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REGULAR ARTICLE

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3D seismic for design and derisking of dual geothermal boreholes in sedimentary sequences and new prospects in the Paris Basin (Adapted methodology using petroleum industry techniques)

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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 (six 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 [Michel *et al.* (2013) Application of Azimuthal Seismic Inversion for Shale Gas Reservoir – *Proceedings of the 11th SEGJ International Symposium, Yokohama*]; 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 and 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 carbonate 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 Triassic sandstones which stay an interesting prospect for deep geothermal projects.

New prospects are proposed in the Paris Basin: Regional faults 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 first site that will use this approach could be instrumented and used as an experiment with a small addition of measurements and sensors, thus becoming a showcase for geothermal energy in France. 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 also, to realize the thermal modelling of the site for different options.

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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 [1]. 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 (Fig. 1).

The second conclusion of the Soultz research project concerns the sedimentary layers above the basement. The heat flow propagates upwards by conduction [1]. 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.

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 m^3/h has been obtained. It validates the horizontal drains design. That provides better results than vertical boreholes [2]. 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 (Figs. 2 and 3a). This geometry is not adapted to horizontal layers.

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 (Fig. 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) and 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.

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

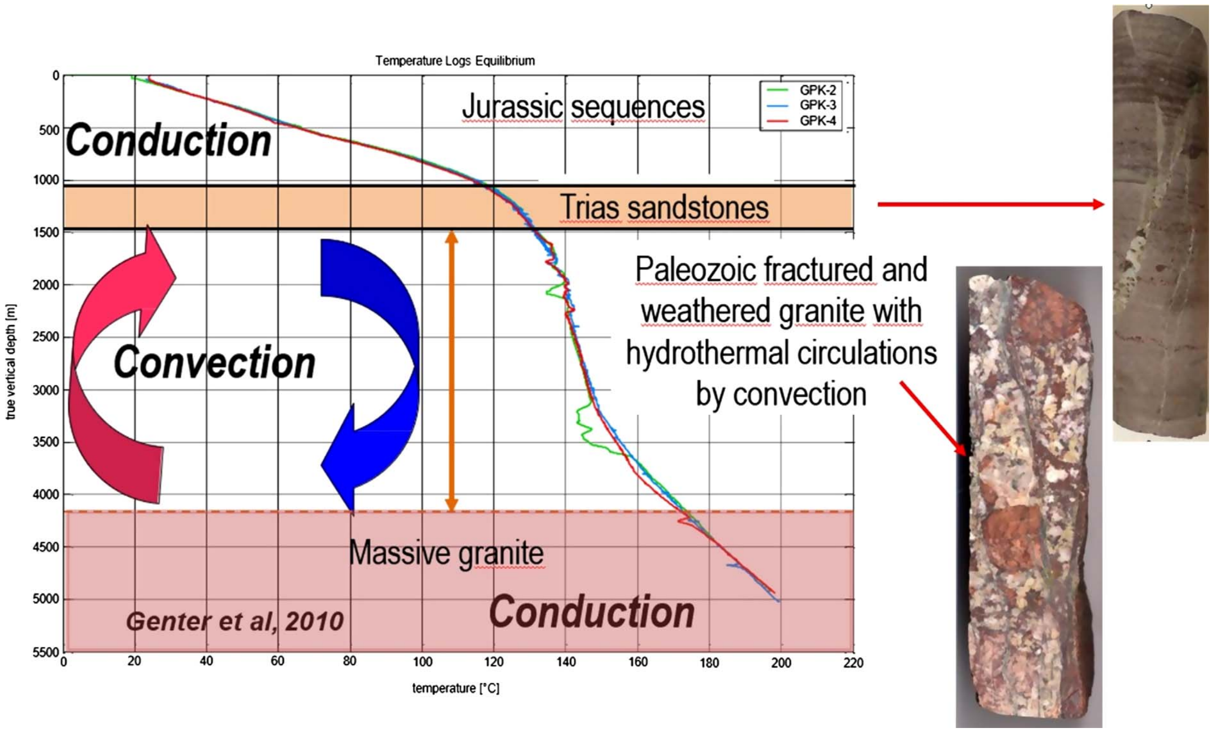

Fig. 1. Thermal profiles in boreholes at Soultz, in the upper Rhine graben [1].

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

2.2 Architecture proposed for doublet and 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 1–3 km 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 to 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, Vertical Seismic Profile [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, etc.).
- 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.

2.3 Continuous logs for a better calibration of the seismic dataset

To design horizontal wells in thin layers (limestone or sandstone), a good precision of converted seismic data in depth is required. Softwares for building a synthetic trace give this required precision if the borehole measurements are precise and continuous.

In other words, to avoid a bad calibration of the seismic dataset and, consequently, a bad time-depth conversion of the 3D seismic tainted with high uncertainty, continuous logs are necessary on the whole length of the borehole for the Sonic and the Density.

The aim is to obtain a synthetic seismogram without artefacts due to the lack of measurements at the casing shoes and changes in the diameter of the borehole.

To do this, it is necessary to make a "pocket" of about 15 m (depending on the total length of the measurement tools and the position of the sensors on each tool) to have common measurements in both runs of logs. With

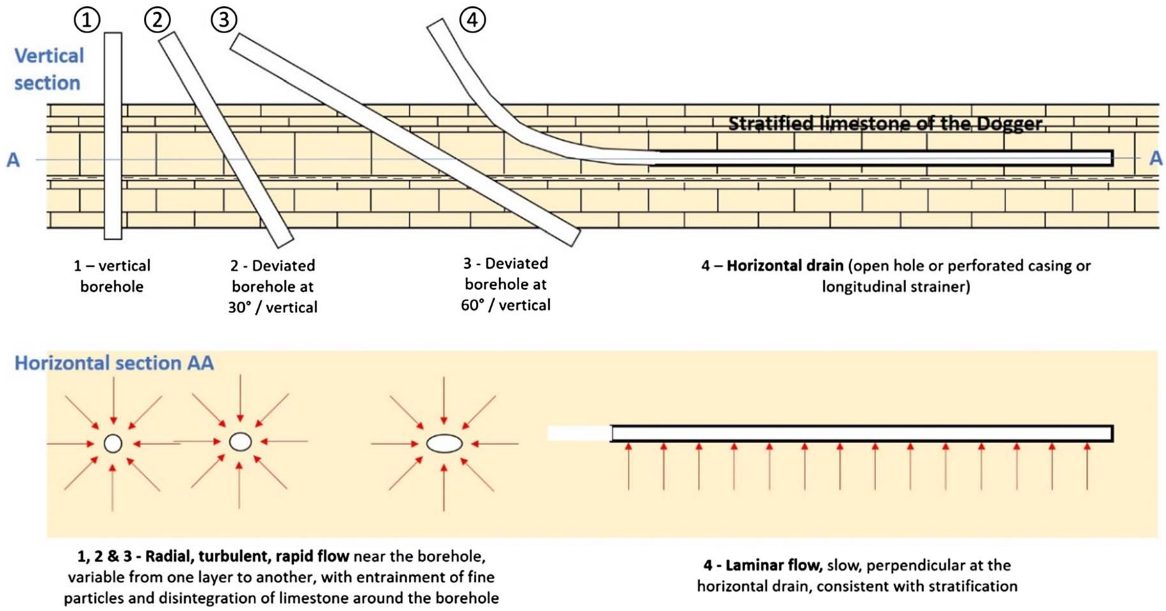

Fig. 2. Type of flow in the aquifer depending on the geometry of the borehole.

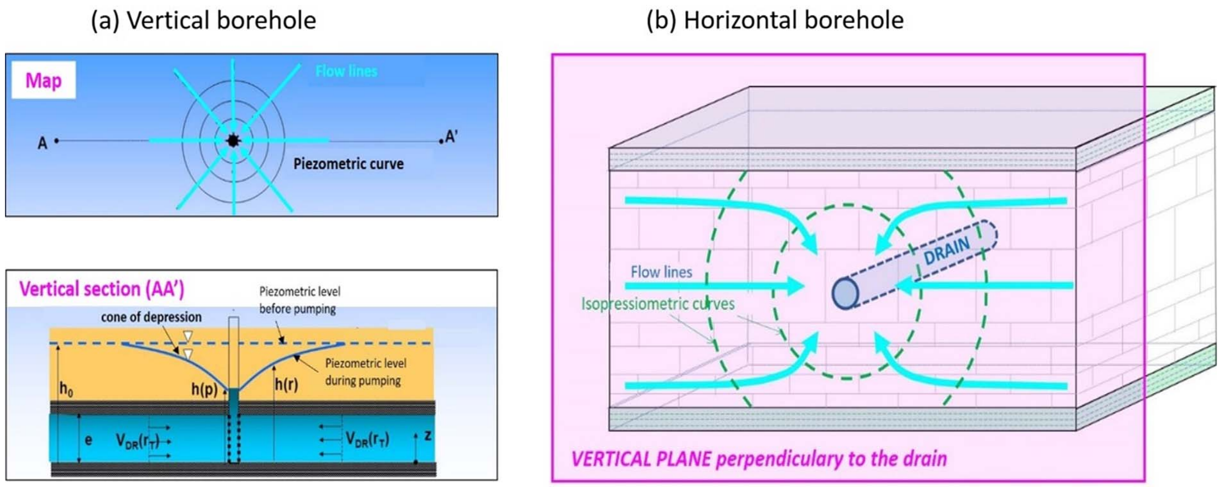

Fig. 3. Comparison of flows in a vertical borehole (a) and in a horizontal drain (b).

this method, Sonic and Density logs recorded from two runs can be concatenated and then combined properly (Fig. 5).

