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Deep geothermal energy in the Lower Carboniferous carbonates of the Campine Basin, northern Belgium: An overview from the 1950's to 2020

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Abstract: Geothermal energy is seen as one of those energy sources bringing us closer to a sustainable energy mix. Deep geothermal developments in Flanders focus on the Lower Carboniferous Limestone Group in northern Belgium. However, deep geothermal energy in the Belgian Campine Basin is not a new development. In fact, the first steps were already taken in the 1950's when the Turnhout well was drilled, revealing the presence of a geothermal reservoir at depth. Hydraulic properties were favourable and the temperature of almost 104 °C measured at 2,225 m depth was higher than expected. Nevertheless, it took until the late 1970's for a new project to materialise. This led to the drilling of the Meer well in 1980–1981, which did not reach the Lower Carboniferous Limestone Group. Another attempt in Merksplas-Beerse in 1983 was more successful and provided a wealth of information, including hydraulic, chemical and radiological data. However, it did not result in the development of a geothermal site providing heat to consumers. Renewed interest from 2009 onwards eventually led to the Balmatt project in Mol, with the aim of demonstrating the technical and economic feasibility of a geothermal site in the Lower Carboniferous Limestone Group at a depth of more than 3,000 m. Three wells were drilled between 2015 and 2018. The project faced several challenges, with induced seismicity probably the main issue to be dealt with. The most recent project is in Beerse, where two wells were completed in 2020.

Keywords: geothermal energy, limestone, karst permeability, Dinantian, Campine Basin

1. Introduction

Geothermal energy, both shallow and deep, plays a substantial role in the sustainable energy mix of the future as it is a local, sustainable, and reliable source of energy below our feet. Shallow geothermal energy (0–100 m) has been used for decades in Belgium, with both open and closed systems. Previously only three deep geothermal projects (>1,000 m) were operational in Belgium (Mons Basin, Wallonia), providing heat to heating networks (Hoes et al. 2020). Recent renewed interest in the use of deep geothermal energy in Flanders has risen since the early 21st century. This has led to geothermal projects by VITO in Mol (Bos & Laenen 2017) and by Janssen Pharmaceutica in Beerse, both in the Lower Carboniferous Limestone formations. This increased interest followed an earlier development in the Netherlands where the development of new geothermal projects started in 2005, mainly in the horticultural sector (greenhouse; Provoost et al. 2019). However, these recent developments in Flanders do not represent the first steps taken in the field of deep geothermal energy. Although not (initially) aimed at geothermal energy, several deep exploration wells in the 1950's (Turnhout) and 1960's (Heibaart) already pointed out the potential of geothermal energy. In the 1980's, attempts were made to further explore the potential and even start a full project with heat delivery to nearby consumers (Vandenberghe et al. 1988, 2000). Due to the economic situation at that time and the low demand for alternative energy resources, and the productivity (flow rate) below what was projected, these attempts turned out to be unsuccessful and further interest in deep geothermal energy in Flanders faded, until 20 years later.

The activities in the 1950's and 1980's have provided a wealth of information that turned out to be very useful for the recent developments motivated by the search for a more sustainable source of heat. In that sense, they have set the stage for later developments.

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2. Geological setting

The Belgian Campine Basin covers a major part of the Flemish provinces of Antwerpen and Limburg (Fig. 1; Bless et al. 1983; Langenaeker 2000; Laenen et al. 2004). It is part of the northwestern European Carboniferous Basin (NWECB). 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 early Palaeozoic subcrop of the Caledonian London-Brabant Massif (Langenaeker 2000).

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 northeastern part of the Campine Basin, 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 chalk and predominantly clastic Cenozoic deposits.

The area is crosscut by a predominant set of (N)NW–(S)SE striking normal faults. The main fault activity occurred during Jurassic times (Late Kimmerian tectonic phase; Demyttenaere 1989). A number of faults were later reactivated as reverse faults during tectonic inversion in Late Cretaceous times, followed by normal faulting when the current Roer Valley Rift System developed from mid-Cenozoic (Oligocene) times onwards, still continuing today (Van Wijhe 1987; Demyttenaere 1989; Langenaeker 2000; Michon et al. 2003; Deckers et al. 2014). Fault throw is in the order of tens to 200 m, exceptionally up to 400 m. Some Kimmerian faults were inherited and were already active in the Early Carboniferous, as suggested by sedimentary differences due to block tectonics (Muchez & Langenaeker 1993). The resulting pattern is a

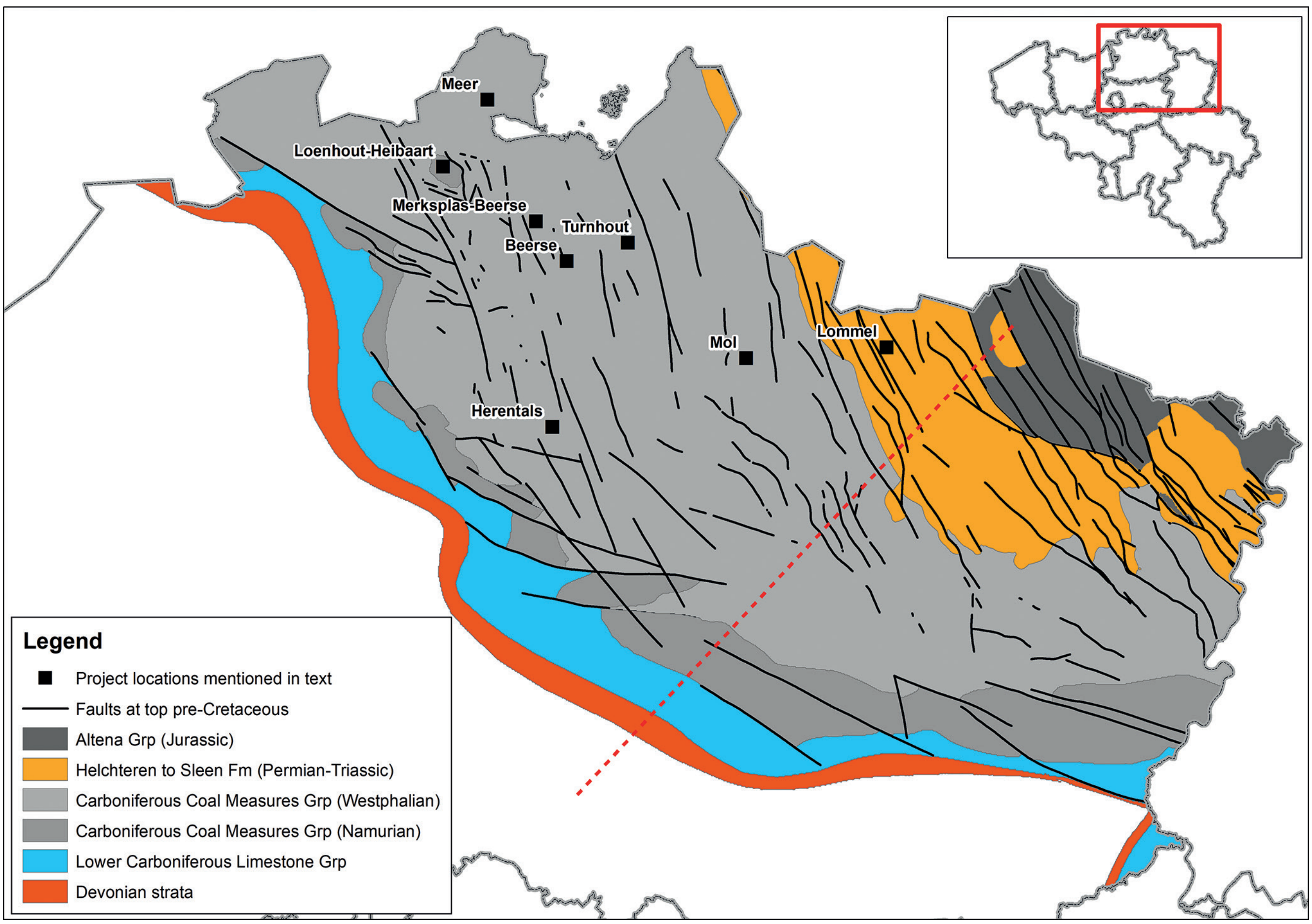

Fig. 1: Pre-Cretaceous subcrop map of the Belgian Campine Basin based on the G3Dv3 model by Deckers et al. (2019). The locations of projects mentioned in the text are indicated. The red dashed line indicates the approximate position of the cross-section in Fig. 2.

