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THE MERKSPLAS-BEERSE GEOTHERMAL WELL (17W265) AND THE DINANTIAN RESERVOIR

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(7 figures and 7 tables)

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Abstract. The Merksplas-Beerse well (North Belgium) is a low-enthalpy geothermal production well targeting the Dinantian karstic limestones to a total depth of 1761 m. The presence of methane gas in these limestones generated a particular interest in this well. This paper describes the geological profile of this well and the Dinantian reservoir. The Namurian-Visean boundary at 1630 m is determined by the base of the dipmeter draping pattern in the radioactive Chokier shales (base of the Namurian) on top of the karstified Dinantian limestone. The stratigraphic composition of the transitional interval from Dinantian to Silesian correlates closely to the nearby Turnhout well. The two fractured intervals at 1630-1656 and 1739-1747 m respectively were identified in the Dinantian limestones. They are associated with siliciclastic sections in between pure limestones.

The reservoir water is a sodium chloride brine of about 74°C and at a pressure below the hydrostatic. The water is slightly radioactive because of the contact with the Chokier hot shales. A carbon dioxide gas with methane and nitrogen admixture is dissolved in the water. The gas liquid ratio at standard conditions is about one and the bubble point is around 200-400 psi at reservoir temperature. A long duration pumping test shows a high fracture permeability and a productivity index of 5.4 m3/h/bar with a productivity to injectivity ratio of 1.45.

KEYWORDS: Lower Carboniferous, Dinantian, geothermics, karst reservoir, natural gas, North Belgium

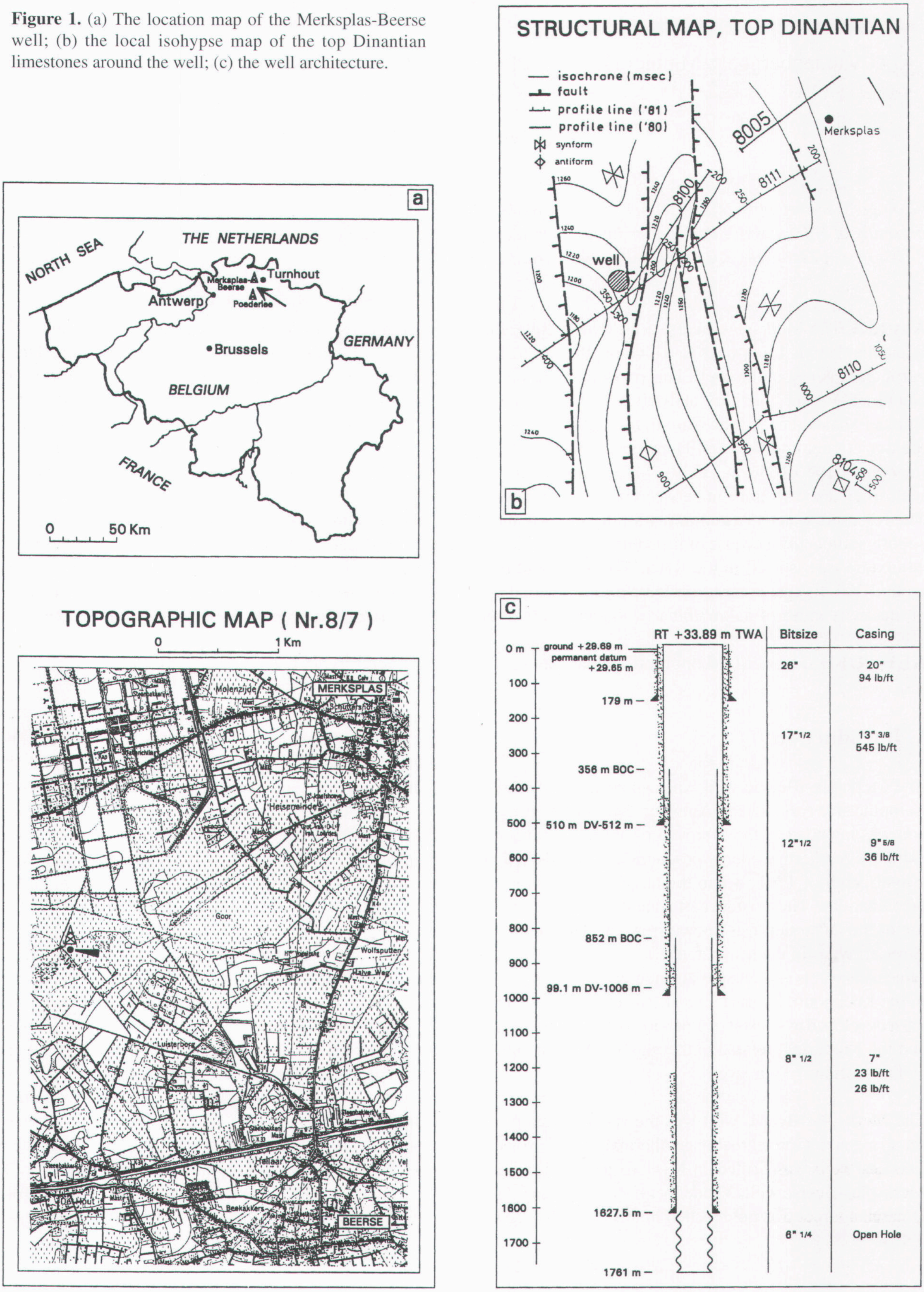
1. Introduction

The Merksplas-Beerse well was drilled in 1983 in the Campine area (province of Antwerp, Belgium, Figure 1) and was intended as the first well of a doublet for low-enthalpy geothermal energy production. It was drilled to a total depth of 1761 m into the targeted karstic top of the Dinantian. The existence of a karstic reservoir at the top of the Dinantian was known from the Turnhout and Heibaart wells in the same area (Bless et al., 1976). The same reservoir is exploited as an underground gas storage in the Loenhout-Heibaart area (Bless et al., 1981). The karst developed as a result of emersion between the Visean and the Namurian, related to the regional Sudetic uplift and a low relative sea level.

The Merksplas-Beerse well was the second attempt to set up a doublet low-enthalpy geothermal energy project. The first well was drilled in Meer to the north of the Merksplas-Beerse well (Vandenberghe et al., 1988). The Dinantian target was not reached in this well because of the well's location to the north of the Hoogstraten fault, which, unknown at that time, had downthrusted the Dinantian by several hundreds of meter along a listric shaped fault (Vandenberghe, 1984). The new Merksplas-Beerse location was selected based on the new geological map of the top of the Dinantian (Dreesen et al., 1987, Figure 1) and the proximity of potential users for the geothermal energy.

An extensive summary report and interpretation of all the drilling and testing activities, together with the technical reports are available from the files of the Belgian Geological Survey under well label 17W/265. The well is number 165 in the series of deep boreholes in the Campine Basin. The Lambert topographic coordinates are x = 181 937.769, y = 225 856.222 and the topographic height z = + 29.69 m TAW. The well head reference (KB) is + 4.2 m above the ground level, hence KB reference is + 33.89 m TAW. All depths given in this paper refer to this KB level. The final well architecture is also shown in Figure 1.

Figure 1. (a) The location map of the Merksplas-Beerse well; (b) the local isohypse map of the top Dinantian limestones around the well; (c) the well architecture.



