Petrographic and Petrophysical Study of Metamorphic and Crystalline Rocks beneath the Paris Basin for Geothermal Potential

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ABSTRACT

Basement cores retrieved from the Variscan belt under Paris Basin are studied in order to understand in-situ rock properties and petrographical characteristics of deep potential reservoirs. Within the frame of the European MEET project (Dalmais et al., 2020), core logging is performed on schists, gneisses and quartzites to identify structural patterns and particular mineralogical occurrences in relationship with structures such as veins or faults and fractures. In addition, plugs are analyzed in order to quantify physical properties (porosity, permeability, P/S wave and electric velocities, ASM and their anisotropies) to characterize rock types and reservoir capacities for a possible geothermal resource underneath the basin.

In the scope of this work, the analytical approach integrates three mains aspects:

- The core logging reveals the evolution in the rock type, which gives clues about the emplacement of metamorphic units. To complement these observations, the presence of mains structures, fractures and cleavages allow relating the structural units to a tectonic sketch and potential pathways for fluid circulation.
- Thin-section are examined for detailed mineralogical characterization under Optical Microscopy, SEM, and Raman spectroscopy. These types of analysis give indications about the processes leading to precipitation and possibly the nature of paleo-fluids.
- Plug samples from the drill cores are analyzed for various rock physics properties that help us to understand the distribution of porosity/permeability and their anisotropy in the different kinds of basements medium. This step is treated in a second time and is not part of this paper.

While the investigation of deep Variscan rocks for geothermal exploration is realized, a complementary approach on the overlying Triassic deposits is also led in the European MEET project (Sengelen et al., 2020), showing that the Paris basin could count on several potential reservoirs in order to diversify its geothermal resource.

1. INTRODUCTION

In the frame of a European-wide research and development scheme willing to evaluate the feasibility of EGS techniques and heat recovery on a large part of the continent, the Horizon 2020 MEET Project “Multidisciplinary and multi-context demonstration of EGS Exploration and Exploitation Techniques” provides new perspectives on various geothermal reservoirs through the investigation of many types of geological terranes (Dalmais et al, 2020). Each of the subsurface settings is coupled with a demonstration site where operational and academic works are conducted in order to appraise the maturity of the geological conditions for energy production. Some analogue sites are chosen for all cases to complete the 3D approach of reservoirs.

The stages of progress for each of the geological province is somehow different: (1) Regarding volcanic settings, the Reykjanes sites gives the opportunity to apply Organic Rankine Cycle (ORC) small units to productive sites currently providing both electrical and district heating. (2) In the case of deep crustal rocks and associated faults, EGS sites are either fully running in Soultz-sous-Forêts or on track with the deep-drilling operations of United Down Deep Geothermal Project (UDDGP). Several aspects such as optimization of heat recovery with new surface installations, or chemical stimulation of faults are under development. (3) As for sedimentary domains, the emplacement of operational sites for heat recovery and small-scale turbines using ORC are under discussion in the Paris and Aquitanian basins with relatively short-term achievement goals. Here, the objective resides in the transfer of technology from mature oil fields to geothermal, which would lead to energy co-production from the same reservoirs. (4) The metamorphic terranes of Europe are also under investigation at the Havelange historical site, University of Göttingen campus and within the Paris Basin. In those latter areas, geologists are clearly on the exploratory curve and there is a strong possibility of future discoveries of geothermal exploitation sites on the basis of research-driven strategies.

The study presented here intends to provide the first elements for the characterization of some mineralogical properties of metamorphic rocks underneath the Paris basin. An in-situ approach is conducted with the collection of samples from deep boreholes reaching the Variscan metasediments below Paris sedimentary basins. Schists, gneiss and quartzite have been retrieved from several wells in order to perform petrographic, mineralogical and petrophysical analysis (Figure 1). In total, 32 samples from 6 wells in the Paris basin are examined. This material allows investigating mineralogical content through optical microscopy, Scanning Electron Microscopy coupled with Energy Dispersive Spectrometry (SEM-EDS) and Raman spectroscopy, lately completed by XRD and microprobe analysis, as well as rock physical properties such as porosimetry, permeability and anisotropy of magnetic susceptibility. The textural organization, nature of microstructures, mineralogical composition and rock physical properties of these deep samples will then be analyzed in order to give some appreciation of rock formation and will allow to consider them as potential medium for fluid circulation.
2. GEOLOGICAL SETTINGS