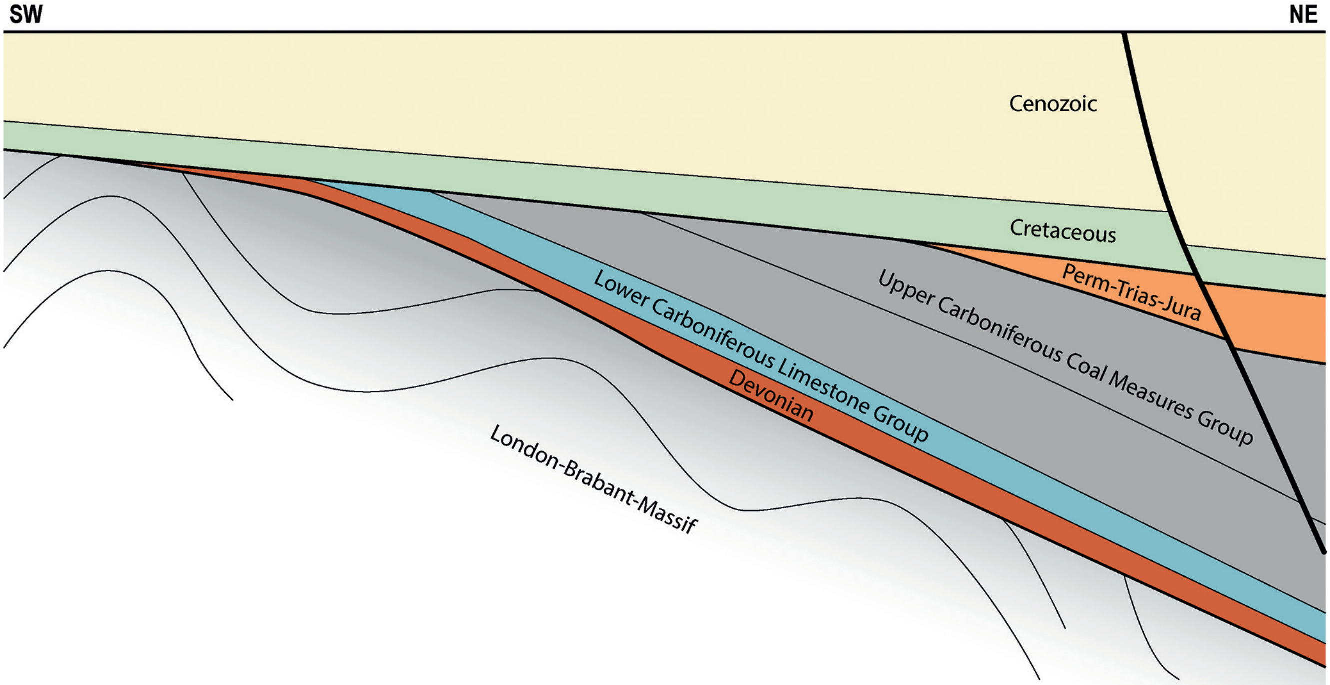

Fig. 2: Schematic SW–NE cross-section through the Belgian Campine Basin illustrating the gradual deepening of strata to the NE. NW–SE oriented normal faults are present towards the Roer Valley Graben. The cross-section shows the angular unconformity at the base of the Cretaceous sediments, at the base of the Permian deposits and at the top of the Cambrian to Silurian London-Brabant Massif. The position of the cross-section is indicated in Fig. 1.

series of elongated, (N)NW–(S)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 (Fig. 2).

Geological formations can serve as deep geothermal reservoirs if their permeability and temperature are high enough to allow a sufficient volume of water to be produced, and for a sufficient amount of heat to be extracted. In northern Belgium (Flanders), the average geothermal gradient is in the order of 30 °C/km. Therefore, deep geothermal reservoirs should be found at a depth of at least 500 to 1,000 m. The Campine Basin presents a favourable geological setting with permeable formations present at significant depth. Four stratigraphic intervals qualify as potential reservoirs (Berckmans & Vandenberghe 1998; GEOHEAT-APP 2014): (1) carbonate rocks of the Maastricht and Houthem formations of Late Cretaceous and Early Palaeocene age, (2) sandstone layers within the Triassic Buntsandstein Formation, (3) sandstone layers of the Upper Carboniferous Neeroeteren Formation, and (4) carbonate rocks of the Lower Carboniferous Limestone Group. The latter present the highest potential due to their larger depth (compared to the Cretaceous strata) and their wider extent (compared to the sandstone formations of Triassic or Late Carboniferous age).

The carbonate sediments deposited in the Early Carboniferous are grouped in the Lower Carboniferous Limestone Group. They range in age from Tournaisian to Viséan (Dinantian). Bless et al. (1976) provide an overview of their occurrence in the Campine Basin and adjacent regions. A lithostratigraphical subdivision of strata from this stratigraphic interval in Belgium is presented by Poty et al. (2001), but their focus was on sedimentation areas south and east of the London-Brabant Massif. It was Laenen (2003) who subdivided the sequence in the Belgian Campine Basin based on lithological data from core descriptions in combination with biostratigraphical data (Fig. 3). A more recent overview of the presence of the Lower Carboniferous Limestone Group as seen in seismic sections and in wells in the southern Netherlands and northern Belgium is described by Reijmer et al. (2017), although a detailed correlation between Dutch lithostratigraphic divisions and the units defined by Laenen (2003) and Lagrou & Laenen (2014) is not presented. A map showing the depth of the top of the Lower Carboniferous Limestone Group and the wells reaching the top is shown in Fig. 4.

Within the Belgian Campine Basin, the carbonate sequence reaches a thickness of 300 m to 1,000 m. The large differences in thickness are interpreted to relate to block faulting (Bless et al. 1981; Muchez et al. 1987; Muchez & Langenaeker 1993; Langenaeker 2000). The lower (Tournaisian age) part of the sequence is largely made up of dolomite of the Vesdre Formation. The overlying Viséan strata are dominated by limestone. Viséan grainstones and algal-microbial boundstones formed reefal structures on a shallow marine carbonate platform, affected by early diagenesis and