The pocket is simple to do. Drillers have to locate each casing shoe at 15 m above the bottom hole. Cement will plug the entire borehole bottom and then will go up between the casing and the formation. The drilling during the following phase will destroy the column of cement below the casing shoe. And the following log run won't see any cement during the measurements.

A VSP survey over the reservoir interval and above it would complete the calibration of the well to the surface seismic image.

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 [3].

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 [4].

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

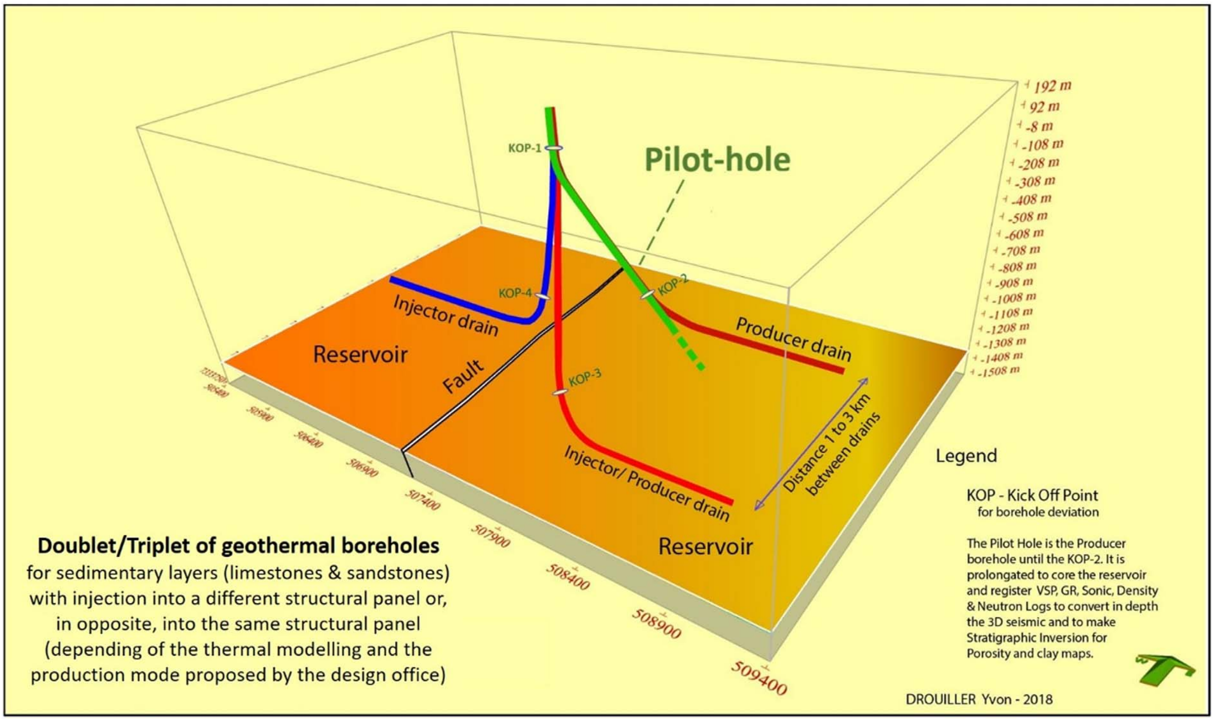

Fig. 4. Example of architecture of boreholes with horizontal drains inside the reservoir. The better knowledge of the reservoir allows to inject cold water in a different structural panel or, in opposite, in the same structural panel.

- Inventorying all aquifer reservoirs of the sedimentary series between the topographic surface and the granitic basement.
- Mapping the fault network (Fig. 8).
- Characterizing each reservoir, whether carbonated or clastic, to know all the petrophysical characteristics (porosity, clay content, fracturing, etc.).
- Checking hydraulic connectivity between the two 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 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 km^2) 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 (Fig. 6b). 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, Figure 6 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 [5, 6].

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 [7, 8].

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

Among the latest generation of exploration techniques, the so-called "broadband" 3D seismic currently delivers the

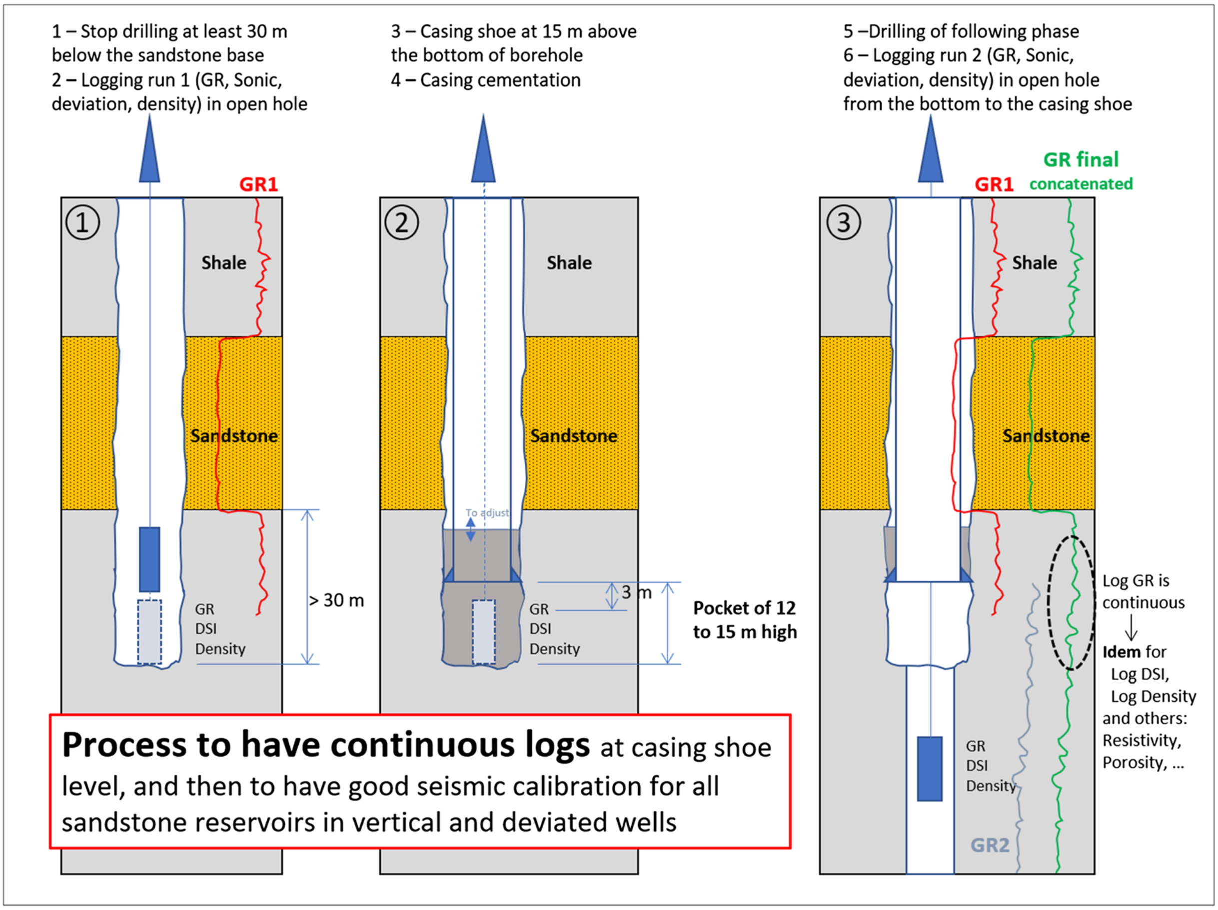

Fig. 5. Process for obtaining continuous logs at the casing shoe levels.

highest resolution seismic images (frequency spectrum 2–128 Hz covering at least six octaves – Fig. 7). The high quality of the images enables a 3D mapping of the faults with the greatest precision ever achieved (Fig. 8).

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 [9].
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 [9].

Seismic artefacts which were often existing in the three-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 [10]. 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 [9].