2. The geology of the Merksplas-Beerse well

The well traversed the Cenozoic and Mesozoic sequences of the Campine basin before crossing into the Upper Carboniferous underneath the Upper-Cretaceous/ Westphalian unconformity. It then drilled through the Westphalian to its target in the Visean limestones.

2.1. The Cenozoic, Mesozoic and Upper Carboniferous

The correlation of the post-Paleozoic stratigraphy is based on drill cutting samples and on the geophysical wireline logs. A summary stratigraphic log for the Cenozoic and the Mesozoic is presented in Table 1. The top of the Upper Maastrichtian to Danian chalk arenite is situated at 693.5 m KB. The bottom of the Mesozoic consists of Campanian Zeven Wegen fine chalk followed by about 40 m of smectitic marl of the Campanian Vaals Formation. The unconformity between the Upper Cretaceous and the underlying Westphalian is recognised at 1005 m KB.

The interpretation of the Silesian stratigraphy is based on the geophysical well log signatures and on a comparison with the nearby cored Turnhout well (Delmer, 1962). The Silesian in the Merksplas-Beerse site and in the Turnhout site was correlated using seismic reflection profiles. The results of this stratigraphic interpretation of the Silesian are summarised in Table 2 and a detailed stratigraphic correlation with the Turnhout and Meer wells is given in Table 3.

Westphalian A Coal Measures form the top of the Silesian section 1005 m KB to 1297 m KB. Coal seams are present to a depth of 1045 m KB. The Namurian Andenne Formation is recognised from 1297 m KB to 1614 m KB. These two formations are part of the Northwest European paralic basin.

The Coal Measures are characterised by rhythmic siliciclastic sediments deposited on a rapidly subsiding low lying continental shelf. This shelf remains emerged most of the time and is interrupted by relatively few and short lived cyclic marine incursions which can be recognised as high gamma ray signatures on well logs. The structural dip from the dipmeter log varies generally from 5 to 10° with azimuths between 50 and 90°. Sedimentary cross bedding is present in the sandstone. This eastward dip coincides with the dip direction of the top of the Dinantian as mapped from seismic data (fig.1) (Dreesen et al., 1987).

The marine shales with high radioactivity at the base of the Silesian are assigned to the Chokier Formation (Alportian-Arnsbergian). They were deposited during the Namurian transgression over the underlying drowned Visean karst plain. Elsewhere the sediments which overlay or invade the karstic limestone morphology of the top of the Visean are also known to be radioactive (Legrand, 1957; Fransolet et al., 1974).

Reflectivity measurements on organic particles in the Paleozoic (Figure 2) show the expected general increase with depth, but anomalous high values in the hot shales of the Chokier Formations and about 100 m of sediments above these shales. Considering also the amount of radiogenic heat in these 'hot' formations, the anomaly might be caused by the mechanisms outlined in Hood et al. (1975), related to the burial history and the effect on the maturation.

2.2. The transition between the Namurian and the Visean

The exact determination of the Namurian-Visean boundary in the Campine area is made difficult by the presence of a lithological transition zone in between the typical siliciclastic Silesian and the typical Visean (Warnantian) limestones (Figure 3). The sequence from 1614 m KB to 1656 m KB contains both silicilastic and carbonate rocks. In addition the radioactive shales at the base of the Namurian are filling in the underlying karst features. The limestones below the base of the Namurian also show dissolution features (Dreesen et al., 1987).

The base of the Namurian is determined at 1630 m KB based on the wireline log response, especially the dipmeter information and from detailed lithological comparisons with the Turnhout well. The structural dip information provided by the dipmeter log provides the most conclusive evidence to determine the Namurian-Visean boundary. The dip plot displays a characteristic drape pattern in the formations from 1605 m KB to 1630 m KB (Figure 3). The structural dip increases gradually from regional dip to the stratigraphic dip of the local, irregular karst topography. This drape pattern is subdivided into several units separated by undoubtedly local faults which accommodate the shale mass over the irregular topography. The existence of this drape pattern indicates that the formations above 1630 m KB were deposited on top of a pre-existing karstic topography and at a time considerable later than the limestones, to allow for emergence and karstification.

The interpretation of the Namurian-Visean boundary at 1630 m KB depth is confirmed by the detailed lithological comparison between the Merksplas-Beerse and the Turnhout well (Figure 3). The latter well was extensively cored, but no wireline logs were run at the time. When the core lithology diagram from the Turnhout well and the petrophysical wireline analysis in the current well are lined up at the top of the pure limestones (1656 m

depth (m)	level	lithology, lithostratigraphy	time stratigraphy
0,0 - 47,0	+29,7- -13,1	Sands, clays, Campine Sand and Clay	Tiglian
47,0 - 65,0	-13,1- -31,1	Shelly sands, Lillo Formation	Plaisancian
65,0 - 121,0	-31,1- -87,1	Diest Formation	Upper Miocene
65,0 - 107,0	-31,1- -73,1	Medium glauconitic sands	
107,0 - 121,0	-73,1- -87,1	Fine glauconitic sands, Dessel Sands	
121,0 - 169,0	-87,1- -135,1	Glauconite rich sands, Berchem Formation	Lower Miocene
169,0 - 305,0	-135,1- -271,1	Boom Clay Formation	Rupelian
305,0 – 318,5	-271,1- -284,6	Ruisbroek Sands (Zelzate Formation)	Rupelian
318,5 - 380,0	-284,6- -346,1	Maldegem and Zelzate Formations	
318,5 - 323,0	-284,6- -289,1	a4	Watervliet Clay
323,0 - 328,5	-289,1- -294,6	s3	Bassevelde Sands
Upper Eocene			
328,5 - 330,5	-294,6- -296,6	a3	Onderdijke Clay
330,5 - 341,1	-296,6- -307,6	s2	Buisputten Sands
341,5 - 355,0	-307,6- -321,1	a2	Zomergem Clay
355,0 - 360,0	-321,1- -326,1	s1	Onderdale Sands
360,0 - 380,0	-326,1- -346,1	a1	Asse and Ursel Clay
380,0 – 397,5	-346,1- -363,6	Wemmel Sands (Maldegem Formation)	Lutetian
397,5 – 435,0	-363,6- -401,1	Lede, Brussel, Panisel Sands	Middle Eocene
435,0 - 576,0	-401,1- -542,1	Ieper Group Clays	Lower Eocene
576,0 - 676,5	-542,1- -642,6	Landen Group	Paleocene
576,0 - 596,0	-542,1- -562,1	Lagoonal clay, with shells	
596,0 - 645,0	-562,1- -611,1	Sandy clay	
645,0 - 676,5	-611,1- -642,6	Marly clay	
676,5 - 693,5	-642,6- -659,6	Heers Formation	Paleocene
676,5 - 689,0	-642,6- -655,1	Gelinden Marl	
689,0 - 693,5	-655,1- -659,6	Glauconitic Orp Sand	
693,5 - 724,0	-659,6- -690,1	Maastricht and Houthem Calcarenites	Upper Maastrichtian / Danian
791,0 - 882,0	-757,1- -848,1	Upper Gulpen Chalk (Vijlen-Lanaye, Beutenaken)	Maastrichtian
882,0 - 916,0	-848,1- -882,1	Beutenaken Marl	Lower Maastrichtian
916,0 - 966,0	-881,1- -932,1	Lower Gulpen (Zeven Wegen) Chalk	Campanian
966,0 - 1005,0	-932,1- -972,1	Vaals Formation, Herve Marl	Campanian

Table 1. Cenozoic and Mesozoic stratigraphy of the Merksplas-Beerse well.

	chrono	litho	
top 1005 m			1005 m
	Westphalian A stage	Chatelet Fm	
		Floriffoux Mbr	1214 m
		Ransart Mbr	
			1297 m
	Yeadonian		
1390 m			
	Marsdenian		
1442 m		Andenne Fm	
	Kinderscoutian		
1607 m			1614 m
	Alportian – Arnsbergian	Chokier Fm	
1630 m			1630 m
	Pendleian ?	Viesville Fm ?	
1643 m			1643 m
	Warnantian		1656 m
end 1760 m			1760 m

Table 2. The Carboniferous stratigraphy of the Merksplas-Beerse well.