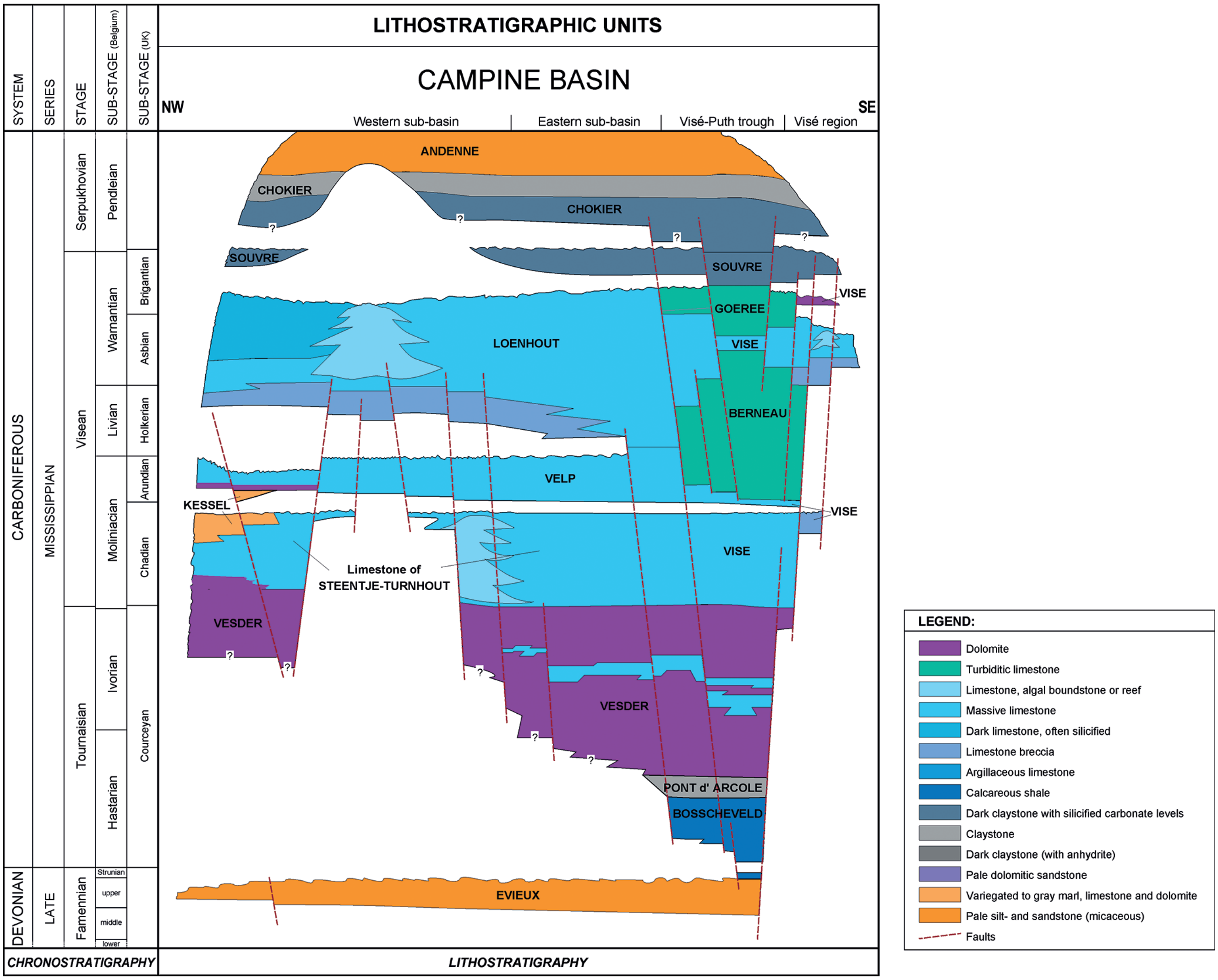

Fig. 3: Lithostratigraphic table with subdivisions of the Lower Carboniferous Limestone Group in the Campine Basin; after Laenen (2003).

displaying evidence for eogenetic karst development during the final Viséan sea-level fall (Dusar & Lagrou 2008). Well data reveal the presence of several intervals of mud losses during drilling, indicative for permeable or karstified zones (Bless et al. 1976; Vandenberghe et al. 2000). This suggests there were several pulses of uplift, emersion and karst formation (Vandenberghe et al. 2000). A possible additional period of palaeo-karstification can be linked to the uplift during the Cretaceous (Dusar & Lagrou 2008).

Development of an underground seasonal gas storage facility in the karstified limestone in the Loenhout-Heibaart area was started in 1981 and taken into operation in 1985 by Distrigas (now Fluxys). Although porosity is low (2–3%), permeability is locally high (up to 2,000–3,000 mD), making the limestone very suitable for high-speed filling and production of natural gas (Dusar & Lagrou 2008). Permeability is related to irregular fractures and vugs, originally created by karst dissolution and collapse. These reservoir properties are also favourable for geothermal use.

These favourable geothermal properties are also known in Wallonia, in the Mons-Borinage area, in the central part of the province of Hainaut. The geothermal potential of the Lower Carboniferous Limestone Group was discovered in 1975 in the Saint-Ghislain well (Delmer 1977) and subsequently confirmed in additional wells in Douvrain and Ghlin. An overview of the characteristics of this karstic reservoir is given by Licour (2014). However, the geological context is different in the sense that karst permeability appears to be related to the presence of evaporites (anhydrite) and their dissolution. This process started in the Mesozoic and continues throughout the Cenozoic until today. Geothermal heat has been used since 1985, with an artesian flow rate around 100 m³/h and a production temperature around 70 °C. Three heating networks are currently in operation using single production wells. As salinity of the water is only 1–2 g/l (Licour et al. 2010), there are no (re)injection wells, and e.g. water at Saint-Ghislain is supplied to a water treatment plant. These networks are managed and still developed

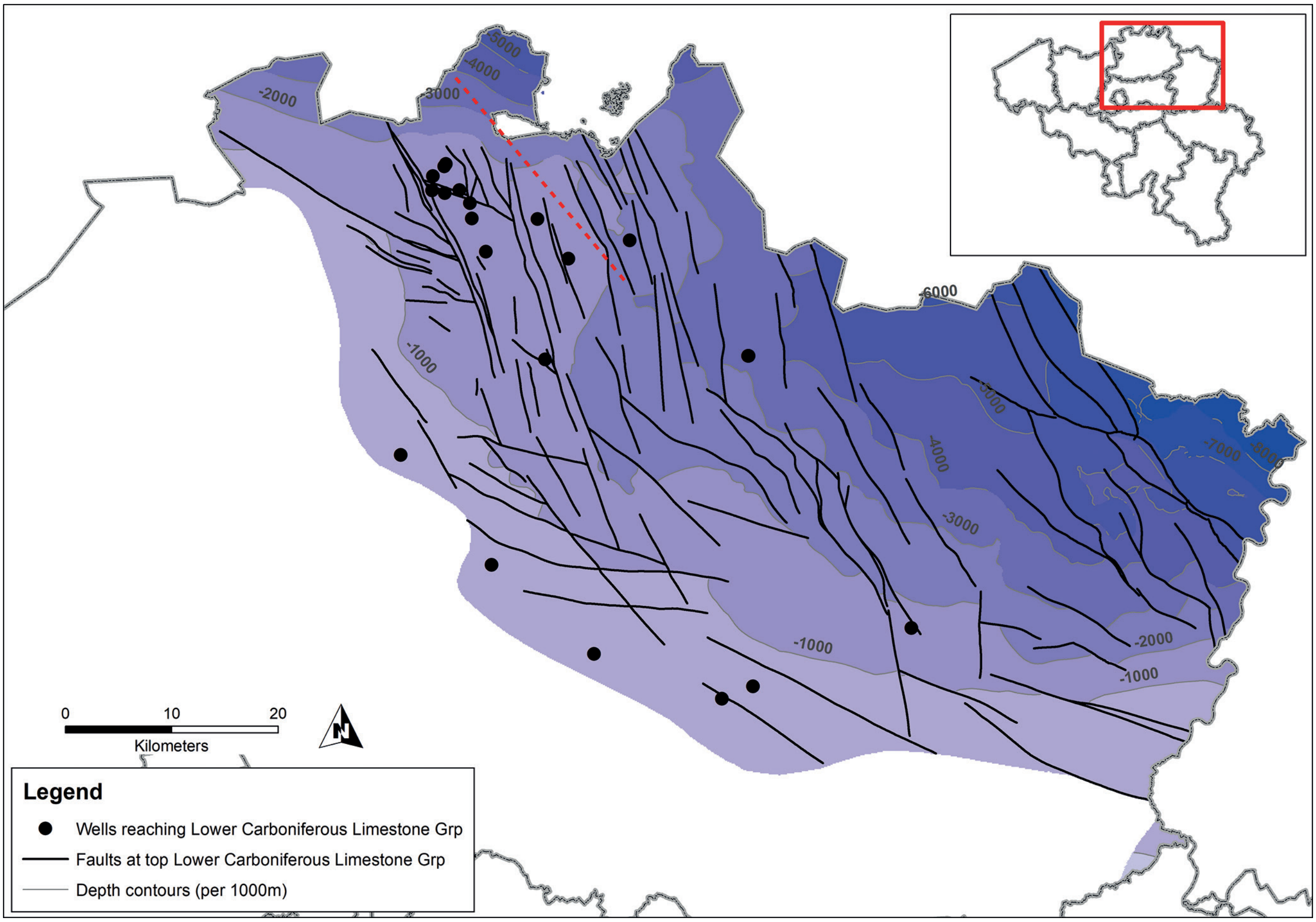

Fig. 4: Depth of the top of the Lower Carboniferous Limestone Group according to the G3Dv3 model (Deckers et al. 2019). Wells reaching the top are indicated, but only a selection of wells is shown for the Loenhout-Heibaart area. Note that the Beerse wells were drilled after the model was finalised. The red dashed line indicates the approximate position of the cross-section in Fig. 5.

by IDEA, the regional economic intermunicipality (Lagrou et al. 2019).

