled for hydrocarbon exploration and production purposes easing the implementation of a database (NLOG), managed by TNO in the framework of the ThermoGis information system (Van Wees et al, 2010), which addresses an abundant well (ca 5900), seismic (ca 70000 km of 2D/3D lines) and petrophysical (ca 60000 core test data) information accessible to the public. An example of a 3D geomodelling study using such information is attached in Figure 13.

Noteworthy is the factual evidence, as a consequence of the hydrocarbon enriched Dutch subsoil, of high solution (natural) gas contents (GWRs higher than 1 val/vol) and occasionally of traces of crude oil slugs requiring due care from geothermal operators and control from the competent mining authority (SODM).

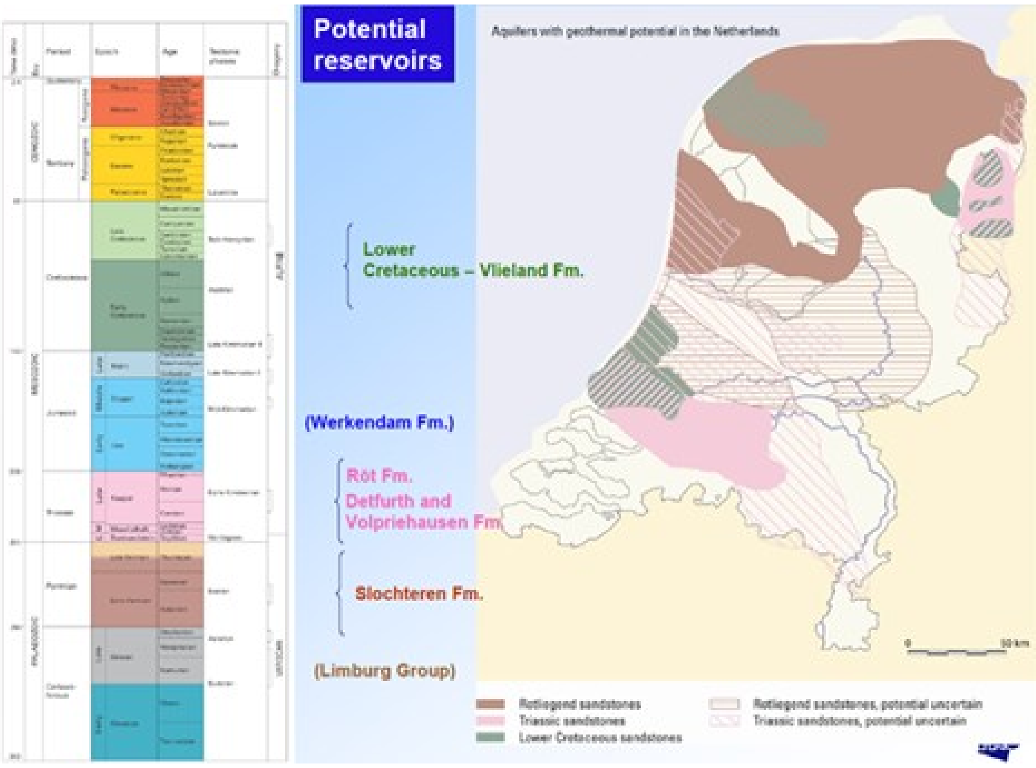

Figure 11: Netherlands Basin. Potential Geothermal reservoirs (source: TNO)