The structural units of the basement of Paris Basin are the relicts of tectonic stacking, which occurred during the Variscan orogeny, producing high relief that was later dismantled by post-orogenic extensional and erosional processes. Several domains compose the deformed part underneath the Paris Basin: the Armorican domain to the west, the internal domain of the orogeny to the south and southeast, the Saxo-Thuringian domain to the east and the Rheno-Hercynian zone to the north (Autran et al., 1980; Guillocheau et al., 2000). The Variscan belt of western Europe extended from Armorican massif to Sudetes and Härz Massifs; the inner part of the chain belonged to Gondwana former margin (Matte, 1991) while the external part finds its origin in the Armorica microcontinent. The fold-and-thrust belt developed to the north of the Rheic sea that separated Armorica and Laurusia, until the Hercynian front, with a northeastward verging. Despite the fact that the Variscan history terminated at late Permian times, it is known that the structural heritage participated to the emplacement of Cenozoic mountain belts, especially during the Alpine cycles with the formation of Vosges-Black Forest massifs driven by extensional system and partly responsible of Jura deep structuration and curvature (Allenbach & Wetzel, 2006). The mains structures of the Paris Basin such the Bray-Vittel fault which affects Mesozoic sediments are also inherited from Variscan history with the Bray fault acting as a transfer fault in connection with the Vittel suture fault. Due to a long history of Mesozoic sedimentation under subsidence regime in the Paris Basin, the Variscan metasedimentary rocks are currently deeply buried below the sag basin and are hardly accessible. In addition, structural features are overprinted by Mesozoic stages of deformation (Beccaletto et al., 2011; Lacombe & Obert, 2000) and difficult to identify at that depth, even though widely represented in the literature. However, rock properties and broad-scale petrography on metamorphic deep cores can bring valuable information to better understand the nature of the subcrop material only known from bottom-hole geology, gravimetry, petrophysics and seismic signature (Baptiste et al., 2016; Autran et al., 1994; Matte & Hirn, 1988). The cores that are retrieved from wells reaching the deep basement of the Paris basin provide various rock types, among which schists, micaschists, “cristaline schists”, quartzite and gneiss, as indicated in Figure 1. The origin of protolith and its evolution to the present-day composition is often lacking, showing the poverty of mineralogical record from deep-seated metamorphic rock. Mention of the bottom-hole lithologies is made in old reports from oil companies, but the characterization of these apparently sealed rocks did not take part of exploration priorities at the time. In this context, new geological data are clearly missing and the opportunity to study basement cores underneath the Paris Basin from different structural units of the Variscan belt, in addition to the independent study of the Havelange drill cores in the fold-and-thrust belt (Figure 1) will provide valuable information. The metamorphic evolution and the link with structural patterns are a key to understanding past fluid-rock interactions, and must be questioned for the eventuality of a present geothermal potential.

![Figure 1: Location and lithologies of deep cores from 6 wells underneath the Paris basin. Borehole Lhuïtre-1 was investigated in details. The nearest demonstration sites “Havelange” and “Soultz-sous-Forêts” of the MEET European project are shown.](image)
3. MATERIAL AND METHODS
This work was conducted on 6 well cores of the Paris basin that represent a total of nearly 100 m of cores. Logging of core sections was done on the storing site and samples were selected on the basis of lithology representativeness in order to perform mineralogical and petrophysical analysis. For that purposes, 21 plugs (2.5 inches diameter) were drilled on site and 18 thin-sections prepared from hand specimen collected from the cores. The petrographic characterization is realized on recovered polished thin-sections of 30 μm thick with several facilities, such as optical microscope in transmitted cross-polarized light or reflected light and the Zeiss Gemini 300 SEM equipped with a field-emission gun (FEG-SEM). SEM acquisitions were performed using electron back-scattered detector (EBSD) mode with a 10kV acceleration tension and 5-30 Pa chamber pressure. A mounted EDX detector allowed collecting compositional spectrum on specific minerals to determine the metamorphic assemblages in presence. The precise identification of particular mineral phases was performed by Raman spectroscopy, for which data acquisition was executed on a Witec Raman confocal microscope equipped with a Nd laser of 532 nm and 75 mW, with 1-2s accumulation time during application of laser beam, repeated 25-50 times. Dedicated mineralogical database such as RRUFF provides Raman spectral libraries of many reference minerals and makes it very simple to identify the right phase on Spectrum analysis softwares like “Peak Spectroscopy Software” for example. Raman microspectroscopy was also used in order to determine the degree of burial undergone by metamorphic rocks, and especially by means of RSCM methodology (Beyssac et al. 2002; Beyssac et al., 2003).

4. RESULTS
The presented data result from the first stage of the study, with the application of the methodological suite to several samples in order to replicate it to the whole set of samples. The full set of data with additional techniques such as XRD, microprobe and petrophysical parameters is planned to be integrated with the ones hereafter.

4.1 Petrography
Most of the observations were performed on several thin sections from the Lhuitre-1 borehole that presents very peculiar features. The information collected from these samples are classified in two different parts for clarity in descriptions, optical microscopy first, then SEM-EDS.