In addition, the geothermal potential of the Lower Carboniferous Limestone Group is also explored in the Netherlands (Reijmer et al. 2017), England (Pharaoh et al. 2021), Ireland (Pracht et al. 2021), northern France-southwestern Belgium (Laurent et al. 2021) and North Rhine-Westphalia, Germany (Arndt 2021).

3. The 1950's

The first indications of the favourable geothermal properties of the Lower Carboniferous lime- and dolostones in the Campine area were derived from the Turnhout well (BGD number 017E0225). The well was drilled in 1953–1955. The Lower Carboniferous Limestone Group was encountered between 2,174 and 2,705 m depth. The well in Turnhout was drilled in the centre of town, with the initial aim of providing the local swimming pool with hot and mineralised water. Water suitable for this purpose was expected to be encountered at a depth of 800 m, in the top of the Cretaceous strata (Maastricht Formation). The Geological Survey of Belgium then decided to extend the well in order to explore the deep subsurface in the area, which was poorly known at the time. The final depth of the well would depend on the technical capability of the drilling rig and on the available budget. The project was realised with support of the town of Turnhout and financial aid from Inichar (Institut National de l'Industrie Charbonnière). Data on the reservoir characteristics of the Carboniferous Limestone Group were published by Gulinck (1956), whereas Grosjean (1954a, b) reported on the temperature data. Their publications highlight both the presence of permeable karstified zones near the top of the limestone as well as the occurrence of an anomalously high temperature compared to the average geothermal gradient of 30 °C/km expected in the region.

Final well TD (Total Depth) was reached at a depth of 2,705 m, short of the intended 3,000 m, and still within the limestone sequence. After drilling through the Carboniferous Coal Measures Group, the well encountered the top of the Lower Carboniferous Limestone Group at a depth of

2,174 m. At 2,175 m depth, so just below the top of the sequence, an artesian aquifer was found in porous dolomite and silicified limestone, of late Viséan age (Gulinck 1956). Cavities of various forms and dimensions were encountered in this interval, as demonstrated by the abrupt drop of the drill bit (and drill string) when the top of this zone was reached. The cavernous interval has a thickness of 46 m (2,174–2,220 m). No other comparable intervals were found deeper down in the Lower Carboniferous strata, the rest of the limestone was found to be homogeneous and compact.

Gulinck (1956) also reports briefly on the well tests carried out. During airlift testing, water of 75 °C was produced at surface, and a flow rate of 30 m^3/h was reached. Water samples were taken downhole (900 m depth), indicating a NaCl rich brine (roughly 135 g/l) with a ferrous iron content of 0.29 g/l. At the time of sampling, the well had reached a depth of 2,247 m.

Another striking feature of the Turnhout well is the high temperature that was encountered. Grosjean (1954a, b) reports on the temperature measurements carried out by means of downhole thermometers in the Namurian and Dinantian intervals of the well. These were put in place while drilling was suspended, prior to reaching TD. They remained close to the bottom of the well for several days. The highest values measured were 103 °C at a depth of 2,185 m and 104 °C at a depth of 2,225 m, significantly higher than expected according to an average 30 °C/km gradient.

The well was abandoned to a depth of 800 m, and water from the Cretaceous aquifer was used for the swimming pool till 1973. In 1982, the geothermal well was taken into production. In 1985, the system was extended by the Flemish Association for Geothermal Systems with the aid of SCK•CEN.

4. The late 1970's to mid-1980's

Renewed interest in the exploitation of geothermal resources in the late 1970's and early 1980's led to several projects targeting the Lower Carboniferous Limestone Group, funded by European Community programs DG XII and DG XVII. Based on the temperature maps of Legrand (1975), it became possible to better evaluate the geothermal potential of various reservoirs in northern Belgium. Several geological formations show some potential, including sandstones of Late Carboniferous age (Neeroeteren Formation) and chalk deposits of Cretaceous age. However, with a minimum required temperature of 60 °C in mind for space heating and greenhouses, the Lower Carboniferous Limestone Group turned out to be the prime target (Vandenberghe & Bouckaert 1980).

Vandenberghe & Bouckaert (1980) discuss the potential of the Lower Carboniferous reservoir and present various aspects that play a role. These include not only the depth and temperature of the limestone strata, but also the occurrence of karstified zones near the top, their thickness and irregular distribution, and how hydraulic communication could be possible between karst voids and between permeable zones in the area due to compartmentalisation into fault blocks. They also mention the static water level and the flow rate that could be achieved when producing from this reservoir. Finally, they also discuss water composition (salt content and presence of H_2S). The insights presented are mainly based on the information obtained from the Turnhout well together with data from the Loenhout wells. The latter were drilled in the western part of the Campine Basin in the exploration for a subsurface gas storage facility in the Lower Carboniferous Limestone Group. Most of the data from Loenhout is unpublished, but they were available to the Geological Survey at the time. They confirm the regional occurrence of karstified zones in this stratigraphic interval. In addition, Vandenberghe & Bouckaert (1980) rely on seismic data acquired in the 1950's and 1960's, and more recently in 1978.

The work of Vandenberghe & Bouckaert (1980) was presented in the context of a new geothermal exploration project in the Meer-Hoogstraten area, organised by the regional economic development organisation G.O.M. Antwerpen (Province of Antwerp Regional Development Organization). The project intended to deliver geothermal heat to greenhouses in the vicinity, with a flow rate of 200 m^3/h during nine months of the year. This flow rate was estimated based on the results from Turnhout where a flow rate of 30 m^3/h was reached by airlift. Taking into account the required production during a project lifetime of 30 years and based on a net reservoir thickness of 30 m with 25 % porosity, it was thought the extent of the reservoir should be at least 5 km^2. Looking at the latest seismic data from the 1978 survey, the fault blocks in the Hoogstraten area were expected to meet these requirements.

The Meer well (BGD number 007E0205) was spudded in July 1980 and reached TD at 2,515 m in April 1981. The results of the well were published by Vandenberghe et al. (1988). Unfortunately, the well did not confirm the geological model and failed to reach the Lower Carboniferous Limestone Group. The main difference turned out to be the increased thickness of the mudstone interval of Westphalian and Namurian, unlike what was known in the area around Loenhout and Turnhout. As a result, the Lower Carboniferous Limestone Group is present only at much greater depth. The increased thickness of Upper Carboniferous formations is however comparable to what was encountered previously across the border in the Rijsbergen well (RSB-01), where roughly 1,500 m of Westphalian strata were found, on top of 1,600 m of Namurian sediments (source: www.nlog.nl).

The increase in thickness had not been recognised on the 1978 seismic data as the top limestone reflector was not picked correctly. This was subsequently confirmed by additional 2D seismic data acquired in 1980 in the border region between Belgium and the Netherlands. The interpretation of the 2D seismic data was reported by Vandenberghe (1984), focusing on a listric normal fault (Hoogstraten Fault) oriented roughly east–west. To the north of the fault, the thickness of the Namurian strata rapidly increases (Fig. 5). This is in line with the observations in the Meer well, where at least 280 m of late Namurian sediments are present (Vanden-

