3D Seismic, a KEY Tool for design & derisking of dual geothermal boreholes in stratified aquifers and in fractured aquifers along regional faults

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ABSTRACT

The use of existing geological and structural maps, previous 2D seismic profiles, boreholes and correlation models between these data is sufficient to understand basin structure and thermal systems on a regional scale. However, this is not sufficient on a scale of a geothermal site to be sure of the hydraulic connectivity (or of the presence of a permeability barrier) between two boreholes 1.5 or 2 km apart.

To ensure that there is enough hydraulic connectivity, it is necessary to understand the controls on the network of fractures which affects the aquifer (fracture permeability) and the physical properties of the rock, namely the porosity and clay content in order to obtain a matrix permeability.

The latest generation of broadband (6 octaves) 3D seismic reflection will provide the following information:

- The similarity attribute will give an accurate structural map of the fault network at the seismic resolution and, in many cases, at a higher resolution than seismic.
- Seismic velocity anisotropy analysis techniques will make it possible to visualize a 3D volume of information on the fracture network [1 - MICHEL L. & al. - 2013].
- Acoustic impedance inversion or petrophysical inversion techniques will predict the porosity throughout the whole volume of the aquifer from a porosity log recorded in a pilot-hole. It allows a real 3D mapping of predicted porosity inside the aquifer much more reliably than from modelling alone.

These seismic techniques were initially developed for petroleum exploration & development. They have rapidly progressed throughout the last decade, both in acquisition, processing and interpretation with new methodologies and high-performance softwares. They are efficient for modelling reservoirs to be produced.

And, consequently, they can be used for geothermal applications as data to design dual deviated drillings with horizontal drains in carbonates and clastic reservoirs - not only for new projects, but also to revisit old ones to improve their performance or develop another reservoir.

Broadband 3D seismic will secure the exploration of stratified aquifers as Triassic sandstones for deep geothermal projects.

Other prospects are faulted aquifers as regional faults which overlap the substratum. Inside faulted zones, hydrothermal circulations arriving by convection at the top of granitic basement could be geothermal objectives, as in the Alsace Upper Rhine Graben.

A production pilot site is suggested to test superimposed aquifers and a regional fault and, at the same time, two different architectures of boreholes doublets: horizontal drains for aquifers and deviated wells for crossing a regional fault.

The geothermal site could be instrumented and used as an experiment with a small addition of measurements and sensors. The objective of this experiment would be to determine the transit time, the heating time of the re-injected water and the circulation speed to define the optimal direction, spacing and length of drains, and to realize the thermal modelling of the site for different options of production.

1. THERMAL SYSTEMS FOR DEEP GEOTHERMICS

During the last 35 years in France, geothermal boreholes have been drilled in Dogger limestones of the Paris Basin and in the granitic basement of the Alsace Upper Rhine Graben, i.e. in two different contexts because of their geology and thermodynamic situation.

The research project of Soultz in the Alsace Upper Rhine Graben demonstrated that natural circulations existed in fractured and weathered granite, particularly in the upper part of the basement [2 – GENTER A. & al. - 2010]. Water is circulating vertically by convection inside fractures. The consequence of this observation is important. Top basement is becoming the geothermal resource which obliges to target faults at the top basement to get a good flow rate (Figure 1).

The second conclusion of the Soultz research project concerns the sedimentary layers above the basement. The heat flow propagates upwards by conduction [2 – GENTER A. & al. -2010]. It’s the reason of the temperature decrease up to the ground surface.

Geothermal production will be different in both cases:

- In the basement fractured and weathered granite, faults with hydrothermal circulations will be searched for,
- In the sedimentary layers, the fracture network will be operated inside porous and permeable reservoirs.

In the Paris Basin, the deepest boreholes have been drilled by oil industry to investigate Dogger limestones and Triassic sandstones. Ante-Triassic basement has been drilled in many boreholes. Temperatures have been registered in the sedimentary basin. They indicate also a natural conductive thermal transfer.

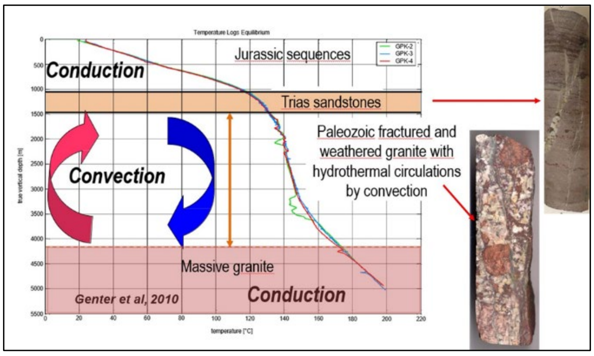

Figure 1 - Thermal profiles in boreholes at Soultz, in the upper Rhine graben [2 - GENTER & al., 2010]

2. BOREHOLE ARCHITECTURE

For geothermal targets in France, more than thirty deep geothermal boreholes have been drilled vertically or with strong deviations up to 60°/vertical to produce the Dogger limestones in the Paris basin and the granitic basement in Alsace.

However, flows pumped from sedimentary aquifers with this boreholes geometry do not systematically reach the minimum flow rate of 300 m^3/h.

The first horizontal geothermal boreholes have been drilled in 2017 in the town of Cachan, close to Paris. They have been drilled along the same vertical section, in opposite directions, in the Dogger limestones. A good water flow rate of 400 m3/h has been obtained. It validates the horizontal drains design. That provides better results than vertical boreholes [3 – UNGEMACH P. & al. – 2011]. Although the hydraulic system is open, direct flow between these two drains is to be feared because they are too close.

