Interreg
North-West Europe
DGE-ROLLOUT

Report on processing of seismic and gravimetry data°- French part

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Introduction

In the French area of “Hauts de France” in the North-West Europe Province, a geothermal reservoir located in the Dinantien limestones, has be recognized as a potential geothermal reservoir in its Belgium’s extension. In 80’s, some explorations were made in the French part of this Dinantien limestone reservoir, without success. The Dinantien limestones have a complex structure. Within DGE-ROLLOUT, it was important, to try to better understand its geometry, depth and petro physical characteristics. Several data, as reflection seismic and boreholes have been acquired in 70’s and 80’s, during the oil and gas exploration. Using these existing seismic and borehole data, a quantitative interpretation was carried out. The study consisted to reprocess the vintage seismic data to obtain a better image of the geometry of the subsurface and also to try to obtain some information about the petro physical characteristics of the Dinantian limestones. The infrared remote sensing data from Landsat satellite, given an indirect information on temperature at the Earth surface was also analysed.

Seismic data

The reprocessing comprises six seismic lines, acquired in 1980 and 1981, with a combined length of around 172 km. These data complement previous studies, carried out in 2018 as part of the thesis work of A. Laurent (2021) and a reprocessing performed in 2005 (Figure 1). The aim of the seismic reprocessing is to obtain subsurface images, allowing increasing the knowledge of the geometry and structure of the potential geothermal reservoirs. Also from the amplitudes of the seismic data and the borehole data, through a quantitative interpretation, it can be possible to have information about the petro physical characteristics of the geothermal reservoirs.

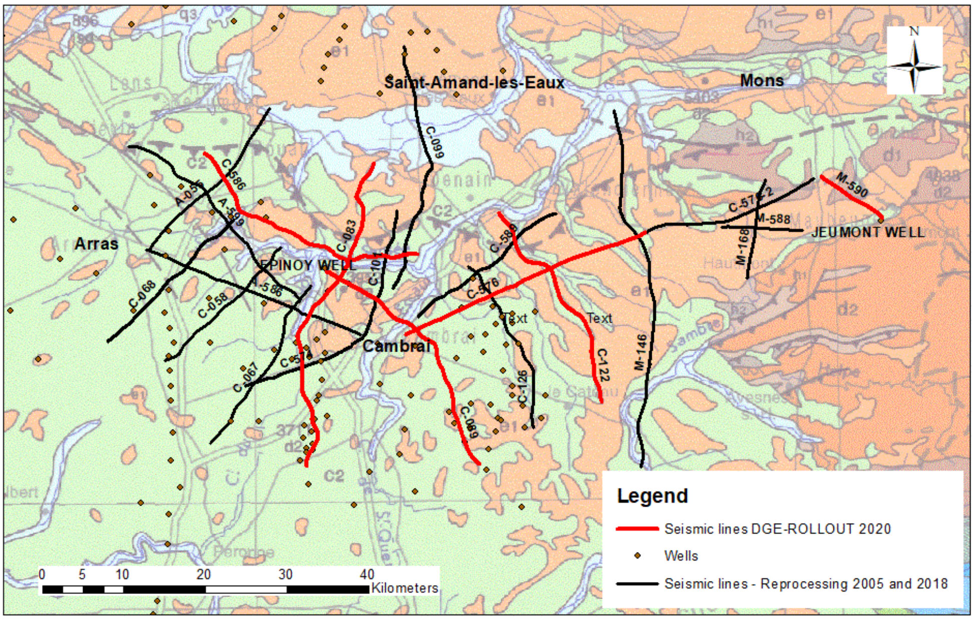

Figure 1: Location map of seismic lines in DGE-ROLLOUT. Backgroung Geological map (BRGM)

The reprocessing of the seismic data performed in depth domain. It needs several steps. The first one is to retrieve the raw data acquired on field from the operator. Before to start the data reprocessing, a quality control is perform, to check the quality of the seismic data (raw shot point) and the field documents (observer reports and coordinate tables) (Figure 2). A processing sequence is applied, preserving the signal amplitudes and allowing obtaining the best image of the subsurface.

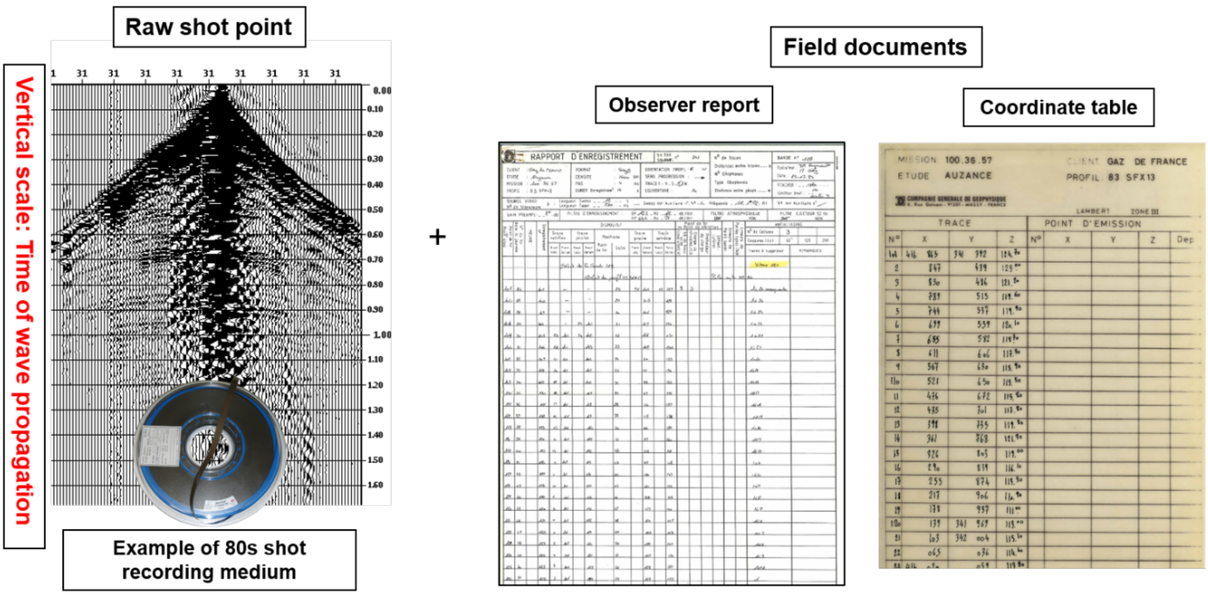

Figure 2: Example of raw seismic data acquired on field

The applied processing sequence is a Pre-stack Depth Migration (PSDM). The seismic data is acquired in time, representing the time travel of the acoustic wave in the ground. There are two major ways to obtain the final image of the subsurface in depth. One is to convert the final image from time to depth (so after the migration of the features in time) and the second one, longer and more expensive, but given better result is to perform the migration of the features directly in depth (Yilmaz, 1987, 2001) (Figure 3).

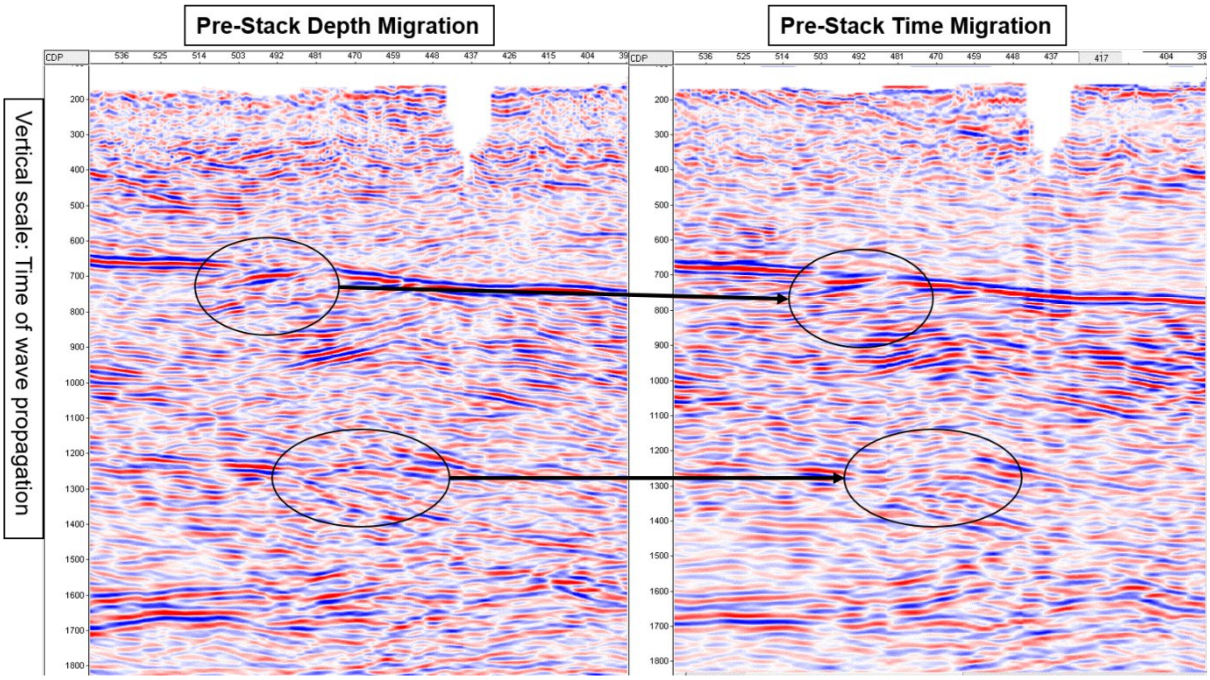

Figure 3: Example of improvement on PSDM (left) versus PSTM (right)

In this work, the migration of the features was performed directly in depth. Work was carried out by the GK Processing center using OMEGA software from Schlumberger. The Seismic Data Processing Report is available in Annex 1.