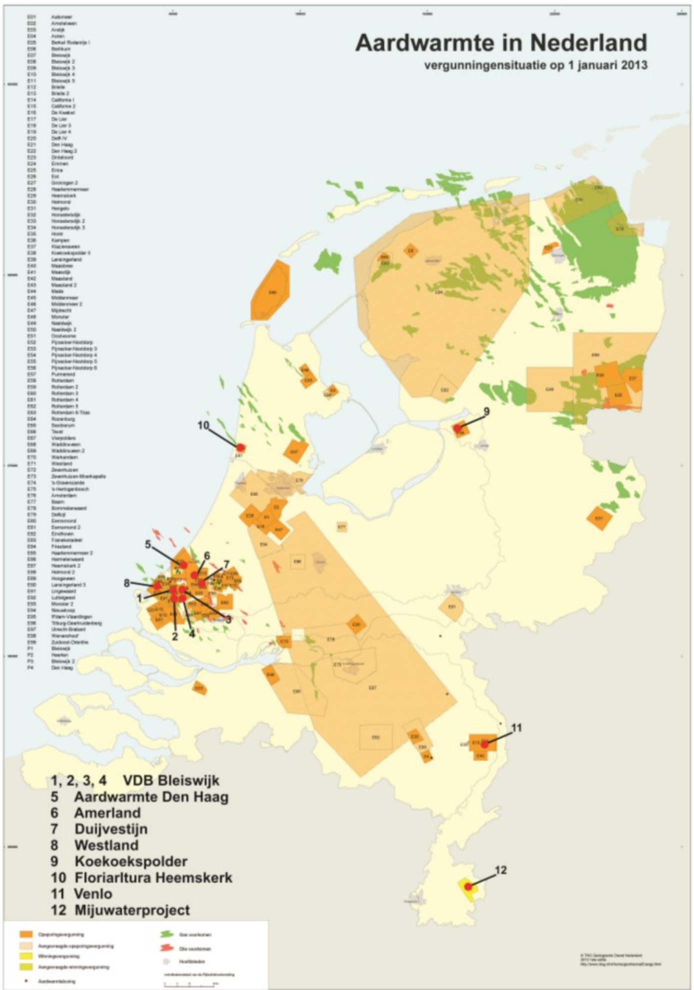

Figure 12: Netherlands Basin. Concession map and space heating locations (@ source: Van Heekeren)

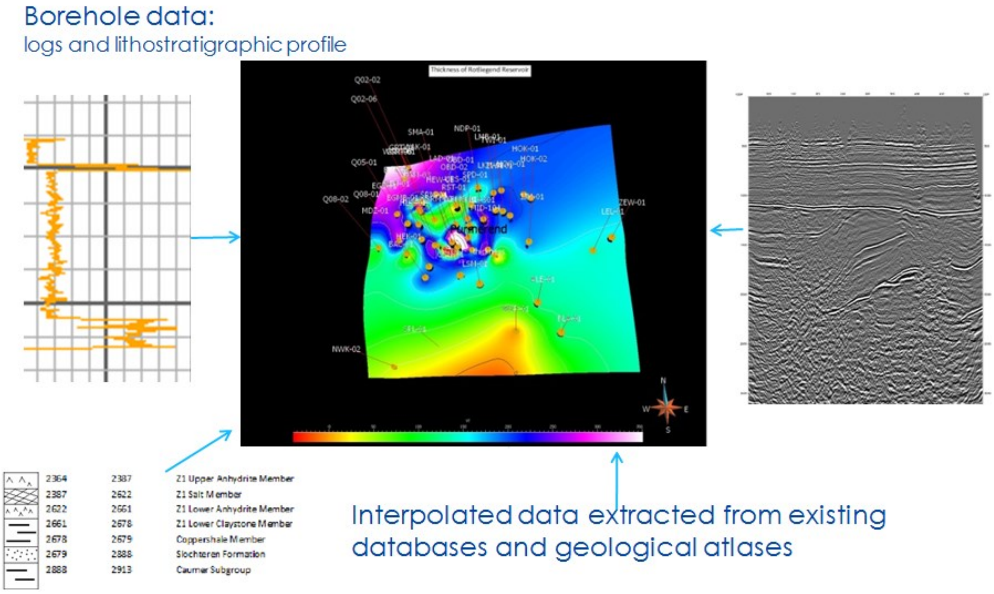

Figure 13: Netherlands Basin. 3D geomodellling. Schlochteren member, Permian reservoir (source: GPC IP)