A new methodology is proposed hereafter to design boreholes geometry for geothermal doublets/triplets to optimize their location inside stratified aquifers. The methodology is based on the use of 3D seismic calibrated by measurements in a pilot-hole. It is for all deep reservoirs, at any depth:

- LIMESTONES as Dogger limestones in the Paris basin,
- SANDSTONES as Triassic fluviatile sandstones.

2.1 Arguments to revise the geometry of geothermal boreholes

In sedimentary layers, the aim is to obtain the desired flows during pumping and re-injecting.

2.1.1 Mode of water flow at the reservoir

The geometry of the boreholes inside the reservoir is of great importance for the water flow when it passes from the reservoir rock into the borehole.

By examining the geometry of the boreholes in the aquifer, whether vertical, deflected at 30° or 60° to the vertical, we see that the flow of water is always radial and turbulent (Figure 2 & Figure 3a). This geometry is not adapted to horizontal layers.

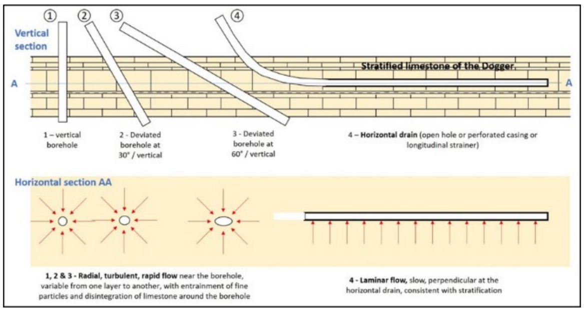

Figure 2 - Type of flow in the aquifer depending on the geometry of the borehole

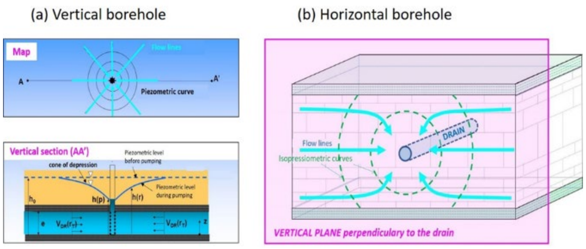

Figure 3 - Comparison of flows in a vertical borehole (a) and in a horizontal drain (b)

Stratification, irregular layer thickness, clay joints strata, as well as fracturing, vertical variations of porosity and permeability from one layer to another, are all factors which constrain the flow of the water along the layers inside the aquifer.

Thus, stratification, matrix porosity and fracturing interact strongly in fluid flows within aquifers. Approaching the borehole, the pressure decreases, and the speed of water flow increases. The flow becomes turbulent.

This radial flow explains the low flow rates obtained and a part of the corrosion problems in the casings.

2.1.2 Advantages of horizontal drains

In the case of horizontal drains (Figure 3b), the current flow lines become radial in a vertical plane which is perpendicular to the horizontal drain.

Therefore, in the horizontal plane, the current lines follow the stratification and the flow is laminar, regular and slower than in the case of vertical drilling.

The advantages of horizontal drains[1] compared to vertical drilling are numerous:

1. Reduced water and gas coning because of reduced drawdown in the reservoir for a given production rate, thereby reducing the remedial work required in the future,
2. Increased production rate because of the greater wellbore length exposed to the pay zone,
3. Reduced pressure drops around the wellbore,
4. Lower fluid velocities around the wellbore,
5. A general reduction in sand production (in sandstones) & in rock parts (in limestones) from a combination of Items 3 and 4,
6. Larger and more efficient drainage pattern leading to increased overall reserves recovery.

All these advantages lead to prefer horizontal drains for the exploitation of a stratified reservoir.

2.2 Architecture proposed for doublet & triplet of Geothermal boreholes in sedimentary layers

Sedimentary layers, and consequently reservoirs, are developed in sub-horizontal directions during the sedimentation. After the compaction phenomena, they keep more or less this geometry. Their dip is generally low as in the Paris Basin.

To exploit the aquifers with a geothermal objective, the proposed architecture conforms to the classical distance of 1 to 3 kilometres between horizontal drains of the producer and injector boreholes inside the reservoir.

Figure 4 shows an example of sophisticated architecture of boreholes (triplet) which becomes possible when a better knowledge of the reservoir is available. Cold water is injected into a different compartment. And a third drain allows to inject or produce hot water, giving the operator both options depending on the season and the needs of the heating and cooling network.

For the methodology which is described hereafter, boreholes will be drilled in three steps:

- Pilot hole drilled to register logs (density, sonic, VSP) from the platform to the bottom for time-depth conversion of the seismic 3D and logs to know rock properties of the reservoir (Gamma-ray, porosity Neutron, resistivity, …).
- Horizontal drain of the producer borehole: cementation of the Pilot bottom hole until the KOP-2, deviation to arrive into the reservoir with the direction of the producer drain. And then, drilling of the horizontal drain.
- Injector borehole (and eventually the second injector/producer borehole), drilled entirely in one phase with two KOP (Kick-Off points) for two deviations.