Processing was started in March 2020 and completed by August 2020. The processing report and the final products were delivered by end of August 2020.

Pre-stack Depth Migration Processing sequence

The acquisition parameters are described in Table 1

Line	First CMP	Last CMP	CMP distance (m)	First SP	Last SP	SP distance (m)	Length CMP (m)
C083	178	1792	25	101	926	50	40350
C089	214	1509	25	119	731	50	32375
C122	296	1405	25	181	699	50	27725
C576	211	1460	25	113	715	50	31225
C586	212	1780	20	111	923	80	31360
M590	223	586	25	122	283	50	9100
						Total	172135

Table 1: Acquisition parameters of the six seismic lines

CMP: Common Middle Point

SP: Shot Point

The Pre-stack Depth Migration (PSTM) processing sequence comprises:

1. Geometry Assignment and Trace Editing
2. First Break Picking
3. Spherical divergence compensation
4. Preliminary velocity analysis and mute
5. Noise attenuation pass1
6. Surface Consistent Deconvolution
7. Surface Consistent Amplitude Compensation (SCAC procedure)
8. Noise attenuation pass 2
9. Refraction statics corrections calculation and application
10. Velocity analysis AV1 (every 1 km)
11. Residual statics calculation and application 1st iteration
12. Multiple waves attenuation in Radon domain
13. Velocity analysis AV2 (every 0.5 km)
14. Residual statics calculation and application 2nd iteration
15. Final velocity analysis AV3 (every 0.5 km) and mute
16. Trim statics corrections
17. Predictive deconvolution in Tau-P domain
18. Trace interpolation and offset regularization
19. Seismic coordinate conversion to 3D domain
20. Common offset sort

21. Velocity field conversion to interval one-way depth
22. Velocity field smoothing
23. Velocity field coordinate conversion to 3D domain
24. VOLCAN velocity model creation (EMB Petrel)
25. Pre-stack Depth Migration 1st iteration
26. Tomographic velocity update 1st iteration
27. Pre-stack Depth Migration 2nd iteration
28. Tomographic velocity update 2nd iteration
29. Pre-stack Depth Migration 3rd iteration
30. CDP gather sort
31. Angle mute application
32. Depth – Time conversion
33. Velocity analysis PSDM (every 0.5 km)
34. Normal Move Out corrections, mute
35. Time Variant filter
36. Raw stack PSDM in time – output in SEGY format
37. Post-stack processing sequence in time with Automatic Gain Control (AGC)
38. Final PSDM in time AGC – output in SEGY format
39. Velocity field calibration with well information
40. Time - Depth conversion of RAW stack PSDM with calibrated velocity
41. Raw stack PSDM in time (with calibrated velocity) – output in SEGY format
42. Amplitude scaling
43. Time - Depth conversion of Final PSDM AGC with calibrated velocity
44. Post stack procrssing sequence in depth
45. Final PSDM AGC – output in SEGY format

Final products of seismic processing

The following deliverables were produced (Table 2).

PSDM CMP GATHER WITHOUT MUTE IN DEPTH (TRUE AMPLITUDE)	format SEG-Y
PSDM CMP GATHER WITHOUT MUTE IN TIME (TRUE AMPLITUDE)	format SEG-Y
FINAL PSDM WITH WELL CALIBRATED IN DEPTH (TRUE AMPLITUDE)	format SEG-Y
FINAL AGC PSDM WITH WELL CALIBRATED IN DEPTH	format SEG-Y
FINAL PSDM IN TIME (TRUE AMPLITUDE)	format SEG-Y
FINAL AGC PSDM IN TIME	format SEG-Y

Table 2: List of deliverables of the seismic reprocessing

Seismic interpretation

The seismic lines of the 2 previous projects (work thesis of A. Laurent (2021) and a reprocessing in 2005) were interpreted and a 3D geological model was performed in the work thesis of A Laurent (2021).

In the DGE-ROLLOUT project, top and base of the Dinatian limestones and the Allochthon Main Basal Thrust (AMBT or Midi Fault) were interpreted on the six PSDM lines (Figure 1) This interpretation has defined the Dinantian limestone reservoir for the quantitative interpretation (Examples: Figure 4 and Figure 5).

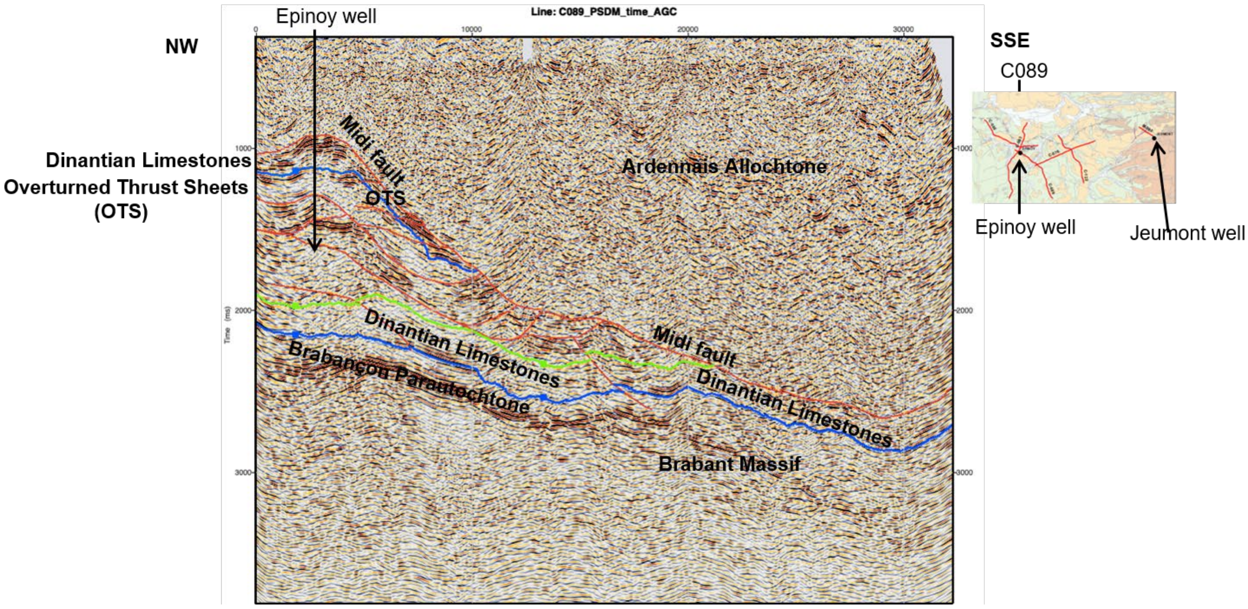

Figure 4: Interpreted C089 PSDM seismic line

Due to the present of overturned thrust sheets, the Dinatian limestones can be split, as in Figure 4. At the location of Epinoy well, the level crossed by the well is the reverse series of Dinantian limestones.

On the eastern part of the study area, the Dinantian limestones is less complex, as on seismic line M590 (Figure 5).