2.4 The Upper Rhine Graben (URG)

The URG is a Cenozoic continental rift system, 30 to 50 km wide, stretching over 300 km from Basel to Frankfurt, already exploited on several geothermal sites (Figure 14). It was formed during the early Cenozoic in response to the Alpine Orogeny, itself a consequence of the colliding Eurasian and African plates, giving rise to an extensional graben edifice and to local Miocene volcanic manifestations. It displays an asymmetric trend and a step wise, *en echelon*, fault block structure dipping eastward towards the Rhine where the crystalline basement depth exceeds 5000 m (Figure 15). Superimposed to the overall graben component (resulting mostly from crustal thinning) are remarkable local heat flow anomalies, with densities as high as 150 mW/m² (*Landau*), i.e., 2.5 times the continental average, attributed to radiogenic granodiorite basement rocks and, moreover, to hydrothermal convection occurring through basement rooted extension faults (Bailleux, 2012) leading to high subsurface temperatures (ca. 150°C at 1500/2000 m depth) shown in Figure 14. Natural hydrothermal reservoirs are found at the Lower Triassic (Buntsandstein)/Crystalline basement contract, where top basement weathering favours the creation of preferential flow paths rather than in the overlying tight Triassic sandstones (Kohl, 2014).

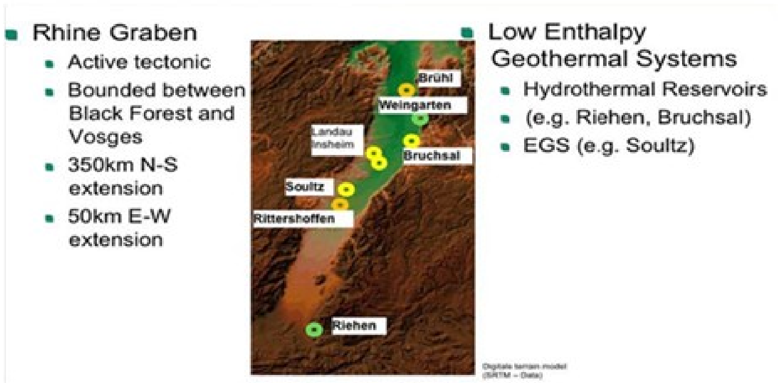

Figure 14: Upper Rhine Graben Overview (source: Beaujard and § ESG, 2014)

Needless to say, such complex tectonics and related facies, permeability and reservoir discontinuities increase the mining risk that, to be mitigated, requires subsurface investigations to secure reasonable drilling success. Accordingly, reflection seismic, passive seismology/microseismic monitoring, geochemistry, neotectonics, 3D geomodelling, enhanced by (re)processing of previous hydrocarbon, mineral and geothermal exploration databases, become a prerequisite to reservoir direct drilling assessments. Figure 16 imaging is an example of 3D structural modeling, based on a first well issued lithostratigraphic, logging/testing data, and a VSP complemented by reprocessing of 2D seismic line, aimed at targeting a second well location (Baujard et al, 2014).

The URG permeable deposits are, in most instances, eligible to CHP geothermal undertakings whose implementation is stimulated by attractive FIT (Feed in Tariff) policies enforced in Germany and France.

Regarding geothermal development, induced seismicity is a major and sensitive issue in a province subject to an important natural seismicity, highlighted by the devastating Basel earthquake in 1356.

Events of magnitude 2.5 to 3, widely echoed by the media, have been recorded further to hydraulic stimulation of either EGS (Basel, Soultz) or hydrothermal (Landau) projects and at exploitation stages (Landau, Ischeim). They have caused the shutdown of the Basel venture and production limitation at Landau (Baumgartner, 2014). These issues are discussed in section 3 of this paper.