Horizon or marker level	Merksplas	Turnhout	Meer
Top Carboniferous	1005 m	1000 m	1186 m
Quaregnon (= base Westphalian B)	—		(1178 m)
Wasserfall (= limit Westphalian Al/A2 base Mons Member)	—	1132 m	1660 m
Girondelle 6 (= base Grande Stampe Stérile)	—	1339 m	1869 m
Girondelle 3 (base coal bearing facies)	1091 m	1412 m	1946 m
Lairesse M.B.	1157 m	1495 m	2019 m
Finefau Nebenbank M.B. (= base Floriffoux Member)	1214 m	1546 m	2075 m
Sarnsbank M.B. (= base Westphalian, base Ransart Member)	1297 m	1668 m	2237 m
Hauptflöz M.B.	1361 m	1777 m	—
Nivoie M.B. (= base Yeadonian)	1390 m	1795 m	—
R. gracile - R. bilingue (= base Marsdenian)	1442 m	1848 m	—
unnamed M.B.	1493 m	1955 m	—
unnamed M.B.	1534 m	2005 m	—
top Rlb sequence, top predominantly marine facies in Turnhout	1590 m	2078 m	—
Base Rlb zone (= base Kinderscoutian)	1607 m	2138 m	—
Top radioactive shales, ‘H2c’ (= top Alportian)	1614 m	2142 m	—
Dinantian-Namurian boundary (= base Arnsbergian)	1630 m	2162 m	—
Base radioactive shales, top carbonates	1643 m	2175 m	—
Top massive limestone	1656 m	2195 m	—

Table 3. Correlation between the Silesian strata in the Turnhout, Meer and Merksplas-Beerse wells

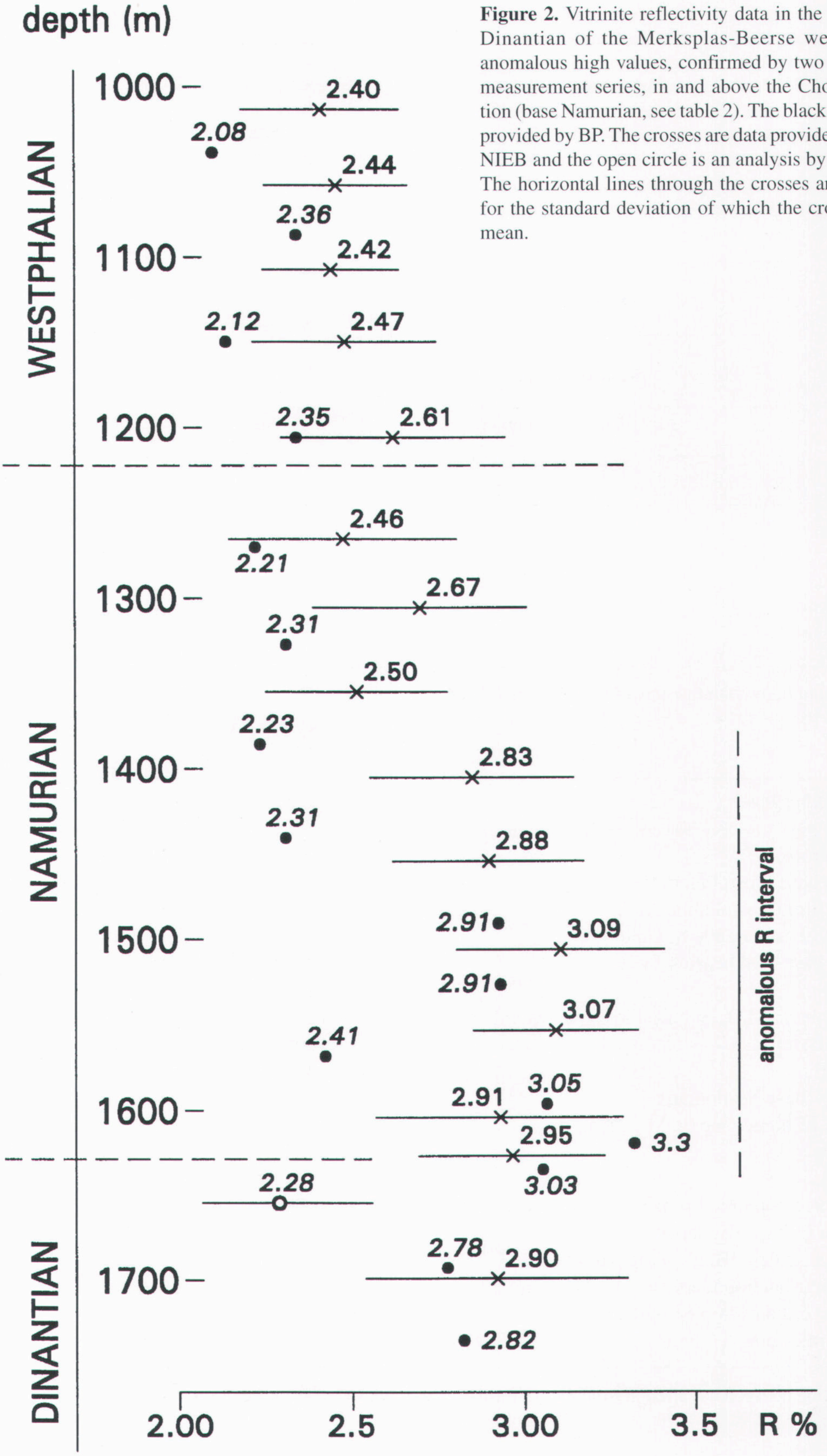


Figure 2. Vitrinite reflectivity data in the Silesian and Dinantian of the Merksplas-Beerse well; note the anomalous high values, confirmed by two independent measurement series, in and above the Chokier Formation (base Namurian, see table 2). The black dots are data provided by BP. The crosses are data provided by INIEX-NIEB and the open circle is an analysis by KFA Jülich. The horizontal lines through the crosses are a measure for the standard deviation of which the crosses are the mean.