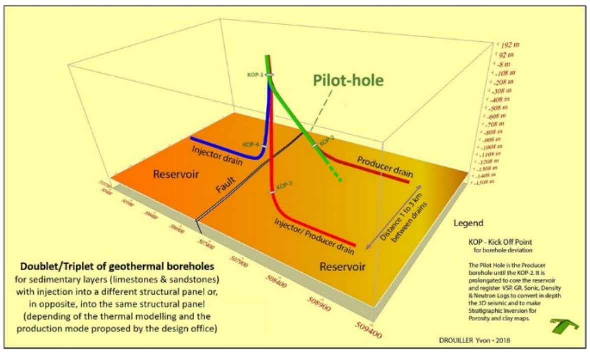

Figure 4 - Example of architecture of boreholes with horizontal drains inside the reservoir which needs a better knowledge of the reservoir to manage (or not) the hydraulic connection. Where the design office will inject cold water? In a different structural panel or, in opposite, in the same structural panel? Faults location is needed.

3 3D SEISMIC TO DESIGN A GEOTHERMAL DOUBLET (OR TRIPLET) OF BOREHOLES

The methodology is based on the latest petroleum techniques which have progressed significantly since 2010 (4 - SALEH A. et al., 2017).

Detailed seismic-reflection images of reservoirs are an essential pre-requisite to assess the feasibility of geothermal projects and to reduce the risk associated with expensive drilling programs [5 - SCHMELZBACH C. & al., 2016].

Specificity of deep geothermal programs, technical and economic at the same time, requires to customize and adapt acquisition, processing and interpretation of the 3D seismic dataset to the targets for:

- Inventorying all aquifer reservoirs of the sedimentary series between the topographic surface and the granitic basement,
- Mapping the fault network (Figure 7),
- Characterizing each reservoir, whether carbonated or clastic, to know all the petrophysical characteristics (porosity, clay content, fracturing, ...),
- Checking hydraulic connectivity between the 2 drains, absence of faults in the panel, sufficient porosity and absence of permeability barriers,
- Positioning the two horizontal drains (one for pumping, the other for reinjection of water) inside the aquifer reservoir in the most suitable areas.

3.1 Previous seismic works

During the 80's and 90's, a lot of 2D seismic profiles have been acquired in France, particularly in the Paris basin and the Rhine graben. Their frequency spectrum of the vibrator

[1] http://petrowiki.org/Fluid_flow_in_horizontal_wells

source was 10-90 Hz to 8-130 Hz with many tests to increase the frequency content.

At this time, source capabilities did not permit to emit low frequencies. The quality of 2D seismic profiles has been improved by good static corrections in Tertiary and cretaceous chalk. And many structures have been found.

The research project called "Dogger 1991-1993" allowed to test vibro-seismic with some 2D profiles, a 3D seismic (16 km²) and a VSP between Villeperdue and Fontaine-au-Bron fields. The goal was to describe a thin reservoir (30 m) at a depth of 1850 m.

The objective of these tests was to obtain at the reservoir level a minimum of 100 Hz in the frequency spectrum to get a sufficient vertical resolution (Figure 5b). At that time, it was not technically possible to push the band pass towards low end frequencies. Now it would be possible to acquire broadband seismic with more octaves, hence higher vertical resolution.

However, the Figure 5 demonstrates that variations of velocity and acoustic impedance are corresponding to variations of POROSITY inside the "Dalle Nacrée" reservoir which is used for geothermal projects in the Paris basin [6 - MOUGENOT D. et LAYOTTE P.C. – 1996; 7 - MOUGENOT D. – 1999].

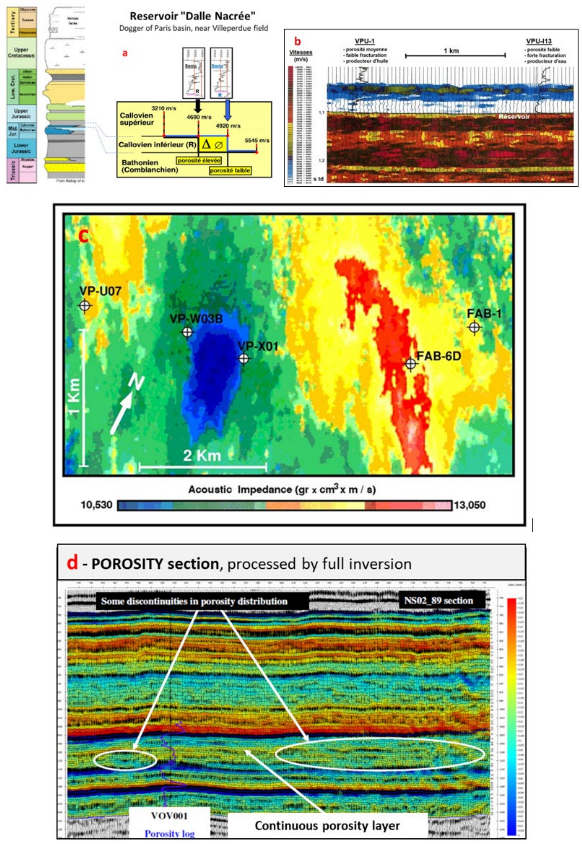

Figure 5 - Reservoir "Dalle Nacrée": Variations of velocity and acoustic impedance explain POROSITY variations on Sonic log (a), 2D seismic profile (b) and 3D vibro-seismic horizon slice (c) – Variations of POROSITY on an inverted seismic section (d) - PICOREF project made in 1991-1993 by DHYCA to promote oil exploration in the Paris Basin [5- MOUGENOT D. et LAYOTTE P.C. - 1996]

The PICOREF program (2003-2009) was located in the south-eastern part of Paris basin, in South Champagne district. Its aim was to select and characterize appropriate sites where a pilot-scale storage of carbon dioxide (CO_2) could eventually be carried out.