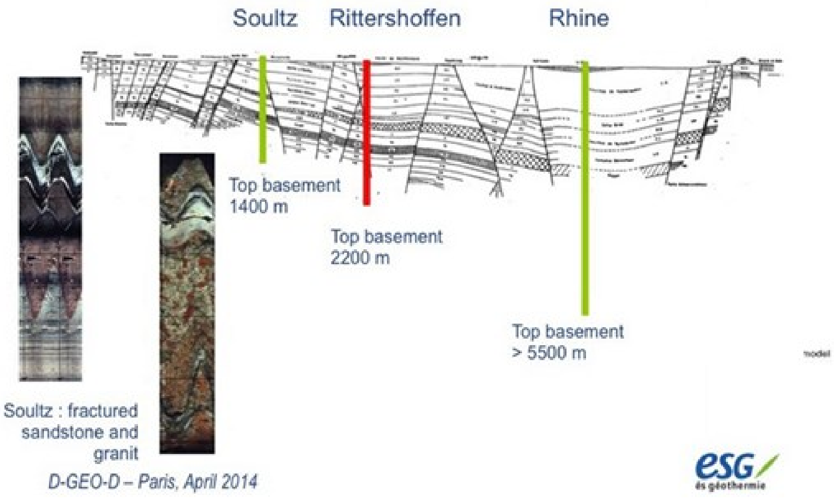

Figure 15: Upper Rhine Graben. EW Structural Cross section (source: Beaujard and § ESG, 2014)

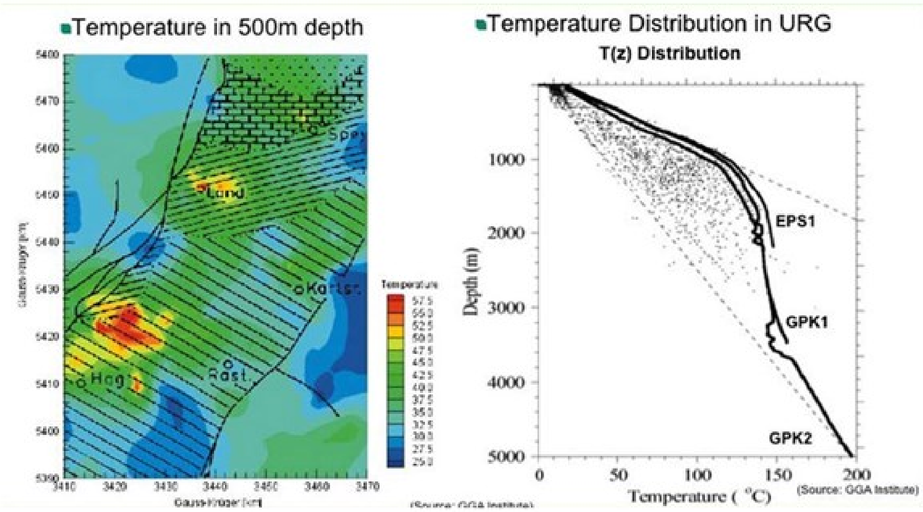

Figure 16: Upper Rhine Graben. Subsurface temperatures (source: CGA Institute)

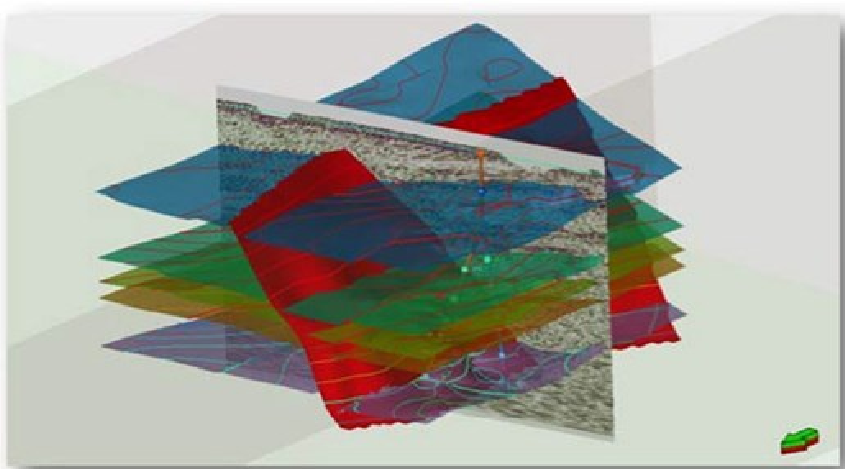

Figure 17: Upper Rhine Graben. Rittershaften project 3D geomodel for targeting well GRT2 (source: Beaujard and ESG, 2014)

3. DISCUSSION

From the foregoing section questions arise about whether the reservoir exploitation, modelling and management strategies proved effective in achieving reasonable drilling success ratios, comprehensive reservoir assessment and sustainable resource development. This includes minimizing mining risks, managing exploitation risks and mitigation of seismic risk.

