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Geothermal reservoir temperature estimation derived from gradient wells in a continental rift context (Upper Rhine Graben)

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ABSTRACT

The temperature profiles performed in the deep geothermal wells drilled in the Upper Rhine Graben, and in particular in Northern Alsace, show a very linear shape with a high slope in the sedimentary cover down to the top of the Muschelkalk formations. Below this depth, the geothermal gradient decreases sharply, indicating the transition between a conductive gradient in the upper part of the formation, and the convective reservoir below. The top of the Muschelkalk is defined as the Cap-Rock of the convection loop of the geothermal brine which induces an important geothermal gradient up to 10°C/100 m in this region. From this observation, a new exploration method emerged, which consists in drilling shallow wells of 200 m depth in the sedimentary part of the graben to measure an equilibrium temperature profile. From this temperature profile, a gradient is computed, allowing to extrapolate the temperature at the top of the Cap-Rock and thus to estimate the temperature at the geothermal target, in the convective reservoir. This study describes the results of a campaign of exploration composed of seven so called “gradient wells” drilled in zones of interest, previously identified by vintage 2D seismic retreatment and interpretation.

A methodology was established using the thermal logs of the deep wells of Rittershoffen and Soultz-sous-Forêts (Alsace, France) and applied to the temperature profiles measured in the gradient wells in order to estimate the temperature at the top of the Cap-Rock and at the geothermal target. Similarly, geological analysis of the cuttings of the boreholes, coupled with field observations of the area, allowed to establish a chrono-stratigraphic log containing information on the nature, depth, thickness and age of the geological formations in each zone. The analysis of the temperature and geothermal gradient curves showed a good correlation between the lithology and the local thermal variations. Indeed, a large number of variations observed on the curves can be explained by local facies changes. This method of exploration was found to be relevant because of its valuable contribution to the estimation of the temperatures at the geothermal target.

1. INTRODUCTION

For more than twenty five years now, the Upper Rhine Graben has been a main target for research on geothermal exploitation in deep fractured rocks (Figure 1). Indeed, the scientific pilot power plant at Soultz-sous-Forêts (Alsace, France), established in a deep fractured granitic massif between 3.5 and 5 km depth has resulted in the development of geothermal exploitation in deep fractured crystalline reservoir and has provided the international scientific community with a unique high quality data set (Genter et al., 2015a). The principle of geothermal exploitation in deep naturally fractured rocks in the Upper Rhine Graben consists in enhancing the low natural hydraulic performance of the geothermal fractured reservoir by thermal, hydraulic or/and chemical stimulations. These stimulations increase the fracture permeability to allow pumping the geothermal brine at economically viable flow rates (Baujard et al. 2015, Genter et al., 2015 b, Maurer et al., 2015). After a complete renovation of the facilities, the plant has been exploiting geothermal brine at 150-160°C with a flowrate of about 30 l/s to produce a gross power of about 1.7 MWe since the beginning of July 2016.

The recent geothermal project located at Rittershoffen, 6 km east of Soultz-sous-Forêts, exploits a geothermal brine trapped in the fractured hard rocks. This geothermal project is designed to produce 24 MWth (170°C, 70 l/s) which is delivered to a bio-refinery located 15 km away. The commercial exploitation of the geothermal plant started on September2016. Two deep wells have been drilled between 2012 and 2014 to 2500 m TVD (True Vertical Depth) for targeting local normal-faults located close to the interface between the clastic Triassic sediments and the top crystalline basement. Due to a poor initial injectivity index, the first well, GRT-1, was developed using various thermo-mechanical and chemical treatments (Baujard et al., 2017). The results were positive, since the initial well injectivity index was multiplied by a factor of five. The second well, GRT-2, was good enough hydraulically after drilling operation and thus, it was not necessary to enhance its natural permeability (Baujard et al., 2017).

Other geothermal industrial projects are planned in the French part of the Upper Rhine Graben in the coming years. Some projects are in the drilling phase in the Strasbourg area (Vendenheim, Illkirch) but other projects are still in an exploration phase. The two main challenges which are conditioning the whole economy when investors want to set up new projects are the estimation of the reservoir temperature and the flow rate before any drilling operation. By applying various kinds of stimulation techniques as described before, the flow rate (injectivity or productivity index) could be enhanced. However, for estimating the temperature range at target depth before drilling, only exploration methods (geophysics, geothermometry, thermal modeling…) are useful.

Thus, this paper proposes to describe how the temperature of the geothermal fluid was estimated at depth by so called “shallow gradient-wells”. This exploration method is classically used for geothermal exploration in volcanic context, but was adapted to the deep naturally fractured reservoir rocks of the Upper Rhine Graben.

2. REGIONAL SETTINGS

2.1 Geological settings

The Upper Rhine Graben (URG) is a 300 km long, 40km width regional rift zone with an azimuthal orientation averaging N020°E between Mainz and Basel (Figure 1). It is associated to the Rhine plain structurally bounded on the South by the folded Jura, on the West by low relief Vosges mountain range, on the East by the Black Forest and Northward by the Neogene shield volcano of the Vogelsberg.

The western edge of the Rhine Graben is limited by two major normal faults (Figure 1). The outermost Vosges fault separates Paleozoic series from Mesozoic/Cenozoic series and has variable vertical off-sets from several hundred meters to over a thousand meters. The innermost Western Rhine fault inconspicuous on the surface separates Mesozoic/Cenozoic series from Rhine plain. On the Eastern shoulder of the URG, the Schwarz Wald fault and the Eastern Rhine faults are dipping westward with similar vertical off-sets (Figure 1).

Stratigraphically, the uppermost part of the Upper Rhine Graben is composed by Plio-Quaternary deposits (mainly composed of sand and gravels which unconformably cover Eocene and Oligocene formations whose deposition began during the regional extensional context started 40 My ago (Figure 1b). The Miocene is absent in Northern Alsace, suggesting a minimum erosion of 17.7 My. The Oligocene is composed of the Niederroedern Layers (Chattien, clay crossed by numerous banks of sandstone and limestone dolls), the Grey Series (Rupelian) and the Pechelbronn formations (lower Rupelian to upper Priabonian [Eocene] homogeneous clay formations). The Eocene formations recover a discontinuous eroded surface of the Mesozoic formations (Figure 1b).