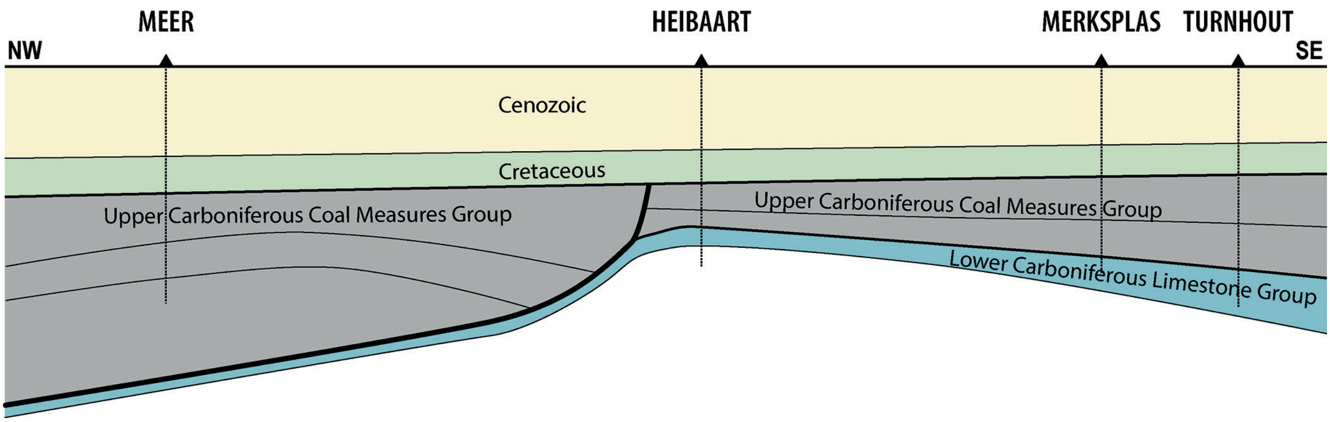

Fig. 5: Schematic SE–NW cross-section through the northern part of the Belgian Campine Basin illustrating the rapid thickening of the Namurian strata north of the Hoogstraten listric fault, based on the interpretation of seismic data from the 1980 survey in the Hoogstraten area by Vandenberghe (1984). This coincides with a deepening of the Lower Carboniferous Limestone Group. The location of wells has been projected onto the section. The position of the cross-section is indicated in Fig. 4.

berghe et al. 1988). The interpretation of seismic data and their correlation with stratigraphic layers encountered in the well was made using VSP and checkshot data, in addition to synthetic seismograms based on sonic log data (Vandenberghe et al. 1988).

Based on further mapping of the top of the Lower Carboniferous Limestone Group in the northern part of the Campine Basin (Dreesen et al. 1987), a second attempt was made to develop a geothermal project in the region. The new project location was positioned more to the south, near Beerse and Merksplas. Potential heat consumers were also identified in the vicinity. These consisted of the Merksplas penitentiary and a greenhouse development area. The first well, known as the Merksplas-Beerse well (BGD number 017W2065), was drilled in 1983, reaching a TD of 1,761 m. Results of the first well were published by Vandenberghe et al. (2000). The project was suspended due to a productivity lower than expected in combination with changing economic conditions (decreasing oil prices). At first, a reinjection into the Cretaceous aquifer at 800 m depth was studied (semi-doublet system), reducing the drilling costs by a factor of 3 compared to a reinjection well into the Lower Carboniferous Limestone Group (Lie et al. 1988). This well was drilled in 1987 (BGD number 017W0280). In the end, the project was abandoned altogether due to administrative hurdles, difficulties in securing finances and the withdrawal of heat demanders in the vicinity of the well.

The initial Merksplas-Beerse well encountered the top of the Lower Carboniferous Limestone Group at a depth of 1,630 m, but only penetrated the top part of the limestone sequence. Vandenberghe et al. (2000) described the presence of fractured reservoir zones from 1,630 to 1,656 m and from 1,739 to 1,747 m depth. These were identified using dip meter logs and the changes in drilling rate (ROP). Production tests reveal a productivity index of 5.4 m^3/h per bar (at a flow rate of 73 m^3/h), with the longest test phases pointing to a permeability of 780 to 1,945 mD. Reinjection was more difficult, with an injectivity index of 3.7 m^3/h per bar and a high skin factor. A production temperature of 70 °C was reached at the wellhead. The tests also allowed analysing water samples, indicating a high salinity of 120–148 g/l, mainly NaCl. Analysis reveals the water is radioactive, caused by the presence of ^{226}Ra (74 Bq/l) and ^{222}Rn (22 Bq/l). Moreover, gas is dissolved in the water (0.7–1.6 m^3/m^3), mainly CO_2 (83–93 $\%_{vol}$), but also N_2 (2–11$\%_{vol}$) and CH_4 (3–7$\%_{vol}$).

In the same timeframe (1985–1986), but outside of the Campine Basin, three wells were drilled into the Lower Carboniferous Limestone Group, in the vicinity of Valkenburg (the Netherlands). Here, the Lower Carboniferous Limestone Group is encountered in the range between 200 and 380 m depth. The wells have produced warm water for the local spa (Thermae). Data on the reservoir characteristics have been published by Krings & Langguth (1987). They mention a temperature of 24.4 °C and a TDS content of 3.5 g/l (mainly NaCl). The published hydraulic conductivity values would be equivalent to an intrinsic permeability in the range of 2,000–3,000 mD. Permeability is related to strata-bound karstification.

5. The late 1980's to early 2000's

No new deep geothermal initiatives were started in the Campine Basin after the Beerse-Merksplas projects. Interest in the use of geothermal energy remained, however, at a lower and scientific level. This is demonstrated by publications of Vandenberghe & Fock (1989) on temperature data and temperature maps in Belgium, and of Berckmans & Vandenberghe (1998) on the potential of geothermal energy in Belgium. The latter examined the geothermal potential of various reservoirs in the Belgian Campine Basin and calculated the amount of heat that could potentially be extracted from each reservoir. The highest recoverable amounts were derived for the reservoirs of the Lower Carboniferous Limestone Group and the Triassic sandstones. These studies were carried out in the framework of European Community efforts.

6. The late 2000's and 2010's

Interest in the use of deep geothermal energy in the Campine Basin renewed in the late 2000's, in the context of a search for sustainable sources of heat in general. In 2006, new geothermal projects were launched in the Netherlands, providing heat to greenhouses. The first projects were targeting reservoirs already known from previous oil and gas exploration (e.g. Cretaceous sandstone). From 2008 on, studies analysed the potential of the Lower Carboniferous Limestone Group as a geothermal reservoir in Horst a/d Maas, north of Venlo (the Netherlands). The projects near Venlo strongly built on the results of the Belgian geothermal projects discussed above. The first project by Californië Wijnen Geothermie (CWG) was a cooperation between a greenhouse company (Wijnen Square Crops) and the greenhouse area development company (Grondexploitatiemaatschappij Californië BV). Based on additional 2D seismic data acquired in 2009, the project targeted zones of increased permeability along the Tegelen fault zone in combination with karstified zones near the top of the formation. The Tegelen Fault forms part of the fault system on the eastern margin of the Roer Valley Graben, and seismic data reveal it has been active until recent times. The fault zone was selected as a target as there was a possibility that broken up zones (damage zone) could still hold significant permeability, not destroyed by later mineral precipitation. The first (production) well CAL-GT-01 was drilled in 2012 and was very successful. It reached the top of the limestone sequence at 1,635 m MD (Measured Depth), equivalent to 1,486 m TVD (True Vertical Depth). Total losses of drilling fluid were encountered from 1,735 m MD on, and well logging (caliper) indicated the presence of cavities in the interval down to 1,800 m depth. Further mud losses occurred around 2,330 m MD, where the Tegelen Fault was expected. Well TD was called at 2,730 m MD (2,510 m TVD), within a sandstone section later interpreted as the Devonian Evieux Formation. Production tests on the lower zone around 2,330 m MD indicated a flow rate of more than 240 m^3/h was feasible, with a productivity index in the order of 50 m^3/h per bar. Water was produced with a temperature above 80 °C at the pump and a TDS of 78 g/l. The injection well CAL-GT-02 was deviated away from the fault zone and targeted only karstified zones below the top. The Lower Carboniferous Limestone Group was found at 1,386 m MD (1,224 m TVD), with well TD at 1,694 m MD. Permeable zones were present close to the top of the reservoir, but no well test data have been published. An additional well was drilled in 2012–2013 (CAL-GT-03), before the geothermal site was put into operation. Production testing on CAL-GT-03 with flow rate up to 125 m^3/h pointed to a productivity index between 4.5 and 7 m^3/h per bar.

A second geothermal project materialised in the same greenhouse development area, this time involving other greenhouse companies (Californië Lipzig Gielen Geothermie – CLG). The doublet wells (CAL-GT-04 and -05) were drilled in 2015–2016, with a setup similar to the wells in the original project. Data and reports are available online from www.nlog.nl (Laenen & Broothaers 2016a, 2016b). CAL-GT-04 reached the top of the Lower Carboniferous Limestone Group at 1,818 m MD (1,577 m TVD below ground level), with TD at 3,038 m MD (2,586 m TVD). A production test was carried out with a maximum flow rate of 370 m^3/h. Productivity varied between 19 and 29 m^3/h per bar. Temperature of the water at the pump inlet rose to almost 80 °C, with a TDS of 85 g/l. CAL-GT-05 was drilled till 2,433 m MD (2,004 m TVD), entering the reservoir at 1,540 m MD (1,357 m TVD). A short production test was done, allowing water samples to be taken (TDS 61 g/l). Temperature measurements were not reliable due to the duration of the test and the low flow rate. Production was followed by an injection test up to 250 m^3/h, with injectivity index around 4 m^3/h per bar.