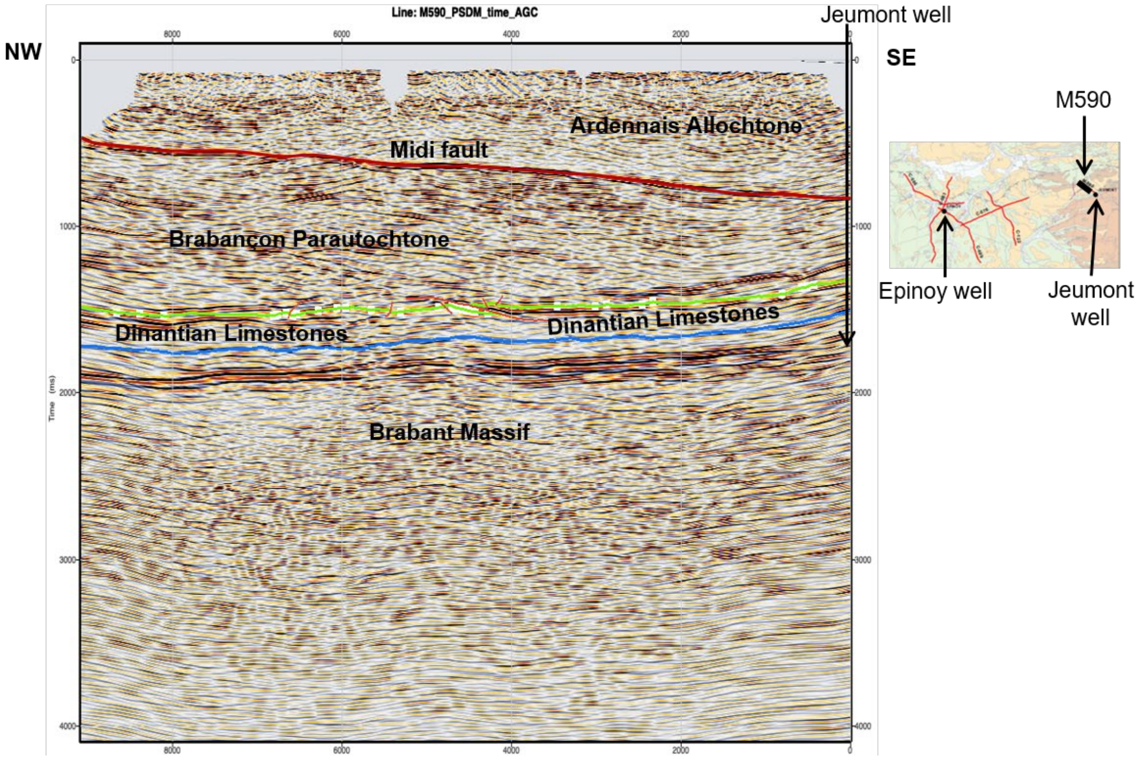

Figure 5: Interpreted M590 PSDM seismic line

Petrophysical study

From the 2 wells, Epinoy and Jeumont, a petrophysical study has shown in the first Dinantian limestone reservoir on Epinoy well, where the serie is reversed, there is no porous level identified and the porosity is no more than 1% or 2% in the Dolomite/Limestones facies (Figure 6).

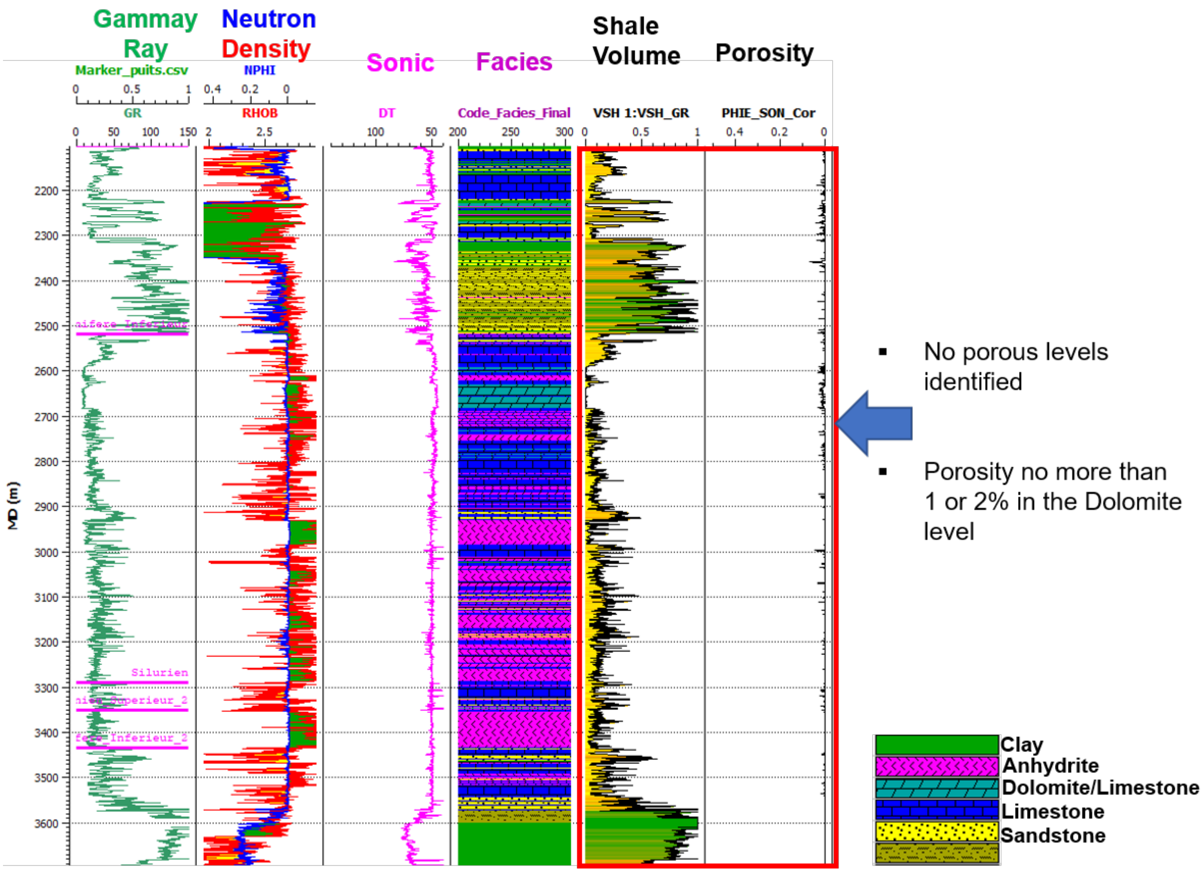

Figure 6: Petrophysical study of Epinoy well on reverse series of Dinantian limestones

From Jeumon well, where there is only on normal serie of Dinantian limestones, a porosity around 5% to 8% between 4115 meters and 4230 meters depth has been calculated (Figure 7).

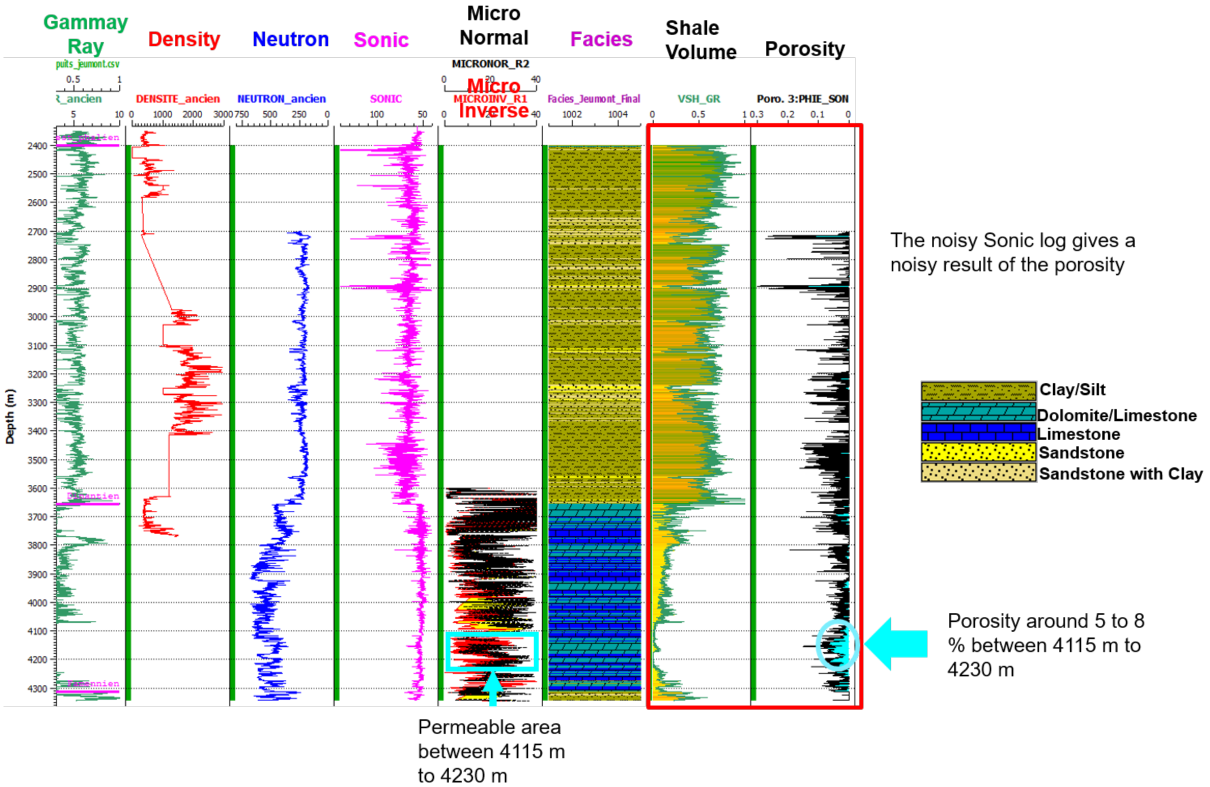

Figure 7: Petrophysical study of Jeumont well on normal series of Dinantian limestones

The micro-normal and micro-inverse logs, on Jeumont well, indicate the presence of permeable area between 4120 meters and 4210 meters depth.

Quantitative interpretation

In order to try to obtain petro physical and facies information on the geothermal reservoir characteristics of the Dinantian limestones, a quantitative interpretation was carried out.

Work was carried out by the BeicipFranlab, using *EasyTrace®* software and *Interwell®* BeicipFranlab's software.

The quantitative interpretation was started in April 2021 and completed by June 2021. The final report and products were delivered by middle of July 2021.