This extension is at the origin of the spacing between the Western and Eastern regional Rhine faults. The sedimentological filling of the basin is syn-tectonic and affected by numerous normal faults resulting from the opening system. Within the Mesozoic era, lack of Cretaceous sequence is observed in the Upper Rhine Graben due to a late Jurassic uplift phase, resulting in a 125 My hiatus in the depositional sequence (Figure 1).

The Mesozoic and Paleozoic formations are exhumed in the rift flanks and are buried below the Tertiary cover, deeper in the center of the graben by tilted blocks. Detailed lithologic studies have been performed from the GRT-1 borehole during Rittershoffen drilling operations (Aichholzer et al., 2016).

The Variscan crystalline basement is mainly constituted of granites and granodiorites which have been set up 320-330 My ago.

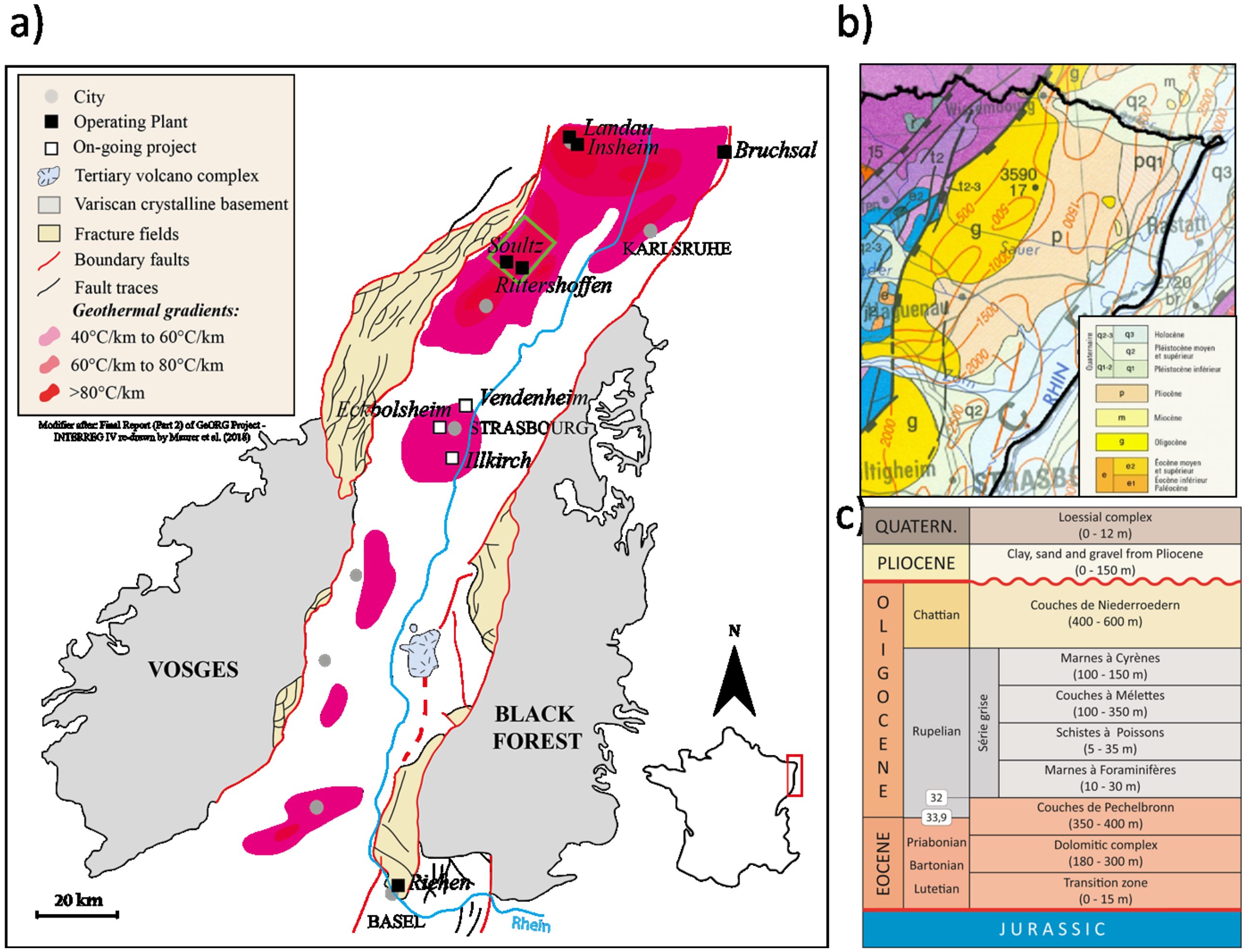


Figure 1: a) Simplified geological map of the Upper Rhine Graben (URG) with geothermal gradient b) detailed lithological log of the Tertiary formations in the URG.

2.2 Hydrogeological settings

For geothermal issues in the Rhine Graben, propitious targets are mainly deep and fractured hard rocks. Natural fracture system governs natural permeability. Boreholes analysis in the Rhine Graben has shown the permeability of the matrix of the deep formations is too low for a geothermal exploitation. Furthermore, each borehole with high productivity rates is associated with natural faults/fractures induced by the complex and polyphased tectonic evolution of the region.

Depending on the local geological conditions, the fractured permeability's efficiency is enough to allow a water circulation and/or its pumping exploitation (Le Carlier et al., 1994). Due to the asymmetrical shape of the Rhine Graben in this area (Figure 2), it could explain that the circulation could take place at regional scale (see Figure 2). Thus convective cells transported geothermal fluids from greater depths (roughly 4-6 km; Sanjuan et al., 2016) to shallower depths (cap rock). It generates higher temperature gradients than in a classical sedimentary basin. Geothermal brine acts as a heat transfer fluid by pulling up the heat towards the shallower formations through convection cells. The geothermal fields of Soultz-sous-Forêts and Rittershoffen confirm the presence of warm and deep circulations (Baujard et al., 2015, Dezayes et al., 2015, Genter et al., 2015b, Sanjuan et al., 2016). Thus, a litho-stratigraphic knowledge is required for an optimal location of the geothermal platform to reach deep-rooted structures where the potential fractured reservoirs are in the shallowest position.