3.2.1 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

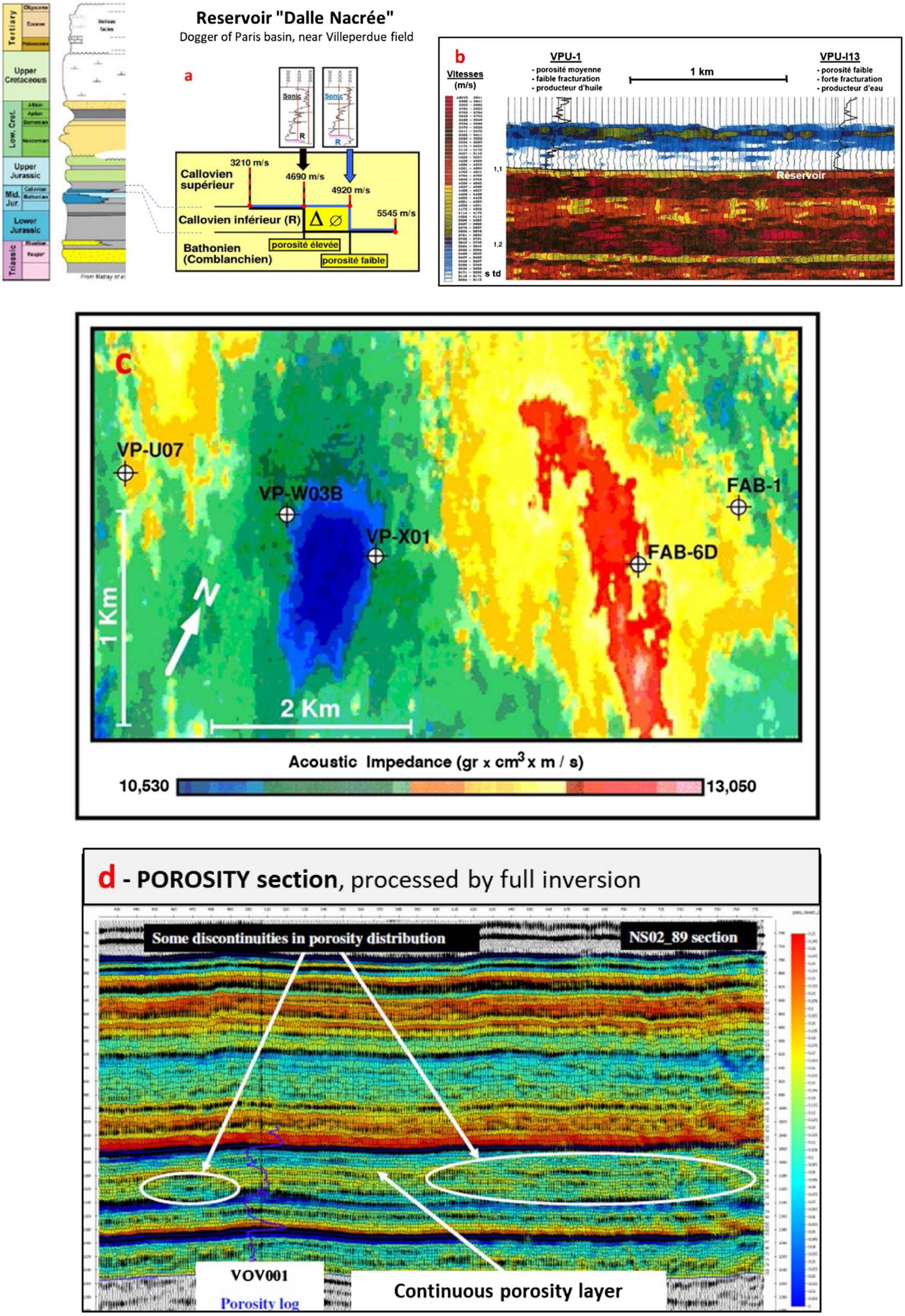

Fig. 6. Reservoir "Dalle Nacrée": Variations of velocity and acoustic impedance explain POROSITY variations on Sonic log (a), 2D seismic profile (b) and 3D vibro-seismic horizon slice (c), Variations of POROSITY on an inverted seismic section (d) – PICOREF project made in 1991–1993 by DHYCA to promote oil exploration in the Paris Basin [4].

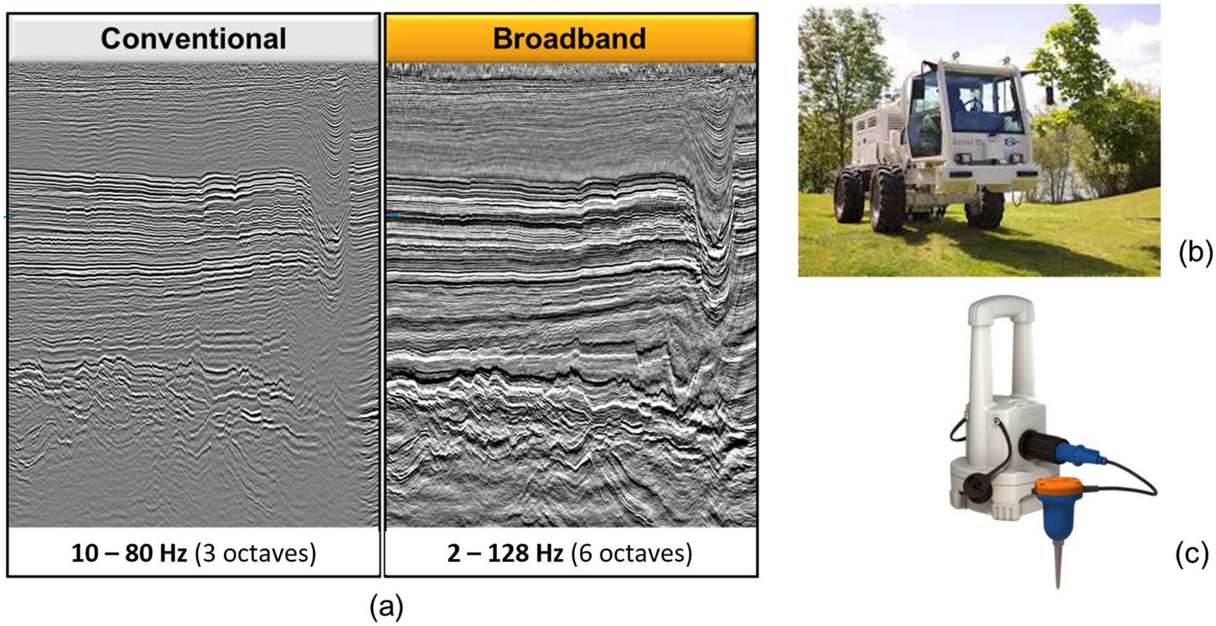

Fig. 7. Onshore 3D seismic acquisition: Progress realized with the six octaves Broadband technique – 2–128 Hz (a), courtesy of PDO, single vibrator (b) and wireless geophones for use on urban sites (c), courtesy of Sercel.

receivers provide a notably high signal-to-noise ratio and fine resolution from very shallow to deep across all reservoir levels [11].

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 [9].

A new generation of high-sensitivity geophones (83 V/m/s *vs.* 20 V/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.

Figure 7 (courtesy of PDO) shows an onshore example. It compares the three-octaves seismic of the 90's with the last generation six-octaves broadband seismic. Lowest two octaves (2–8 Hz) and the highest octave (64–128 Hz) give detailed geological information and improve greatly seismic imaging.

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 three-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 three-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.

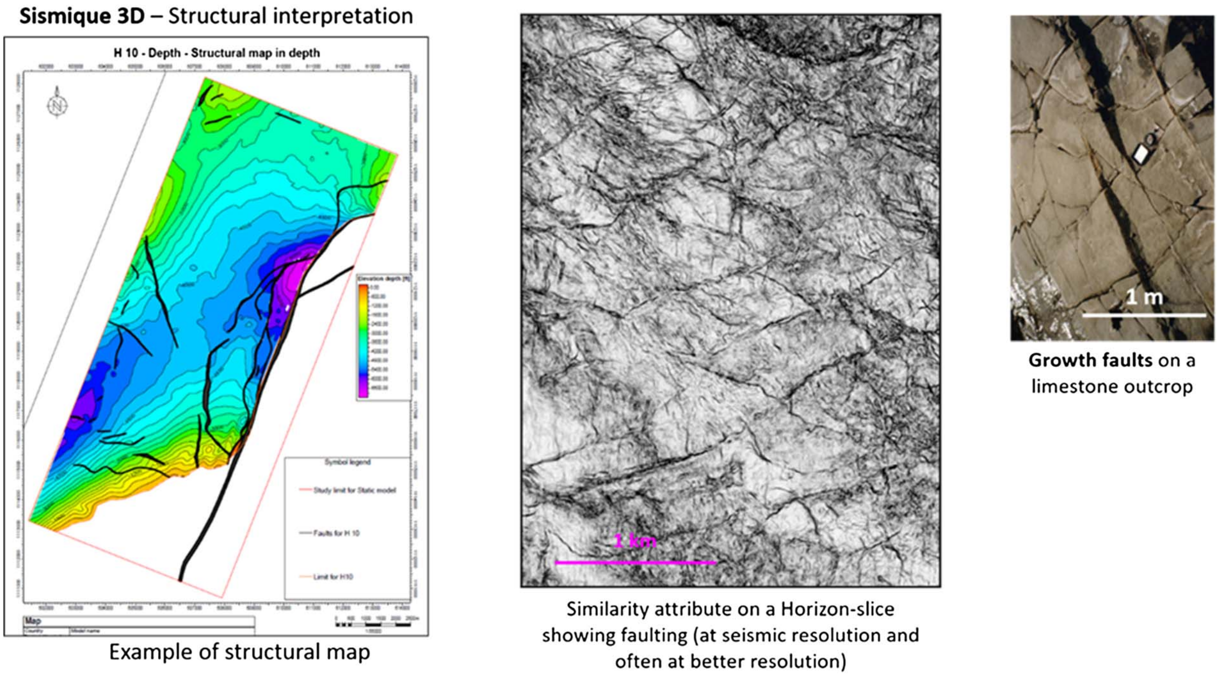

Fig. 8. Structural information obtained in a 3D seismic (mapping and similarity attribute), compared with a fractured limestone outcrop (on the right).

Presently, new three 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 [12].
- And then, an additional cost.

For geothermal projects, P-waves and 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, etc.

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 [13, 14].

3.4.1 Structural information

Figure 8 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.

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 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 [15].

3.4.3.1 Carbonate 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 Figure 9 is a carbonated reservoir from offshore Brazil. Each layer (five in this case), permeable or not, is characterized by a map which shows POROSITY variations along the interpreted horizon [16].

The comparison between Figures 9 and 6 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.

3.4.3.2 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, etc.) and to a lighter footprint by diagenesis.

In the Paris Basin, the Triassic sandstones (Chaunoy and Donnemarie formations) are fluviatile [17], as the Buntsandstein sandstones in the Upper Rhine graben.