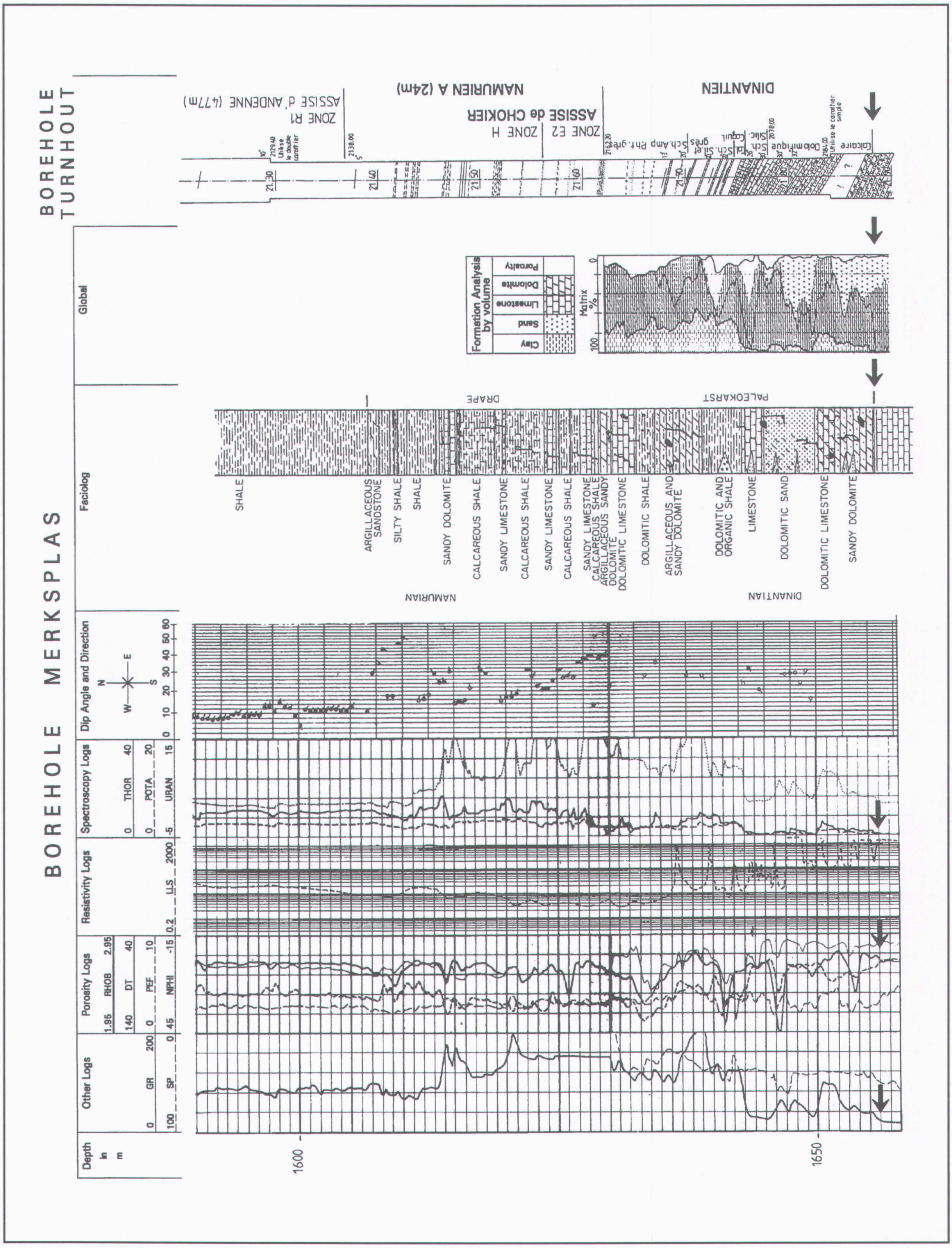


Figure 3. The wireline logging data and the petrophysical interpretation (faciolog and global analysis) of the Merkplas-Beerse well compared to the core lithology and stratigraphic interpretation of the Turnhout well. As both wells are lined up with respect to the top of the compact and homogeneous Warnantian limestone, recognisable in both wells (arrows at the bottom of the figure), the existing stratigraphical interpretation of the cored Turnhout well (Delmer, 1962) can be used for the Merksplas-Beerse well. Note in particular how the base of the drape in the dipmeter record at 1630 m depth in the Merksplas-Beerse well corresponds to the Namurian-Dinantian boundary as identified in the Turnhout well (see also table 3).