3.1 Mining risk

Recorded success vs. failure drilling ratios stand as listed below (@ late 2013):

Basin	Number of wells	Drilling		Success ratio (%)
		Failure	Partial success	
Molasse	44	2	2	90
Paris	127	-	8	94
Netherlands	28	2	2	86
URG	21	3	2	74

Obviously, exploration issues scored well, even in the URG, deemed the most adverse environment owing to its complex tectonics and flow patterns, a credit paid to relevant reconnaissance surveys, 3D geomodelling, drilling programmes, well designs and thanks to previous hydrocarbon exploration/production drillings.

In areas of high geological risk, associated to fractured heterogeneous reservoir (URG, Molasse), reflection seismic campaigns including (re) processing of 2D lines, completion of 3D surveys and VSPs proved decisive in (re)assessing drilling targets particularly in the Molasse Basin.

In less (Netherlands) and poorly (Paris) tectonised basins exploration uncertainties are widely compensated by either continuous reservoir properties (Paris) or/and a dense well (Paris, Netherlands) and seismic (Netherlands) control issued by hydrocarbon exploration/production (Ungemach, 1988) and mostly compiled in accessible databases (Van Wees et al, 2009).

Note incidentally that in the Molasse Basin recent drilling failures (dry holes) and lower than anticipated well performance, mapped in Figure 2, have been noticed, South and East at a distance from the extensively (and successfully) drilled Münich area, which suggest to revisit the former conceptual reef/fault/karst model in these geographically distant areas.

3.2 Exploitation risks

It addresses chiefly the following shortcomings undergone by either production or/and injection wells in relation to corrosion/scaling damage (Paris Basin, URG), formation impairment (Netherlands) induced by production/injection, and electro submersible pump (ESP) failures (Molasse basin), if not provoking irreparable well shut downs, severely penalize exploitation economics and contractual commitments.

Heavy metal (dominantly iron) sulfide supersaturation/precipitation, occurring in the CO_2/H_2S aqueous system, prevailing in Paris Basin (Dogger) reservoir fluids have long affected GDH doublets, causing the abandonment of a number of damaged doublets during the early development stages (the so called infantile disease), before downhole chemical injection lines and inhibition protocols are implemented and chemical damage mastered (Ungemach, 2014).

The Netherlands and Molasse Basins are experiencing well injectivity problems in Permian and Triassic clastics and ESP malfunctioning respectively, regarded as a tribute paid to the learning curve inherent to any new energy route.

Whereas well injectivity problems are likely to be controlled in the near future thanks to adequate fluid chemical (inhibition) and mechanical (particle filtering) treatments (Ungemach, 2003), ESP short life runs remain to be solved. Actually there exist a real challenge from pump manufacturers to meet the requirements of GDH/CHP operators aiming at maximizing geopower ratings and subsequent, FIT boosted, revenues from electricity sales. As a result, 1000 m submersion depths, 150 l/s discharge, and 600 to 800 m heads (i.e., ca. 1.5 MW_{el} rating) in specifications are not uncommon, making the ESP set and tubing string a monster outfit and a true prototype for the industry before achieving routinely a 2 to 3 year life.

3.3 Sustainability

Sustainable reservoir management implies that geothermal exploitation is effective over long periods, exceeding at least the investment (CAPEX) discounted payback time and, preferably, well physical life without depleting formation temperatures (thermal break through time) by controlling reservoir cooling kinetics alongside hydrothermal interferences with nearby operating doublet systems (Ungemach et al, 2007; Papachristou, 2011). Hence, thirty years would be sought a minimum and fifty, if not one hundred, years an optimum. This objective is far from trivial when contemplating the specific, ambivalent, nature of geothermal energy which although *renewable,* as evidenced by the terrestrial heat flow, is *exhaustible*, the connective fluid withdrawal widely exceeding the conductive heat resupply segment.

Therefore reliable reservoir modelling is a key issue to reservoir life assessments as illustrated by the Paris Basin experience. Here the long exploitation history (ca. 35 years) offered a valuable bench test which enabled to validate the multilayered *sandwich* equivalent structure (Antics et al, 2005).