The different facies of the study area were determined from well measurements. For Epinoy well, five lithology have been detected: (1) Clay, (2) Anhydrite, (3) Dolomite/Dolomitic Limestone, (4) Limestone, (5) Sandstone and Clayey Sandstone.

For Jeumont well, also five different lithology have been detected: (1) Clay/Silt, (2) Dolomite, (3) Compact Limestone, (4) Clean Sandstone and (5) Clayey Sandstone.

The P and S waves' impedance logs were built form Sonic and Density logs of Jeumont well. From these impedances and the acoustic seismic inversion, of the six seismic lines, seismic data containing information on interpreted lithology, through the Vp/Vs ratio were obtained. The ratio Vp/Vs can be classified in four categories: limestone, dolomite, clay and anhydrite (Figure 8). The values above 1.84 are for limestone, whose Vp/Vs ratio is rather between 1.84 and 1.99. The Vp/Vs ratio for dolomites has empirical values between 1.78 and 1.84 (Domenico, 1984). Values below 1.78, indicate, the presence of clays, whose Vp/Vs ratio can be lower than 1.7 and anhydrites, with a Vp/Vs ratio of 1.75.

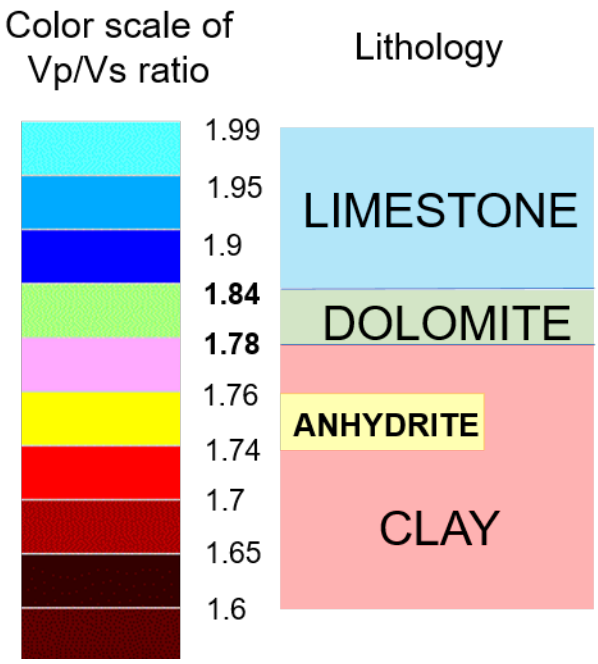

Figure 8: Color scale for the Vp/Vs ratio, with the lithology

The Dinantien has 5 major levels divide into 4 series (Figure 9).

1- The lower series presents 2 major levels: at its base a more schistose part, with sandstone and shale, which can by place be absent and the upper part of this series presents a great homogeneity of facies with limestone and clayey levels: Series 1.
2- The heart of the series is marked by a thick dolomitized series: Series 2.
3- Above, levels of sedimentary breccia are present: Series 3.
4- The summit part of the series is also carbonated with limestone and with clayey levels more and more abundant: Series 4.

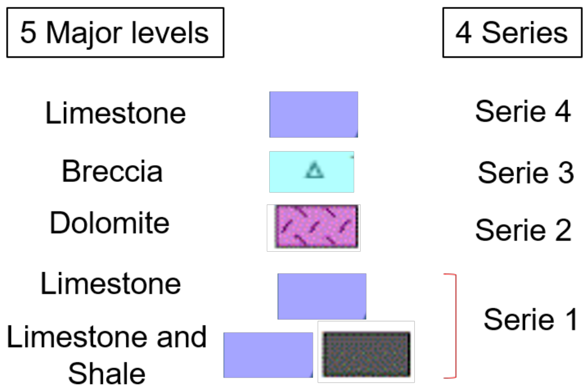

Figure 9 : Color scale of the 5 major levels and 4 series of Dinantian

The results of Vp/Vs ratio can be divided in 4 units (Figure 10), with relatively homogenous Vp/Vs ratio for each of the units.

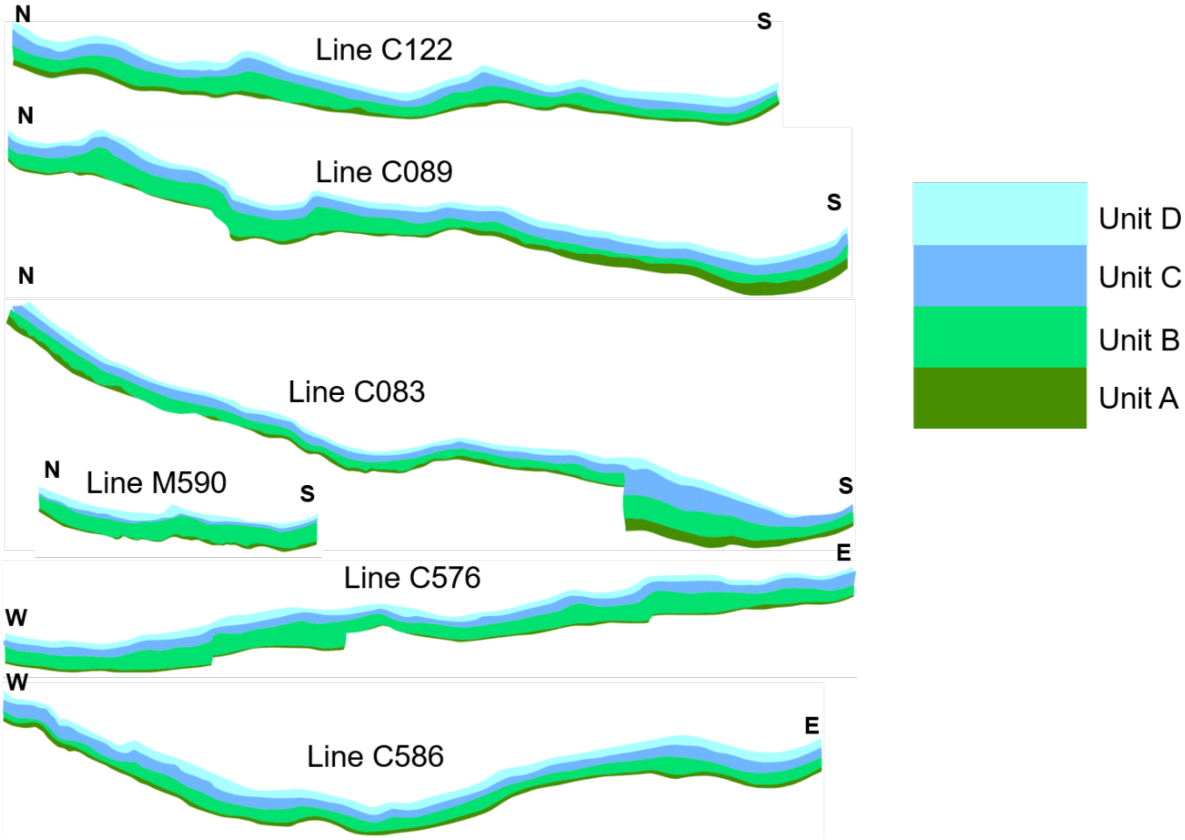

Figure 10 : Color scale of the 4 Vp/Vs units

Unit A, at the base of the Dinantian, has homogeneous Vp/Vs ratio, corresponding mostly to the Series 1 lithology. Inside the Unit A, there are 3 layers. The first one at its base, layer 1 on Figure 11, is composed of schistose and sandstone. The second one, layer 2 on Figure 11 is made of limestone and the third one, layer 3 on Figure 11, in the upper part is clayey. This lithology might potentially be linked to the Hastarian lower part deposits, below the Landelies limestone formation (Figure 12). The layers 1 and 2 might potentially correspond to the Hastarian formation known below the midi fault (or Allochthon Main Basal Thrust (AMBT)). The layer 3 showing lateral variations of facies, could be correspond to the Samme and Pont d’Arcole formations resting directly on Upper Devonian (Figure 12).