Several wells encountered mud losses during drilling, indicative of permeable (karstified) zones just below the top of the formation. Wells CAL-GT-01 and CAL-GT-04 also found high permeability zones near the Tegelen fault zone. Neither of these projects is currently operational: the CWG project was suspended in spring 2018 as it was no longer allowed to inject into CAL-GT-03, the CLG project was suspended after seismicity occurred in late August and early September 2018.

Almost in parallel, new estimates were made of the geothermal potential in the border area between Belgium and the Netherlands (GEOHEAT-APP 2014; Loveless et al. 2014). The re-assessment considered potential reservoirs between 500 and 4,000 m depth and pointed toward a geothermal resource for combined heat-and-power production in the deeper parts of the Campine Basin. In order to explore this potential, VITO started a geothermal project in the region between Turnhout and Mol. The first objective of the project was to investigate the geothermal characteristics of the Lower Carboniferous Limestone Group at a depth of 3,000 m or more. In case the characteristics would point towards the presence of a developable geothermal resource, VITO intended to build a geothermal plant to evaluate the economics of geothermal heat and power production in the Campine area. After an evaluation of available geological data and a new regional seismic survey, a prospect was defined, and a drilling location found on the Balmatt brownfield site, near VITO's offices. The idea was not only to provide heat to an existing heating network, but to demonstrate the technical, economic and environmental feasibility of developing a geothermal plant in the Campine Basin.

In the past, several exploration surveys have been carried out in the Campine Basin. In the northwestern part of the basin, exploration occurred in the framework of subsurface gas storage in the Lower Carboniferous limestone. Seismic surveys in the southeastern 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 in the area between Mol and Herentals. 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. Previous assumptions estimated the depth of the top of the Carboniferous Limestone Group between 2,500 and 3,500 m. The results of the survey confirmed the geological model and depth estimations. The top of the Carboniferous Limestone Group deepens towards the northeast, reaching a depth around 2800 m below surface near the project location (Fig. 6).

The first well (Mol-GT-01) was spudded in September 2015 and drilled vertically (Fig. 7). A vertical well path was chosen to limit complexity at this stage and also offered the possibility of evaluating the impact on permeability of a fault (and damage zone) near the top of the Lower Carboniferous strata. The fault was detected below the project site based on seismic exploration. This well was financed by VITO and Flanders Innovation & Entrepreneurship (Agentschap Innoveren & Ondernemen). In addition, ONDRAF/NIRAS co-funded the drilling to obtain data from the Cenozoic section. As the top of the reservoir was located 370 m deeper than expected, drilling technical issues required the drilling of a side-track Mol-GT-01-S1, reaching the top of the Lower Carboniferous Limestone Group at a depth of 3,175 m (Bos & Laenen 2017). Well TD was called at 3,610 m depth, still within the limestone. 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. Well testing up to a flow rate of 140 m^3/h indicated a productivity index of 4 to 5 m^3/h per bar, with a production temperature up to 128 °C (Bos & Laenen 2017). The formation water proved to have a salt content of 165 g/l (mainly NaCl), with a dissolved iron content of 800 mg/l. The gas content was also elevated (2–2.5 Nm^3/m^3). The main constituent is CO_2 (76–77%$_{vol}$), with N_2 (2–4%$_{vol}$), CH_4 (8–9%$_{vol}$) and H_2 (11–12%$_{vol}$) also present.

A second well (Mol-GT-02) was spudded in March 2016 and deviated towards the northeast, parallel to one of the seismic lines acquired in 2010. The target was an area where the reservoir was not affected by faults to minimise the risk of fault reactivation when injecting 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 3,300 m TVD, again deeper than expected (Bos & Laenen 2017). TD was reached in July 2016 at 4,341 m MD (or 3,830 m TVD). Injection testing revealed an injectivity index of 1.5–2 m^3/h per bar.

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 heating grid would impose a return temperature between 65 and 80 °C, depending on the outdoor temperature, 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. As the two wells did not reach the base of the Carboniferous Limestone Group, VITO planned to drill a third well that would cover the entire limestone sequence and would explore the Devonian sandstones that were expected to underlie the Lower Carboniferous. Budget for well Mol-GT-03 was made available as it was expected that the well could supply heat for new district heating grids in Dessel and Mol. Mol-GT-03 was spudded in December 2017.

The well 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 (Broothaers et al. 2019). The top of the Lower Carboniferous Limestone Group was reached at a depth of 3,643 m MD (or 3,142 m TVD). Mol-GT-03 became the third well in the Belgian part of the Campine Basin to reach the base of the limestone sequence, which was found at 4,654 m MD or 3,992 m TVD (base Vesdre Formation). TD was called at 4,905 m MD (4,235 m TVD) in July 2018. Initial well tests pointed to productivity far lower than anticipated. Production could not be initiated during a nitrogen lift test, whereas a short injection test revealed an injectivity of only 0.2 m^3/h per bar. As a consequence, Mol-GT-03 was classified as a dry well.

In contrast to earlier geothermal wells into the Lower Carboniferous carbonates in the Campine Basin, the project in Mol, which is situated in the deeper part of the basin, did not aim for enhanced permeability in karst zones, but was rather targeting faulted and fractured zones. As the first well (Mol-GT-01) was targeted at a fault zone directly below the well site, the permeability that was encountered is seen as enhanced due to fracturing in the fault zone. The main zone where mud losses occurred during drilling of Mol-GT-01 is present around 3,280 m MD. In an attempt to locate the points of inflow, a spinner-flowmeter was run after the third production test. The flowmeter however was blocked twice by fines and iron flakes. Changes in the temperature log that was run at the same time however provide information about the main points of inflow. Most of the inflow occurs between 3,280 and 3,420m MD, corresponding with the main loss zones during drilling. The top of the interval coincides with a fault zone. Around 3,284 m depth the FMI log shows an increase in bedding dip followed by a decrease in dip. This change in bedding dip is interpreted as a fault cusp (van der Voet et al. 2020b). The third well targeted the same fault zone, and a comparable productivity was anticipated. However, no mud losses were encountered during drilling and well tests indicate a low permeability in well Mol-GT-03. This reveals significant differences in permeability even within the same fault zone. It should be noted that no 3D seismic data were available to accurately trace faults and fault segments. Hence, uncertainty exists in structural interpretations due to limitations of 2D seismic data (Broothaers et al. 2019).

The observations suggest the origin and preservation of permeability along the fault zone, and in the reservoir in gen-