The resource/reserve assessment sequence, from heat in place to recoverable, and ultimately demand compatible, reserves exercised in table 2 clearly demonstrates the benefit of this approach in estimating the recoverable reserve and matching actual production well cooling kinetics (Figure 18). Conventional modelling would have estimated breakthrough time to 4 years instead of the matched 11 year figure.

Table 2: Geothermal reserve and thermal life assessments

Single layer equivalent reservoir	Multilayered sandwich equivalent reservoir
• **Heat in place** $G(J) = \gamma_t Ah (\theta_o - \theta_a)$ **(1)** where: $\gamma_t (Jm^{-3} K^{-1}) = \gamma_w + (1 -) \gamma_r$ **(2)** • **Recoverable heat** $H(J) = \eta \gamma_t Ah (\theta_o - \theta_i) = RG$ **(3)** $R = \eta (\theta_o - \theta_i)/ (\theta_o - \theta_a)$ **(4)** • **Recovery system efficiency** $H(J) = Q \gamma w (\theta_o - \theta_i) x\, t^*$ **(5)** $\eta = (Q/Ah) (\gamma_w/\gamma_t)\, t^*$ **(6)**	• **Heat in place** $G(J) = A [\gamma_t h_1 + \gamma_r h_2] (\theta_o - \theta_a)$ **(7)** • **Recoverable heat** $H(J) = \eta \gamma_t Ah_1 (\theta_o - \theta_i) = RG$ **(8)** $R = \eta \frac{\gamma_t h_1}{\gamma_t h_1 + \gamma_r h_2} \frac{(\theta_o - \theta_i)}{(\theta_o - \theta_a)}$ **(9)** • **Recovery system efficiency** unchanged Nomenclature : h_1 (m) = reservoir (cumulated) thickness h_2 (m) = interbedded aquitard (cumulated) thickness
Nomenclature: **A (m^2) = reservoir areal extent** **G (J) = heat in place** **H (J) = recoverable heat** **Q (m^3/s) = fluid production rate** **R = recovery factor** **h (m) = reservoir thickness** **t^* (s) = production time** **γ ($Jm^{-3} K^{-1}$) = volumetric heat** **η = efficiency of the heat extraction system** **θ = effective reservoir porosity** **θ (°C, K) = temperature** **Subscripts:** **a = ambient (outdoor)** **i = injection** **r = rock** **t = total (rock + fluid)** **w = fluid (water)** **o = initial reservoir state**	**Doublet thermal breakthrough** • **No conductive heat resupply (single layer)** $t_B(yrs) = \frac{\pi}{3} \frac{\gamma_t}{\gamma_w} \frac{D^2 h}{Q}$ **(10)** • **Conductive heat resupply (sandwich)** $t_B(yrs) = \frac{\pi}{3} \frac{\gamma_t h_1 + \gamma_r h_2}{\gamma_w h_1} D^2 \frac{h_1 + h_2}{Q}$ **(11)**

Other reviewed basin samples neither offer the same large scale reservoir properties and regularity, whatever the sophisticated 3D seismic assisted structure imaging, nor the exploitation history required to develop regional heat and mass transfer reservoir simulators, conceived as predictive reservoir management tools, thus concluding the ideal sustainability modelling suite.

