Lower Carboniferous limestone reservoir in northern Belgium: structural insights from the Balmatt project in Mol

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ABSTRACT

In January 2016, the Flemish Institute for Technological Research (VITO) completed the geothermal exploration well MOL-GT-01-S1 in Mol-Donk, northern Belgium. The well targeted a Lower Carboniferous fractured carbonate reservoir at a depth between 3000 and 3600 m. Reservoir temperatures encountered at the bottom of the well at 3600 m were 138 – 142°C and a well test proved the geothermal potential of the limestones. This led to the drilling of a second well to close the geothermal loop. Well MOL-GT-02 was completed and tested in summer 2016. Both wells will be used to deliver heat to an existing district heating network of VITO and adjacent companies. The initial thermal power output of the geothermal plant will only be about 8-9 MW due to limitations imposed by the existing high temperature heating grid. With regard to the addition of extra low temperature heating networks, VITO decided to drill a third well (MOL-GT-03) in 2018, targeting the same faulted and fractured zone as the first well. This well also aimed at exploring the underlying Devonian strata. However, the results were below expectations, initiating a re-evaluation of the data to achieve a better understanding of the reservoir. Part of this evaluation focuses on the structural geology, and more specific on the position and orientation of faults, and their mutual relationships. The available seismic data turn out to be insufficient to deduce how faults continue at depth, and observations from the wells are used to further constrain the fault interpretation.

1. INTRODUCTION AND BACKGROUND

Berckmans and Vandenberghe (1998) examined the geothermal potential of various reservoirs in the Campine Basin in northern Belgium. Their evaluation pointed to the Lower Carboniferous limestone and dolostone sequence as the reservoir with the highest amount of recoverable heat. The first indications of the favourable properties of this stratigraphic interval were derived from the Turnhout well (17E225), drilled in 1953-1955, where the Lower Carboniferous Limestone Group (or Kolenkalk Group) was encountered between 2174 and 2705 m depth. Data on the reservoir characteristics were published by Gulinck (1956), whereas Grosjean (1954) reported on the temperature data.

Renewed interest in the exploitation of geothermal resources in the 1980s has led to several projects targeting the Lower Carboniferous Limestone Group in northern Belgium. The well drilled in Meer (07E205IIb) in 1980-1981 was not continued deep enough to reach the limestone, but the subsequent well in Merksplas (17W265) in 1983 did confirm the positive indications provided by the Turnhout well. Vandenberghe et al (2000) published data on the characteristics and permeability of the reservoir, on temperature measurements and on the composition of the brine. However, the project was suspended due to changing economic conditions and the lack of heat demand in the vicinity of the well.

At the same time, wells drilled in the western part of the Campine Basin, North of Antwerp, also indicated very favourable reservoir properties with permeability in the Darcy range. This eventually led to the development of the underground gas storage site in Loenhout (Heibaert structure).

No further exploration for geothermal energy was carried out in the region until 2009 when VITO became interested in providing heat and electricity from a geothermal plant in Mol targeting the Lower Carboniferous Limestone Group. A prospect was defined, and a drilling location found on the Balmatt brownfield site, near VITO's offices. The idea was to demonstrate the technical and economic feasibility of developing a geothermal plant in the Campine Basin.

2. GEOLOGICAL SETTING

The Belgian part of the Campine Basin covers the major part of the Flemish provinces Antwerpen and Limburg. It is part of the extensive Carboniferous basin of north-western Europe. The northern border of the Campine Basin is formed by the Krefeld high and IJmuiden ridge. Eastward the basin extends into Dutch Limburg, where the NE-SW striking Variscan Anticlinal fault/Oranje fault system forms the boundary with the German Carboniferous Wurm Basin. To the West and South, the basin is bounded by the subcropping early Palaeozoic rocks of the Caledonian London-Brabant Massif (Fig. 1).