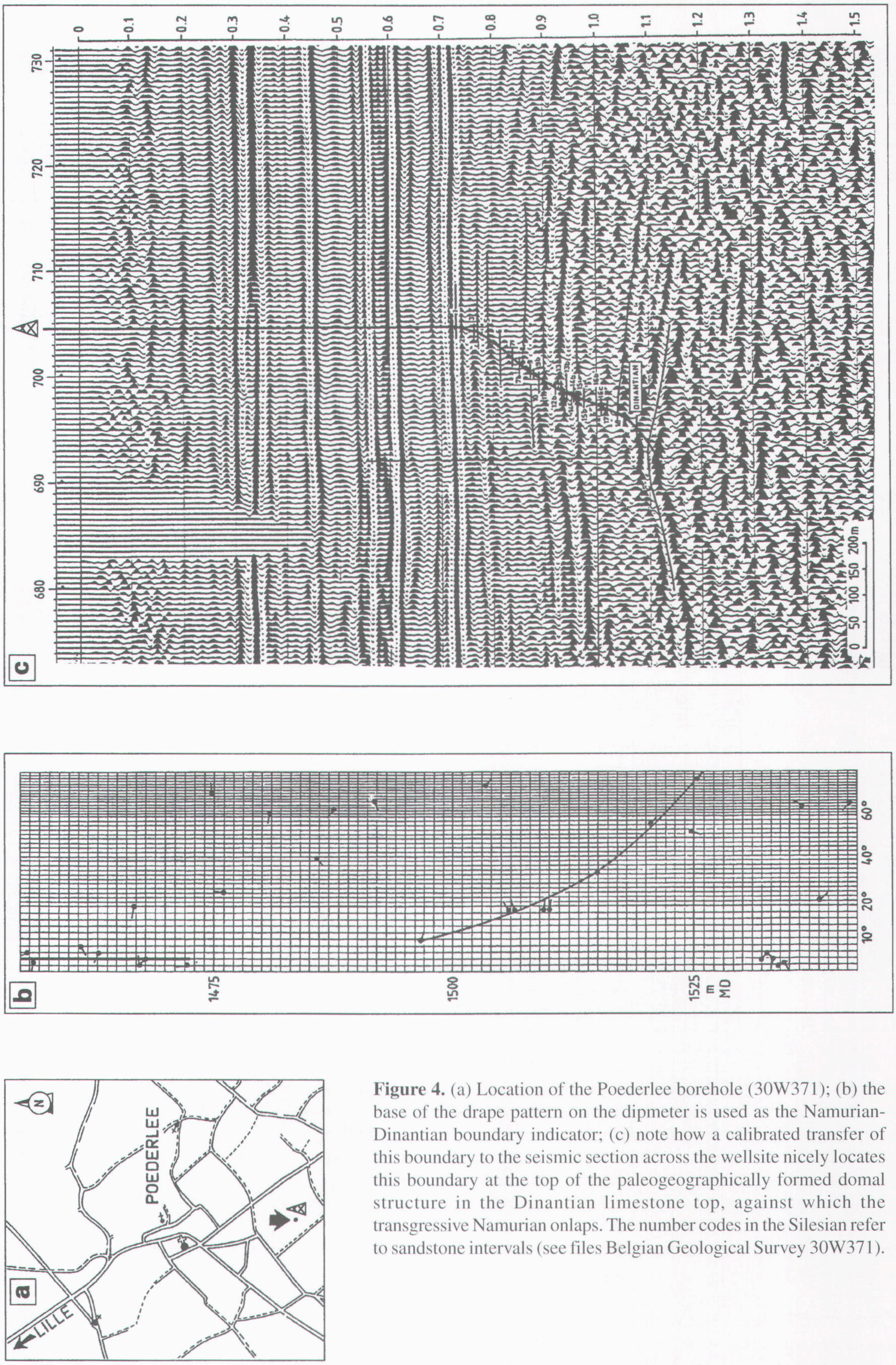


Figure 4. (a) Location of the Poederlee borehole (30W371); (b) the base of the drape pattern on the dipmeter is used as the Namurian-Dinantian boundary indicator; (c) note how a calibrated transfer of this boundary to the seismic section across the wellsite nicely locates this boundary at the top of the paleogeographically formed domal structure in the Dinantian limestone top, against which the transgressive Namurian onlaps. The number codes in the Silesian refer to sandstone intervals (see files Belgian Geological Survey 30W371).

KB), the overlying dolomitic limestones and shaly/dolomitic sections agree very well. The Namurian-Visean boundary in the Turnhout well, which is determined by biostratigraphical evidence, corresponds to the 1630 m KB level at the base of the drape pattern in the Merksplas-Beerse well.

At this same depth, other less marked changes in the geophysical log signatures can be observed (**Figure 3**). These features were used together with the dipmeter drape response in the nearby Poederlee well (Geodoc file number 30W371) to define the Namurian-Visean boundary (**Figure 4**).

2.3. The Visean

According to faciolog interpretation the Visean is characterised by a massive limestone sequence from below the upper karstic and dolomitic layers to 1736 m KB, followed by siliceous limestone, shale and calcareous/dolomitic shale to the total depth of 1750 m KB.

Dipmeter logs display scattered dips in the limestones with only few reliable structural measurements. Such dipmeter response is typical for massive perireefal limestones, wherein the few stratigraphic dips are related to intercalated bioclastic limestone beds.

No biostratigraphic information is available. The biostratigraphy of the Visean is mainly based on foraminifera for which thin sections are required. The close lithological correlation to the Turnhout well suggests a similar close chronostratigraphic position. In Turnhout the limestones were determined to be uppermost Visean (Cf6δ foraminifera biozone, see Paproth et al.,1983).

Oblique stratification is present in the sandstones and the dip trends could be interpreted as a channel fill environment. The presence of clastic sediments suggests that the Brabant Massif could not have been covered by thick Lower Carboniferous limestones or dolomites at that time but that it represented an occasionally emerging structural high. It should also be noted that both fractured and karstic intervals in the Dinantian are associated with clastic karst deposits in contrast to the almost pure limestones. This association of emersion, fracturing and erosion of clastics points to Sudetic uplift pulses of the Brabant Massif.

2.4. Seismic stratigraphical calibration

Standard and extended Vertical Seismic Profile (VSP) surveys and a surface reflection seismic line linking the well to an existing seismic profile grid have allowed a good calibration between the surface seismics and the stratigraphy identified in the Merksplas-Beerse well. The time-depth conversion of the main stratigraphical horizons is presented in Table 4 and stratigraphically interpreted surface seismic sections, with different processing parameters, are shown in Figure 6.

3. The Visean reservoir characteristics

Porous/fractured intervals in the Visean limestones, filled with water and solution gas constitute the geothermal reservoir in the Merksplas-Beerse well.

3.1. Reservoir physical properties

Porous intervals from 1630 m to 1656 m and from 1739 m to 1750 m are identified in the Visean limestones using wireline logs (Figure 3 and Figure 5).
Mud logging records across both intervals describe numerous vein type calcite cuttings, which are not present in the non-porous limestone sections. The drilling Rate of Penetration (ROP) increased considerably across these porous intervals (Figure 5). Natural fracture analysis based on dipmeter resistivity curve response (Figure 5) shows dense, subvertical fractures (dip greater than 75 degrees) at 20 to 30 cm intervals in both sections. Similar fractures have been reported from cores in the Heibaart (7E196) and Poederlee (30W371) wells (Vandenberghe et al., 1986).

The presence of the two porous intervals was finally confirmed by the flow and temperature logs recorded during pumping and injection tests in the Dinantian. Most of the injected fluid is lost in the interval from the base of the casing at 1628 m KB to 1635 m KB.
The reservoir can be best described as consisting of a complex web of subvertical fractures, spaced in the decimetre range, widened by karstic dissolution and partly filled with calcite. Average porosity is probably around a few percent but it can reach peaks as high as 20% in some levels (Figure 3).

Permeabilities were derived from build-up curves using classical Horner plot analysis during the geothermal pumping test. Table 5 summarises the results. Permeabilities are high and 2-3 darcies is probably the realistic value as permeabilities of the same reservoir in the nearby gas storage site are also in the order of 3 darcies (Distrigas, oral com.).

3.2. Reservoir fluid and dissolved gases

Reservoir water samples were obtained (1) at the gas separator outlet at the end of the geothermal pumping of

Stratigraphic boundary	depth below (m)		d→time below MSL (sec)	
	MSL	Surface	OWT	TWT
Top Lower Miocene			0,0475	0,0950
Top Boom Clay	- 135,1	- 164,8	0,075	0,15
Base Boom Clay	- 271,1	- 300,8	0,153	0,306
Base Lower Rupelian Sands	- 281,1	-310,8	0,1585	0,317
base s4	- 284,6	- 314,3	0,160	0,32
base a4	- 289,1	- 318,8	0,162	0,324
base s3	- 294,6	- 324,3	0,165	0,33
base a3	- 296,6	- 326,3	0,1655	0,331
base s2	- 307,6	- 337,3	0,1715	0,343
base a2	- 321,1	- 350,8	0,1795	0,359
base s1	- 326,1	-355,8	0,182	0,364
base a1	- 346,1	-375,8	0,1925	0,385
Base 'Wemmel Sands'	- 363,6	- 393,3	0,200	0,4
Base 'Lede'	- 380,06	- 409,76	0,209	0,418
Base Lede / Brussel / Pan.	- 401,0	- 430,7	0,2195	0,439
Ieper Z	- 429,56	- 459,26	0,2365	0,473
Y	- 440,06	- 469,76	0,240	0,480
X	- 446,06	- 475,76	0,242	0,484
Base Ieper Clays	- 542,1	- 571,8	0,288	0,576
Base Upper Landen (contin)	- 562,1	- 591,8	0,300	0,6
Base Marine (?) Landen Sands	- 611,1	- 640,8	0,323	0,646
Base Lower Landen	- 642,6	- 672,3	0,338	0,676
Base Gelinden Marl	- 655,1	- 684,8	0,342	0,684
Base Heers	- 659,6	- 689,3	0,344	0,688
Houthem Chalk	- 690,1	- 719,8	0,360	0,720
Base Maastricht Chalk	- 757,1	- 786,8	0,3765	0,753
Base Upper Gulpen Chalk	- 848,1	- 877,8	0,405	0,810
Beutenaken Marl	- 882,1	- 911,8	0,416	0,832
Base Lower Gulpen Chalk	- 932,1	- 961,8	0,432	0,864
Vaals Formation	- 972,1	- 1001,8	0,4425	0,885
Sarnsbank - shale	- 1189,06	- 1218,76 m	0,496	0,992
- sandstone base	- 1205,06	- 1234,76 m	0,500	1
Din. / Nam. boundary	- 1596,06	- 1625,76 m	0,593	1,186
Top Compact Limestone	- 1622,06	- 1651,76 m	0,5985	1,197

Table 4. Time-depth conversion table for the main lithological markers in the Merksplas-Beerse well. OWT= one way travel time; TWT = two way travel time; MSL = mean sea level.