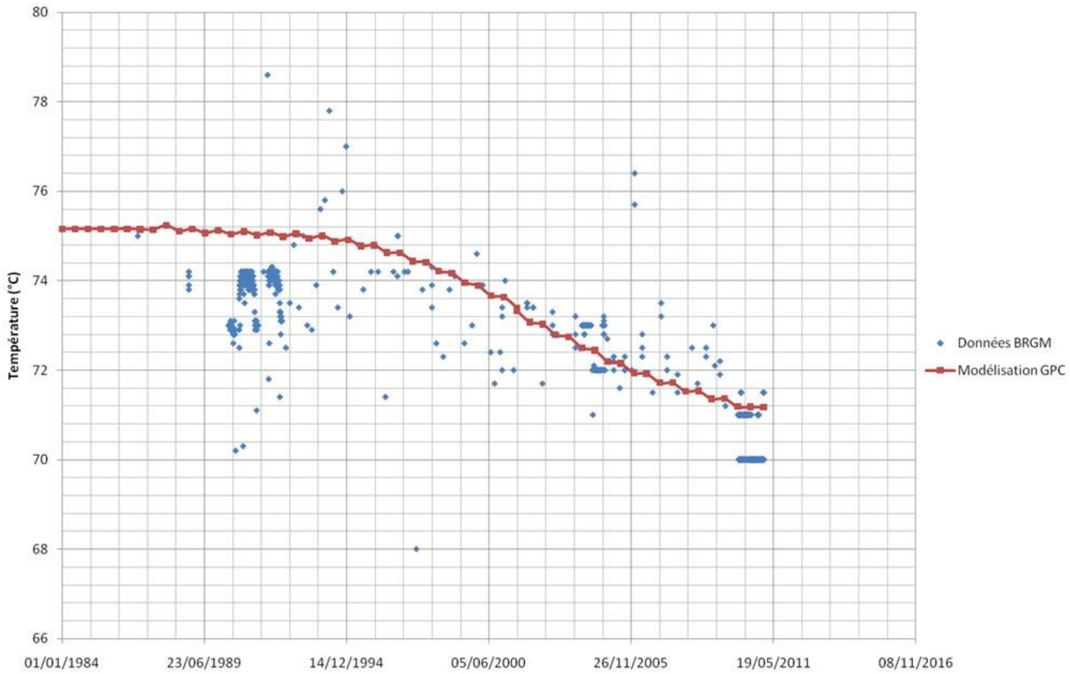

Figure 18: Reservoir life assessment. Computed vs measured temperature decline

3.4 Seismic risk

Induced seismicity is a well-documented topic among subsoil activities of which the petroleum and geothermal sectors hold an important share. Geothermal fields located in active seismic and tectonic provinces generate frequently earthquakes, most of them in the microseismicity range, and occasionally a few of larger magnitudes (up to 4, seldom 5).

Within the four selected basin samples, the Rhine Graben is the only concerned by micro earthquakes of significant magnitudes, in spite of an event, higher than routinely monitored, in the Gröningen gas field in northern Holland.

The Basel episode, obviously a direct consequence of a massive hydrofrac experiment initiated in early December 2006, deserves a special comment. The main shock peaked at a 3.4 Richter magnitude a few hours after well shut in, further to a series of earthquakes attaining the critical magnitude threshold (2.9 ML). Following, a series of events of high magnitude persisted over several months, finger printing the near vertical lens shaped microseismic cloud displayed in Figure 19 (Haring et al, 2008), (Deichmann et al, 2013).

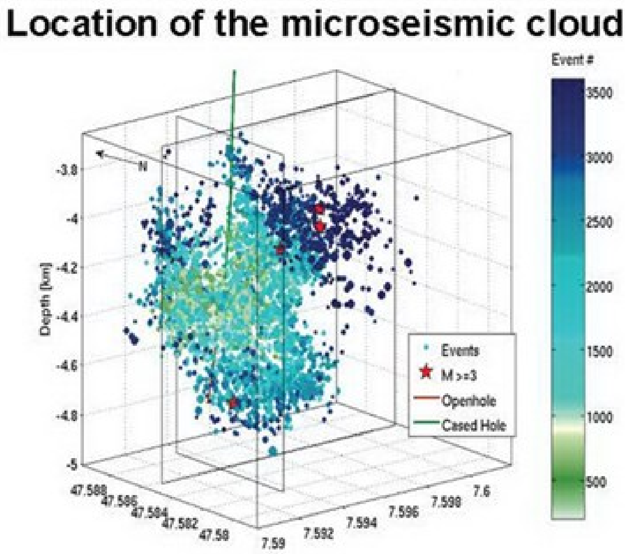

Figure 19: Induced seismicity. Mapping of the Basel microseismic cloud (source: Deichmann et al, 2008)

The events remain located at ca. 1 km from the well, starting from bottomhole (ca. 4.5 km deep). It is elsewhere quite clear that massive water injection into a tight, near impervious crystalline basement, located in an extensively fractured and stressed fault compartment (Figure 20), generated an accumulation of stress (Fabbri, 2010) which were released long after water injection ceased. Obviously, the Basel site was not the best location for such an ambitious EGS project, neither was the fracturing sequence protocol nor the drilling pad, close to inhabited buildings, a suitable site given the likely environmental hazards.