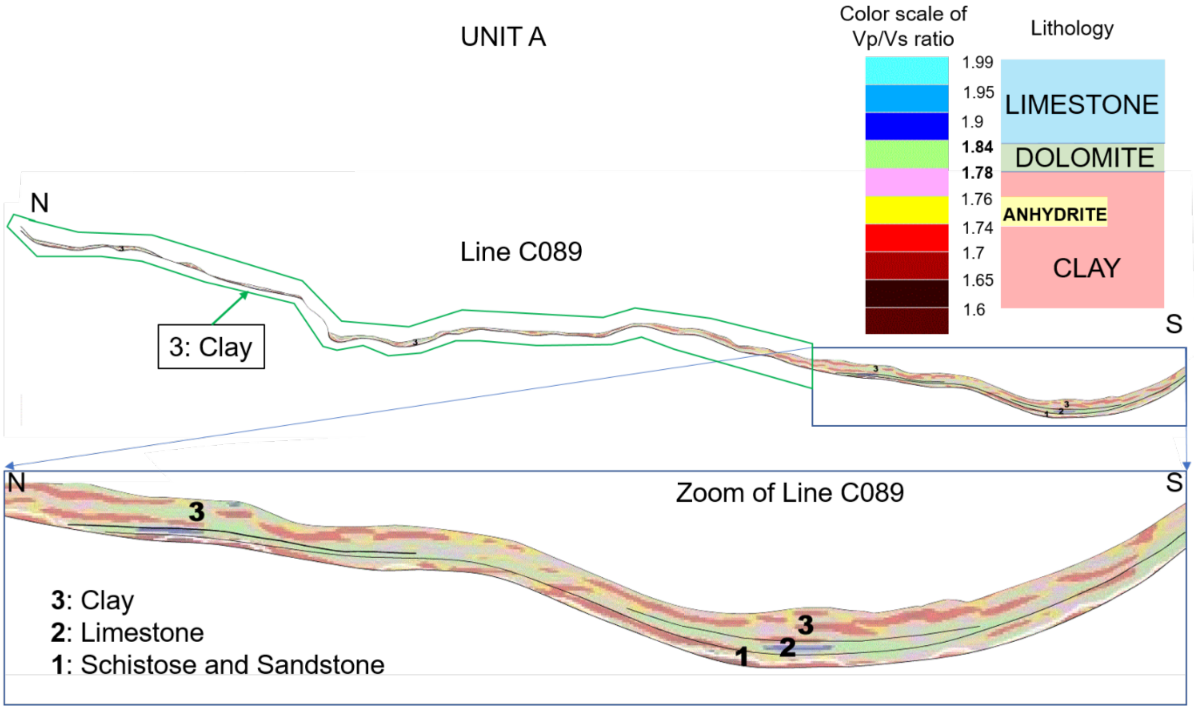

Figure 11: Vp/Vs ratio on line C089 of Unit A with the illustration of lithology

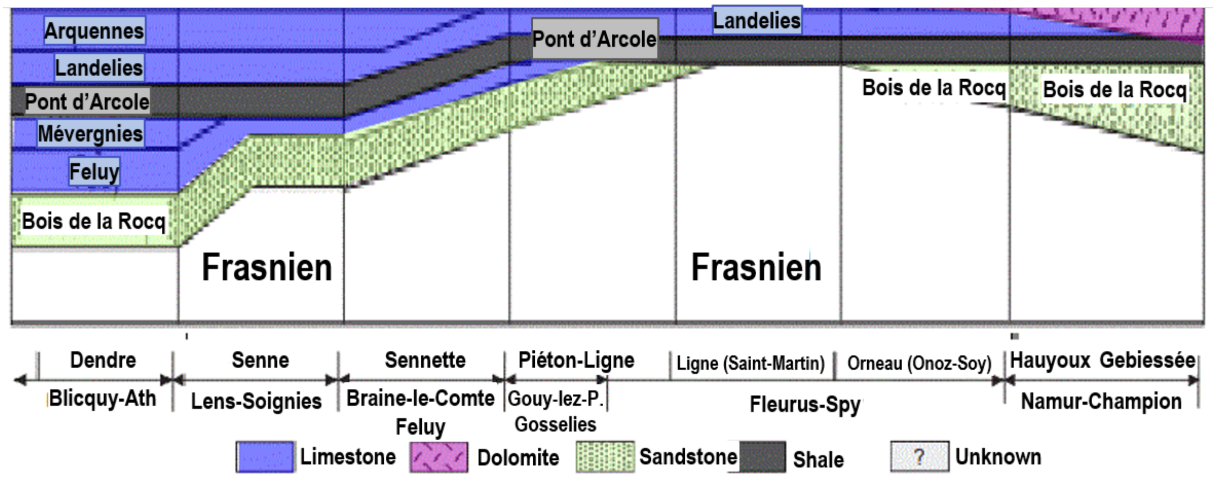

Figure 12: Hastarian lower part lithology (from Poty et al. 2001, 2006; Hance et al 2006)

Unit B presents many variations in thicknesses, Vp/Vs ratio and lateral continuity (Figure 13). Nevertheless the unit B has prevailing Vp/Vs ratio values in limestone and dolomite. This unit B could be linked to the dolomitized part of the Dinantian: the Series 2. In this Series 2, it is possible to have clay formations. It is visible on Figure 13, on south part of line C083.

This Unit B might potentially correspond to the upper part of the Hastarian with the Ivoirian and Molinacian (Figure 13). The Unit B can be divided in 3 layers: named 4, 5 and 6. The upper part of the Hastarian located at the base is composed of the Landelies limestones, which could potentially be linked to the layer 4 having a Vp/Vs ratio corresponding to limestone and dolomite (Figure 13 and Figure 14). The layer 5 (Figure 13), shows more clay Vp/Vs ratio. This layer 5 might potentially correspond to the Orient and Lalaing clayey formations at the base of Ivoirian (Figure 14). The layer 6 with limestone and dolomite Vp/Vs values could potentially be linked to the dolomitized limestone series of the Upper Ivoirian and Molinacian (Figure 14).