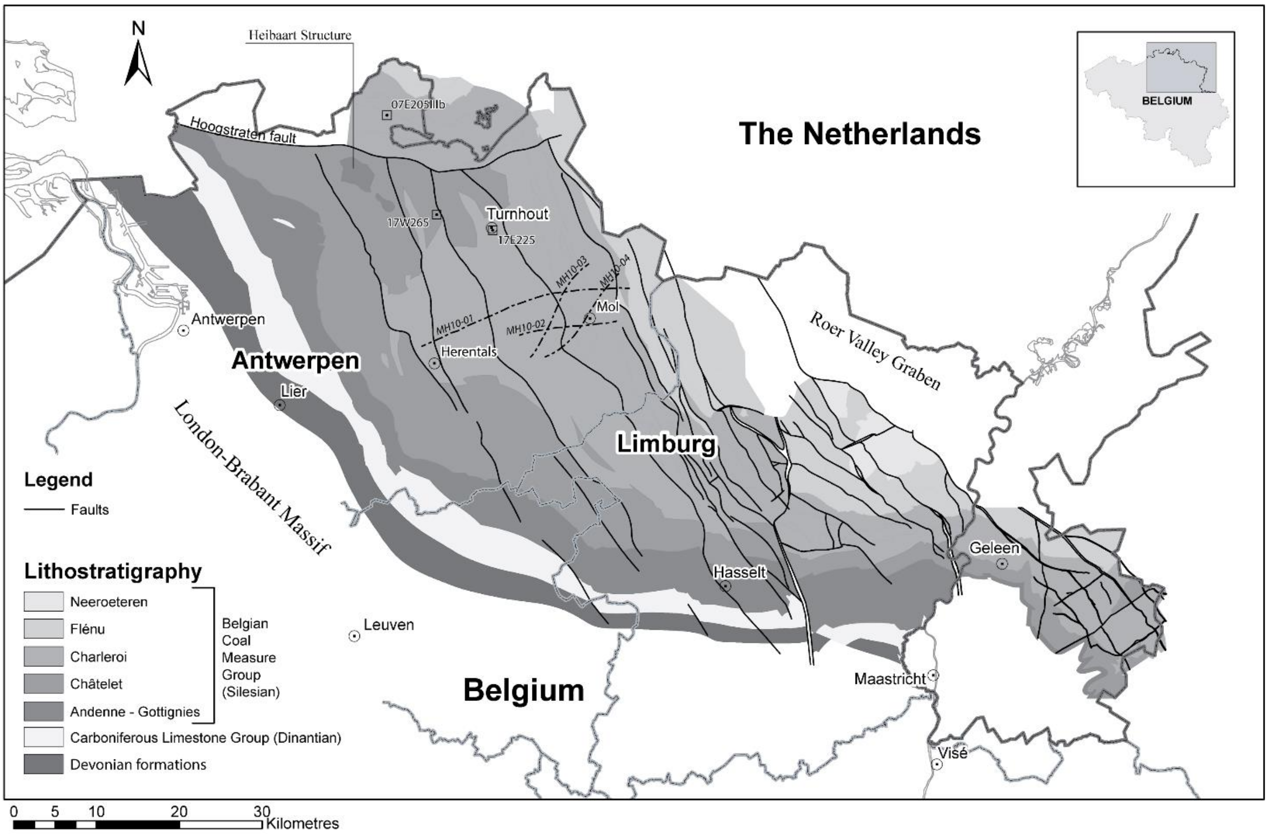

Figure 1: Pre-Permian subcrop map of the Campine Basin in northern Belgium (compiled after Langenaeker 2000, and Patijn and Kimpe 1961).