For this project, 750 km of 2D seismic lines have been reprocessed and 450 km of new 2D seismic lines have been acquired. The geological characterization of the Sector has been as exhaustive as possible, with all these seismic lines and the collection of a complete well-data base (146 oil wells).

This survey is a good example for characterizing sedimentary formations potentially rich in aquifer units, at the same scale as geothermal projects: first at the regional scale, then on dedicated sites [8 - BROSSE E. & al., 2010; 9 - DELMAS J. & al., 2010].

3.2 Broadband 3D seismic (up to 6-octaves)

Among the latest generation of exploration techniques, the so-called "broadband" 3D seismic currently delivers the highest resolution seismic images (frequency spectrum 2-128 Hz covering at least 6 octaves - Figure 6). The high quality of the images enables a 3D mapping of the faults with the greatest precision ever achieved (Figure 7).

The characteristics and benefits of six-octave bandwidth seismic (offshore and onshore) are determined by:

Wavelet: With more than six octaves of bandwidth, the seismic wavelet becomes sharp and impulsive, and with sufficient low-frequency content (down to 2.5 Hz), side lobes are minimized [10 - DENIS M. – 2013].

Low-frequency texture: Low frequencies pick out subtle and gradual acoustic impedance variations and give geologic layers a distinctive signature. Vertical resolution is improved.

Ease and accuracy of interpretation: The characteristics of the broadband wavelet facilitate processing and interpretation by removing interference from side lobes and therefore simplifying seismic images and revealing more subtle details [10 - DENIS M. – 2013].

Seismic artefacts which were often existing in the 3-octaves seismic of the 90's, disappeared mostly.

In addition, automated horizon picking has been shown to be quicker (more data driven with fewer manual interventions) and more accurate, and horizon amplitude extractions are cleaner and less noisy.

Deep imaging: Low frequencies are less affected by attenuation and help to image deep targets and areas beneath absorbing formations and complex overburdens.

AVO and inversion: Seismic inversion benefits from the extended low-frequency bandwidth [11 - MICHEL L. & al., 2012]. This leads to more accurate and quantitative results which have a larger dynamic range and a more realistic stratigraphic distribution and that match well-log measurements more closely [10 - DENIS M. – 2013].

Onshore broadband seismic

The onshore broadband seismic has different constraints that offshore seismic because the image bandwidth is limited by the interplay of coherent noise, sampling, near-surface effects, and our ability to increasing source and receiver density.

When arrays are reduced to a single element, we end up with single-source, single sweep, single-receiver acquisition which brings further acquisition efficiencies. On the subsurface imaging side, we observe that high-density, long-offset, wide-azimuth surveys recorded with single source and single receivers provide a notably high signal-to-noise ratio and fine resolution from very shallow to deep across all reservoir levels [12 - SEENI & al. - 2011).

The use of dense single source, single sweep and single receivers yields the following benefits:

- Higher productivity from independent single vibrators that may shot simultaneously,
- More accurate azimuthal measurements in case of full azimuth acquisition,
- Improved coherent noise attenuation,
- Improved near-surface model and surface-consistent processing thanks to denser spatial sampling (small bin size) and shorter near offset traces (statics, deconvolution, etc.),
- High signal-to-noise ratio and minimal acquisition footprint,
- Optimal imaging at all target depths.

Low frequencies provide a range of benefits from improved seismic interpretation in general to deep imaging and more quantitative inversion results. The preferred onshore source is vibroseis, particularly for high-productivity operations on dense source grids [10 - DENIS M. – 2013].

A new generation of high-sensitivity geophones (83V/m/s versus 20V/m/s), is now available with a natural frequency of 5 Hz. These are specifically designed for single-sensor application and provide excellent low-frequency recording.

The Figure 6 (courtesy of PDO) shows an onshore example. It compares the 3-octaves seismic of the 90's with the last generation 6-octaves broadband seismic. Lower three octaves (2-16 Hz) gives detailed geological information and improves greatly seismic imaging.

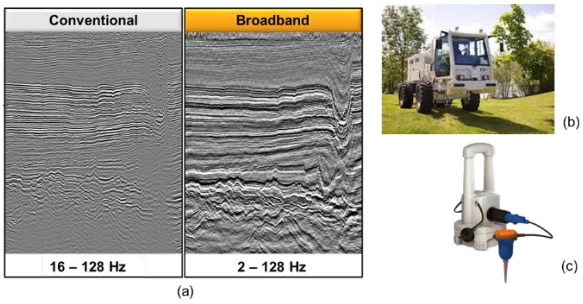

Figure 6 - Onshore 3D seismic acquisition - Progress realized with the 6 octaves Broadband technique - 2-128 Hz (a), courtesy of PDO, single vibrator (b) and wireless geophones for use on urban sites (c), courtesy of Sercel

Acquisition parameters must be determined finely to get the best 3D seismic dataset for several geothermal projects possible in the same area, from a shallow depth (800 m) to the top of basement (for EGS projects).