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

- Sedimentation mode.
- Deposit geometry.
- Sedimentary discontinuities.
- Compaction and diagenesis.
- Tectonics, etc.

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

For these purposes, 3D-seismic six 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, etc.).
- Characterize each selected reservoir with a 3D mapping of the porosity and the clay content.
- Check the hydraulic connectivity between two 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 (Figs. 10 and 11a), but more difficult on the vertical sections (Fig. 11b).

Figure 12 is an onshore example to show the anisotropy and the porosity at the base of a clastic reservoir (Nimr). Data are extracted from seismic dataset by stratigraphic inversion. The interest of this figure is to show that porosities distribution can be very different in two superposed reservoirs. Characterization of the sandstone reservoir will begin during the pilot-hole drilling with the complete coring of the reservoir. Then, 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 10 km 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.

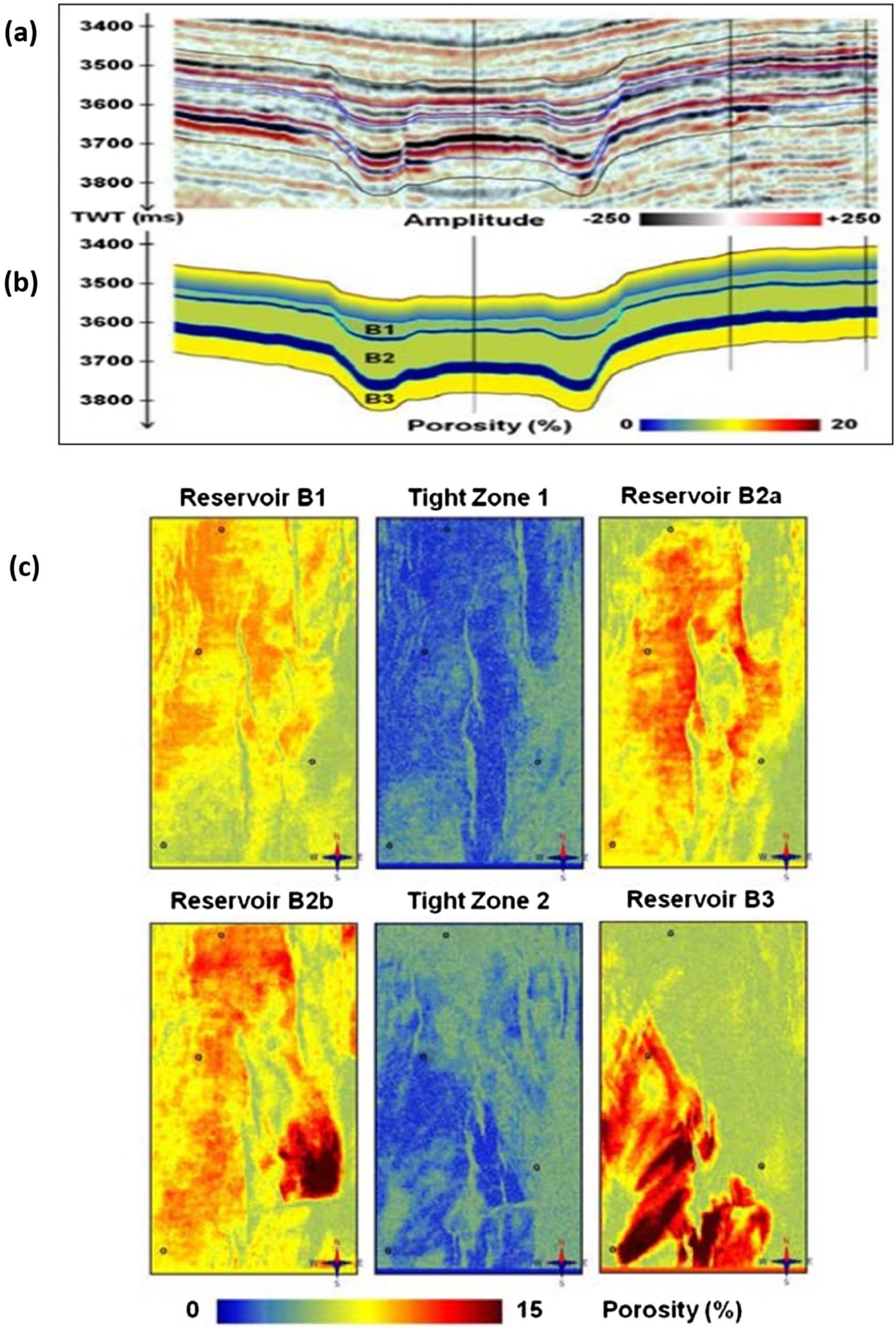

Fig. 9. Carbonate Reservoir (Brazil Offshore): Seismic section (a), initial porosity model (b) and maps (c) showing lateral evolution of the porosity in the different reservoirs and intermediate impermeable layers obtained by petrophysical inversion of the 3D seismic dataset [16].

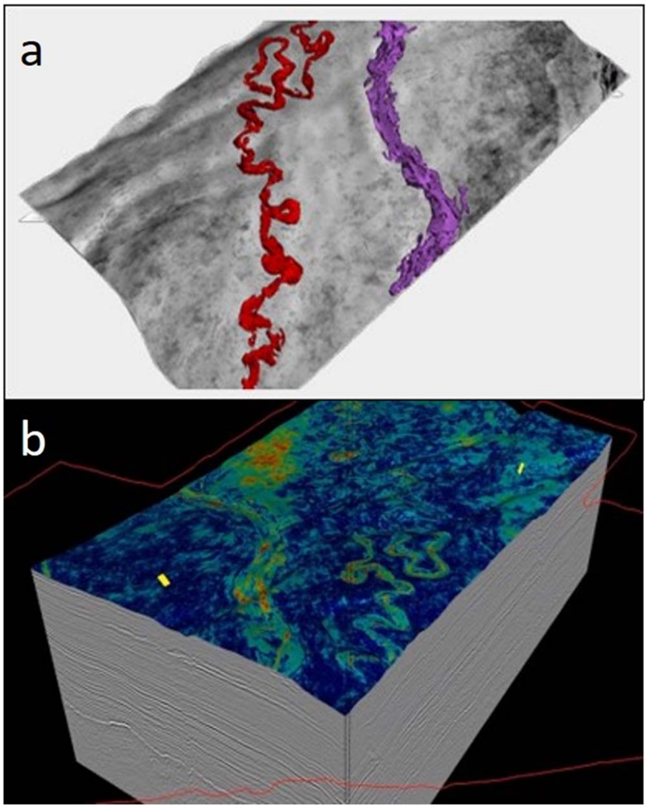

Fig. 10. Examples of fluvial systems which can be observed in 3D seismic (Courtesy of Eliis).

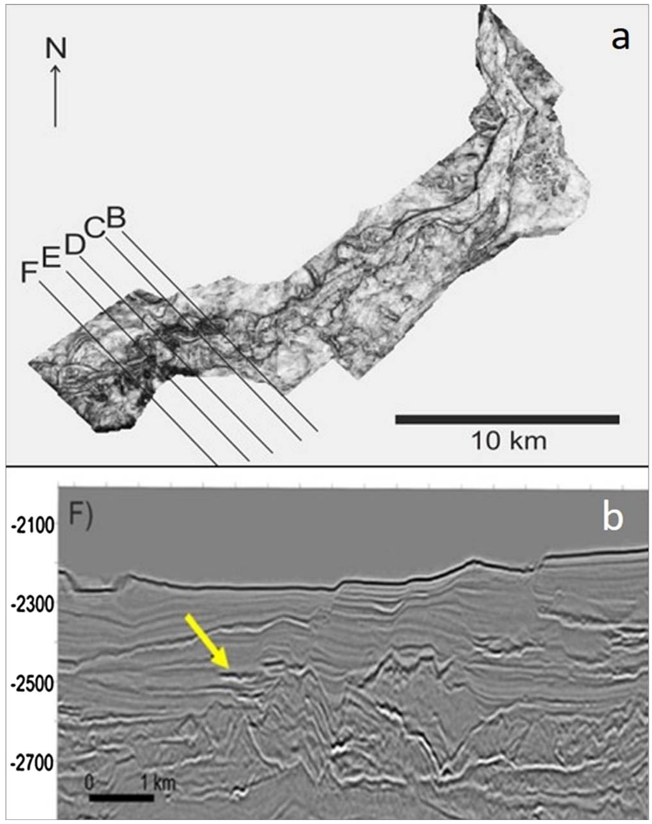

Fig. 11. Horizon-slice (a) showing the fluvial system visible on the section (b) [18].

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 (Fig. 13) can follow the following steps:

- Acquisition of a high-resolution broadband 3D seismic (*i.e.* with a frequency spectrum of six 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 two 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 (Fig. 14), 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 (Fig. 15).

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.