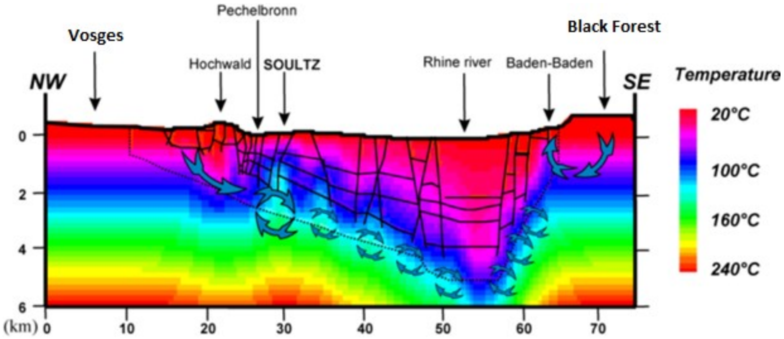


Figure 2: NW-SE schematic sections of hydrothermal circulation in the Upper Rhine Graben (from Le Carlier et al., 1994)

2.3 Thermal settings

In the case of a relatively high thermal flux, high temperature gradients can be associated with low thermal conductivities. For instance, the low conductivity of the Late Triassic, Early Jurassic and Tertiary marls and sands of the Soultz area which overly the limestones of the Muschelkalk is manifested by a “pillow” effect that tightens the isotherms at the bottom of the concerned sediments leading to a linear gradient of up to 10°C/100 m. Based on the geothermal wells of Soultz-sous-Forêts and Rittershoffen, the occurrences of natural brines circulating via the fracture and fault system have been clearly demonstrated (Baujard et al., 2017; Genter et al., 2010). Such framework induces a hydrothermal convection up to the top of the Muschelkalk formation which has a high intergranular or fracture permeability. The Keuper and the Lias formations form a thick layer, mainly composed of clays and marls that disallow all circulation of fluids. This clay-marly cover continues upwards with the Tertiary formations whose lithology is finally not very different.

Hence, the top of the Muschelkalk constitutes a cap-rock limit for the convection (Vidal et al., 2015). According to the Soultz-sous-Forêts and Rittershoffen temperature profiles (Figure 3), this effect explains the high temperature gradient at shallow depth and the extremely stable linear shape of the temperature profile. This linear thermal behavior in the uppermost part of the sedimentary filling in this area allows to assess the temperature at the depth of the cap rock by extrapolation of the thermal gradient measured at shallow depth.

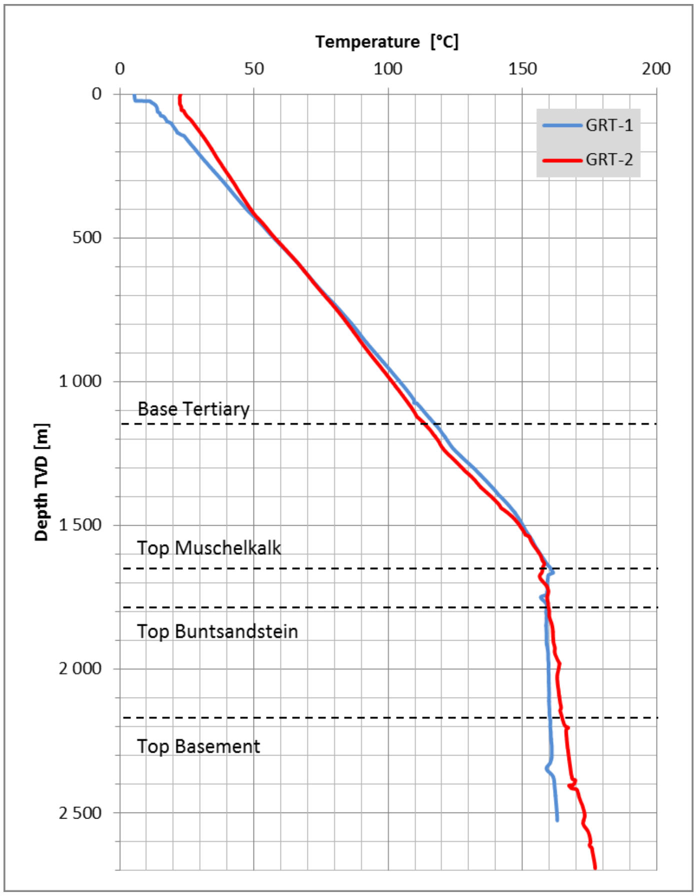


Figure 3: Geothermal temperature profiles at Rittershoffen GRT-1 and GRT-2 wells (from Baujard et al., 2017)

3. ACQUISITION

3.1 Set up of the exploration campaign

In the framework of the geothermal exploration in Northern Alsace, seven shallow vertical wells equipped with double geothermal probes were drilled, later called "gradient wells" in this study. The wells were drilled at 200 m depth, which is the limit set by the French drilling authorities under which the declarative regime applies and not the regulatory one. The main goal of this exploration campaign by gradient measurement was to select the best place to settle the next geothermal plant and the principal criteria of selection is the estimation of temperatures at target.

Based on the retreatment and the interpretation of old 2D seismic profiles the major deep-rooted structures were identified and the depths of the major geological interfaces, including the top of the Muschelkalk formation (top of the cap-rock), were computed. From this study, several areas of interest were identified.

The gradient wells theoretical locations were chosen on the top of the expected target, supposedly at the level of the faults polygons at the level of the top Buntsandstein of the deep-rooted structures previously identified by the seismic study. In the context of an exploratory phase, the greatest amount of information has to be acquired at a fixed budget. One idea was to be able to carry out at least one profile of three boreholes perpendicular to a major fault in order to see if a thermal variation of the gradient is seen from each side of a given fault. Then, the number of boreholes was degraded to two boreholes for another zone and to one in the last two zones (Figure 4).