4.1.1 Optical microscopy
At a large scale, LHU-1 samples show alternating schistose bands of quartz and micas (mostly muscovite from hand-specimens). When looking into details, one can easily distinguish wide grey phases that crystalized within the micas zones (Figure 2a., 2b., 2e. and 2f.). These porphyroblasts display internal schistosity with shearing figures marked by rotation of carbonaceous material (Figure 2a and 2b), aligned with external schistosity. This pervasive schistosity is abundant in the matrix with the succession of carbonaceous material, metals, quartz and micas along shear planes (Figure 2i. and 2j.). Oblic microstructural features, as shear bands and micro-folding or crenulation cleavage were observed. In the quartz bands, the triple points are plentiful and quartz grains frequently show stretching features, while in some cases polycristaline quartz could exhibit dymetric lenticular shape. This might be the testimony of different stages of quartz recrystallization. Boudinage of pseudomorph oxides (Figure 2c. and 2d.) show that a pervasive schistosity is marked by shear planes (Figure 2i. and 2j.) are the only types of oxides that occur in the Lhuitre-1 samples. Titanium oxides are verified on h1 (Figure 2h.) and are the only types of oxides in the samples even though the different reflecting colours identified earlier. At this stage, it is not possible to distinguish between rutile, brookite and anatase.

These petrographic observations serve as a basis for mineral identification and are completed by a Raman spectroscopy approach that will be detailed in the in the following paragraphs.
Figure 2: Petrographic features of the Lhuïtre-1 schist. (a. non-analyzed transmitted light; b. analyzed transmitted light): external schistosity in continuity with internal schistosity in albite porphyroblast underlined by dark aligned carbonaceous material. (c. non-analyzed; d. analyzed): boudinage of rutile in micas. (e. non-analyzed; f. analyzed; g. SEM EBSD with EDS analyzed area): grey albite porphyroblast (g3) interfingered with calcite (g2) and possibly ankerite (g1). (h. SEM EBSD with EDS analyzed area): albite porphyroblast (h2) within a deformed matrix of micas and in contact with rutile (h1). (i. non-analyzed; j. reflected light): succession of banded carbonaceous material associated with metallic oxides of different reflected light but similar rutile composition.
4.2 Raman spectroscopy

The techniques of Raman spectroscopy were employed for two purposes in this study, one is mineral identification and the second is the quantification of the degree of organization of carbonaceous material.

4.2.1 Identification of specific minerals

Once the acquisition is completed in the Raman spectrometer, with the difficulty of analysis location in a confocal surface-dependent imaging where to place the point of Raman laser beam, one can only retrieve Raman spectrum and compare them to the RRUFF spectral library. Thanks to this existing database, we could compare the spectra of LHU-1 samples from the deep metasedimentary basement to the curve of albite feldspar plagioclase. The result is that it fits very well with the 6 spectra obtained out of the grey porphyroblasts, whereas labradorite plagioclase was somehow much less convenient and most of the times peaks did not match correctly, although they were quite close. As for Titane oxides, Raman spectra database is also very clear and spectral matching prefers rutile to any other polymorph.

4.2.2 Degree of organization of carbonaceous material for temperature evaluation

The appreciation of degree of metamorphism from deeply buried rocks has been performed by Raman microspectroscopy on carbonaceous material (RSCM). This method allows measuring the evolution of organic matter from sedimentary primary rocks and its progressive transformation into graphite within the metamorphic rock. It is a good indicator of the degree of metamorphism. The six spectra presented in Figure 4 are the first results and show that Raman Shifts are the same for all D1 band (1350 cm\(^{-1}\)) and G band (1580 cm\(^{-1}\)) at a first order. The data are in good agreement with acceptable ranges for D1 and G bands defined in Beyssac et al., (2003) even though it would certainly be of greater quality if the carbonaceous would be analyzed below the polished surface of the thin-section where friction can affect the temperature evaluation. The plan is to investigate more this part by increasing the number of measurement to decrease the uncertainty on the G band and the D2 band. The deconvolution of Raman spectra is then necessary to quantify the height, full-width at half-maximum (FWHM) and area of the D1, G and D2 peaks (Figure 5). It must be realized on a baseline-curve in order to allow addition of Gaussian-type functions to mimic the Raman spectrum.
Figure 4: Superposition of the 6 spectra obtained on carbonaceous material from the banded micro-layers observed in Lhuître-1 borehole. There is a strong homogeneity in the type of carbonaceous, as attested by the centered Raman shifts recorded at 1350 cm\(^{-1}\) and 1580 cm\(^{-1}\).

Figure 5: Deconvolution of Raman spectrum obtained from LHU-2 thin-section (target 4). This process follows the protocol established for RSCM geothermometer (Beyssac et al., 2003), with the determination of peak estimates, peak width and height, as well as full-width at half-maximum (FWHM), taking care to use a baseline-corrected curve.