Processing is also a key step that cannot be neglected. We assist nowadays to the development of fast automatic "real-time" processing even in straight in the doghouse. This product may be interesting for QC purposes, but in no case taken as a final product. Quick and dirty processing of data in processing centre can also be a project killer. Processing has to be done by experienced geophysicists with a strong geological background and in good interconnection with the client geoscientists team.

3.3 P-waves only or 3-Components registered in the dataset?

The choice of the type of data which will be registered is a key decision: one (PP waves) or three (PS waves) components.

Until now, P-waves are registered classically in 3D seismic dataset for oil exploration. And 3-components (P-waves and S-waves) are seldom used to get petrophysical and mechanical parameters inside reservoirs.

The benefits of PS-wave and converted-waves are numerous in exploration seismic:

- enhanced near-surface resolution,
- improved lithologic characterization,
- mechanical properties,
- anisotropy

Presently, new 3 components MEMS sensors allow to register P-waves and converted waves for a 3D-seismic acquisition.

Whatever the estimation of fracture orientation and fracture density as well as understanding the stress state of the subsurface is of great importance in geothermal exploration, difficulties appear for each step of a 3D seismic:

- Challenging field logistics (e.g., increased number of channels compared to 1-C surveys)
- A different processing of converted waves compared to P-waves. Difficult registration of PS time (longer) into PP time (shorter)
- Difficulties in interpreting the resultant PS-wave images [13 - STEWART et al., 2003)
- And then, an additional cost.

For geothermal projects, P-waves & PS-waves will be used at least in the pilot hole with a VSP profile to image the reservoir.

3.4 Information given by 3D seismic

P-waves seismic-reflection techniques allow to investigate geothermal reservoirs by providing:

- The necessary high-resolution fault and fracture characterization in all the sedimentary layers, from ground to basement top.
- The geometry and stratigraphy of all layers and reservoirs,
- The sedimentological interpretation and the geometry of geobodies,
- The reservoir characterization, ...

Seismic attributes are used to visualize this information extracted from the 3D seismic dataset. They are quantities that can be derived from seismic data in order to extract structural and lithological information of the subsurface [14 - CHOPRA & MARFURT, 2005; 15 - CHOPRA & MARFURT, 2007].

3.4.1 Structural information

The Figure 7 shows two examples of structural maps obtained from two different 3D seismic datasets: the first one is the result of the interpretation by picking horizons ; the second is the result of a similarity attribute applied on seismic dataset along an interpreted horizon. This similarity map shows faults and fractures at different scales.

This attribute can be applied to the whole volume of the reservoir. The network of small fractures can be appreciated to evaluate the hydraulic connectivity and the fracture permeability in the prospective zone.

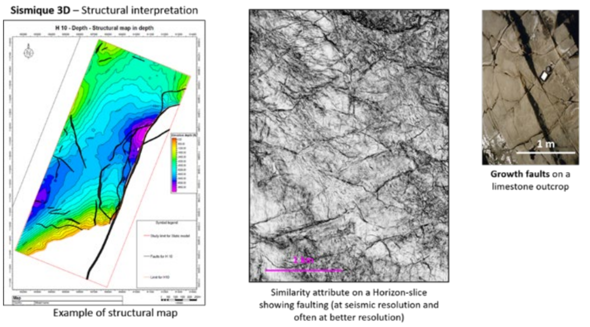

Figure 7 - Structural information obtained in a 3D seismic (mapping and similarity attribute), compared with a fractured limestone outcrop (on the right)

The knowledge of the fractures network allows to locate horizontal drains into the reservoir by proceeding in several steps:

- Avoid faults, so that the two (2) drains are in the same structural panel, if a hydraulic connectivity is desired,
- Or use faults to separate two parts of a reservoir for a different thermal objective,
- Then, look for diaclases (fractures without displacements) within the panel because they promote a so-called "fracture" permeability.

3.4.2 Stratigraphic and sedimentological information

Geometrical attributes are used in stratigraphic and sedimentological interpretation. They confirm the continuity of layers and locate unconformities and faults. They evaluate also dip, azimuth and curvature of the interpreted horizons.

If the amplitude 3D seismic dataset is transformed in acoustic impedance (true or relative impedance) domain, geobodies and lithological limits are directly visualized. The sedimentological interpretation becomes easier because impedance changes are corresponding directly to the lithological interfaces. It's a way to better know the reservoir before drilling.

3.4.3 Lithological information and physical parameters

Physical attributes have a direct link to physical parameters in the subsurface and are generally used for the characterization of lithology and reservoirs [16 - BROWN – 1996].

Carbonates reservoirs

Carbonate reservoirs are notoriously heterogeneous.

Using Broadband 3D-seismic and inversion techniques (either petrophysical or acoustic impedance), it will be possible to extrapolate the pilot-hole porosity measurements in the entire volume of the aquifer covered by 3D seismic. Thus, a true 3D mapping of porosity is obtained throughout the reservoir volume.

The example of the Figure 8 is a carbonated reservoir from offshore Brazil. Each layer (5 in this case), permeable or not, is characterized by a map which shows POROSITY variations along the interpreted horizon [17 – COLEOU Th. & al. – 2012].

The comparison between Figure 8 and Figure 5 shows the great progress of the seismic interpretation softwares during the last 20 years. Images quality improved hugely.

The result is more accurate and reliable than a modelling from 2D seismic profiles that remains interpretative and influenced by the parameters chosen for the interpolation that may give hazardous results in the space between the 2D seismic profiles.