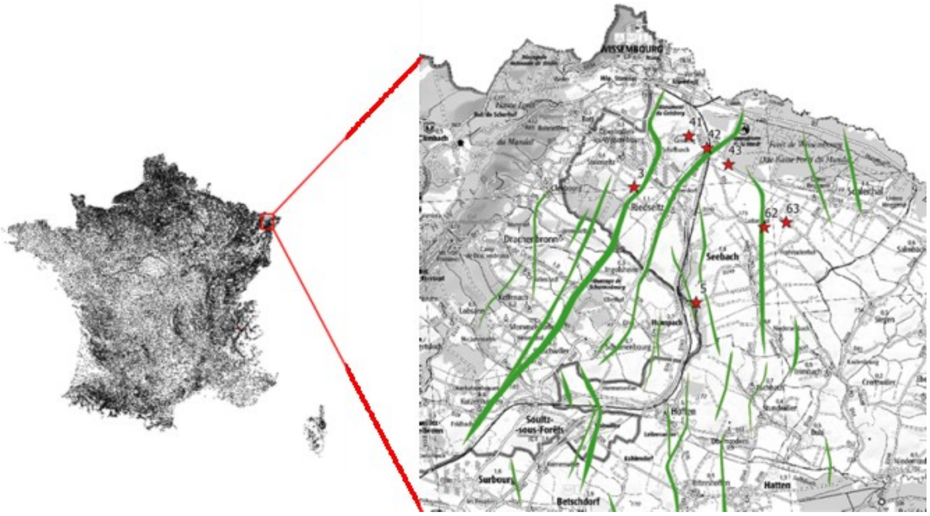


Figure 4: Locations of the borehole (red stars) and the fault polygons (green lines) at the level of the top Buntsandstein.

During the drilling, a geological sampling was performed every two meters. Despite this dense sampling rate, the distance between two samples does not allow for a fully continuous sampling. Indeed, layers whose thickness is less than 2 meters may not be seen and also bias may exist in the evaluation of the layers thicknesses. Moreover, samples were only cutting, and not drill core, which do not allow to identify sedimentary structures. After the drilling operations, two "U" shaped probes were set up in each well and partially filled up with water by the drilling company. A few days after the cementation operation of the wells, the probes were fully filled with water.

3.2 Measurements

The instrument chosen to perform the temperature measurements is a small ball (diameter of 20 mm), which is dropped in a probe and falls down by gravity while recording the temperature and the pressure (resolution: 1.0 mbar, < 0.01 K). Once the sensor is at the final depth (200 m), a pump launches the water circulation in the probe, making the small sensor to come back at the surface and extract the thermal data.

After the installation of the probes, several weeks are required to reach the thermal equilibrium, mainly because of the exothermic reaction generated by the cementing operations. The measurement is then performed by releasing two sensors in each of the dual "U" probes of each well, in order to have a synchronized redundant measurement.

A few weeks later, this protocol is repeated, in order to have a redundancy of measurements for each well over time. This protocol makes possible to have a double redundancy of measurements, on the one hand by the use of the two sensors in the dual "U" probes and, on the other hand, by the doubling of the measurements over time.

For all the wells, the temperature profiles were found to be very coherent between the two probes, since the maximum difference was less than 0.1°C. The same result was found by computing the difference between two measurements over time in a same probe, thus demonstrating a high consistency of the temperature profile measurement in a same well.

For measurements of temperature profiles in the gradient wells, a sampling frequency of 1 Hz was chosen. The speed of descent of the sensor in the vertical geothermal probes was found to be constant for all the measurements made, at around 24 cm/s. A measurement every 24 cm is sufficient to carry out a linear regression and to estimate the geothermal gradient since the linear regressions to estimate the geothermal gradient were performed on at least 5 m, thus on a minimum of twenty measurements.

3.3 Methodology of computation of the geothermal gradient

The methodology implemented was as follows:

- Since the first tens of meters are often impacted by temperature measurements that are not representative of the deep thermal regime, only the last 80 meters of each well are considered.
- Several linear regressions are calculated between 120 m to 200 m depth on each interval larger than 5 m.
- A weighted average gradient is then calculated from all these linear regressions that takes into account the length of the interval used for the linear regression and its standard deviation
- This weighted average gradient allows to estimate the temperature at the top of the Cap-Rock.

This methodology was tested on the temperature profiles of the existing Soultz and Rittershoffen deep wells, which allow to calculate the difference between the estimated temperature and the effective temperature at the top of the Cap-Rock. The Figure 5 shows the result of this statistical analysis for the Soultz well EPS1, which cross-cut the entire sedimentary succession and penetrated in the granite reservoir to 2.2 km depth (Genter et al., 2010).