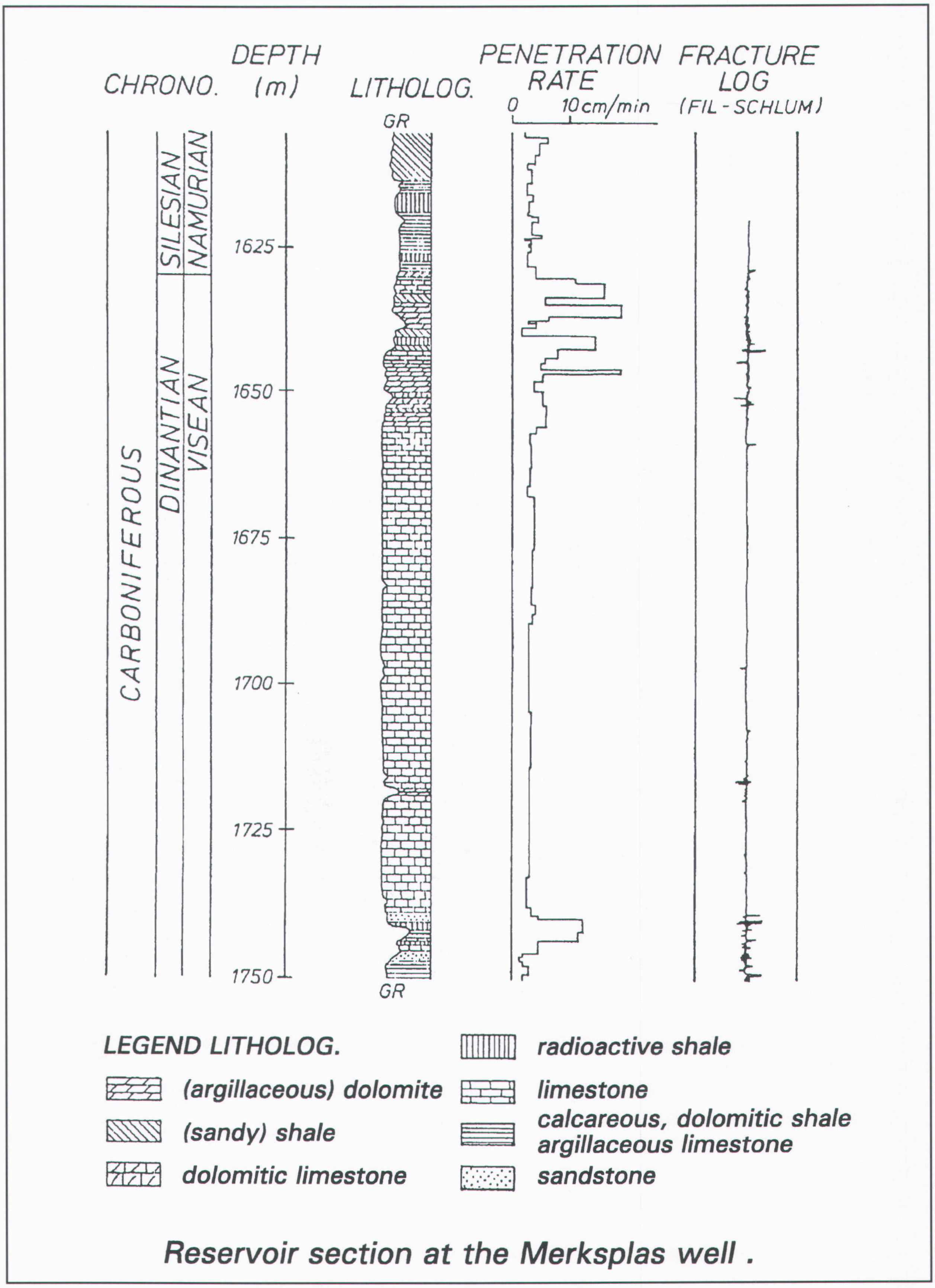


Figure 5. The lithology of the Dinantian section; the drilling penetration rate log and the fracture identification log, based on the dipmeter records. The two logs identify the reservoir sections in the Dinantian and show a relationship with admixed clastics in the reservoir sections whereas the compact limestone has a pure calcium carbonate lithology.