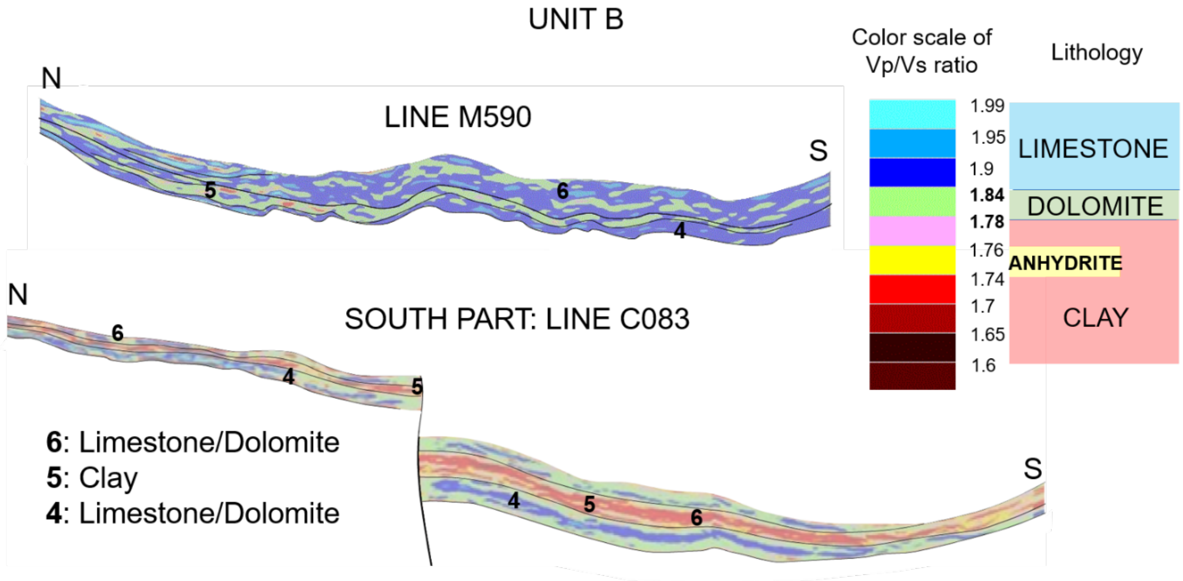

Figure 13: Vp/Vs ratio of Unit B - illustration of Unit B variations

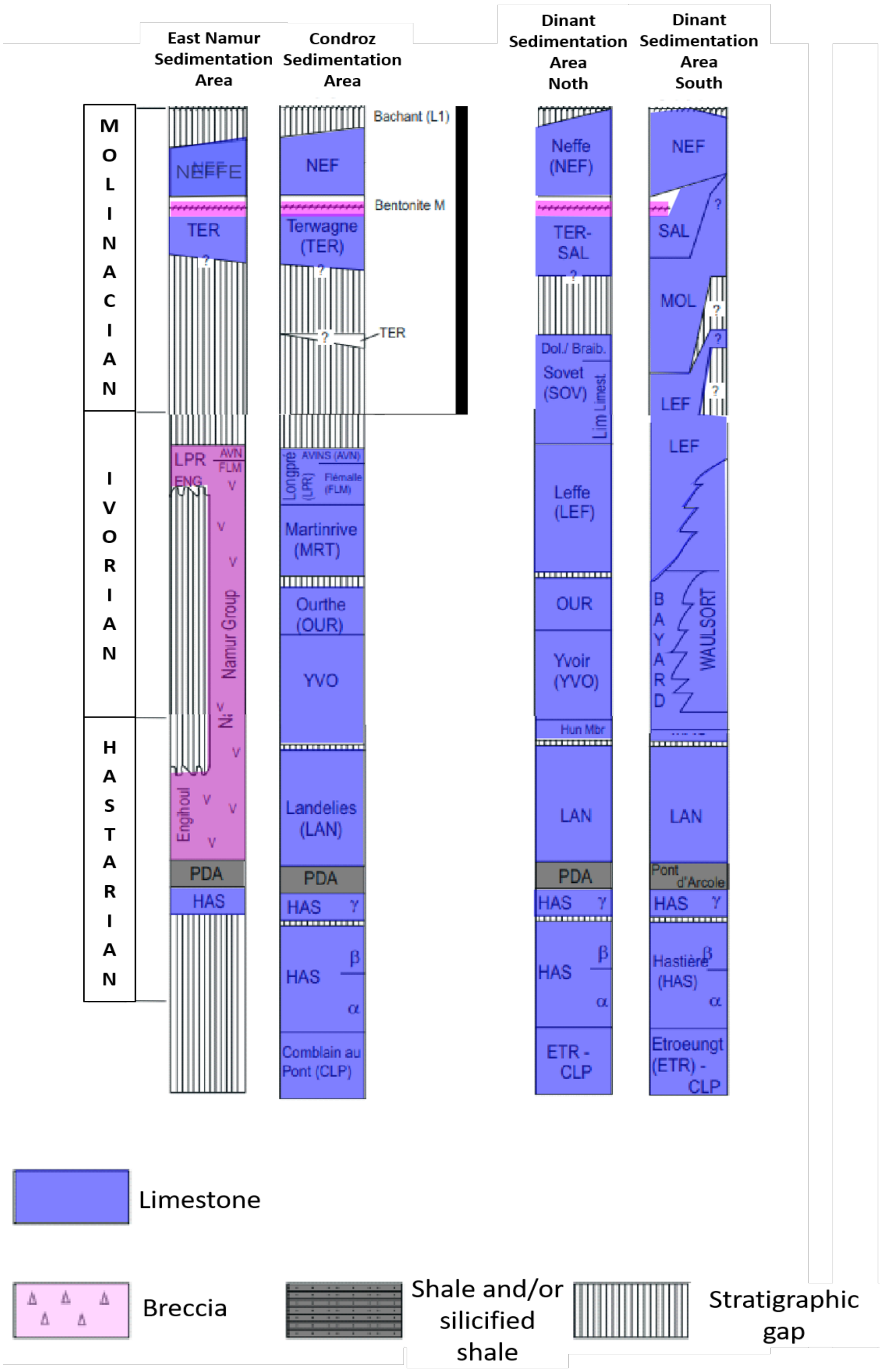

Figure 14: Hastarian upper part, Ivorian and Molinacian lithologies (from Devuyst et al. 2006, Poty et al. 2001, 2006; Hance et al 2006)

Unit C is characterized by low Vp/Vs ratio in comparison with the whole of the Dinantian (Figure 15). The Unit C can be divided in two layers: 7 and 8. These two layers could be distinguished with the Vp/Vs ratio below 1.78 (in red colour) for layer 7 and layer 8 with the Vp/Vs ratio above 1.78 (more in green colour). Layer 7 seems to be associated with the brecciated facies and layer 8 seems to be associated with limestone and chert complexes (Figure 16). In the outcrop and in the drilling, the brecciated levels are present. This unit C could potentially be linked to the limestone and breccias of the Livian formation (Figure 16). These rocks constitute the geothermal reservoir identified in Belgium.

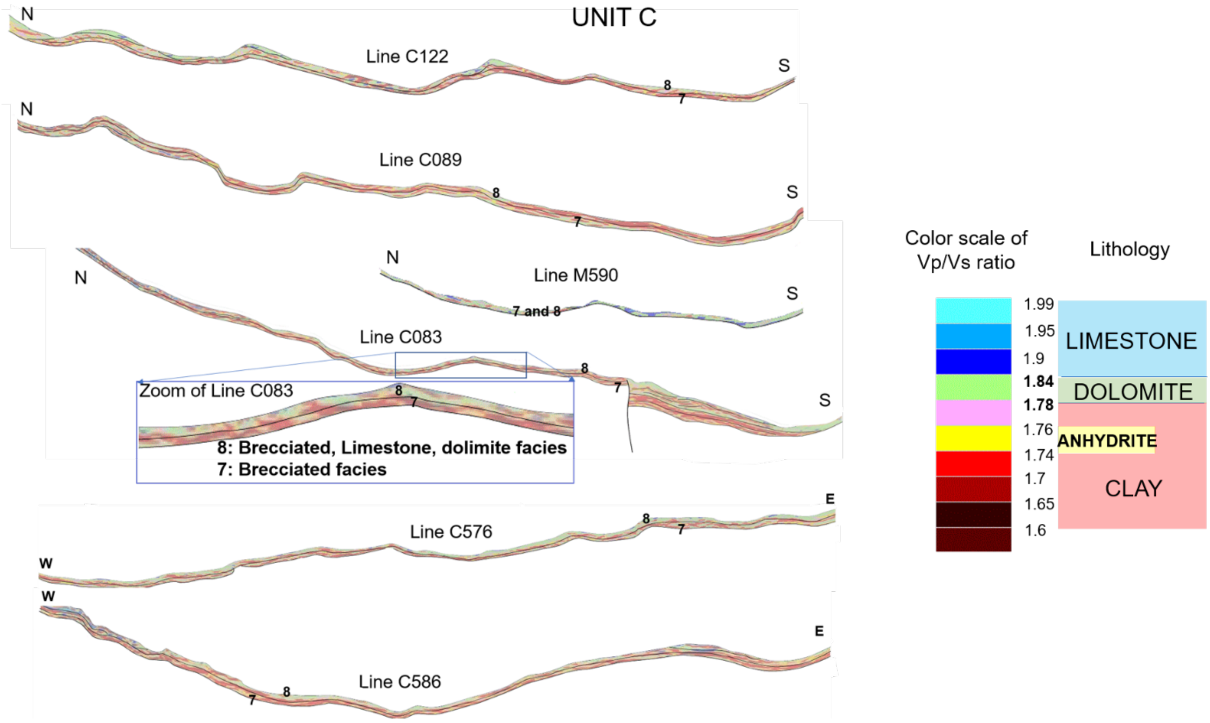

Figure 15: Vp/Vs ratio of Unit C

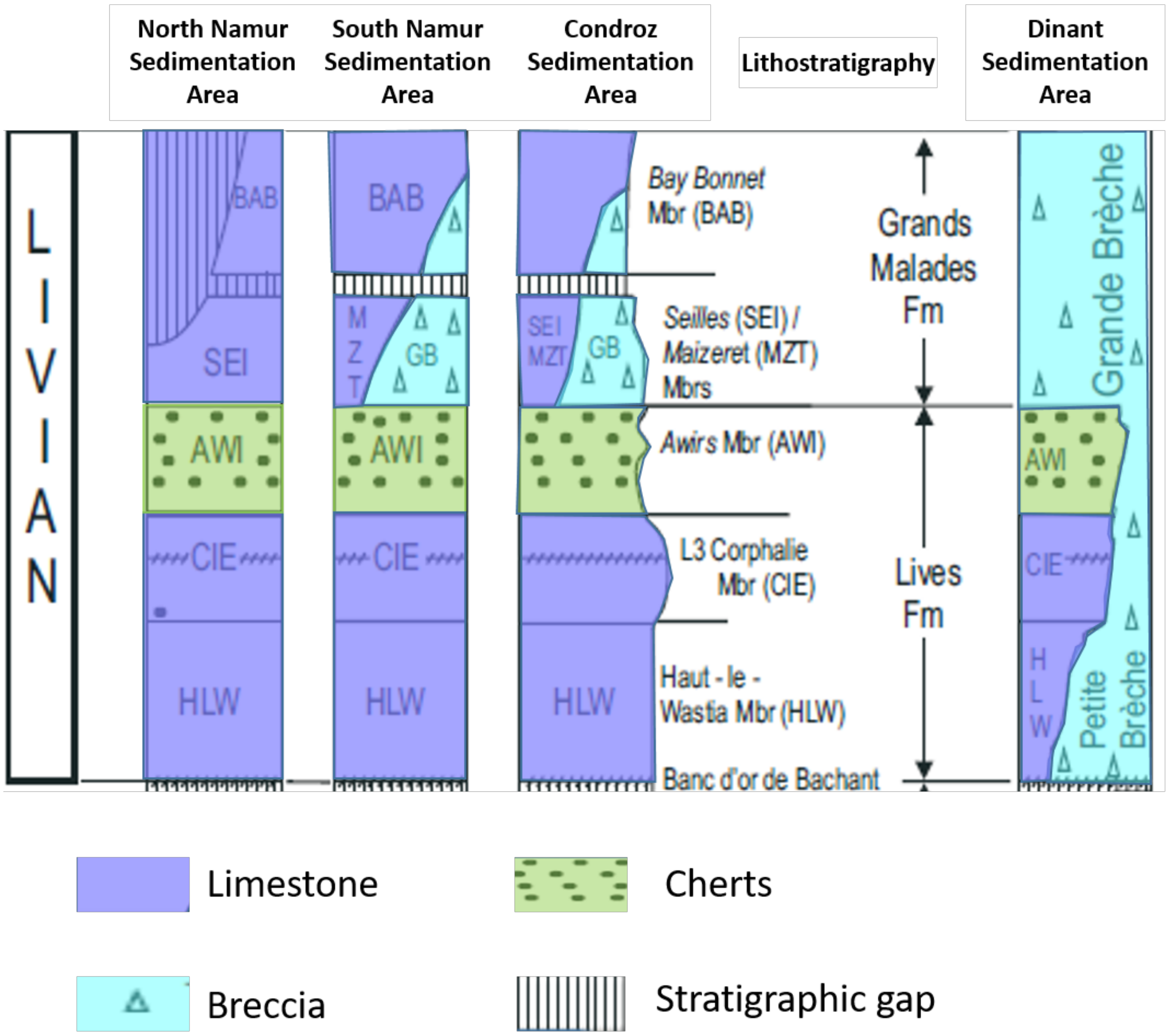

Figure 16: Livian lithology (from Poty et al. 2001, 2006; Hance et al 2006)

Unit D is constituted by a single layer: layer 9. On all the profiles, Vp/Vs ratio values indicate the presence of limestone and dolomite (Figure 17). This unit might potentially correspond to the limestones known on the top of the Dinantian series, in Warnantian (Figure 18).