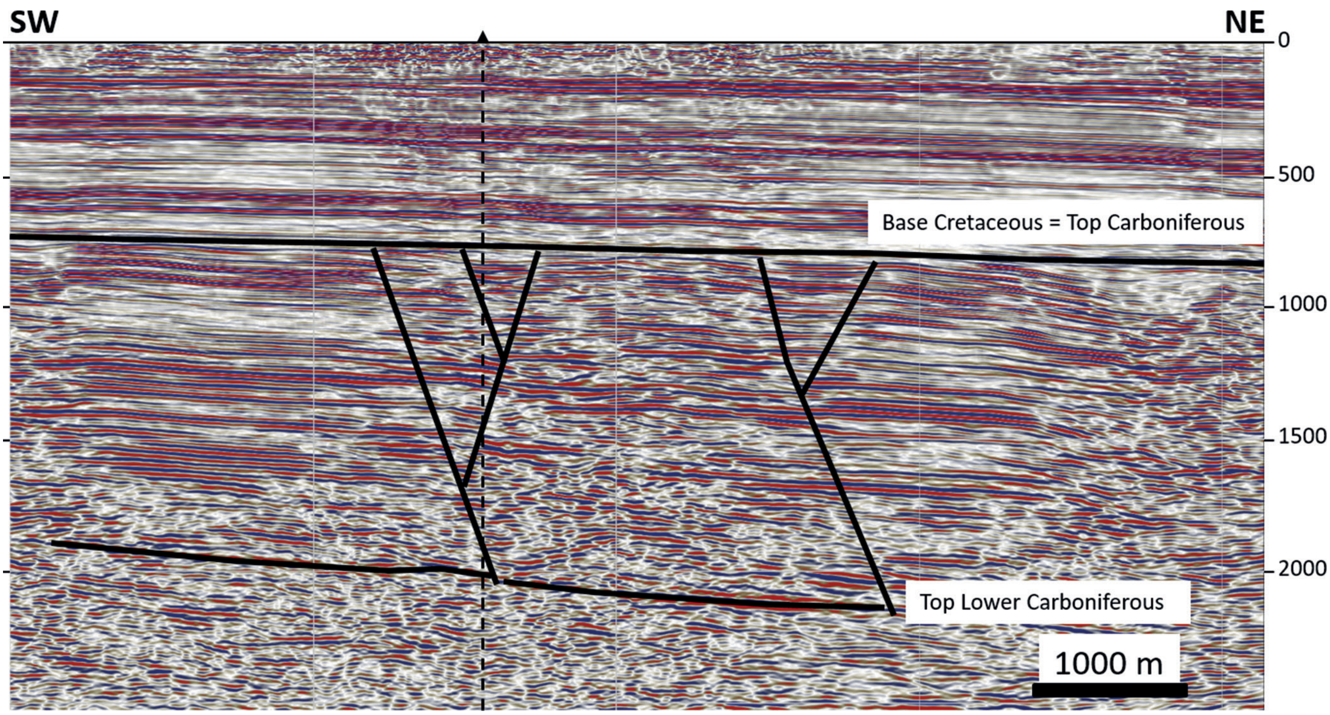

Fig. 6: Part of seismic section MH1004 close to the Balmatt site in Mol (projected onto the section, dashed line). The interpretation of top Carboniferous and top Lower Carboniferous is shown, together with possible faults in the vicinity of the project location. The interpretation shown was made after drilling wells Mol-GT-01 and Mol-GT-02. The vertical scale is in milliseconds TWT.

eral, is a complex interplay between different processes. Several factors can be envisaged to have played a role, including (1) the structural setting and the presence of faults and their orientation within the current stress field (slip and dilation tendency; e.g. Ferrill & Morris 2003), (2) the presence of fractures and their relation to the mechanical properties of the strata, (3) the stratigraphic succession and depositional environment, (4) the diagenetic processes that impacted the reservoir rocks, and (5) the presence of gas (although in solution). The contribution of the various factors and their interplay is not well understood yet.

The differences between the three wells drilled at Balmatt spurred further research, at first focusing on structural aspects (Broothaers et al. 2019). Uncertainty in fault interpretation on the 2D seismic data, as well as on the lateral correlation of faults remained. Therefore, Broothaers et al. (2019) evaluated indications for the presence of faults in the wells, based on observations during drilling (changes in ROP, mud losses), differences in mineralogy of the cuttings, and analysis of marker beds pointing to changes in overall bedding orientation and/or interval thickness. This approach seems useful for fault identification in the Upper Carboniferous strata, but marker bed analysis did not confirm large faults within the Lower Carboniferous reservoir section. Correlation of faults between wells remained difficult and more work should be done to finetune the structural model around the site. Van der Voet et al. (2020b) analysed the occurrence of fractures and their possible relation to faults in Mol-GT-01, based on FMI log data. In addition, van der Voet et al. (2020a) also analysed the FMI log in Mol-GT-03. They identified seven possible fault intersections. The intersection with highest certainty is situated at 4,352 m MD. The first analysis of the sedimentary succession (lithology, mineralogy) was also started (Broothaers et al. 2020). Petrographic analysis of core samples from Mol-GT-01 confirm the presence of deposits in a restricted environment, as suggested by well log data (spectral gamma). Analysis of the cuttings mineralogy reveals the presence of fluorite and delicate anhydrite crystals, suggesting active fluid circulation.

Fourteen periods of test operation were carried out between late 2018 and mid-2019, with production from Mol-GT-01 and injection into Mol-GT-02. In total, roughly 50,000 m^3 of geothermal brine was produced (and reinjected) and 3,200 MWh of heat was extracted. The results from the wells together with the start-up phase of the project pointed out the presence of several technical challenges, including the presence of natural radioactivity (Vasile et al. 2017), free gases in the installation, solids in the brine, and induced seismicity.

Due to the composition of the brine, the gas content and composition (mainly CO_2 and CH_4), both corrosion and scaling can occur in the system (Pauwels et al. 2021). This depends on the position in the system, as pressure and temperature conditions vary strongly, in combination with chemical changes due to degassing of CO_2. The impact of corrosion and scaling is controlled by the use of inhibitors, and verified by inspection of system elements and analysis of material in the filters.

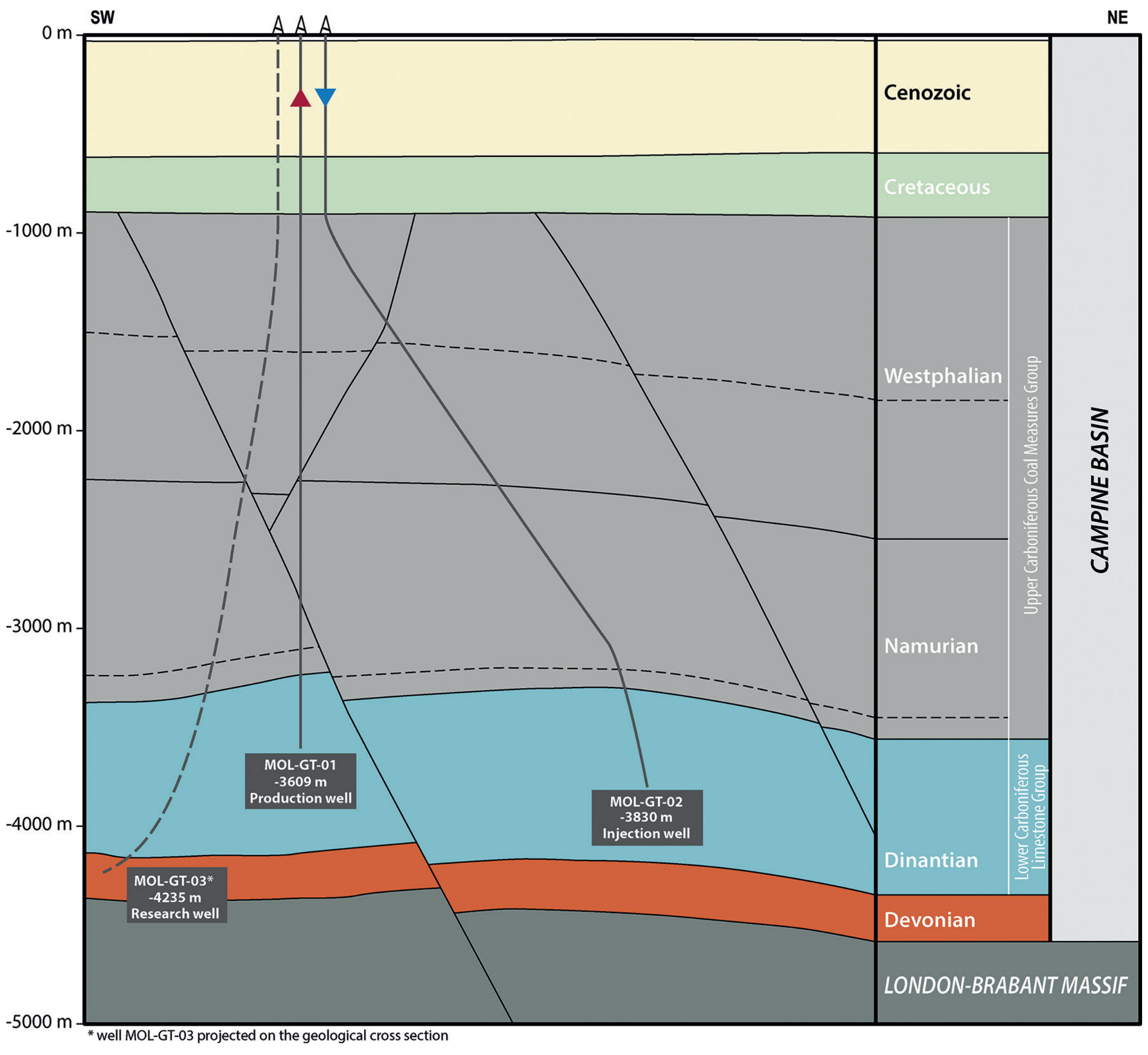

Fig. 7: Cross-section showing the local geology at the Balmatt geothermal site in Mol, and the well trajectories. Mol-GT-03 is projected onto the section, its relation with respect to faults is therefore not entirely correct.