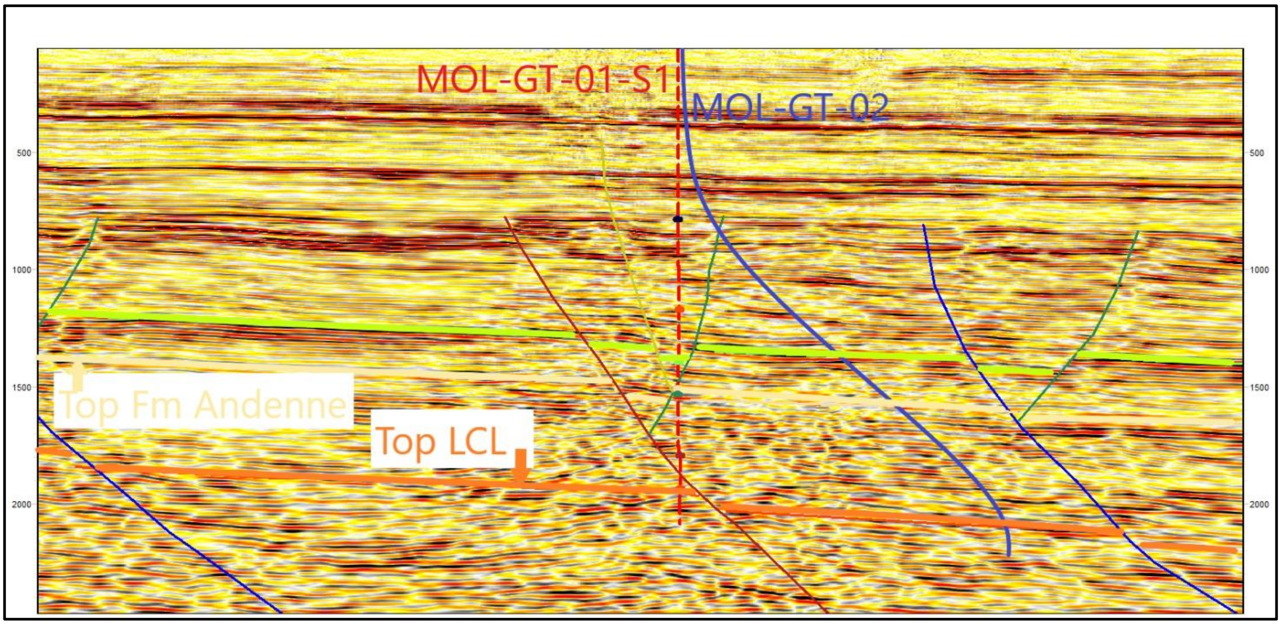

Figure 2: Seismic section (line MH 10-04) showing the interpretation of the data after drilling wells MOL-GT-01 and MOL-GT-02. Top of the Lower Carboniferous Limestone Group (LCL) is indicated in orange. The length of the cross-section from left (Southwest) to right (Northeast) is approximately 6 km. Vertical scale is approximately 2.500 ms TWT.

Predominantly clastic Devonian sediments are present above an angular unconformity at the top of the Caledonian basement. The Devonian strata are covered by Lower Carboniferous dolostones and limestones. In a large part of the basin, these carbonates are intensely karstified. The transition from the Lower to the Upper Carboniferous is marked by a shift from a carbonate to a siliciclastic setting that is characteristic for the Upper Carboniferous paralic coal basin of northwestern Europe. The Silesian sequence starts with marine sediments, gradually becomes more proximal and finally ends with the deposition of fluvial sandstones in the latest Westphalian. In the north-eastern part of the study area, the Westphalian rocks are disconformably covered by sediments of late Palaeozoic and early Mesozoic age (Permian, Triassic and Jurassic strata). The Palaeozoic and Mesozoic successions are disconformably covered by a 300 to 1.000 m thick sequence of gently dipping Upper Cretaceous carbonates and predominantly clastic Tertiary deposits.

The area is transected by a predominant set of (N)NW - (S)SE striking normal faults. Most of these faults already existed during the Carboniferous. The most striking ones have been reactivated during the Jurassic, and some are still active today. A tectonic inversion of these reactivated faults during the Late Cretaceous and Early Tertiary was followed by the subsidence of the Roer Valley Graben in the mid-Tertiary (Van Wijhe 1987; Langenaeker 2000). The resulting pattern is one of a series of elongated, NW-SE striking fault blocks that are generally tilted towards the North-Northeast. The tilting was caused by the uplift of the London-Brabant Massif during the Kimmerian orogenic phases (Langenaeker, 2000). It causes the Carboniferous subcrop to deepen quickly towards the North and Northeast.

3. EXPLORATION LEADING TO THE PROJECT

3.1 Past exploration (pre-2010)

In the past, several exploration surveys have been carried out in the Campine Basin. In the north-western part of the basin, exploration was initially aimed at finding pockets of natural gas, but later exploration was continued in the framework of subsurface gas storage in the Lower Carboniferous limestone. This eventually led to the development of the subsurface gas storage of Loenhout in the mid-1980s. Seismic surveys in the south-eastern part of the basin were executed in the framework of coal exploration and focused on the extent of coal-bearing formations North of the mining area in Limburg.