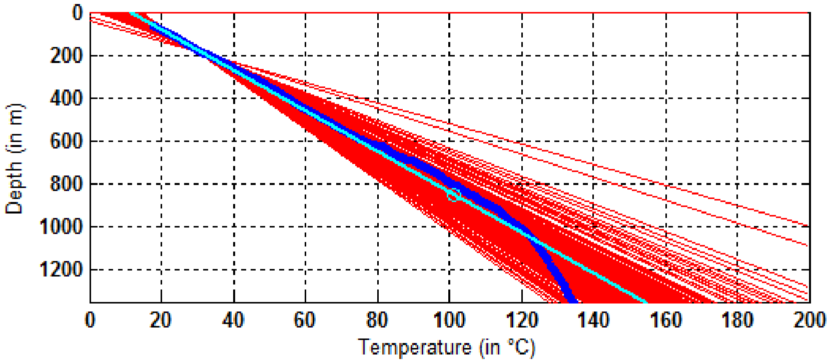
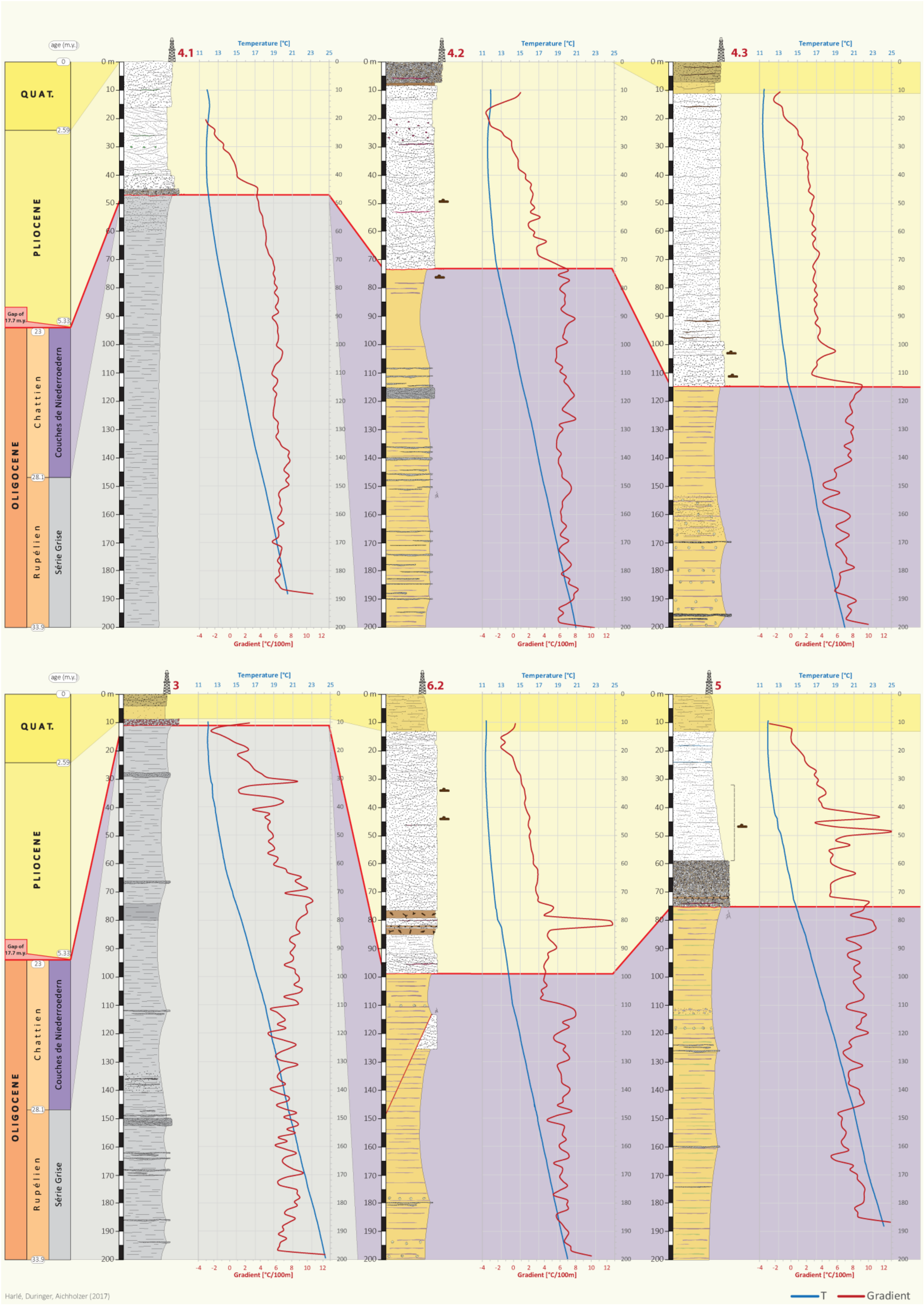


Figure 5: Statistical analysis realized on the thermal log of the EPS1 thermal profile by simulating a well of 200 m depth. The difference temperature between the estimated temperature and the effective one is less than 2.5 °C.

4 RESULTS

The cuttings sampled in each borehole were studied to build the stratigraphic logs. Litho-stratigraphical units identified were correlated with the geological series observed in the area by correlations with relevant outcrops (Ménillet et al., 2015), in order to locate them on the stratigraphic scale.



Harlé, Duringer, Aichholzer (2017)

Figure 6: Stratigraphic logs of the gradient wells associated to temperature profiles and geothermal gradients in the Wissembourg area.

Figure 6 shows that the Quaternary was entirely eroded for wells 4.1 and 4.2C. However, the thickness of these formations in the other wells seems to vary slightly (between 9 and 12 meters thick).

On the contrary, the Pliocene appears in all the wells but its thickness varies strongly (from 2 meters of thickness for the well 3 to 104 meters for the well 4.3). This formation is characterized by a succession of fine to coarse sands up to gravely/pebbly occurrences. Centrimetric to decimetric clayey level are numerous from base to top of the formation. Also, the presence of levels rich in poorly decomposed large plant debris in wells 4.2 to 6.2 is noticed. The Miocene is absent in all wells.

The Layers of Niederroedern (Chattien) have a minimum thickness of 127 meters (well 4.2). The depth of the wells (200 meters) does not allow reaching the base of this formation, so its maximum thickness can't be estimated but a thickness of 400 m was measured in an adjacent region. This formation was completely eroded in the wells 3 and 4.1. This formation consists mainly of yellow clays purple striped given to the formation a unique facies. Numerous banks of sandstone and limestone dolls characterize also this formation (wells 4.3, 5 and 6.2). There are also more sandy clay levels in wells 4.3 and 5, traces of plants in wells 4.2, 5 and 6.2 and some pebbles in well 5.

The Gray Series (Série Grise from the Rupelian) is crossed only in wells 3 and 4.1. It is a homogeneous clay to marly clay formation that can contain some sandstone beds. Based on well 4.1, its minimum thickness is estimated at 153 meters. As with the Layers of Niederroedern, it is not possible to evaluate its maximum thickness but it exceeds 500 m in the center of the Pechelbronn basin.

Wells 3 to 5 do not appear to have any objective tectonic structures.

However, well 6.2 (Figure 6) crosses inside the Niederroedern formation a unit of medium to coarse grey sand between 113 and 125 meters identical to that of the Pliocene sands encountered between 92 and 99 meters deep (same color, same granulometry) . From 99 meters onwards, there is a change of series (a reddish-yellow red silty clay unit) corresponding to the summit of the Niederroedern Layers. According to Ménillet and Geissert (1976), these clay layers do not contain coarse sand banks. Thus, it can be assumed that the sandy unit encountered in the multicolored clays actually belongs to the Pliocene. We observe an insertion of a younger formation between two samples of an older series. Thus, based on the existing datasets, we can then assume that the well 6.2 passes through an inverse fault.

A statistical analysis was performed on each well, and as an example, the Figure 7 shows the result for the well 6.2.

The left-hand side of Figure 7 shows the temperature profiles measured with the linear regression finally chosen, and the temperatures obtained on all the profiles performed at an average depth estimated at the top of the Muschelkalk (Cap-Rock). The horizontal line in red indicates the depth from which the linear regressions were calculated. Thus, a depth of 120 m was chosen to avoid the impact of the surface temperature on the calculation.

On the right-hand side of Figure 7, are shown from top to bottom:

- The set of linear regressions calculated, giving an idea of the quality of the regression finally chosen by the tightening of the lines. The linear regression in cyan is the finally chosen geothermal gradient.