Clastic reservoirs

Clastic deposition environments, including river deposits, though they look particularly complex, are easier to interpret due to the presence of typical figures (channel, levees ...) and to a lighter footprint by diagenesis.

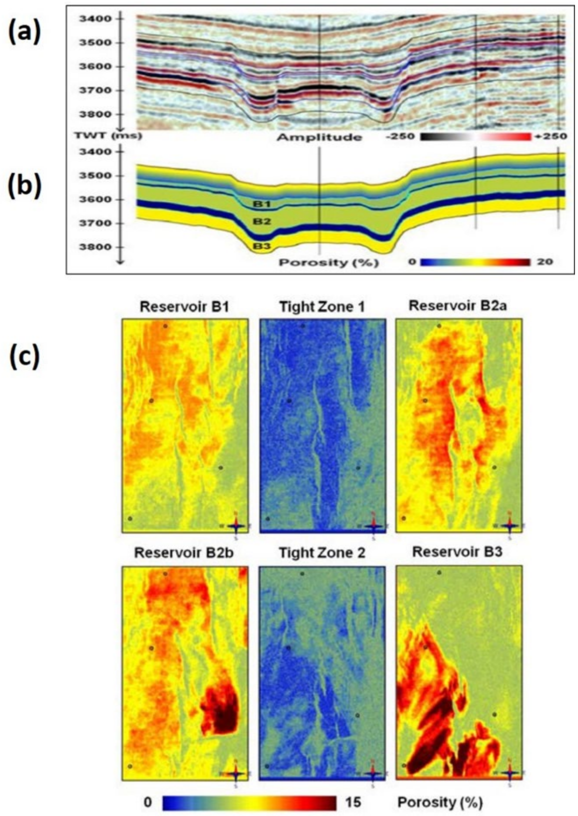

Figure 8 - Carbonate Reservoir (Brazil Offshore) – Seismic section (a), initial porosity model (b) and maps (c) showing lateral evolution of the porosity in the different reservoirs and intermediate impermeable layers obtained by petrophysical inversion of the 3D seismic dataset [17 – COLEOU Th. & al. – 2012]

In the Paris Basin, the Triassic sandstones (Chaunoy and Donnemarie formations) are fluviatile [18 – BOUCHOT V. & al. (2012) – CLASTIC-2], as the Buntsandstein sandstones in the Upper Rhine graben.

The circulation of fluids within such reservoirs is influenced by many factors:

- Tectonics: faults, fractures, folds, …
- Sedimentation mode, deposit geometry,
- Sedimentary discontinuities,
- Compaction and diagenesis, …

Precise prediction of reservoir quality in clastic systems is a key challenge for exploration and exploitation of these reservoirs.

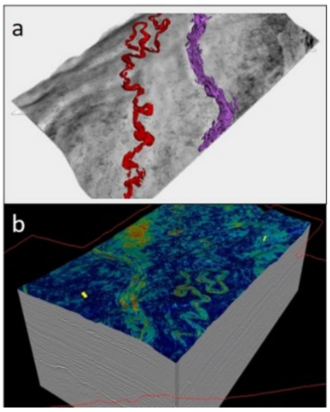

Figure 9 – Examples of fluvial systems which can be observed in 3D seismic (Courtesy of Eliis)

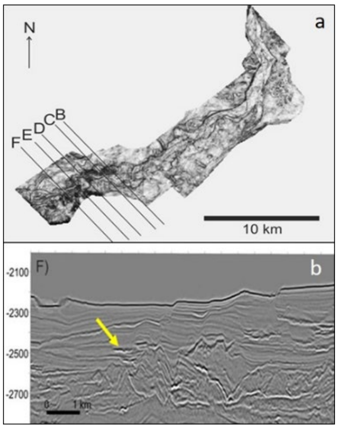

Figure 10– Horizon-slice (a) showing the fluvial system visible on the section (b) – [19 - ORTIZ-KARPF A. (2016)]

For these purposes, 3D-seismic 6 octaves is the tool that will allow to:

- Locate the sandstone deposits that will be thick enough, continuous and extended for the desired purpose,
- Determine the type of clastic deposit (fluviatile, wind, marine, progradation, beach, delta, channels, ...),
- Characterize each selected reservoir with a 3D mapping of the porosity and the clay content,
- Check the hydraulic connectivity between 2 points in the survey area.

The extension of sandstone deposits such as a fluvial system is visualized very well in a 3D seismic on the horizon-slices (Figure 9 and Figure 10a), but more difficult on the vertical sections (Figure 10b).

To get sandstone properties in the reservoir, 3D seismic is transformed using petrophysical or acoustic impedance inversion techniques to obtain a 3D mapping of the porosity and clay content.

3.5 Survey steps of a Geothermal site

This methodology, using last generation of petroleum techniques for a better knowledge of the reservoir before drilling investments, changes the survey process of geothermal sites. It is adapted to the specific case of geothermal doublets of boreholes.

3.5.1 The choice of the site, first step

The use of deep geothermal energy is first decided based on economic criteria, namely the needs of the customer and users in a well-defined place.

The feasibility of the project in this location will be based on existing data on the targeted aquifers, i.e. wells and regional 2D seismic profiles.

These data enable, with regional modelling, to roughly size the project, but do not allow the final design of geothermal boreholes.

Thus, the porosity measured in the nearest borehole, often more than ten kilometres away, gives a regional indication, but cannot be used for the implantation of horizontal drains because the variations of porosity inside the limestone can be very large and can change locally, from one layer to another, but also laterally inside the same layer.