As Mol is located in between both regions, the amount of seismic data available for interpretation of deep strata was very limited. Few recent seismic lines were acquired in the area near Mol, except those for reconnaissance of the shallow subsurface (down to the Chalk Group). This prompted VITO to carry out a 2D seismic survey in 2010.

3.2 Seismic survey of 2010

The seismic survey carried out in 2010 (2D Mol-Herentals 2010) covers the area between the towns of Herentals, Mol and Turnhout. The survey comprises four lines with a total combined length of 67,5 km. The proposed location of the geothermal plant in Mol (Balmatt site) is located in between the four lines and is positioned roughly 350 m to the nearest line. To the west, the seismic survey can be correlated with other surveys.

The data acquired in 2010 were used to interpret the geology, in particular the Palaeozoic strata. The results of the survey confirmed the geological model and depth estimations. Previous assumptions estimated the depth of the top of the Carboniferous Limestone Group between 2500 and 3500 m.

The data revealed that strata dip towards the Northeast. The depth of the base of the Chalk Group increases to more than 850 m in the Northeast of the survey area. The Carboniferous strata of the Coal Measures Group and Carboniferous Limestone Group dip more steeply. As a result, younger strata are present below the base Cretaceous angular unconformity towards the Northeast. The total thickness of the Coal Measures Group increases in this direction. Accordingly, the top of the Carboniferous Limestone Group deepens. In the West of the survey area it is in the order of 1730 m, whereas the depth amounts to more than 3400 m in the north-eastern part of the survey area. For the project location, the depth estimate varied around 2800 m below surface, in line with previous expectations. However, uncertainties about the top reservoir interpretation were significant in the order of several hundreds of metres. This uncertainty resulted mainly from the correlation of the top-limestone seismic reflector over the faults downthrowing the limestones to the East (Bos and Laenen 2017).

The Carboniferous strata are affected by a series of faults, dominantly oriented Northwest-Southeast (Fig. 2). Most faults show a normal displacement and dip steeply to the Northeast. However, some faults have dip in the opposite direction.

4. DRILLING OF WELLS

4.1 Results

The first well (MOL-GT-01) was spudded in September 2015 and drilled vertically. The well design was made considering an anticipated top of the Lower Carboniferous Limestone Group at 2800 m vertical depth. As the top of the reservoir was encountered roughly 370 m deeper, drilling technical issues required the abandoning of the deepest well section and the drilling of a side-track MOL-GT-01-S1 (Bos and Laenen 2017). The side-track reached the top of the Lower Carboniferous Limestone Group at a depth of 3175 m. Well TD was called at 3610 m depth. Total mud losses were encountered while drilling in the reservoir section, indicating the presence of transmissivity at least in the immediate vicinity of the well. This was later confirmed by well tests.

A second well (MOL-GT-02) was spudded in March 2016 and deviated towards the Northeast, parallel to the seismic line MH 10-04. The target was an area where the reservoir was not affected by faults to minimize the risk of fault reactivation when injection water under pressure. This would also provide the opportunity to test the reservoir characteristics of the limestone sequence away from faults. The top of the Lower Carboniferous Limestone Group was encountered at 3300 m TVD, some 200 m deeper than expected. This indicated a larger throw of the normal fault positioned west of the entry point (Bos and Laenen 2017). TD was reached in July 2016 at 4341 m MD (or 3830 m TVD).

Following the completion of both wells, work started on the construction of the surface installations of the geothermal plant and on the connection to the heating network of VITO (and adjacent companies), already in place. The existing high temperature grid would impose a return temperature as high as 80°C, therefore limiting the thermal power output of the geothermal plant to 8-9 MW. Connecting low temperature heating networks, that could go as low as 30°C, would double the thermal output. Regarding this addition of extra low temperature heating networks, VITO drilled a third well in 2018, MOL-GT-03.

MOL-GT-03 targeted the same faulted and fractured zone as MOL-GT-01-S1, although now in a Southeast direction at 1,6 km distance to MOL-GT-01-S1. The well also aimed at exploring the lower lying Devonian strata. MOL-GT-03 was spudded in December 2017. The top of the Lower Carboniferous Limestone Group was reached at a depth of 3643 m MD (or 3142 m TVD below surface). For the first time the entire sequence was drilled, and the base was found at 4654 m MD or 3992 m TVD (base Vesdre Formation). Due to failure of equipment, a side-track had to be drilled, reaching TD at 4905 m MD (4236 m TVD) in July 2018. Initial well tests pointed to productivity far lower than anticipated.