Whatever the metamorphic gradient, there is a linear correlation between the peak temperature (or also degree of metamorphism) and the R2 area factor that was defined by Beyssac et al. (2002) as followed:

\[
T \text{ (°C)} = -445 \times R^2_{\text{area}} + 641
\]

Where \(R^2_{\text{area}} = \frac{D^2_{\text{area}}}{(\epsilon_{\text{area}} + D^1_{\text{area}} + D^2_{\text{area}})}\)

So, based on the identification of peaks and their geometrical characteristics, it is possible to evaluate the peak temperature of the samples retrieved from the metamorphic units underneath the Paris basin. Table 1 summarizes all peak data, as well as R1 and R2 ratios and maximum temperature can then be deduced from equation (1) with a 50°C uncertainty on the method (Beyssac et al., 2002). The maximum temperatures range from 472°C to 500°C.

5. DISCUSSION

With these new data, it is now interesting to interpret how mineral and burial data can be understood together in an evolutionary scenario of a metamorphic cycle. This would tell us what conditions reached these rocks during Variscan times. This may be important to the European geothermal community since there is a need of new knowledge about deep terranes currently undercovered that could have undergone severe metamorphic gradients with potentially high fluid temperature during the way down in the crust.
At first, we know that albite formed while schistosity was already developed and that deformation continued long after its formation in schists since we distinguish rotational features of the internal schistosity. Albite is known to be part of typical mineral assemblages of greenschist metamorphic facies together with chlorite, quartz, epidote and actinolite. The stability field of albite alone cannot tell us realistic P-T condition reached by the samples (Nicollet, 2010) but the fact that quartz and chlorite are also well represented in the samples would indicate us that this hypothesis can be valid. Sphene was also identified, as well as rutile, the association of which can trace an anomalous Ti-rich composition that can be due to metamorphic evolution of an igneous protolith (Kornprobst, 2002). The microlayers and more specifically the carbonaceous material that occurs in the samples contradict this theory and tend to prefer a very different picture, with sedimentary-originated protolith. As the location of Lhuitre-1 borehole is very close to the Vittel Fault (Figure 1) that separates terranes of Gondwana affinities and microcontinent that were transported northward, this sample may have deposited on the former margin and collected organic matter from continent. It was later integrated into the Variscan belt and its travel into the accretionary wedge at increasing depth induced an increase of temperature and pressure. The quantification of temperature maximum between 472 and 500°C by RSCM corroborate the greenschist metamorphic facies.

Other investigation regarding fracture filling by calcite and transformation of albite into other phases that may trace the way up to the surface by retro-morphosis are still on track. This may be of great interest for a better understanding of the full metamorphic cycle of the basement rocks that are located underneath the Paris basin. In addition, petrophysical measurements have started and samples without significant fractures tend to be very tight and with very low permeability values.

6. CONCLUSION
The mineralogical content of deep core sections from LHU-1 well and the investigation of their condition of burial are studied and give informations about currently unexplored formations underneath the Paris basin. The understanding of the metamorphic cycle of these rocks is key to the possibility of evaluating geothermal potential in such intricate rock units. Petrographical characterization allowed identifying albite, chlorite, sphene, rutile minerals and boudinage structures, which might be a possible signature of the greenschist metamorphic facies between 350-500°C and 0.2-1GPa. RSCM methodology on disordered carbonaceous material was performed to determine the peak temperature reached by these rocks that is evaluated at 472-500 °C based on R2 area ratio from Raman spectra. These first elements of description and analysis of deep basement rocks can be seen as a starting point for a broader study integrating rock physics and other mineralogical techniques of investigation that would help building a complete metamorphic scenario.
Table 1: Synthetic table of Raman spectroscopy data collected on banded carbonaceous material of LHU-2 thin-section. R1 and R2 are calculated from D1, G and D2 bands and Maximum T°C has been deduced from R2 based on Beyssac et al. (2002).

<table>
<thead>
<tr>
<th>Target</th>
<th>D1 band</th>
<th>G band</th>
<th>D2 band</th>
<th>R1 intensity ratio</th>
<th>R2 area ratio</th>
<th>Max T°C (Beyssac et al., 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shift (cm⁻¹)</td>
<td>Height (intensity)</td>
<td>FWHM (cm⁻¹)</td>
<td>Area (cm²)</td>
<td>Shift (cm⁻¹)</td>
<td>Height (intensity)</td>
</tr>
<tr>
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<td>1348,9017</td>
<td>18,1856</td>
<td>24,5556</td>
<td>581,5858</td>
<td>1576,8693</td>
<td>48,3617</td>
</tr>
<tr>
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<td>22,8252</td>
<td>631,1964</td>
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<td>54,9149</td>
</tr>
<tr>
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