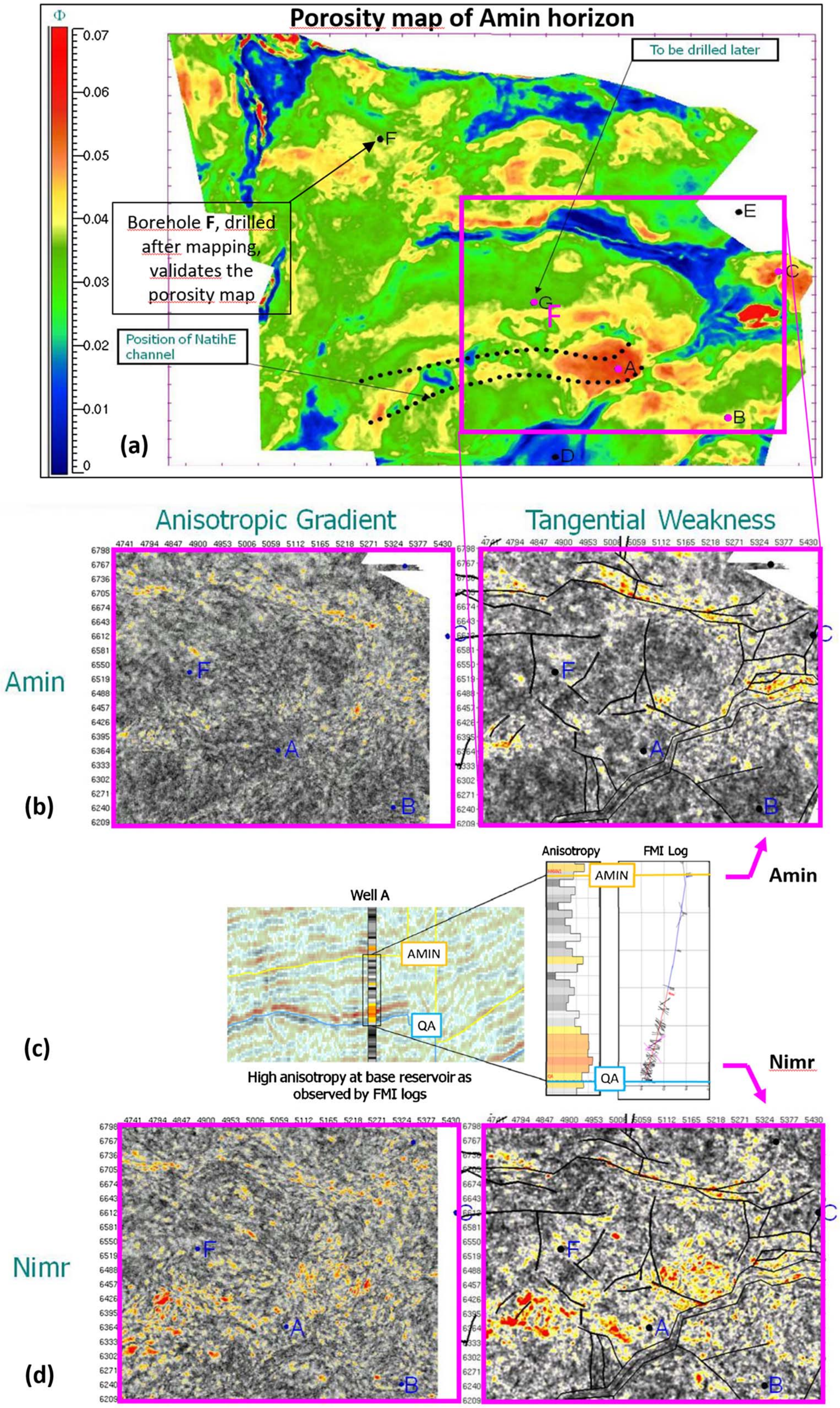

Fig. 12. Onshore Gas Play in North Oman: Clastic reservoir with higher anisotropy at the base (Nmir horizon). Porosity map of Amin horizon (a), anisotropic gradient and tangential weakness of Amin horizon (b), seismic section with both horizons (c), anisotropic gradient and tangential weakness of Nmir horizon (d) [19].

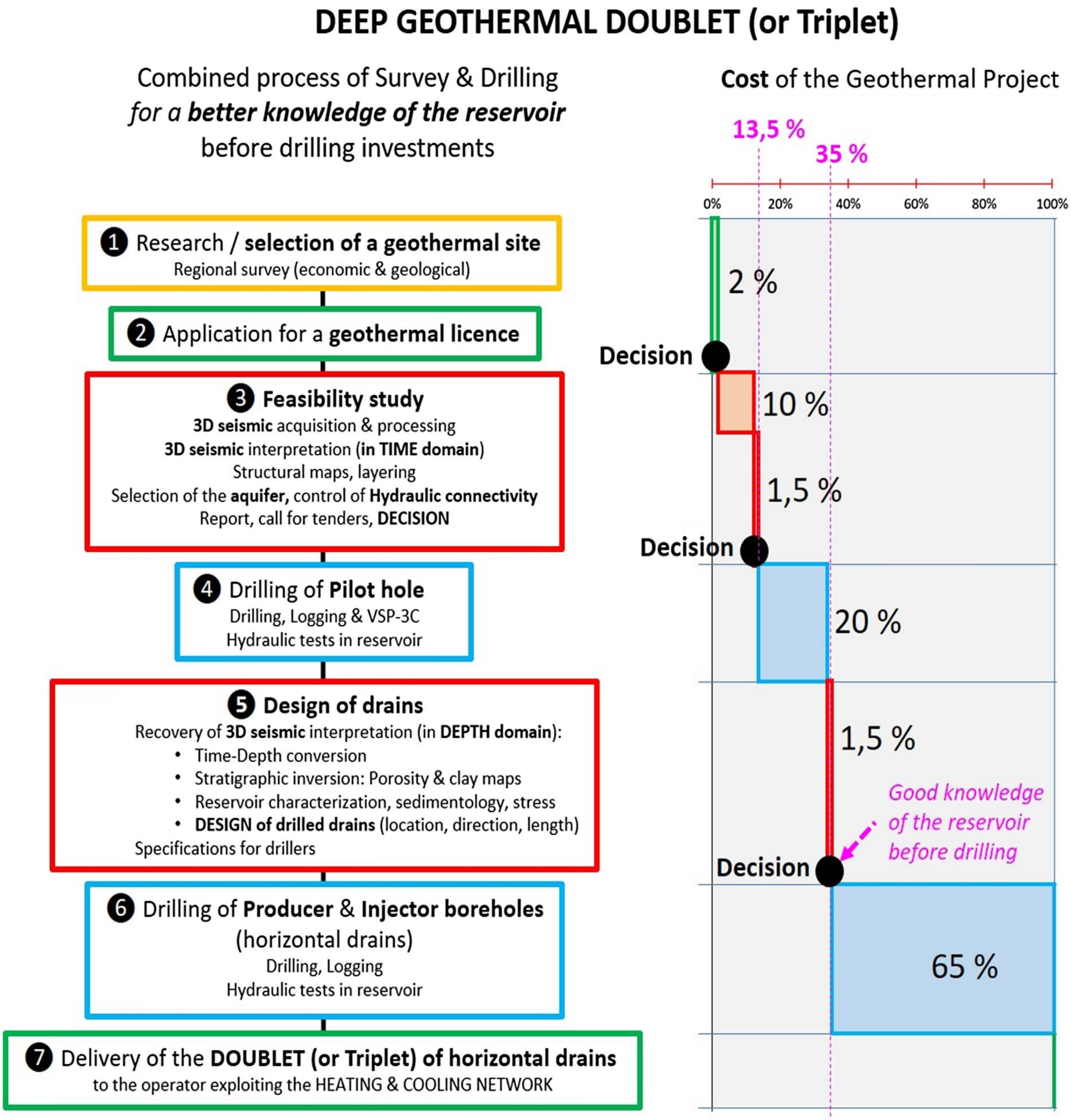

Fig. 13. Process for the survey of geothermal doublets/triplets before drilling investments.

3.6 To conclude on the need to use 3D seismic in deep geothermal projects

The methodology using broadband 3D seismic and 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 six 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

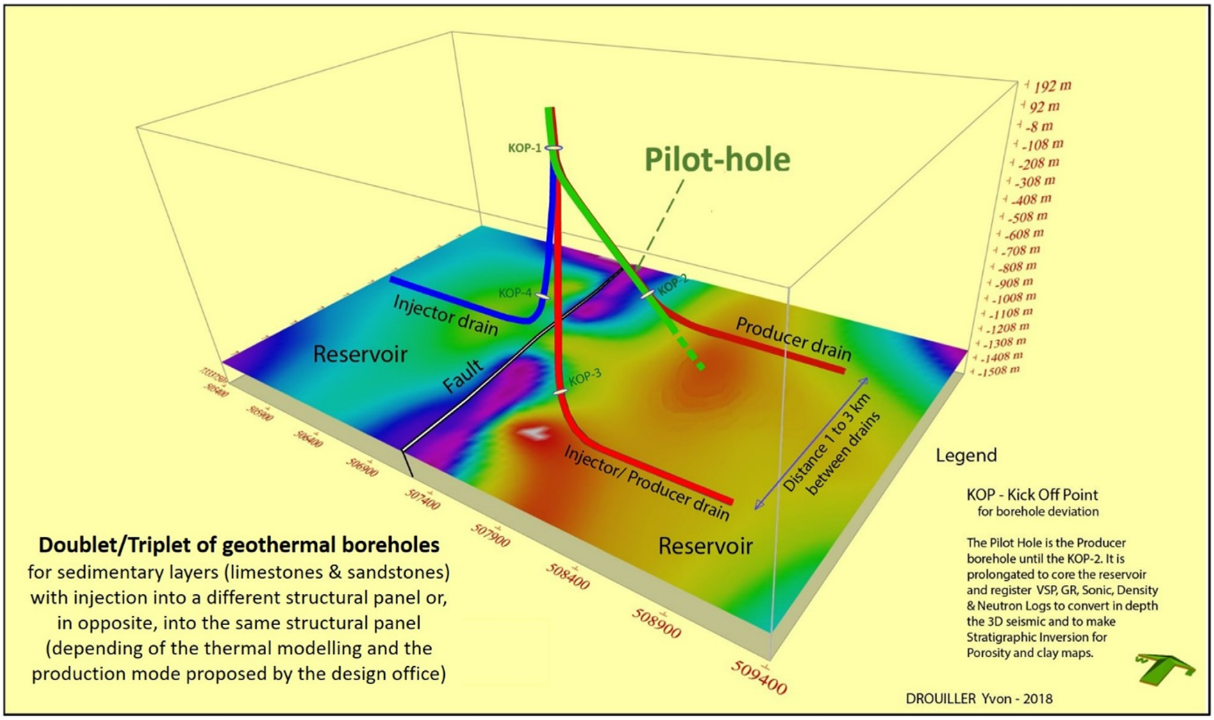

Fig. 14. Example of a geothermal triplet with horizontal drains inside the reservoir. The porosity map (simulation here) characterizes the reservoir in each side of the fault. The better knowledge of the reservoir allows to inject cold water in a different structural panel. The third drain allows to inject or to produce hot water, giving the operator both options depending on the season and the needs of the heating and cooling network.