4.2 Differences between observations and expectations

Observations in the well immediately show that the Lower Carboniferous Limestone Group is present at considerably greater depth than anticipated. Where a depth around 2800 m was expected in MOL-GT-01, the limestone sequence was only encountered at 3300 m. The larger depth can be explained by both errors or uncertainty in the interpretation of the seismic data and the time-to-depth conversion of the data, and by the larger throw of normal faults (for MOL-GT-02).

Another striking observation was that MOL-GT-03-S1 did not provide the anticipated productivity. More specific, productivity was expected to be in the same order of magnitude as in MOL-GT-01-S1, as both wells target the same fault zone (Fig. 3). As no mud losses were encountered during drilling, and since well tests did not reveal significant permeability, the exact position of the fault zone in MOL-GT-03-S1 is questionable. The low productivity of the well has led to an analysis of all data (still ongoing) to attain a better understanding of the reservoir and to clarify why well MOL-GT-01-S1 is successful and well MOL-GT-03-S1 is not.

The structural geology, i.e. the position, orientation and continuation of faults, makes up one of the fields under consideration and is highlighted in the following paragraphs.

5. INDICATIONS FOR FAULTS

5.1 Indications from seismic data

Seismic lines MH 10-01, MH 10-02 and MH 10-04 run closest to the project location on the Balmatt site. In 2011, additional processing was carried out on the closest line (MH 10-04), with both CRS processing and pre-stack time migration (PSTM). As the structural aspects were looked at in more detail, VITO decided to carry out a similar processing (CRS and PSTM) on the other three lines to have all lines at comparable quality.

The reprocessed data confirm the main structures already identified. However, several additional faults can also be distinguished in the Upper Carboniferous section (800-1500 ms TWT). The continuation of faults at larger depth remains uncertain, and several different interpretations seem possible.

The interpretation of the seismic sections is hampered by the quality of the data, which decreases with increasing depth. Moreover, some parts of the lines are of lower quality because of factors impacting acquisition. For example, parts of lines MH 10-01 or MH 10-02 are located close to houses and busy roads, causing higher noise levels in the data and requiring the use of reduced force by the vibrator trucks, both resulting in lower signal/noise ratios.

The data quality and the limitations inherent to 2D seismic data sets lead to higher uncertainty in the interpretation of both horizons and faults at reservoir depth (below 2500 m). There is uncertainty on whether fault interpretations are reliable. For faults in particular, there are questions whether their extent is correct both in a vertical (depth) direction as in a horizontal direction (correlation between seismic lines).

For the moment, we must accept that it is very difficult to use the available seismic data to deduce how faults continue at depth. Different interpretations remain possible on which faults dominate, which faults continue in depth, and how faults interact. As there is no unique solution, additional data are required to constrain the structural interpretation. Observations from wells can be used for this purpose.

5.2 Indications during drilling

Several parameters are monitored during drilling, both technical and geological. Technical parameters include e.g. rate of penetration (ROP) and weight on bit

(WOB). Geological parameters include the lithological or mineralogical description of cuttings (e.g. accessory minerals) and the amount and composition of gas (either free gas or gas coming out of solution). Some observations may demonstrate or point to the presence of a fault (cut by the well). Individually these observations are not strong enough as arguments to prove the presence of a fault. However, combined with other observations or arguments, there is a strong(er) indication that a fault was cut (Fig. 4).

5.3 Indications based on thickness variations

Another method to evaluate the presence of a fault based on well data, is the comparison of the thickness of stratigraphic intervals in each well. Differences may point to the presence of faults where part of the stratigraphy is faulted out or repeated. However, not every variation in thickness can be attributed to a fault, as layer thickness may gradually change from one location to another.

This approach can be used in the strata of the Belgian Coal Measures Group (Westphalian and Namurian age) as there are several marker beds or intervals that can be identified and correlated. Considering the differences between true vertical and true stratigraphic thickness for the defined zones, the assumptions on the exact dip only have a minor impact on the results.