In addition, the high CO_2 and CH_4 content has an impact on the operational pressure of the surface installations (e.g. filters and heat exchangers), which should be high enough (above bubble point) to make sure no gas comes out of solution. Degassing of CO_2 has a significant impact on the pH and chemical equilibria within the brine and increases its scaling potential. Moreover, degassing and venting of CO_2 into the air was not considered a viable option from an environmental point of view. The start-up phase indicated that a working pressure of 36–39 bar was not sufficient, and system components were replaced to allow an increase to 55 bar.

As water is extracted from a limestone reservoir, it was expected that the total suspended solids were rather limited. However, it appeared that the lifetime of filter units was only several hours, initially, later-on increasing to days. Roughly 25 mg/l of solids was captured. Analysis revealed galena and halite as the main phases with minor amounts of laurionite, witherite, rhodocrosite and sylvite (Pauwels et al. 2021).

The occurrence of radioactive elements in the formation water from the Lower Carboniferous Limestone Group was already mentioned by Vandenberghe et al. (2000). The brine produced from well Mol-GT-01 contains naturally occurring radioactive materials (NORM; Vasile et al. 2017). Analysis of radioactive elements in the samples taken directly from the loop pointed to an activity of 95 to 110 Bq/l for ^{226}Ra, and around 8.5 Bq/l for ^{228}Ra (Vasile et al. 2017). Consequently, the supervisory authorities (Federal Agency for Nuclear Control – FANC) need to be informed and licences are required. People potentially coming into contact with the brine, with precipitates and with components possibly contaminated by NORM need to follow procedures and wear protective equipment when performing their duties. Waste also needs to be disposed of according to regulations.

Another key challenge for the geothermal operations at Balmatt is the occurrence of seismicity. 2D seismic data did not reveal a fault near the injection well (hence the location chosen). The fracture pressure of the rock and the possible pressure impact from operations on faults in the vicinity was evaluated prior to drilling and testing, for different permeability scenarios. No slip or dilation tendency analysis was carried out. Seismicity was first detected during the initial testing phase of the wells in 2016 by borehole seismometers managed by the Royal Observatory of Belgium. This led to the installation of a seismic monitoring network made up of seven borehole stations and the setup of a traffic light system in 2018. Seismic events were detected during the start-up phase between late 2018 and mid-2019, with the largest event (M_L 2.2) recorded in June 2019. This occurred after the longest test period, but also three days after operations had been suspended abruptly. Depth of the events is in line with the reservoir depth, but there is still some uncertainty on the precise position of the seismic events, with the event cloud either centred around the injection well or slightly to the west of it. Seismicity appears in several dense spatial clusters. The total event cloud has an elliptic shape, with the long axis oriented NW–SE, parallel to the regional normal faults. However, focal mechanisms seem to suggest strike-slip events along NNE–SSW or WNW–ESE oriented fault planes, consistent with the regional stress field. Analysis of the seismic events is yet to be published. Further research is required to obtain a better understanding of the seismological behaviour of the subsurface in Mol. For this purpose, the monitoring network has been extended to 12 borehole stations in early 2021.

In addition to the extended seismometer network, a number of changes were implemented including e.g. a new production pump for a lower flow rate, the increase in operational pressure, a pressure sustaining system on the injection well and an injection tubing. After a suspension of more than 18 months, the Balmatt geothermal site has resumed operations in spring 2021.

Even before VITO's project in Mol was realised, Janssen Pharmaceutica developed plans for a geothermal site on their research campus in Beerse. Geological analysis showed the feasibility of a geothermal doublet for this campus, which is located in between the older wells of Merksplas-Beerse and Turnhout. Plans materialised in December 2019 when the first well (Beerse-GT-02) was spudded, intended for injection. The well reached TD at a depth of 2,725 m (2,052 m TVD). The production well Beerse-GT-01 was spudded in February 2020 and was terminated at 2,558 m (2,235 m TVD), again within the Lower Carboniferous Limestone Group. The wells were tested in the summer of 2020, and positive results were announced by Janssen Pharmaceutica in December 2020, with a temperature of 85 °C. The company is currently working on the surface installations and heating network and intends to bring the geothermal system into operation in fall of 2021. The aim is to reduce CO_2 emissions by 30 %. Detailed results of the wells have not been published yet.

The geothermal project in Beerse revealed another challenge for the development of geothermal energy in the Campine Basin, which is the possible interference with the subsurface gas storage site in Loenhout. This facility is operated by Fluxys in the same reservoir and is located less than 10 km from the site in Beerse. Pressure data from the gas storage site and from nearby monitoring wells, in combination with test data from Beerse, should be analysed to detect and quantify interference. This would provide valuable input for reservoir models.

7. 2020 and beyond

The future of deep geothermal energy in the Campine Basin involves several projects. There is the Balmatt project in Mol that started-up again in spring 2021, and it is expected that the doublet in Beerse will become operational in fall 2021. In addition, HITA, a local development company, is exploring the potential for deep geothermal energy in several locations in the area (Turnhout, Olen-Herentals, Lommel). HITA is analysing the feasibility of geothermal projects and closely cooperating with interested local authorities and potential heat consumers, either industry or district heating. Its first development is near Turnhout, where HITA has carried out seismic exploration in 2020, with the aim to start drilling in 2022. There the local hospital (AZ Turnhout) and a planned district heating network could be supplied with geothermal heat. In 2020, HITA has completed another seismic survey in the area between Olen and Herentals, where they also target the Lower Carboniferous Limestone. They plan further exploration in 2021 near Lommel.

8. Conclusions and challenges

The interest in deep geothermal energy in the Campine Basin in northern Belgium is not new, it looks back to a long history starting in the 1950's, and projects in the 1980's helped in collecting data and improving our knowledge of thermal conditions and hydraulic properties of the Lower Carboniferous limestone reservoir. The potential in terms of transmissivity and temperature was first revealed in Turnhout and subsequently confirmed in wells in the Loenhout area and in Merksplas-Beerse. However, productivity was not always as high as expected, indicating considerable variation in reservoir properties. The same wells also pointed out challenges for exploitation of the reservoir, like scaling and corrosion (high salinity and iron content). Furthermore, the Merksplas-Beerse well showed that gas is dissolved in the brine (mostly CO_2), and that the water contains naturally occurring radioactive materials. These challenges needed to be addressed in future projects, by careful selection of materials, the use of inhibitors, increased system pressure in surface installations, and/or procedures for handling NORM.

By the end of 2020, five deep wells were drilled and two doublet systems are expected to become operational (again) in 2021. Further research at the Balmatt site, in combination with the analysis of data from the Beerse geothermal wells, will also improve our understanding of the reservoir, how it performs, and where best to explore its potential. For a regional perspective over the Campine Basin, the insights from the geothermal wells should be combined with the regional geological model (Deckers et al. 2019) and any future updates.

However, not unlike the situation in other countries, the development of deep geothermal energy is faced with technical challenges. The main challenge now is the risk of induced seismicity, and several studies in different countries are aimed at better understanding the mechanisms leading to seismicity. VITO is setting up a research program on its geothermal site in Mol to analyse the seismological behaviour of the reservoir, to get a better view of the maximum magnitude that may occur and the frequency of events. These insights will help in better understanding the risks involved and how to mitigate them. In addition to scientific understanding, communication to stakeholders, authorities and to the general public are paramount for making the development of deep geothermal energy acceptable in the region. In this respect it should be mentioned that an update of the evaluation of the occurrence of natural and induced seismicity (seismic risk) is being carried out on behalf of the Flemish Government.

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