3.5.2 Process for the study of the site and design of horizontal drains

The study of the site is of great importance to better characterize the subsurface target zone (especially the faults network) and successfully perform the geothermal project.

Reducing the risk of having insufficient flows for the geothermal operator will be achieved through a series of measurements acquired and interpreted over the drilling target area.

The overall methodology (Figure 11) can follow the following steps:

- Acquisition of a high-resolution broadband 3D seismic (i.e. with a frequency spectrum of 6 octaves sweeping the frequencies 2-128 Hz) after having adapted the parameters to the geological target, using VSP results in the nearest borehole. The acquisition of a new 3D seismic image is worth the investment only if the acquisition relies on the latest high productivity techniques. Those techniques enable affordable acquisition of high-resolution data, thus avoiding mimicking the narrow bandwidth and low trace density parameters used for the vintage acquisitions from the 80s.
- Tailored processing, including geological modelling of static corrections, preserved amplitude processing, interpolation, densification and time-to-addition migration,
- Interpretation of 3D seismic in time - Structural mapping of the site at the reservoir level using similarity attribute and analysis results of seismic azimuthal anisotropy,
- Design of the pilot-hole,
- Drilling of the pilot-hole crossing the deepest objective reservoir,
- Recording of logs and VSP in pilot-hole
- Time-Depth conversion of the 3D seismic dataset,
- 3D mapping of porosity by using the technique of inversion of acoustic impedance (with seismic 3D),
- Design of the doublet of deviated boreholes with their horizontal drains in the most porous zones, by making sure of the hydraulic connectivity between the 2 drains, or of hydraulic barriers, depending of the thermal model used for the exploitation of the site.

In this methodology, the pilot-hole is a key deliverable (Figure 12), enabling the recording of the logs (GR, density, sonic, porosity, resistivity, and diameter) and the VSP. Logs and VSP are the key information required to successfully complete the time-to-depth conversion of the 3D seismic and the 3D mapping of the aquifer porosity.

The combination of 3D seismic and VSP will enable studying all high-potential geothermal aquifers, located between the topographic surface and the metamorphic and/or granitic basement.

Each aquifer could be equipped with independent doublet of geothermal boreholes, using the same 3D seismic dataset (Figure 13).