Within the Andenne Formation, differences in thickness are in the order of 5-25% of the average value, reflecting gradual thickness variations between the well locations and differences in local dip direction and dip of the layers. However, there is an interval where the thickness observed in MOL-GT-01 is only 60-65% of what is measured in the other two wells (Fig. 4). Instead of a TVD thickness of 179-180 m, MOL-GT-01 shows a reduced thickness of only 114, suggesting a section of 60 m is missing (faulted out).

The approach can also be used for the well sections through the Lower Carboniferous Limestone Group. Here, calculations consider a structural dip of 10° to the Southeast. The results show that there are no significant thickness variations in the upper part of this section. Further down, stratigraphic intervals appear to be systematically thicker in well MOL-GT-03. This would suggest that the Lower Carboniferous strata increase in thickness towards the southeast. The latter analysis is however complicated due to varying bedding orientation as demonstrated by the FMI data in MOL-GT-03.

As wells MOL-GT-01-S1 and MOL-GT-02 did not reach the base of the Lower Carboniferous Limestone Group, there are insufficient data to do the analysis on the lowermost part of the sequence.

5.4 Indications based on changes in dip direction/dip

If the depth of a layer is known in three locations, the XYZ data of marker beds in the well can be used to determine the orientation of the layer (strike/dip or dip direction/dip). As horizons can be identified and correlated between all three wells, this approach can be used to look for marked changes in orientation which may due to the presence of faults. However, care should be taken to interpret the orientation too strictly, as this approach assumes that the orientation of the bedding plane is constant between the three wells. In case of changes in strike or dip, or if a fault is present between the three wells, the resulting strike/dip or dip direction/dip will not be correct but will only reflect the overall deepening of the horizon. This is then called an apparent strike/dip.

The analysis indicates that dip direction and dip magnitude vary regularly throughout the Carboniferous strata. In some cases, this can be clearly related to a fault, i.e. below the Sarnsbank (forming the boundary between the Namurian Andenne Formation and the overlying Châtelet Formation of Westphalian age). Here the dip direction changes from Northwest (N308) to Northeast (N034). Another strong change in dip direction occurs deeper in the Andenne Formation, between 2824 and 2939 m MD in MOL-GT-01: from N320 to N031 (Fig. 4).

Below the suspected fault cut in the Andenne Formation, dip direction and dip magnitude show only gradual changes. Within the Lower Carboniferous Limestone Group, the apparent dip direction is gradually changing from Northeast (at the top) towards East. Different dip directions in this interval in MOL-GT-03, as demonstrated by FMI data, suggest care should be taken when drawing conclusions at this depth.

It should be noted that with increasing depth the distance between the wells is also increasing. The effect is that displacement along faults is “smeared out” or smoothed over a larger distance. Therefore, changes in dip direction and dip due to faulting are less pronounced.

5.5 Indications from FMI in MOL-GT-01-S1 and MOL-GT-03-S1

FMI data (Formation Micro Imaging) were gathered in both MOL-GT-01-S1 and MOL-GT-03-S1, providing information on the orientation of both bedding planes and fractures. The occurrence and orientation of fractures is analysed in more detail by van der Voet et al. (2019).

Based on the bedding planes that are showing strong differences in bedding dip, several tectonic zones could be defined. For example, the orientation of bedding planes between 4300 and 4400 m MD in MOL-GT-03-S1 shows strong variations which could be interpreted as a drag zone around a fault (Fig. 5).