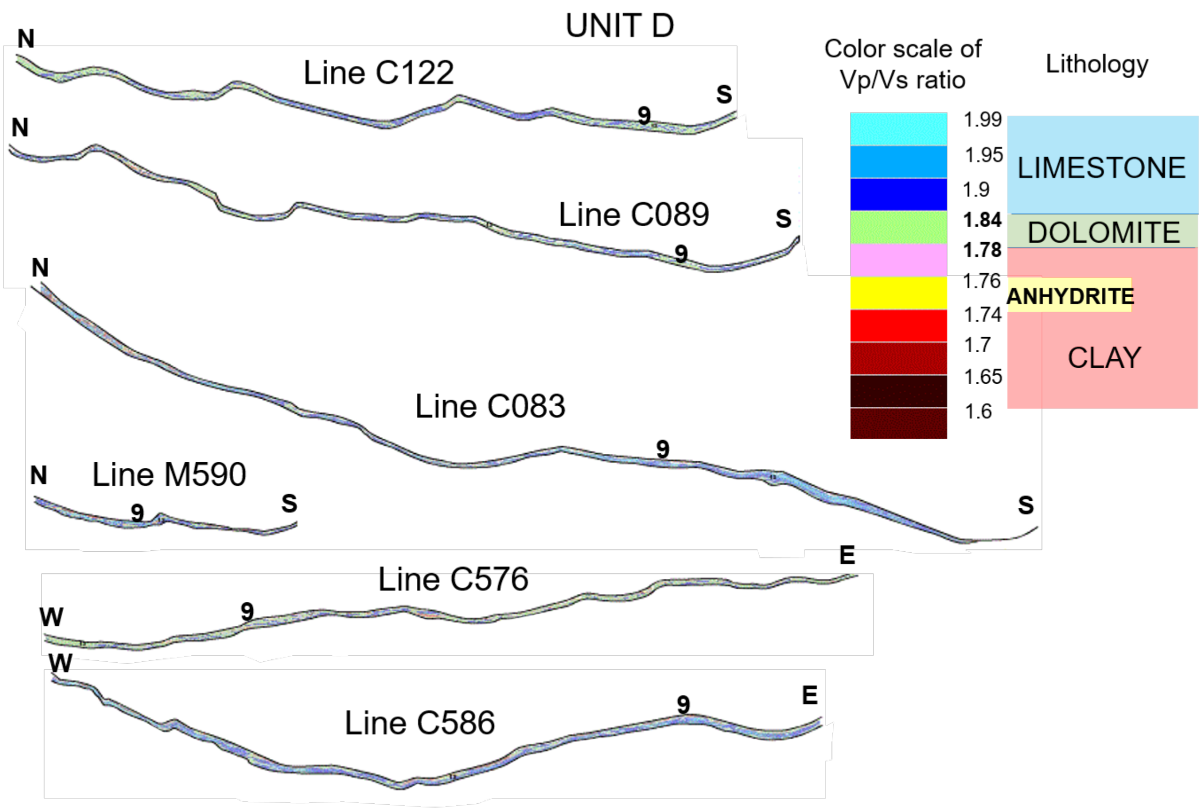

Figure 17: Vp/Vs ratio of Unit D

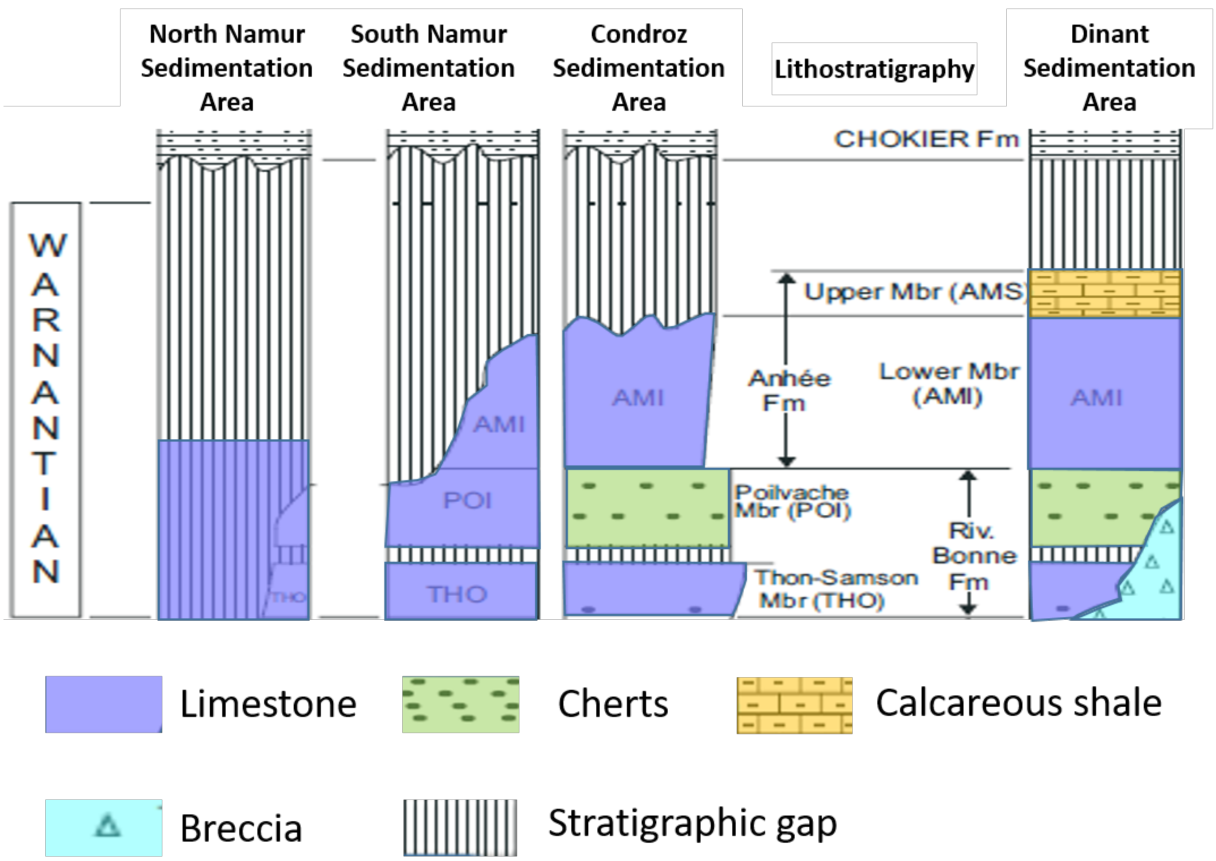

Figure 18: Warnantian lithology (from Poty et al. 2001, 2006; Hance et al 2006)

The Figure 19 shows the distribution of the Vp/Vs ratio of the Dinantian reservoir. The Vp/Vs results were obtained from the only borehole with available and usable data in the Dinantian, the Jeumont borehole. The seismic data available in the study area are old and have a limited signal in terms of depth of investigation and are very noisy. This has a particular impact on the Vp results obtained.

Even if the results of the quantitative interpretation are to be taken with great care, it results that:

- It was possible to identify different units within the Dinantian seismic complex,
- These 4 units seem to have Vp/Vs ratio in relation with lithologies known in the Dinantian reservoir,
- These lithologies can be potentially linked to the known lithostratigraphies in the study area.
- Nevertheless, the seismic characterisation, also limited by the quality of the input data, allowed to highlight on the 6 seismic lines where potentially dolomitic zones are identified.