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, etc.).
- 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.

3.6.1 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.

3.6.2 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.

4 Geothermal prospects in the Paris Basin

In the Paris Basin, four aquifers (Albian, Neocomian, Dogger and sandstone Triassic) are identified until now for deep geothermal energy in the Mesozoic series [16].

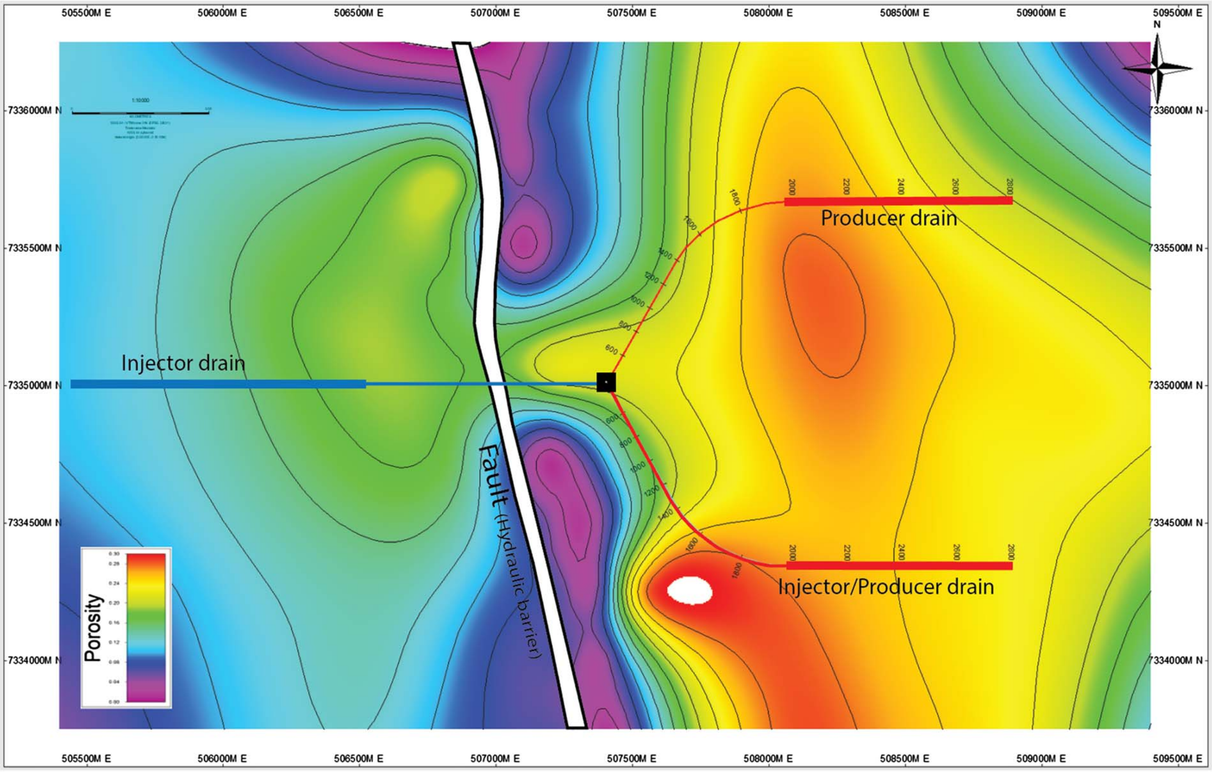

Fig. 15. Porosity map (simulation here) used to locate the three horizontal drains in the most porous and permeable zones. Note the role of the fault that separates two non-communicating thermal zones: hot and cold zones.

Presently, Albian, Neocomian and Dogger aquifers are exploited by geothermal projects.

4.1 Geological aspects to consider

The Dogger of the Paris Basin shows in the current zone of exploitation a relative homogeneity, except for the variations related to the depositional environments or the diagenesis. It appears relatively isopaque at the regional scale, in the centre of the basin.

The story is more complicated below: during the Lias, the synsedimentary activity of the major faults varies the thickness from single to double over small distances.

The Triassic deposits are developing towards the East with, in particular, the Buntsandstein sandstones whose thickness can reach 400 m in Lorraine and in the Rhenan graben. This formation is reduced very quickly towards the West, to disappear in Champagne and to be taken in relay by the sandstone facies of Keuper.

These Triassic reservoir formations, well known by oil industry geoscientists (Grès de Chaunoy, Donnemarie sandstone, etc.), have a limited extension and are the lateral equivalents of the marly and salt facies of Keuper. Unlike the Dogger, their presence, their thickness and their facies are linked to regional faults which have most often submeridian directions (Saint-Martin de Bossenay, Etampes, Saint Germain, etc.) or Armorican directions (Bray, Malnoue, Seine, etc.).

In the central area of the Paris Basin, seismic is the only tool to highlight the faults pattern that guides the distribution of these reservoirs. Some areas, poorly recognized at that time, are of interest especially with the axis of the Seine, from Paris to Rouen, as well as the Northern fault of the Pays de Bray considering the replay of this regional fault and the existence towards Picardy with a basal detrital bevel of the Triassic.

4.1.1 Ante-Mesozoic substratum

Under the Triassic, following a logic of distribution close enough, develops the Permian. Of sedimentary origin, locally disturbed by volcanic episodes, it corresponds most of the time to continental deposits in which shales predominate, but also with sandstone facies. Their thickness can exceed 1000 m in the syncline of Sarreguemines.

Other scattered basins of medium size exist such as:

- The basin of Brie, poorly recognized by seismic and drilling.
- The basin of Contres in the South of the Loire river.

Some small scattered basins associated with faults are distributed in the West and the North of the Paris area:

- The Coulommes basin associated with the Bray fault.
- The basin of Saint Maur in line with the anticline of Margny-les-Compiègne.

- The Vernon basin on the Seine fault.

The Carboniferous is present on the outskirts of the Paris Basin, in the East beyond the Marne rift, south of the Loire rift in relation to the meridian faults of the Massif Central and to the north of the Variscan front underlined by the "Midi" fault.

With maps of gravimetry anomalies (Fig. 16) and magnetometry, 235 boreholes (Tab. 1 and Fig. 17) and seismic sections, J. Baptiste [20] has built the structural and lithologic map of the Ante-Mesozoic substratum (Fig. 18). This map is covering the southern part of the Paris basin, from Brittany in the West to Vosges mountains in the East. All the basin centre was mapped, including the thickest part in the south-East of Paris.

The Carboniferous Coalfields of northern France rest on karstified limestones known as Dinantian. The latter is a geothermal resource in Belgium (Saint-Ghislain) and further north in the Netherlands. In France, it can represent medium and high energy targets in the Hauts-de-France, on the outskirts of the Nord-Pas-de-Calais coalfields, but also further south in Picardy with large overlaps.

4.1.2 Seismic profile ECORS "North of France" and processing progress

Indeed, the seismic profile Ecors "North of France", recorded in 1983 and recently reprocessed by CDP-Consulting, illustrates the deep structuring. This profile, 228 km long from Dreux to Cambrai, is crossing the major faults (Seine fault, Bray fault). It shows their deep set and their relationship with the tangential faults emerging in the North of France. It demonstrates that these major faults are crustal faults.

The exploitation of these data is a guide to better understand the deep hydrothermal circulations.

This reprocessing is a progress. It shows the way to resolve an old problem of reflection seismic multiples which made it difficult to see clearly the Palaeozoic and the granitic basement in the centre of the basin.

New generation seismic sections (six octaves), better calibrations with the wells (continuous logs, synthetic and VSP) and a suitable processing sequence would improve the basement image and would make it possible to define prospective zones near large cities.

4.2 Prospects to explore

Deeper targets may be considered, particularly with the Triassic or even the Permo-Carboniferous and the basement.

These deep sedimentary targets are associated with major faults that affect their distribution, thickness, facies and fracturing.

4.2.1 Triassic sandstones are still a prospect in the Paris Basin

Triassic sandstones are not yet explored and stay today a geothermal prospect. Some boreholes (Achères 1, Pontoise) have drilled them with geothermal objectives, but they encountered low porosities and permeabilities.

A dedicated exploration is needed for this prospect.

4.2.2 Regional faults, a new geothermal prospect in the Paris Basin

In the intracratonic Basin of Paris, regional faults 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.

Regional faults are organised as a pull-apart (Fig. 19) which explains the deepening of the basin during Lias and Triassic. A pull-apart is defined classically by four orthogonal faults: two strike-slip faults to expand and two normal faults to extend the layers in the concerned area.