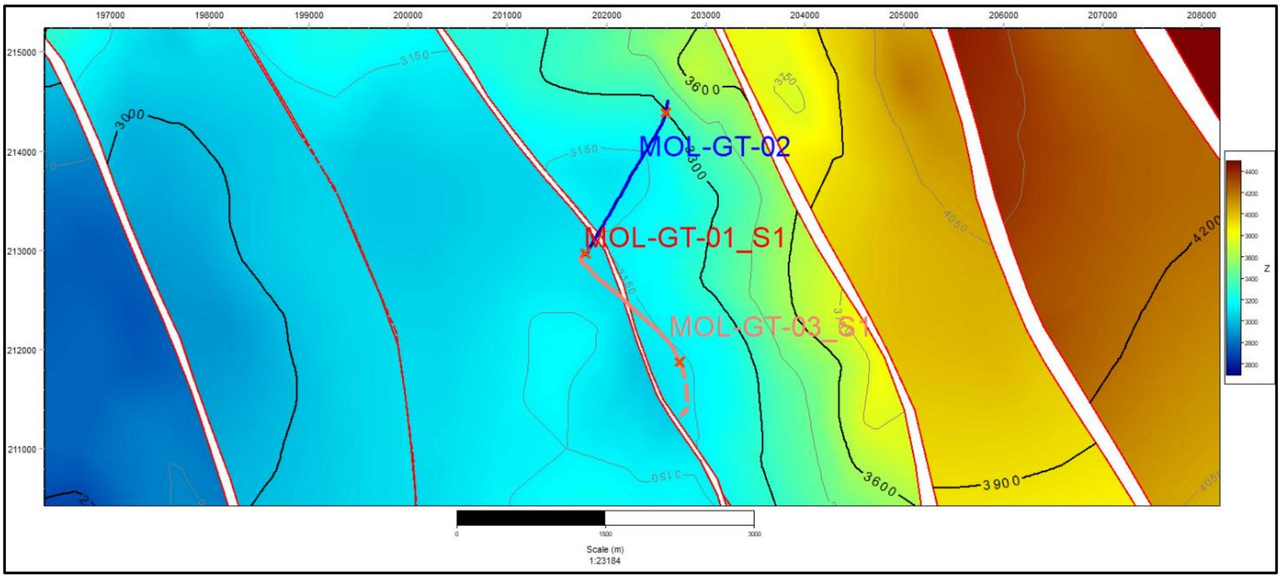

Figure 3: Depth map of the top of the Carboniferous Limestone Group, with depth values corrected after drilling all three wells. Well trajectories are shown. Entry-points into the top of the Lower Carboniferous Limestone Group are marked in red.