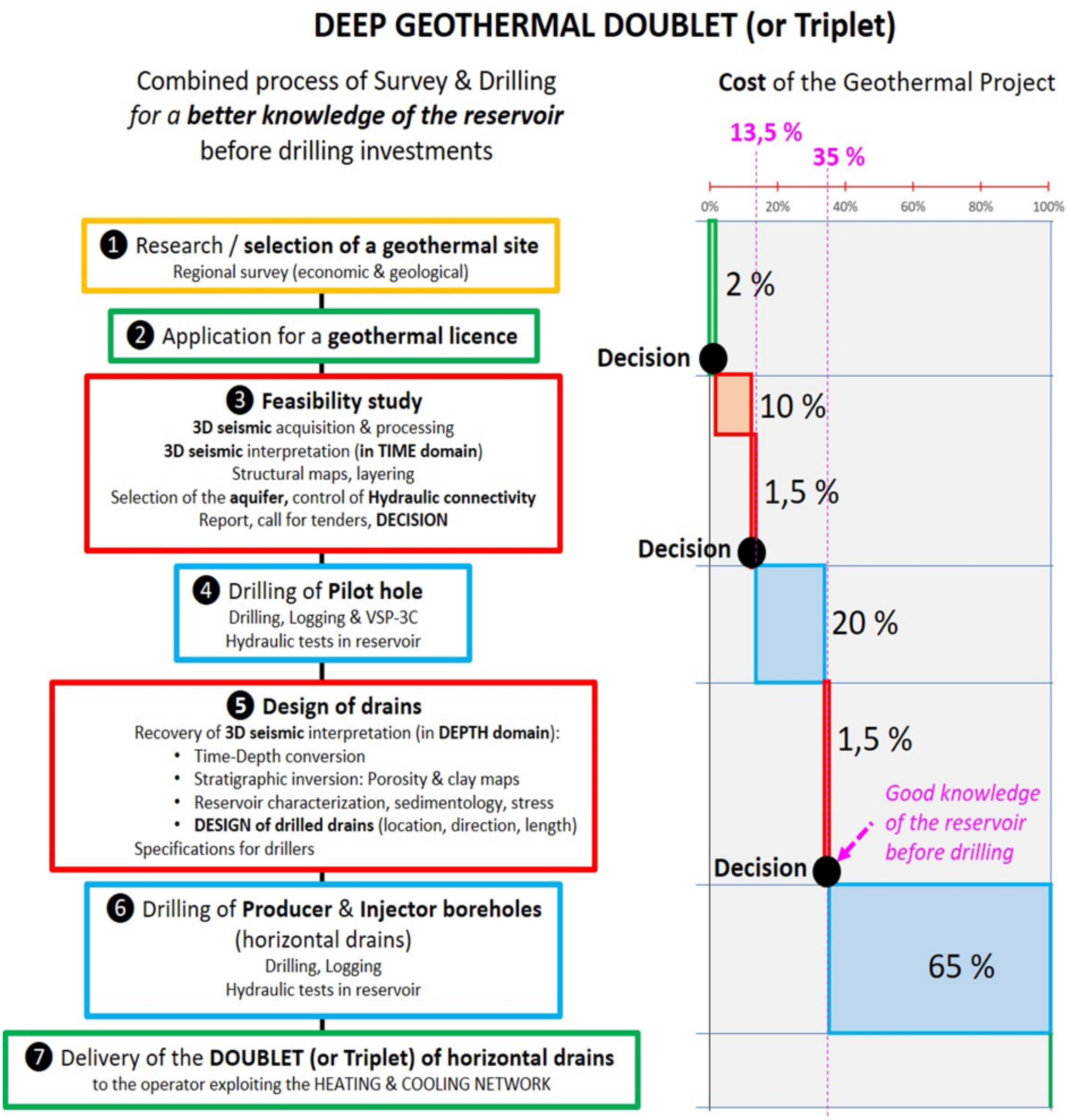

Figure 11 - Combined Process for the survey of the objective aquifer (stratified or fractured) and design of geothermal doublets/triplets before drilling investments

4. CONCLUSIONS

To conclude on the need to use 3D seismic in deep geothermal projects, the methodology using broadband 3D seismic & pilot-hole with VSP and logging is valid, whatever the depth of the reservoir, for:

- Carbonated aquifers as Dogger limestones in the Paris basin,
- Clastic aquifers as the Triassic in the Paris basin or the Upper Rhine graben,
- The recovery of existing geothermal doublets to add horizontal drains and perform better the site with less maintenance in the future,

but also, to map big faults at the top of a granitic basement.

Modern 3D seismic (Frequency spectrum: at least 6 octaves) offers a set of tools that allow the geothermal operator to have a much greater confidence on the properties of the geothermal site at the reservoir level than classical modelling and simple interpolation between wells. Applying the technique is worth the effort in order to reduce the risk before the large investments of drilling and surface installation.

Modern 3D seismic gives the Design Office essential information to develop the project, including:

- 3D network of faults with structural maps,
- Inventory of aquifers usable in geothermal energy, between the topographic surface and the granitic and/or metamorphic basement,
- Knowledge of the internal structure of each carbonate and/or clastic reservoir (seismic stratigraphy for the delineation of lithological bodies, 3D porosity and clay maps, ...),
- Checking of hydraulic connectivity and/or hydraulic barrier between the pumping and re-injecting drains,

to allow the installation of horizontal drains in the best zones of the reservoir or in different structural panels.

In other words, seismic tools are perfectly suited to the study of geothermal sites and adapted for derisking geothermal projects in sedimentary locations where the seismic imaging is fair to good. They allow also to indicate difficulties along the borehole's trajectories to the drillers … before the drilling.

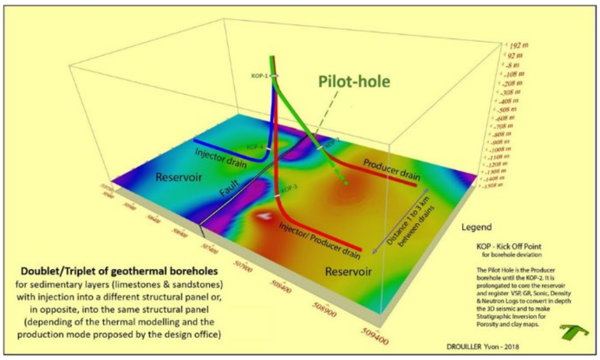

Figure 12 - Example of a geothermal triplet with horizontal drains inside the reservoir. The porosity map (simulation here) characterizes the reservoir in each side of the fault. The better knowledge of the reservoir allows to inject cold water in a different structural panel. The third drain allows to inject or produce hot water, giving the operator both options depending on the season and the needs of the heating and cooling network.

RECOVERY OF EXISTING SITES

The recovery of old doublets may be possible to preserve the initial investment:

- Either to improve their performance in the same reservoir,
- Or to develop another reservoir in the sedimentary series.

The recovery of old geothermal sites may need additional information on the reservoir to repair old boreholes or to locate new drains in best porous and permeable zones.

A customized solution between a VSP and a small 3D seismic dataset to investigate around the site could be better and less expensive to understand the origin of the problems that led to the recovery of the project.

NEIGHBOUR LICENCES

In addition, neighbouring license operators will be able to jointly acquire a unique 3D seismic, not only to reduce the financial cost, but also to avoid interferences between neighbouring doublets on the base of the same physical dataset of the reservoir.

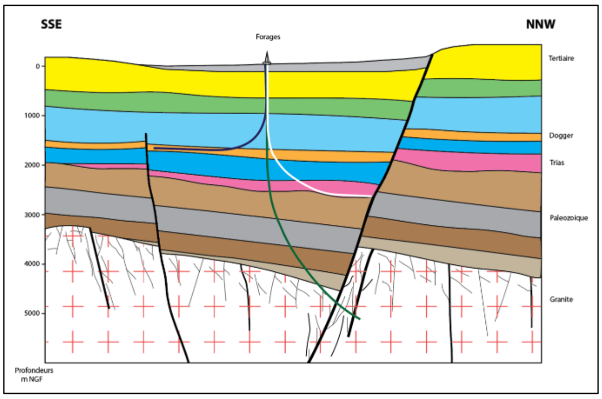

Figure 13 – Project for geothermal exploitation of several superimposed aquifers: two stratified reservoirs and a fractured aquifer along a regional fault affecting the granitic basement, using the same 3D seismic dataset.

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