This pull-apart is not regular because of re-using old faults which have replayed several times, but we can distinguish the four directions of main faults:

- The East-West main fault: In the North, the East-West main fault is formed by Bray fault, Malnoue fault and Vittel fault. These three faults are *strike slip faults* and are well visible on the gravimetry map, from the Channel to the Vosges mountains (Fig. 16).
- Along these regional faults, two thermal stations (Forges-les-Eaux in the West, Vittel in the East) underline a geothermal interest.
- North-South main faults: A second system of major faults, with a North-South direction, are relaying from Rouen to Nevers: Seine fault, Rambouillet fault, Etampes fault, Sully fault, Sancerre fault, Sancoins fault.
- The Etampes fault is a dextral *strike slip fault*.
- NE-SW normal faults: Chailly and Saint-Germain faults present a NE-SW direction and limit at the NW the pull-apart.
- NNE-SSW normal faults: St-Martin-de-Bossenay fault and Perreuse fault present a NNE-SSW direction and limit the pull-apart at the South-East.

The pull-apart is corresponding to the thickest Mesozoic sequences and the area of most of petroleum discoveries.

Hydrothermal circulations are expected along the major faults as the thermal stations (Forges-les-Eaux and Vittel) suggest.

The aim is to capture water-flows coming from faulted zones in the Palaeozoic and granitic basement.

Indeed, it is important to image the deepest faults that are mostly very old basement faults, reactivated during the Permo-Carboniferous, Triassic and Liassic sediment depositions. The detritic reservoir facies are generally located near the faults, laterally passing to clays or even evaporites.

The Cities located near regional faults (Tab. 2) could be interested by this deep geothermal resource.

4.3 Suggestion for a production pilot site to test superimposed aquifers and a regional fault

In France, there is no experimental site for deep geothermal in sedimentary sequences. To reduce costs, an industrial site

Table 1. Short list of wells which have drilled Palaeozoic basement in the Paris Basin, mainly metamorphic.

Well name	Geological age	Lithology	TD meter
Trois Fontaines 102	Scythian	Metamorphic	1937
Chaunoy 001	Paleozoic	Schist	2515
Pays de Bray 101		Gneiss	1082
Saint Martin de Bossenay 001	Sinemurian	Quartzite	2681
Le Teich 2	Paleozoic	Schist	3464
Soudron 001	Paleozoic	Quartzose sandstone	2503
Saint Just Sauvage 1	Norian	Mica schist	3073
Courdemanges 1	Paleozoic	Schist	2135
Charmottes 001	Paleozoic	Schist	3000
Saint Germain Laxis 1	Paleozoic	Schist	2424
Vulaines 01		Gabbro	3057
Vert le Grand 001	Paleozoic	Mica schist	2209
Maincy 001	Paleozoic	Mica schist	2420
Ivry 101D	Paleozoic	Mica schist	2430
La Chandeliere 1D	Paleozoic	Gneiss	1656
L'Orme 1D	Paleozoic	Quartizite	1897
La Croix Blanche 1D	Paleozoic	Quartizite	2125

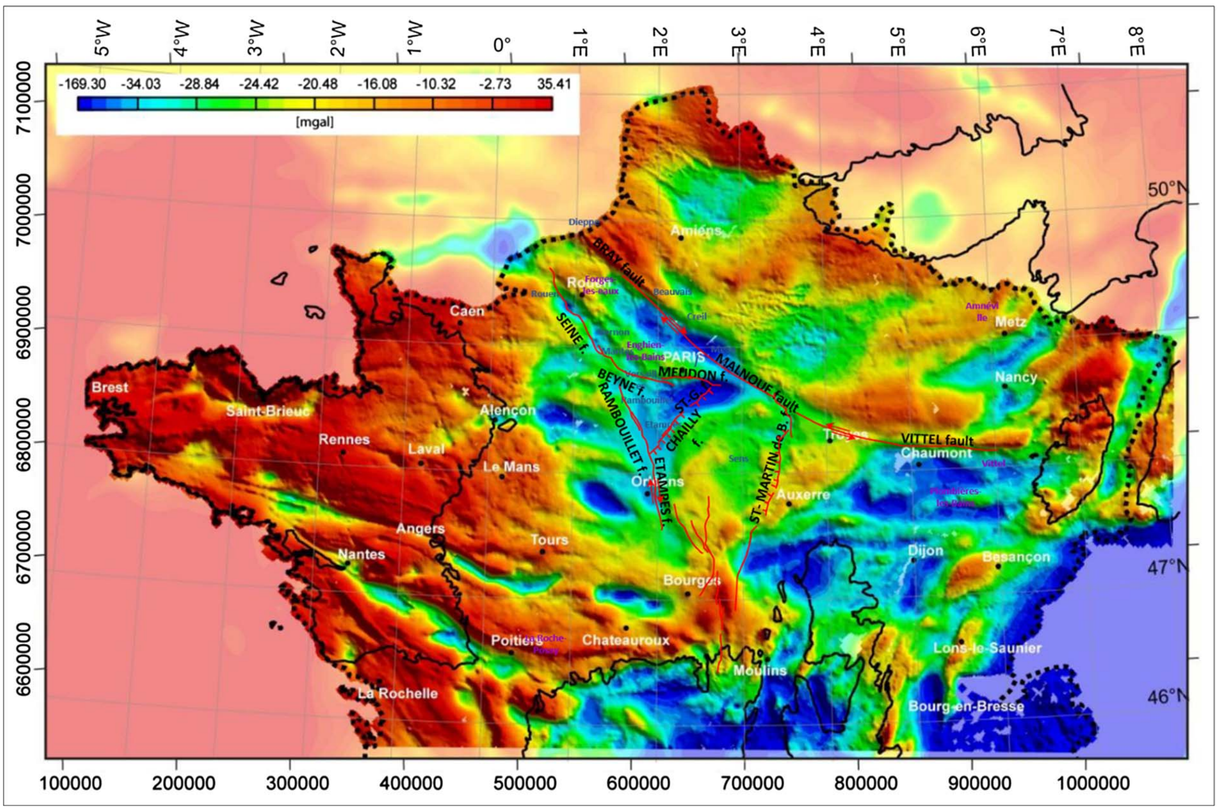

Fig. 16. Gravity map (Bouguer anomaly) of France modified by adding of selected regional faults (in red) [20].

for heat production could be used for a series of experiments.

The best site in the Paris Basin would integrate the four aquifers (Albian, Neocomian, Dogger and sandstone Triassic) and a regional fault which is overlapping the granitic basement. Two types of well architecture would be drilled: horizontal drains for aquifers and deviated wells for crossing the regional fault.

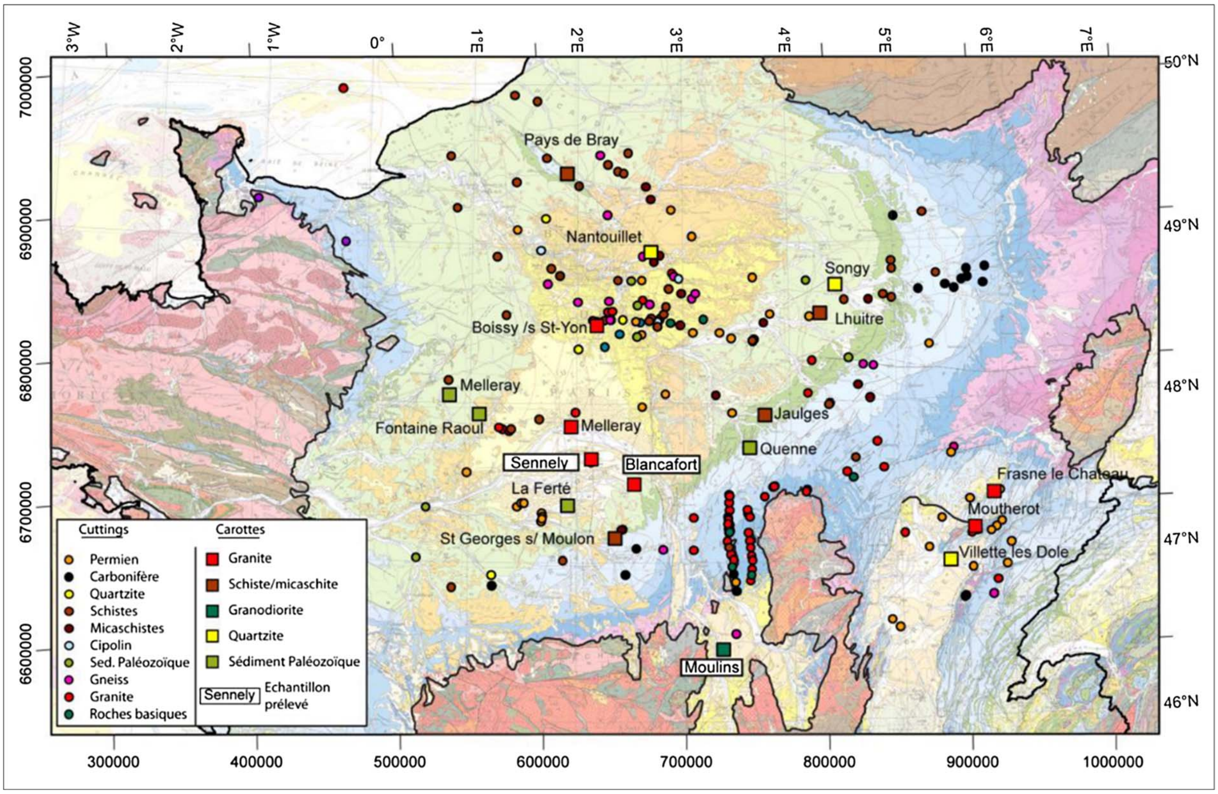

Fig. 17. Location of boreholes (cored and cuttings) having reached the basement (Palaeozoic or granitic) of Paris Basin [20].