- A Gaussian law is fitted on a histogram of the weighted gradient to estimate the range of the error done on the computation of the geothermal gradient (68% confidence (σ), 95.4% confidence (2σ) or 99.7% confidence (3σ)).

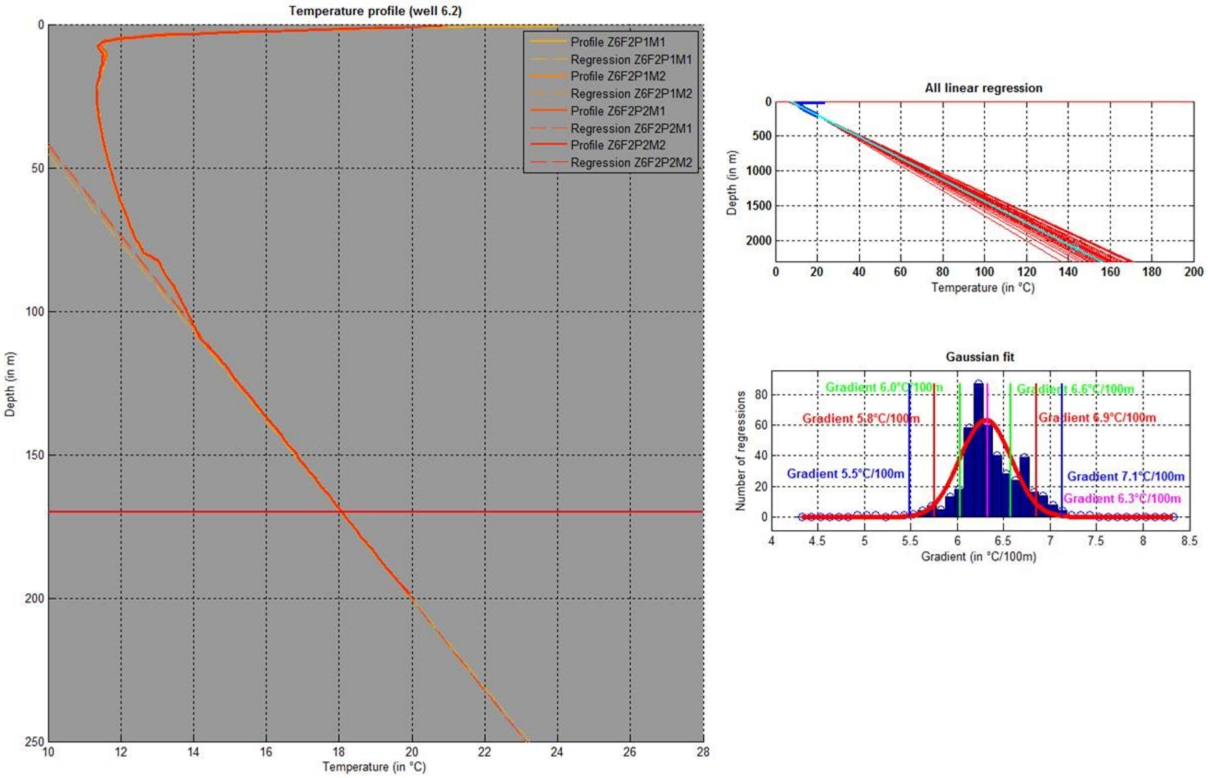


Figure 7: Left: Geothermal gradient obtained for the well located in the zone n°6.2 (see Figure 4). Upper right: set of all linear regressions calculated. Down right: Gaussian law fitted on a histogram of the weighted gradients used to estimate the error done on the geothermal gradient measurement.

The same statistical methodology was applied on each well to calculate the geothermal gradient and to estimate the temperature at the top of the Cap-Rock.

In the geothermal wells of Soultz-sous-Forêts and Rittershoffen, below the top of the Cap-Rock, the gradient is not completely negligible. Indeed, a low gradient persists below this depth. To estimate the temperature reached at the geothermal target, an estimated gradient of 1°C/100 m was applied below this depth. This value was estimated on the basis of the thermal profiles observed in the Rittershoffen and Soultz-sous-Forêts wells. Hence the temperature of the geothermal brine was also estimated.

5 DISCUSSION

Firstly, at a first order, the gradient shows significant changes with depth. Indeed, the gradient appears to be less important in the sandy units of the Pliocene than in the Oligocene clay units (wells 4.1 to 6.2). Thus, a first order correlation between a gradient variation and a major change in lithology seems to be observed. In general, an increase in the gradient with depth in the sand of the Pliocene is observed at first order. On the contrary, in the Oligocene clays, the gradient appears to stabilize over the entire thickness of the layer, inducing a linear increase of the temperature in these units.

Secondly, finer variations have to be considered. Gradient inflections seem to systematically indicate particularities within the formations. For example, in well 6.2, the peak observed on the gradient curve between 78 and 86 meters deep indicates a very steep gradient increase and is located at the exact location of the pure plant debris levels included in the medium to coarse grey sand bank. This same sharp increase in gradient is found on the curve of well 5, between 40 and 50 meters deep (probably caused by wood fossils remains) and at a depth of 72 meters. The gradient also appears to be sensitive to the presence of sandstone beds. Indeed, the gradient of well 3 is very irregular at the height of the Gray Series, and the latter is very sandy in this well. Well 6.2 has one particularity: it is the only well in which a fault has been detected in lithology. Indeed, this suspected inverse fault allows the insertion of a sand bank of the Pliocene in the clays of the Oligocene. The temperature seems to be sensitive to it, since there is a slight drop on the temperature curve and a significant increase of the gradient at the level of the sand bank towards 110 m. However, it is difficult to know whether these visible variations on the curves are due to the fault itself (possible circulation of water in the fault) or to the change in lithology that it generates (sand to clays).