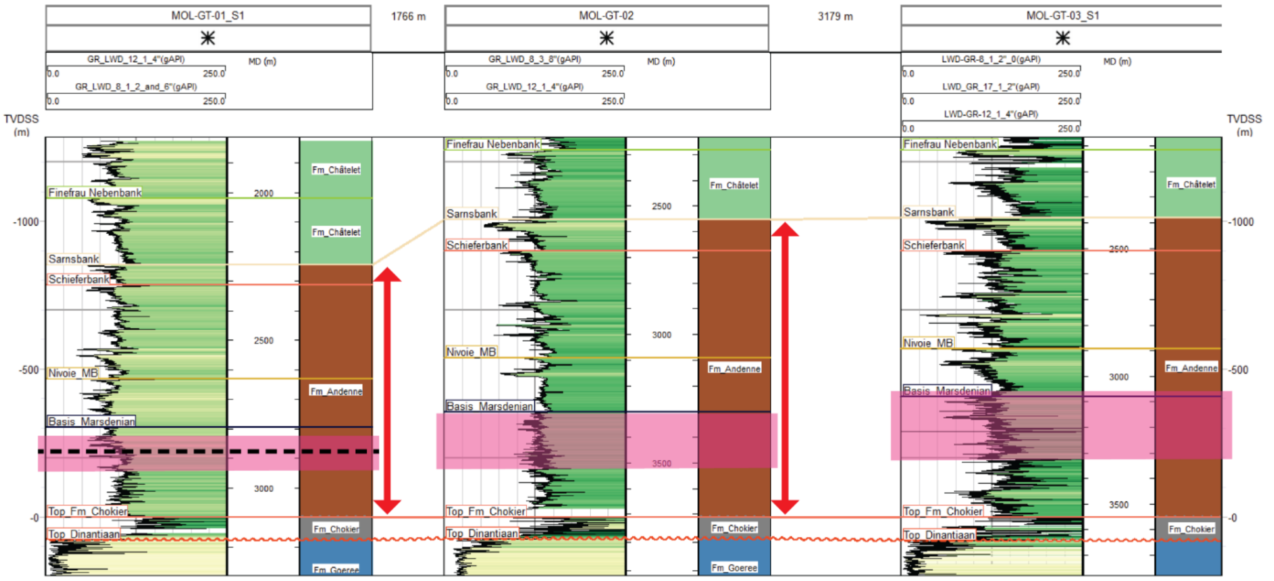

Figure 4: Correlation scheme between the three wells for the middle part of the Carboniferous sequence (Andenne Formation). Correlation panel is flattened at base Andenne Formation. The thickness in MOL-GT-01 is reduced compared to wells MOL-GT-02 and MOL-GT-03 (as highlighted by vertical arrows). More specific, the pink interval is roughly 60 m thinner (TVD thickness) in MOL-GT-01. This coincides with a change in dip direction from NW (320/06) to NE (031/04). Finally, the dashed black line indicates the position in MOL-GT-01 where an increase in ROP was registered and where calcite and anhydrite were identified in the cuttings.

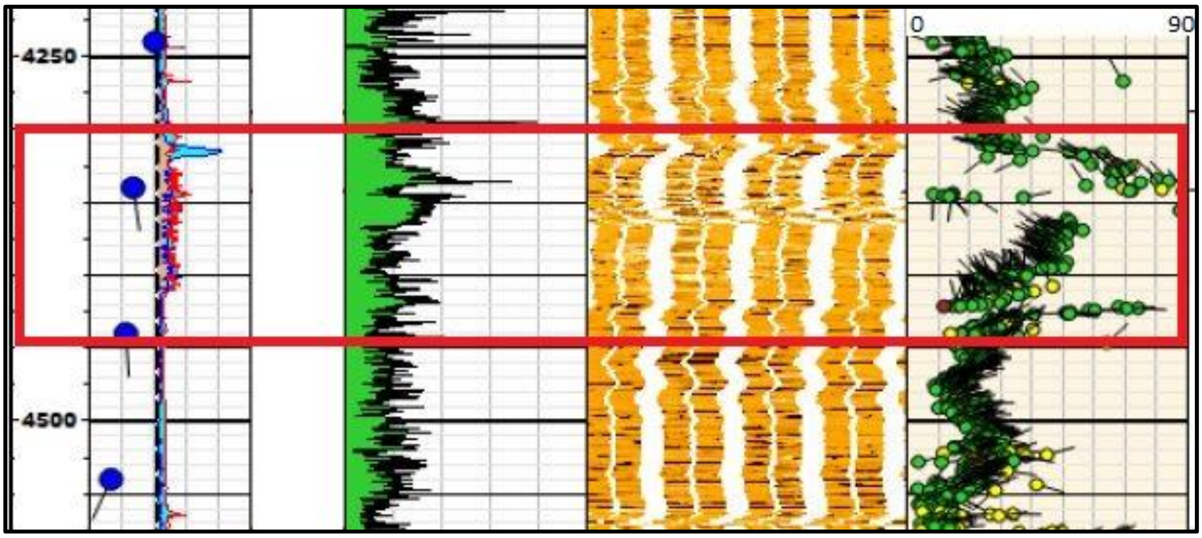

Figure 5: Extract of part of the FMI data taken from MOL-GT-03-S1 showing indications for a fault between 4.300 and 4.400 m MD (data and interpretation from Schlumberger). Structural bedding dip is indicated by green tadpoles in the righthand column. The dip magnitude varies from 0 to 90°.

6. CONCLUSIONS

In the structural evaluations evidence has been sought for the presence of faults. This has been done by using 1) seismic data, 2) drilling parameters, 3) stratigraphic marker interpretation data and 4) FMI data.

An evaluation of the stratigraphic marker interpretations, has given several possible locations for faulting in the Upper Carboniferous intervals. The fault expected in the Andenne Formation in well MOL-GT-01 is confirmed by the analysis of stratigraphic markers (thickness and orientation) and coincides with observations made during drilling. No FMI data are present for this well section.

The extension of faults into the Lower Carboniferous Limestone Group remains more difficult. From the FMI data, it was found that a fault might be present in MOL-GT-03-S1 at depths between 4300 m and 4450 m, as previously expected. However, as the other wells did not reach the same depth and stratigraphic interval, changes in thickness and bedding orientation cannot be used to confirm the FMI data.

Even though the analysis of drilling parameters, stratigraphic markers and FMI data can complement the interpretation of the 2D seismic data, uncertainty remains on how the lateral connection and vertical extension of faults.

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