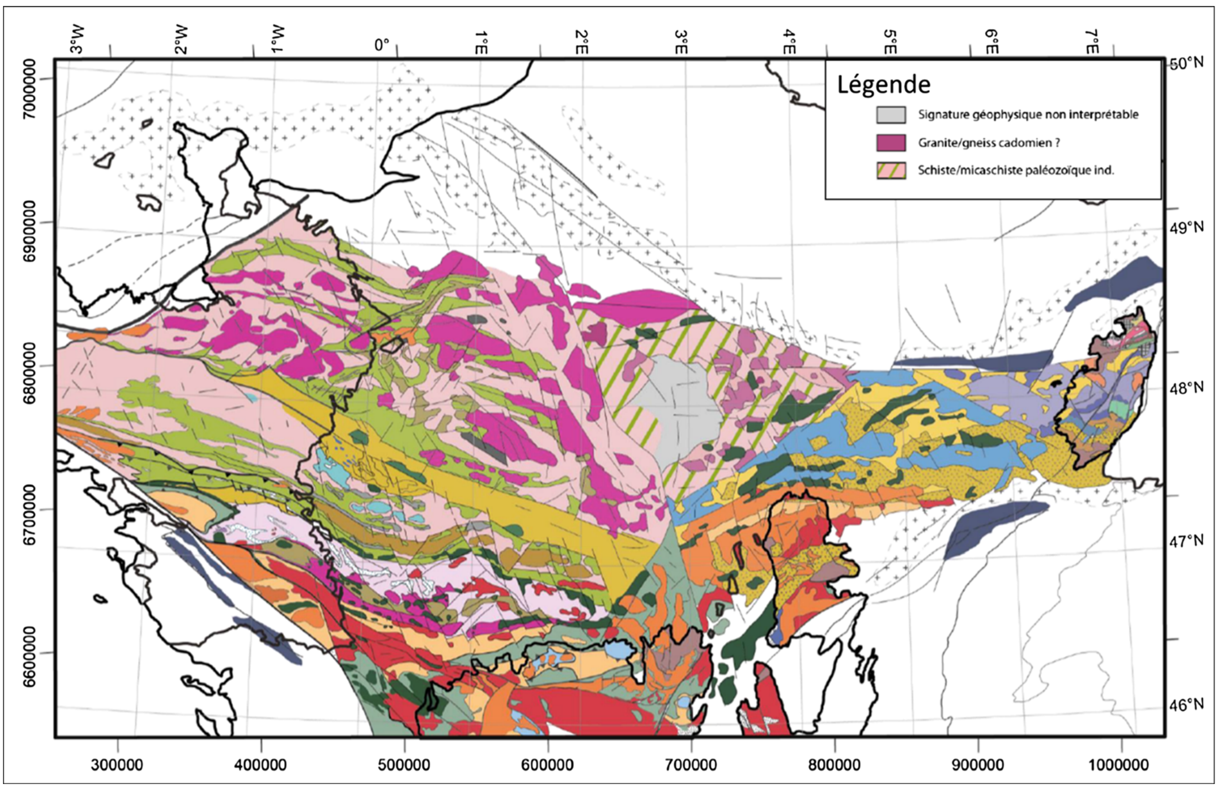

Fig. 18. Geological map of pre-Mesozoic basement of the Paris Basin [20].

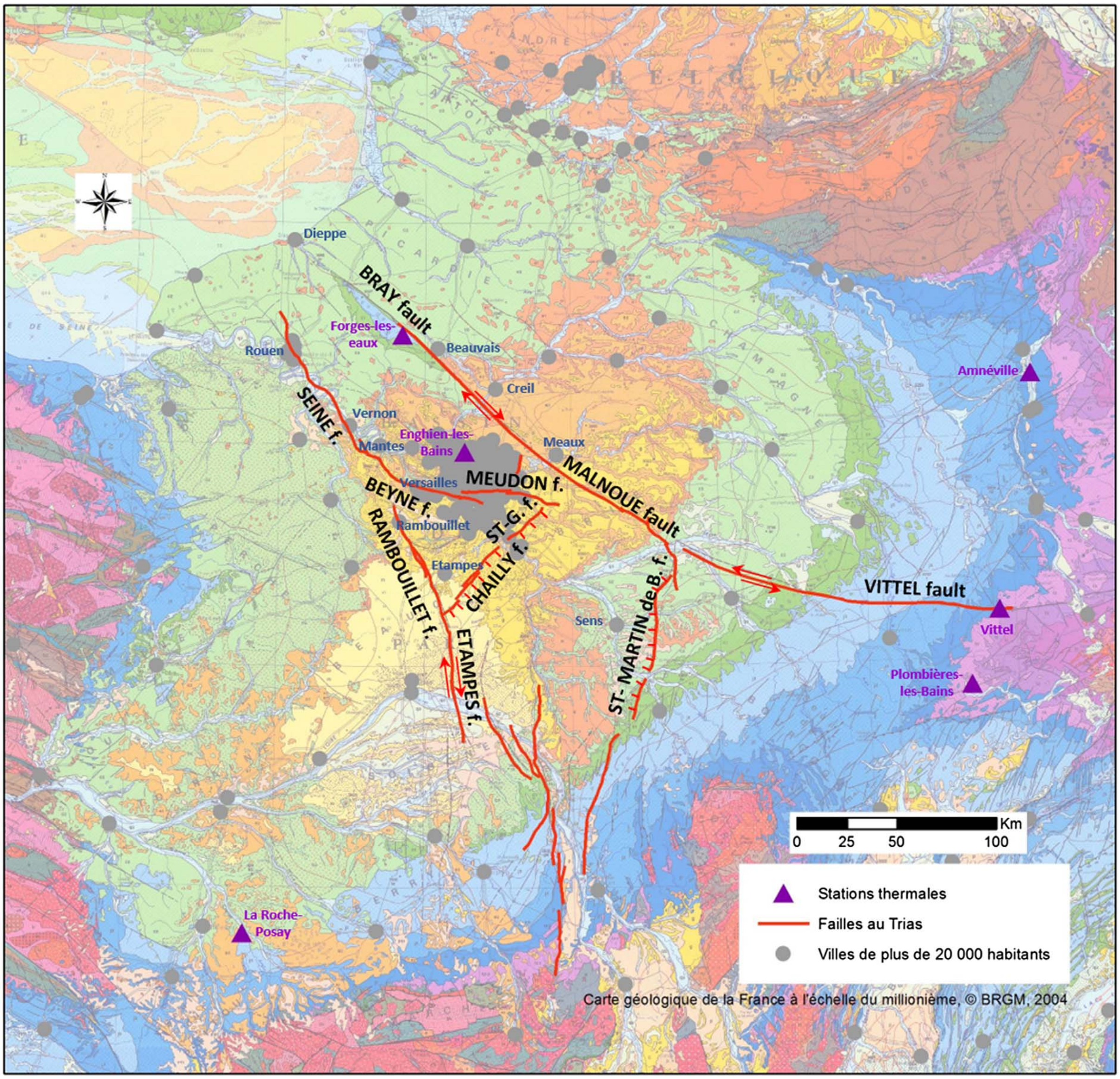

Fig. 19. New prospects of regional faults in the Paris Basin, with cities of over 20 000 inhabitants along faults.

Table 2. Location of cities of over 20 000 inhabitants along regional faults.

Regional faults	Cities located near regional faults
Bray fault, Malnoue fault	Dieppe, Beauvais, Creil, Meaux
Seine f., Beyne f., Meudon f.	Rouen, Mantes, Versailles and the South of Paris
Chailly f., Saint-Germain f.	Melun
Rambouillet f., Etampes f.	Rambouillet, Etampes

The 3D seismic methodology, described in this paper, will be used to know precisely reservoirs and faults before drilling.

For the carbonate reservoirs (Dogger), the aim is to image correctly drains in high velocity layers. Parameters of acquisition of the 3D seismic will be chosen to get a good vertical resolution at the reservoir level.

After drilling, numerous experiments can be useful to perform the geothermal capture system of the site, but also to adapt the process for surveys of future sites:

- Permeability and flow measurements.
- Fault and Fracture permeability at different scales.
- Matrix porosity: The actual porosity of the rock matrix can be measured on cores which have been sampled while drilling. But coring is expensive.
- Another way to get this information could be the real-time automatic analysis of cuttings by modern tools such as RoqSCAN. This tool allows to supplement the core data and to validate economically. This method is more attractive than the coring, because allowing to control the drilling and to optimize the completions of the horizontal drain [21].
- Comparison of measured porosity with the predictive 3D maps realized by the technique of the 3D seismic inversion.
- This comparison will make the method reliable and assess the risk reduction compared to the old method without 3D seismic.
- Clay content in clastic reservoirs.
- Transit time between drains.
- Temperature measurements.
- Modelling of critical parameters.
- Calculation of the better distance between drains (horizontal or deviated).
- Thermal modelling of the site, etc.

The thermal modelling is specific of both the site and the geothermal project. It cannot be extrapolated simply to another site. It is depending of the geology, characteristics of each aquifer, faults and fracturing, thermal conditions of the site and exploited water-flows.

A general process would be interesting to precise the best conditions of site, the best technology and the less-risked methodology for future projects.

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