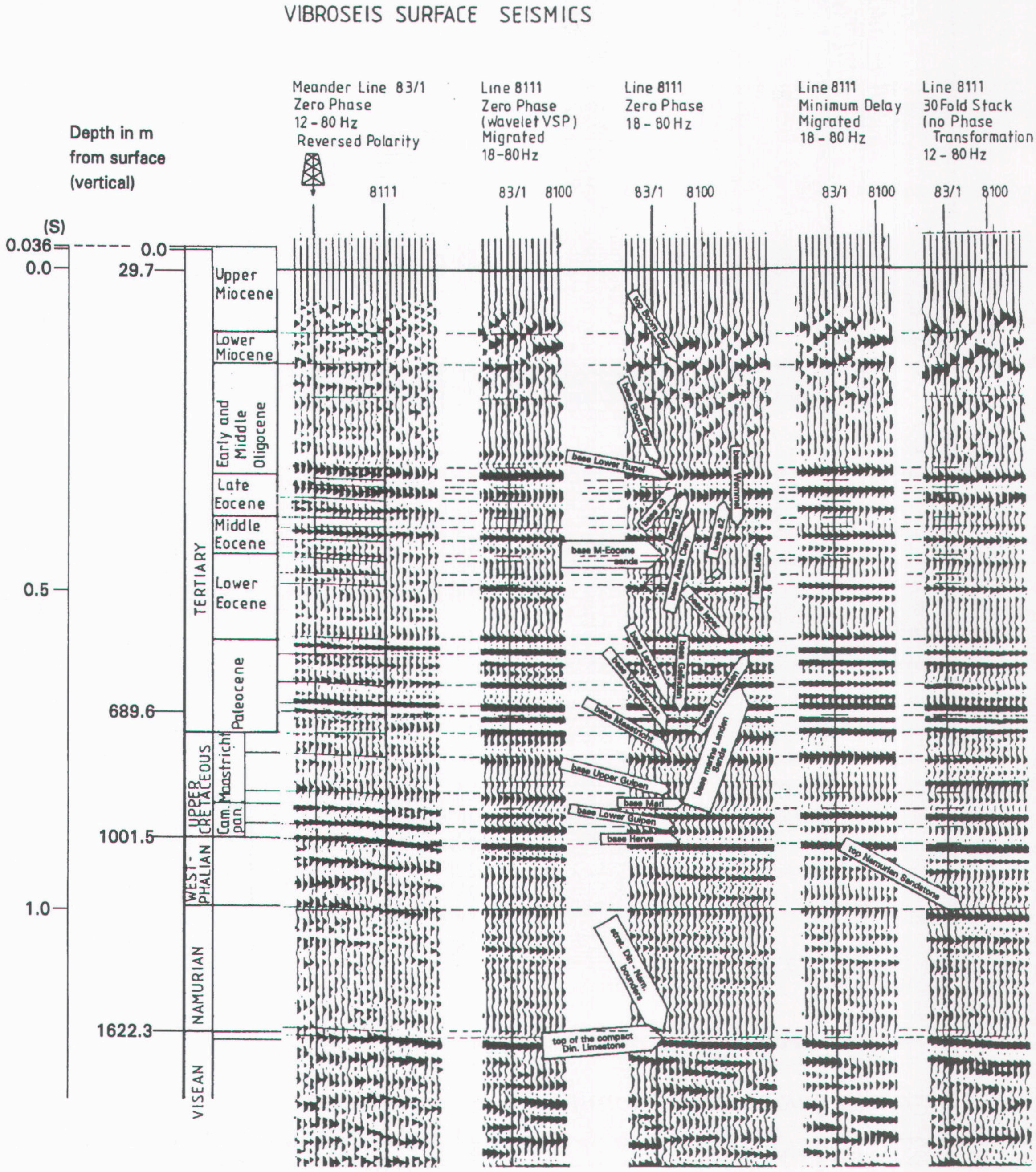


Figure 6. The lithostratigraphic identification of some selected seismic reflections in differently treated vibroseis sections near the wellsite. The left section shows a meander line linking (thin lines) the Merksplas-Beerse well and the 8111 line used in the other sections.

q	tp	m	Pwf	P1h	k	S	D Pa
113 m^3/h = 17056 bbl / day	8 min	26,1 psi	—	—	0,3345 D	—	—
113 m^3/h = 17056 bbl / day	8 min	8,7 psi	—	—	1,003 D	—	—
73 m^3/h = 11020 bbl / day	1915 min	2,9 psi	148,6 bar = 2154,7 psi	160,8 bar = 23331,16 psi	1,945 D	63,37	11,03 bar
73 m^3/h = 11020 bbl / day	1915 min	7,25 psi	148,6 bar = 2154,8 psi	2330,15 psi	0,778 D	25,1	10,92 bar
73 m^3/h = 11020 bbl / day	1915 min	7,25 psi	2139 psi	2330 psi	0,778 D	24,11	10,49 bar
173 m^3/h = 20681 bbl / day	5 min	46,4 psi	—	—	0,288 D	—	—
173 m^3/h = 20681 bbl / day	5 min	20,3 psi	—	—	0,521 D	—	—
72 m^3/h = 10869 bbl / day	720 min	2,9 psi	2156 psi	162 bar = 2349 psi	1,918 D	69,9	12,2 bar

Table 5. Summary of the hydrodynamic properties of the Dinantian reservoir in the Merkplas-Beerse well calculated from build up curves. q = flow rate; t_p = production time preceding the build up; m =pressure differential (psi) per ((t_p + dt)/dt log cycle) with dt = time since shut-in; Pwf = stabilised flowing well pressure at q; P1h = extrapolated pressure after 1 h; k permeability in D= darcies) according to k=(152.6 q.μ.B)/m.h with μ= viscosity (0.53 cps), B = water formation volume factor (1.015), h = thickness of the reservoir (170.56 ft); S = dimensionless skin according to S= 1.151 (P1h-Pwf)/m – log k/μ.P.C.r_w^2 + 3.23; C = compressibility ($1.03.10^{-5}$ psi^{-1}); r_w = well radius (0.52 ft); P = porosity (5,4 %); DPa = pressure drop due to skin according to DPa = q.B.μ.S/7.08 k.h. The initial reservoir pressure is 162 bar. All monitoring is carried out at 1608 m amerada depth.

	Analysis 1	Analysis 2	Analysis 3	Analysis 4
Na^+	39,19 g/1	41 g/l	33,5 g/l	38,4 g/l
K^+	1,94 g/1		1,79 g/l	1,82 g/1
Ca^{++}	8 g/1	7,4 g/1	10,1 g/1	9,58 g/1
Mg^{++}	1,7 g/1	1 g/1	0,97 g/1	0,943 g/1
Fe^{++}		35 mg/1	4,1 mg/1	0
Fe^{+++}	16 mg/1	< 0,1 mg/1	36,2 mg/1	3,12 mg/1
Mn^{++}		1 mg/1	4,51 mg/1	3,01 mg/1
Ba^{++}		1,5 mg/1	3,08 mg/1	9,78 mg/1
Si	< 10 mg/1			
$H\,Si\,0_3^-$		44 mg/1		
$Si\,0_3^-$			46,6 mg/1	47,2 mg/1
Cl^-	78,46 g/1	81 g/1	70,9 g/1	71,25 g/1
SO_4^-	708 mg/1	670 mg/1	652 mg/1	700 mg/l
Ra^{226}		20.10^{-10}Ci/1		
Rn^{222}		6.10^{-10}Ci/1		
$H\,CO_3^-$		839 mg/1	350 mg/1	427 mg/1
NH_4^+			174 mg/1	168 mg/1
total solids	126 g/1	142 g/1 (110°C) 120 g/1 (600°C)	137,5 g/1 (105°C)	147,75 g/1 (105°C)
equivalents	S^+ = 2,294 S^- = 2,228	S^+ = 2,235 S^- = 2,312	S^+ = 2,099 S^- = 2,021	S^+ = 2,282 S^- = 2,032

Table 6. Chemical analysis of the Dinantian reservoir water. Analysis 1 by Tessenderlo Chemie, water from gas separator outlet; analysis 2 by the Nuclear Energy Research Centre, Mol, water from a closed corrosion loop; analysis 3 & 4 by Flopetrol from downhole samples.

more than 3000 m3 reservoir water, (2) taken from a corrosion test loop (operated by the Nuclear Energy Research Center) and (3) sampled downhole after nitrogen lifting of the reservoir fluids for gas testing. The analytical results are presented in Table 6. The water is a sodium chloride brine of a composition which falls within the general compositional range of oilfield brines. Br content and its ratio to other chemical components show that evolving seawater is the most probable origin of the brine and that dissolving evaporites can not explain the brine composition. The sulphate content appears to be relatively high (650-700 mg/litre) when compared to waters from the Hainaut geothermal province, ranging from 710 mg/litre in the Baudour tunnels to 1126 mg/litre in the St. Ghislain borehole, where the waters are equilibrated by Visean anhydrite (Marlière, 1976; Delmer et al., 1982; de Magnée et al., 1986). Anhydrite equilibrated waters however have very low TDS contents, such as is the case in the Hainaut geothermal province (TDS < 2gr/litre) and unlike the situation in the Merksplas-Beerse well.

The reservoir waters are slightly radioactive due to their contact with the radioactive Chokier shales. Spectral gamma ray logs indicate increased radioactivity from finely distributed uranium. The radioactivity in the water is caused by the presence of Ra^{226} (20.10^{-10} Ci/litre) and Rn^{222} (6.10^{-10} Ci/litre). Radium is the first element in the U^{238} decay series that is significantly soluble in reducing low sulphate waters. The radon present is the short-lived first daughter of the radium in the water. Comparison with data in the literature for normal deep reservoir waters shows that these radioactivity values are not exceptional.