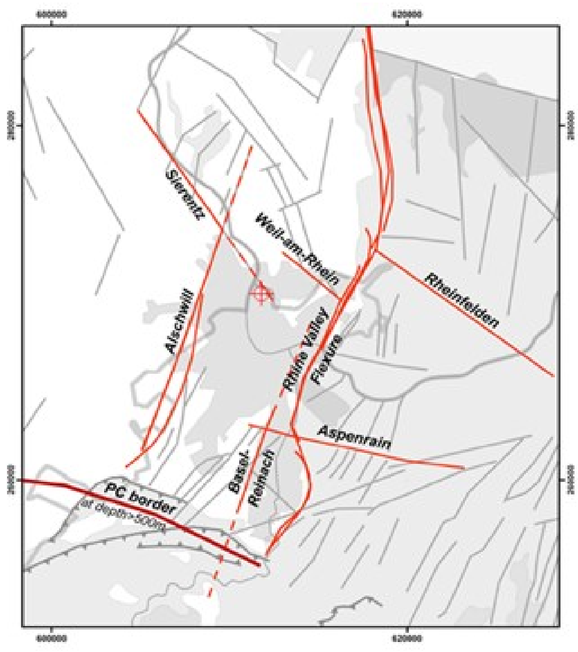

Figure 20: Induced seismicity. The Basel tectonic setting

Closer to conventional hydrothermal concerns, the Landau CHP project undergone microseismic events during commercial operation of the plant attributed to high injection pressures, indicative of the development of the injected reservoir (Baugmgaertner, 2013). Here again microseismic shocks were observed further to well shut in. It could be reasonably hypothesized that microseismicity would persist with reservoir growth until a stabilized pressure regime be reached. This is most likely a signature common to similar imbalanced, production vs. injection permeability contrasts in hard basement fracture rock environments (it is recalled that the reservoir develops here at the tight Triassic sandstone /weathered Permian Crystalline basement interface).

In conclusion, induced seismicity is a sensitive, when not emotive, matter among the public, widely echoed by the media. It requires due care in communication transparency, implementation of *ad hoc* microseismic monitoring grids complying with protocols and recommendations elaborated by authorized academic and institutional, preferably competent, bodies, in order to gain awareness and acceptance from the public and authorities (Baria, 2013).

4. CONCLUSIONS

Four sedimentary regions, representative of the European low to medium enthalpy geothermal reservoir environments, have been reviewed and their outlook assessed from the exploration and exploitation stand points and related risk and sustainability implications. As a result the following conclusions may be drawn.

- Geothermal exploration and production proved a mature technology in achieving comprehensive conceptual modeling, relevant assessments and sustainable development of target reservoirs.
- Mining risk has been mitigated by (mostly existing) 2D seismic line (re) processing and (new) 3D surveys including VSP and 3D geomodelling (second doublet well targeting) in complex, fractured/carbonate/clastic, environments as those encountered in the Molasse Basin and Upper Rhine Graben leading for those areas alone to drilling success ratios nearing 85%, indeed a rewarding score.
- Sustainable exploitation over thirty years has been recorded in the Paris Basin with only one thermal breakthrough among the 34 long lasting referenced doublets; hence reservoir life exceeding fifty years and more becomes a realistic objective provided relevant mining infrastructures and resource management policies be implemented. Similar trends may already be anticipated from recently developed reservoirs.
- Modelling suites should address structural 3D geomodelling and heat and mass transfer, history matching and predictive modelling, should account for multilayering (and representation of equivalent structures) a distinctive feature of many sedimentary aquifers (Paris, Dutch Basins) in order to exercise reliable reservoir simulations.
- Interactive database/real time management is deemed a key to sustainable reservoir development initiated in the Dutch and Paris Basins.
- Induced seismicity, focused presently on Upper Rhine Graben undertakings, is still a sensitive reservoir stimulation and water injection issue. It is however gaining improved awareness and acceptance from the public thanks to implementation of *ad hoc* microseismic monitoring networks and protocols and, last but not least, communication transparency.

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