Finally, in general, two phenomena could explain the variations observed on the curves: the presence of fluids in the soils and the thermal conductivity differences of the units. Conductivity is primarily related to the nature of the rocky material. Consolidated rock (e.g. clay or sandstone) conducts heat better than unconsolidated rock (e.g. sand or gravel). However, the thermal conductivity increases with the water saturation of the medium. The presence of fluids in the rock is directly related to its porosity. Thus, a porous medium is likely to contain fluids and therefore to be subject to higher thermal conductivity. A sand or gravel bank saturated with water may then have a higher conductivity than consolidated clay. If the pores of the formation in question are connected together, then this unit is permeable and allows the circulation of fluids and therefore the transport of heat. Thus, sands, gravels or sandstones are permeable rocks in contrast to clays whose sheet structure prevents water from circulating. A variation in lithology, and thus in thermal conductivity, accompanied by a significant variation in permeability causes a change in the circulation of the fluids which affects temperature. In the case of the transition between the Pliocene sands and the Oligocene clays, a lower gradient increase is observed from the clays. Water hardly circulates in the clays, so the increase in temperature is almost no longer due to the circulation of fluids but almost only to the increase in depth, which may explain the linearity of the temperature curve in this formation. Finally, the strong increase in gradient and temperature observed at the level of the fault in the well 6.2 may be due to the higher permeability generated by the fault but also to the lithology itself. Indeed, this fault induces a sand bank (thus a lithology with high permeability) in well consolidated clays (less permeable). In general, it is difficult to differentiate the effect of thermal conductivity and the effect of an increase in permeability on the temperature curve. For this reason, thermal response tests are planned in order to know the thermal response of the formations traversed.

A comparative analysis of all the investigated zones shows strong heterogeneities of the geothermal averaged gradients measured from one zone to another. The geothermal gradients range from 6.3°C/100 m in zone 6.2 to 7.6°C/100 m in zone 5 (see Figure 8). The highest gradients measured are not necessarily related to the presence of known large fault structures, as shown in zone 5, where, according to the interpretation of the old seismic, the fault targeted does not affect the Triassic sandstones of the Buntsandstein and the basement very much.

This observation leads to consider the non-negligible contribution of faults not visible by 2D seismic on a regional circulation scheme. Indeed, since geothermal water acts as a heat transfer fluid, an important geothermal gradient implies a high permeability of the underlying terrane in order to allow the convective circulations of hot and deep geothermal fluids to the top of the Cap-Rock. These fractured zones, not visible on 2D vintage seismic, could be interpreted as normal having a limited apparent vertical off-set or as fracture corridors with no off-set, induce significant permeability over large distances within hard rocks such as sandstones and granites without necessarily generating offsets. They are therefore impossible to detect on conventional 2D seismic reflection (resolution > 50m at 2.5 km), but can be detected by innovative processing with a 3D seismic. The contribution of such a method to the selection of promising zone will be extremely powerful in defining the geothermal target of future geothermal drilling.

In this way, this method of exploration by gradient wells shows extremely powerful potentialities on regions subjected to convective circulations in the underground such as the Upper Rhine Graben.

However, it should be noted that the depth of the Cap-Rock taken for the calculations remains an approximation given by the 2D seismic retreatment. Given the current uncertainty on this parameter, it will be imperative to refine this estimate with a new seismic acquisition in order to be able to specify the expected temperature at the top of the Cap-Rock.

The expected differences along a profile established perpendicular to a fault were not observed in comparison with the temperature values measured at Soultz and with the numerical models (see zones 4 and 6). In future exploration campaigns, it will be necessary to better distribute the drillings over the whole explored area in order to maximize the chances of observing gradient heterogeneities. It should be noted to remain cautious with the use of this method in regions with water table which may mask the linearity of the temperature profiles.

Moreover, the temperatures estimated at the top of the Cap-Rock are all between 143 and 150°C (see Figure 8). This observation also raises a question about the homogenization of temperatures at the level of the faulted zones and consequently of the fluid circulation at the level of the Cap-Rock, at a regional scale. The geothermal brine, through its convective circulations, would allow a homogenization of the temperatures of the roof of the Cap-Rock at this spatial scale. According to that hypothesis, the differences observed in the geothermal gradients in this region would be actually only due to the depth of the Cap-Rock. To test this hypothesis, drilling should be performed in an area that is not affected by a major fault, but where normal faults with small off-set or fracture corridors are suspected.

This hypothesis, if verified, would make possible the extension of the favorable site of implementation of deep geothermal projects by targeting other minor faults. Moreover, it would reduce the risks related to micro-seismicity induced by geothermal operations and to position projects closer to heat consumers on the surface.