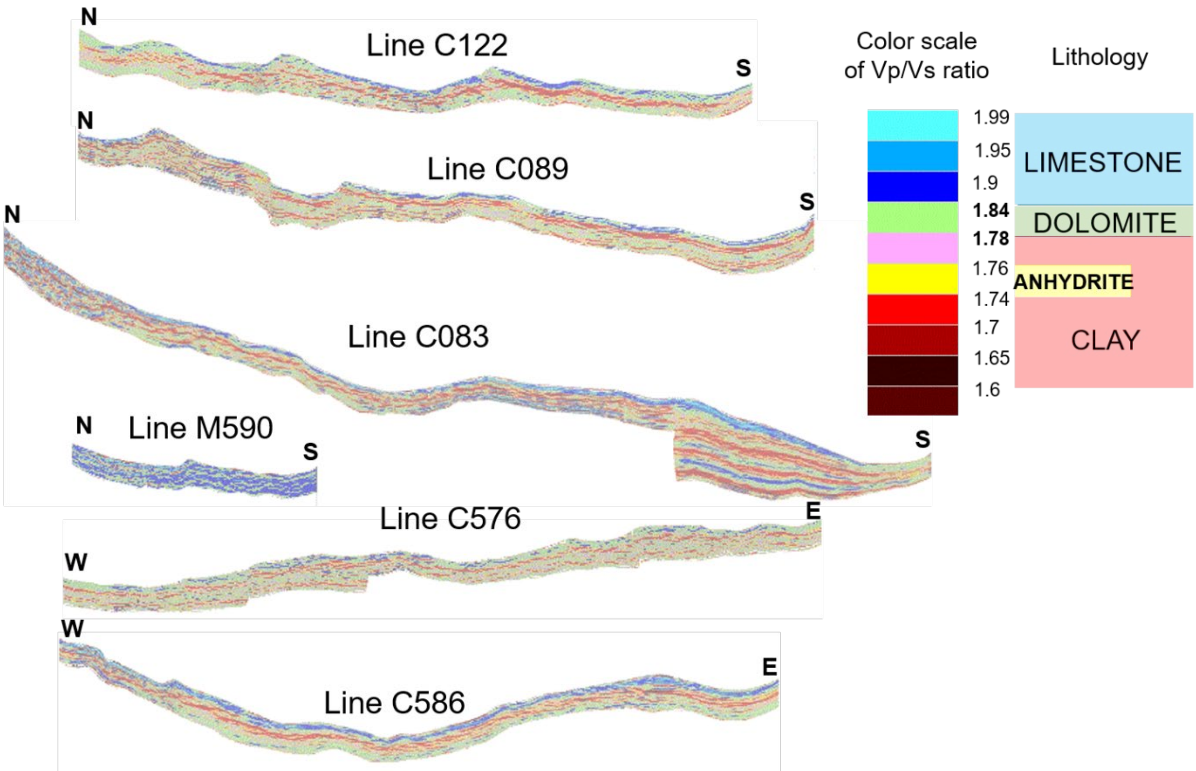

Figure 19: Vp/Vs ratio of the Dinantian reservoir

Thermal Infrared from remote sensing data

Analysis of thermal infrared remote sensing data can provide information on soil thermicity at the surface of the Earth. Many satellites have been launched since the 1980s, some equipped with thermal sensors. The Landsat program has launched 8 satellites. Some Landsat satellites are equipped with the infrared thermal sensor (IRTS) which could provide qualitative information on the temperature of the Earth's surface, day and/or night.

The analysis of the images allows to identify contrasts in thermicity due to variations in humidity in the targets (soils, cities, forests, water, etc.) and to appreciate the fracture network. The identification of linear discontinuities called "lineaments" can then be the basis for comparisons and interpretations with other data, such as surface water networks, faults and fractures known. Three types of lineaments can be recognized: thermally cold lineaments, thermally hot lineaments, and thermally undifferentiated lineaments (straight line between a cold and a hot zone). The hot zones have a white signature and the cold zones a dark signature. The thermicity is representative of a thermal trend in relation to the surrounding rock. The observed lineaments, called "cold", are colder than the bedrock. The observed lineaments called "rather hot" are warmer than the surrounding rock. The study area is covered by 2 night infrared thermal images, of Landsat 7, identified by paths 56 and 57 for row 219 and only few images has been found. There is no image without cloud for path 57, row 219 (Figure 20

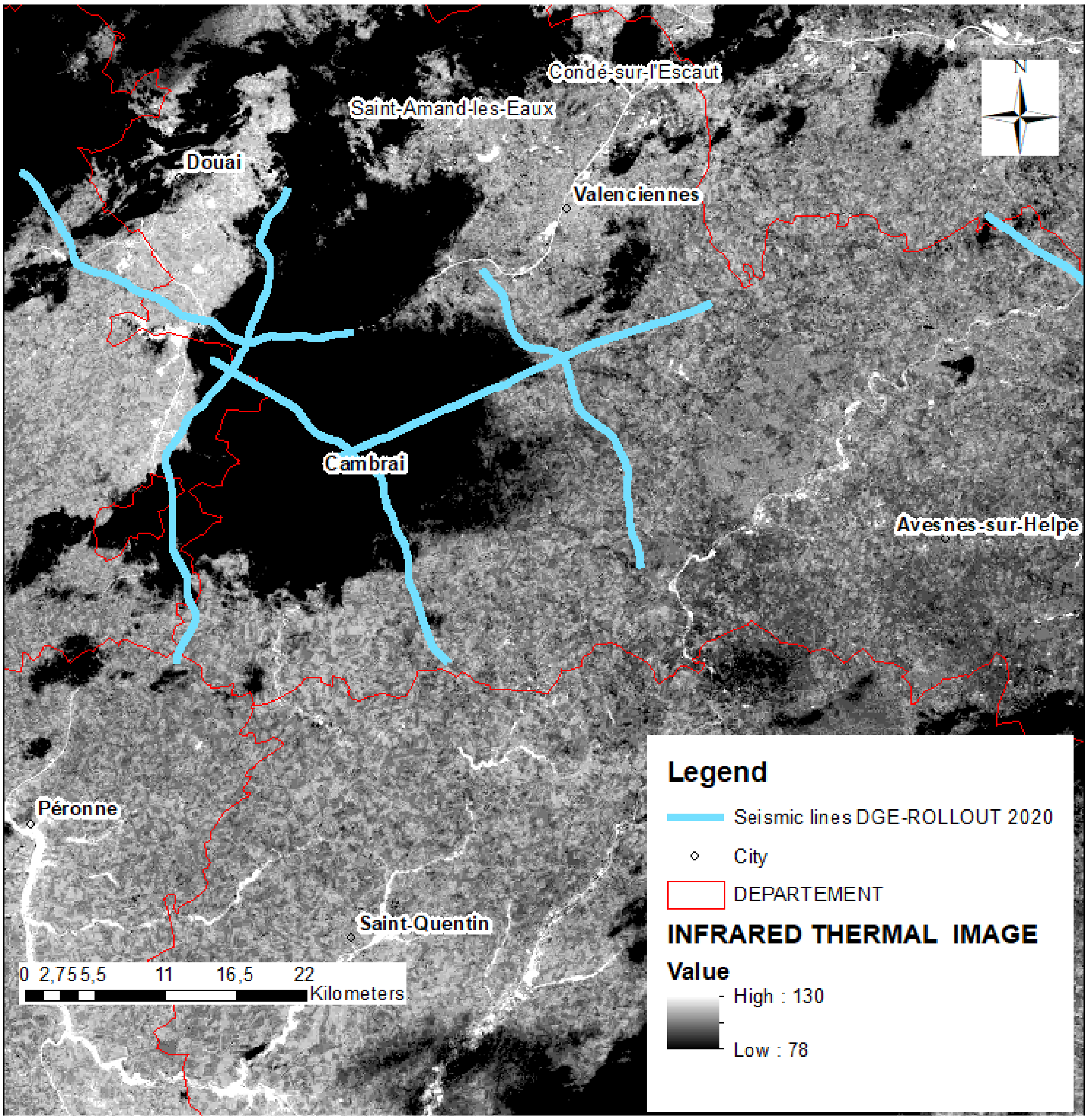

Figure 20: Infrared thermal image from Landsat 7

The only none noisy infrared thermal image available, covering the entire study area was acquired on April, 18th, 2001 during the night (LE07_L1GT_057219_20010418_20200917_02_T2_tir.tif). On Figure 20, the black color corresponds to clouds hidding the thermal information. Outside of cloud areas, no obvious hot or cold lineanments are visibles. Also the spatial resolution with a pixel of 100 meters by 100 meters may not provide sufficient resolution.

Conclusion

The thermal infrared method, in this region where the presence of man has strongly modified the landscapes both by the population density and by the anthropic infrastructures has been studied. The thermal infrared images did not allow to bring any elements to account for the thermicity of the study area. Some hot or cold lineaments are identified. They are most often associated with large geological structures known in the area such as surface water networks, faults and fractures known.

The seismic reprocessing allowed to obtain images of the underground in the Hauts de France region. The seismic interpretation of the Dinantian has provided information on its geographical position, thickness and structure.

The quantitative interpretation carried out in the Hauts de France region was done on an exprimental basis. It is the first time that this method is applied in a highly structured area and with seismic data from the 80s. The results are to be taken with precausion. The results reflect trends but do not allow to identify unequivocally the reservoirs and their lithological nature with precision. However, the method used provides valuable clues on the structure and continuity of the Dinantian as well as on lithological contrasts. Thus, the results of this study show, the 4 lithological categories: limestone, dolomite, clay and anhydrite identified on Vp/Vs ratio. In terms of Vp/Vs ratio, the Dinantian is characterized by 4 units: A, B, C and D. The geothermal reservoir is located in the unit Cand seems to have a relatively constant thickness, except in some fault zones.

The proportion of dolomite in the Dinantian reservoir, can present large uncertainties, due to the poor quality of the seismic and well data. To improve the result, on a chosen area, a well with appropriate logs is mandatory to confirm or not the obtained result.

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Annexes

Annex 1: Seismic data processing report from GK Processing

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