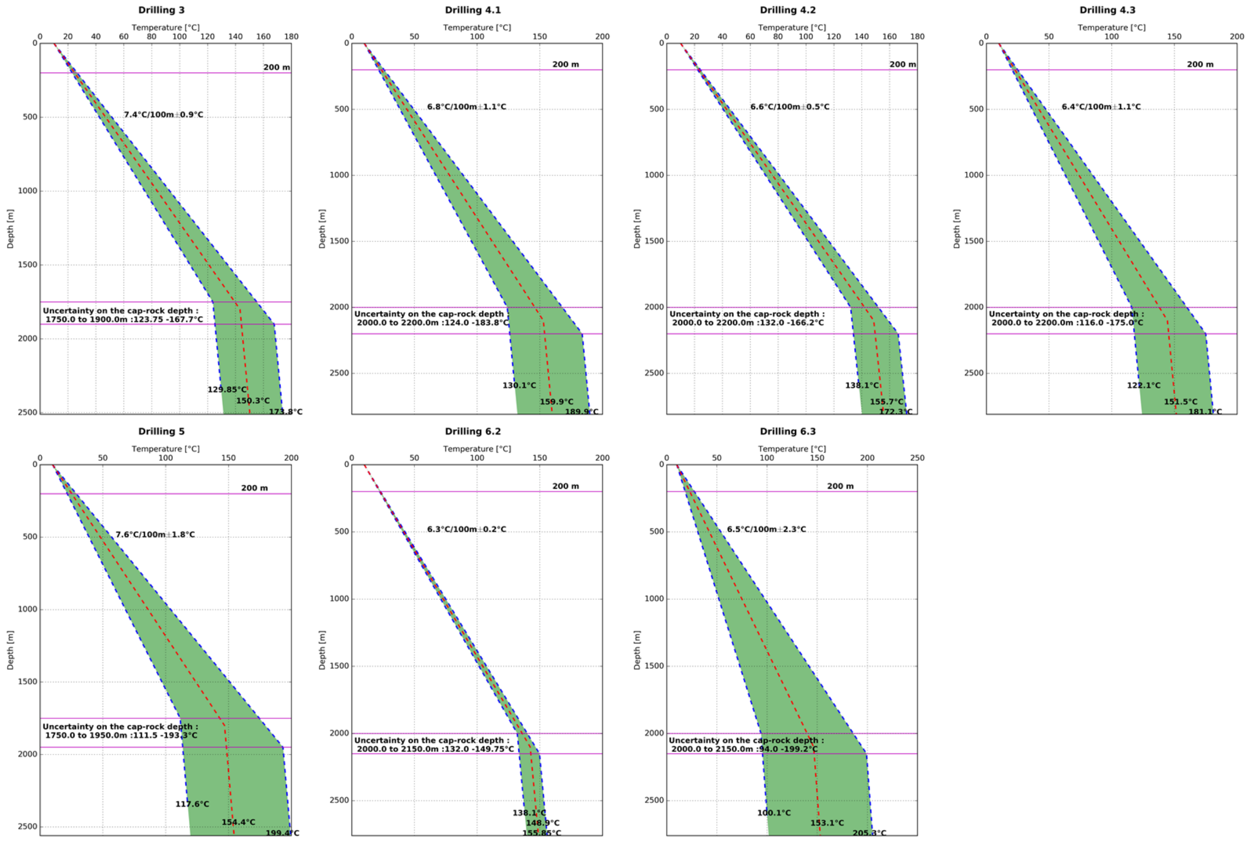


Figure 8: Results of the gradient wells exploration campaign. The figures show for each measurement the best and the worst cases (bleu dashed lines) and the median case (red dashed lines). Depth of the gradient wells and uncertainties on the depth of the cap-rock are shown by purple line. Temperatures at target for each case are indicated at the bottom of each curve.

6. CONCLUSION AND OUTLOOK

The project consisted in drilling seven boreholes of 200 m depth in the Northern Alsace region equipped with geothermal probes to measure temperature profiles and to estimate the local geothermal gradient. It has been proposed to concentrate on the two geographical areas which have a more interesting geothermal potential (zones 4 and 6) by drilling a profile of 3 boreholes on zone 4 and drilling 2 boreholes on zone 6. Only one drilling was carried out on zones 3 and 5.

Similarly, a methodology was established using the thermal logs of the deep wells of Rittershoffen and Soultz-sous-Forêts and applied to the temperature profiles measured in the gradient wells in order to estimate the temperature at the top of the Cap-Rock defined as the top of the Muschelkalk formation. Controls on the acquisition parameters and on the consistency of the measurements were realized and showed a very good coherence of the measurements acquired, from one probe to the other in the same borehole and on two successive measurements over time.

Analysis of the cuttings of the boreholes, coupled with field observations of the area, allowed to establish a chrono-stratigraphic log containing information on the nature, depth, thickness and age of the geological formations in each zone. The analysis of the temperature and geothermal gradient curves showed a good correlation between the lithology and the local thermal variations. Indeed, a large number of variations observed on the curves can be explained by local facies changes.

In general, the first-order changes in the temperature (and gradient) evolution in the well are related to large variations in lithology (e.g. Pliocene to Oligocene) accompanied by a change in thermal conductivity. This thermal conductivity is linked both to the properties of the rock itself and to its water saturation.

The permeability of the geological units is another factor to be taken into account, inducing a modification of the thermal response generated by the circulations of fluids. For example, the highly permeable sandy formation of the Pliocene seems to be particularly favorable to the circulation of fluids. It appears with a higher, but more variable gradient than in the Oligocene clays, where the gradient is more stable and more important. In the same way, the suspected inverse fault observed in the well 6.2 could favor the circulation of heat transfer by fluids. However, its influence on the geothermal gradient and on the temperature is also likely due to the insertion of the sand bank (permeable) in the clays (impermeable) due to the fault.

The distinction between the effect of the thermal conductivity of the formations and the effect of the permeability variation is difficult to distinguish. Only a thermal response test measured continuously in the gradient wells would allow to know the thermal conductivity of the various formations traversed. In addition, by evaluating the thermal conductivity of the formations crossed by deep wells, a correction of the gradient could be established in order to more accurately estimate the temperature at the top of the Cap-Rock. However, the very linear trend of the temperature curves from the top of the Oligocene clay formations suggests a rather constant geothermal gradient beyond the 200-meter depth of the gradient wells. This observation allows to extrapolate the temperature up to the top of the Cap-Rock and thus to estimate the geothermal target temperature for each of the zones studied in order to choose the most favorable location for a future deep geothermal plant.

A comparative analysis of all the zones investigated shows strong heterogeneities in the values of gradients measured from one zone to another. The gradients range from 6.3°C / 100 m to 7.6°C / 100 m. The measured gradients allow to calculate the expected temperatures at the top of the Cap-Rock and to estimate the temperature at the geothermal target. However, it should be noted that the depth of the Cap-Rock taken for calculations remains uncertain. It is imperative to reduce this uncertainty by a new seismic acquisition in order to be able to refine the structural model and thus to specify the expected temperature at the Cap-Rock and at the depth of the geothermal target.Zone 6 has the least interest with a temperature at target of between 139 and 153°C. Zone 3, although with a higher gradient than in zone 6, shows a rather low temperature for the studied area of about 145°C to 157°C at the target, as the Cap-Rock is shallower in this zone. Zone 4 is of interest with a maximum temperature estimated at drilling 4.1 of 163°C at the geothermal target. Zone 5, on the other hand, clearly stands out with the highest gradient (7.6°C / 100 m) with an expected temperature of about 164°C at 2560 m depth.

The strongest gradients measured are not necessarily linked to large fault structures, as shown in zone 5 where, according to the interpretation of the 2D vintage seismic, the target fault only affects slightly the Buntsandstein Triassic sandstones and the basement. This observation leads us to consider the significant contribution of fractured zones that are not visible by 2D seismic on a regional circulation scheme at the scale of the studied area. Indeed, since geothermal water acts as a heat transfer fluid, a strong geothermal gradient implies a high probability of a high permeability in the underlying terrain, in order to allow the convective circulations of hot and deep geothermal fluids towards the top of the Cap-Rock. This type of faults cannot be detected on conventional 2D seismic reflection, but may be seen by 3D seismic.

This method of exploration was found to be relevant because of its valuable contribution to the estimation of the temperatures at the geothermal target. It shows strong gradient heterogeneities at the scale of the studied area. On the other hand, profiles of gradient wells perpendicular to a fault did not show significant variations. In the future, it will be advisable to privilege geometries with a larger spread on the area of interest rather than profiles of gradient wells.

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