An important property of the reservoir fluid is the high dissolved gas content, mainly carbon dioxide. Reservoir gases were first detected at the flame ionisation detector at the well site during the routine analysis of the circulating drilling muds. After the drilling operations the mud was replaced by water after which the gas content increased. After acidification the well, in an attempt to remediate the skin, gas content increased again. For security reasons, circulation was stopped and the well architecture was adapted to test the gas content in a drill stem testing (DST) and with nitrogen lifting. Both tests failed to initiate a continuous gas flow. Nevertheless, petrophysical analysis of the log responses, using different commercial software programmes, shows detectable quantities of hydrocarbons. As no oil staining was observed in the cuttings, the calculated hydrocarbon is assumed to be gas. However the reliability of this analysis can probably be questioned in such an irregular fractured and karstic interval. Downhole sampling showed free, non-flammable gas, in only one of the eight samples taken. The gas composition of the dissolved gas in the downhole samples is shown in Table 7. The main composition is carbon dioxide with admixtures of methane (3 to 7% vol), nitrogen (2 to 11% vol) and small amounts of oxygen. Samples collected at the separator during well testing contained a systematically higher methane content of up to 12 % vol. This is explained by the higher relative carbon dioxide solubility in water. Traces of hydrogen sulphide, hydrogen, helium and ethane were recorded. It should be noted that the radioactivity in the well could decompose some water molecules, accounting for some of the gas fractions.

Carbon isotope analysis was carried out and the differences between the δ^{13}C of methane (- 29.5 pro mille ± 0.2) and carbon dioxide (- 2.3 pro mille ± 0.2) are probably best explained by fractionation at equilibration temperatures of about 250°C. The methane carbon isotopes are compatible with the Upper Carboniferous gas composition and the high carbon dioxide and the nitrogen contents are comparable to some highly evolved Upper Carboniferous gases in NW Europe. It is suggested that the gases have migrated from deeper Upper Carboniferous levels north of the Hoogstraten fault southwards into the top of the Dinantian karstic reservoir.

The theoretical equilibrium constant K of the carbonate precipitation/dissolution reaction was calculated for the reservoir temperature and pressure conditions and compared to the actual value of K calculated from the

	CO_2	CH_4	N_2	0_2	H_2S	C_2	GLR	Mol. mass.	density (air = 1)	bubble psi (73,9°C)
1646 m	93,67	3,40	2,71	0,22	0	0	1,62	42,529	1,468	385
1646 m	92,25	3,21	4,43	0,11	0	0	1,11	42,355	1,462	215
1740 m	83,11	6,27	10,15	0,47	0	0	0,96	40,426	1,395	385
1740 m	93,10	3,57	3,25	0,80	0	0	0,71	42,456	1,465	185
1646 m	87,95	4,43	7,51	0,11	0	0	1,22	41,521	1,433	420

Table 7. Dissolved gas composition measured on downhole samples (Flopetrol analysis).

activities of the chemical elements in the water. Both the actual and the equilibrium K values do not differ significantly and it can therefore be assumed that the reservoir water is in equilibrium. Nevertheless the geometry of seismic reflections in younger strata above the top Dinantian karstic depressions in the area shows that the karst was still active in the Upper Cretaceous and even in the Cenozoic (Dreesen et al., 1987), suggesting continuing dissolution and therefore probably also continuous arrival of carbon dioxide into Cenozoic times.

4. Geothermal aspects

An extended pumping test was carried out to define the reservoir aspects specific to the geothermal requirements of the project: water temperature, deliverability and discharge.

4.1. Reservoir data

Subsurface temperatures and gradients were inferred from maximum temperature readings during wireline logging and from a continuous temperature logging in the 8_ inch section between 1008 and 1631.34 m (Vandenberghe & Fock, 1989, Figure 7). The continuous temperature logging in the Upper Carboniferous section shows temperatures of 48.8°C at 1100 m and 66.6°C at 1600 m, leading to a thermal gradient of 3.56°C/100 m depth increase. The maximum temperature measured at 1760.5 m KB is 72.2°C. During the long duration pumping, the temperature recorded on ameradas positioned at 1608 m KB was 69.8°C whilst at the well head a constant temperature of 70°C was recorded. The higher temperatures obtained using extrapolation techniques correcting for cooling while drilling (Dowdle and Cobb,1975; Leblanc et al., 1981) are considered as unreliable. An extrapolation towards lower temperatures of the sulphate geothermometer for sodium chloride type geothermal waters (Oustrière & Leleu, 1979) leads to an estimated formation temperature between 70 and 75 °C, well in agreement with the direct measurements.

The density of the reservoir water is affected by its temperature and by the exsolution of gas from the water. A 1.096 gr/cm^3 density is measured at 15°C and an in situ reservoir water density of 1.067 gr/m^3 at 70°C is derived.

Water levels were measured in the well and pressures recorded in ameradas at 1608 m depth with a normal reservoir water pressure of 161.9 bar at this level. A submersible pump was positioned at 200 m KB in the well to carry out a stepwise pumping test for a total of 50 hours with pressure recovery registration during an additional 97 hours. A volume of 3253 m^3 was pumped and stored in a specially built reservoir. A stabilised flow rate of 72 m^3/h was established at a pressure 148.7 bar for a pressure drop at the ameradas of 13.2 bar. This equates to a productivity index of 5.4 m^3/h/bar. The water level measured in the well during the pumping stabilised at 190 m KB. The 13.2 bar pressure drop represents a reservoir water column of 124 m indicating that the equilibrium water column head is at approximately 66 m depth. As the water column cools, its head will descend. The produced water was reinjected after proper treatment and an injectivity of about 3.7 m^3/h/bar was obtained, establishing a productivity/injectivity ratio of 1.45.

The analysis of the pumping test curves computed high permeabilities in the Darcy range, but the calculated skin values were also very high (Table 5). This high skin value is confirmed by calculating the theoretical drawdown for zero skin, using a classical radial flow to well formula. The radius of influence was obtained from the Gray formula and confirmed by direct observation in the Loenhout gas storage DZH 5 and 9 wells (radius of influence about 10 km).

4.2. Conditions for a doublet production

The reservoir pressure, the productivity index and the reservoir temperature are at the low end of the range for a potentially viable geothermal doublet project provided a suitable application could be found in the immediate vicinity of the doublet. In order to develop the well for geothermal energy purposes however the specific water quality properties have to be matched by appropriate doublet design and choice of materials. Amongst those properties causing concern are the high salinity at high temperature, the presence of dissolved gas at a gas-liquid ratio (GLR) of 0.44 during production and 0.71-1.62 in down hole samples (Table 7), the presence in the gas of methane, the presence of reduced iron dissolved in the water and the radioactivity of the water (see also Tas et al., 1988). During production of the reservoir water, at 73.9°C with a density of 1.067 gr/cm^3, the bubble point of the reservoir gases corresponds to degassing of the water at about 127 to 277 m depth below the water level in the well (Table 7).

As the distribution of karst porosity in the reservoir is probably irregular, a major problem in the development of geothermal wells in the area will be the choice of a sufficiently productive part of the karstic reservoir. A methodology, based on a seismic AVO analysis was shown to be a potentially successful approach in the case of the reservoir between shales and compact limestones as in the Merksplas-Beerse well (Vandenberghe et al., 1986).

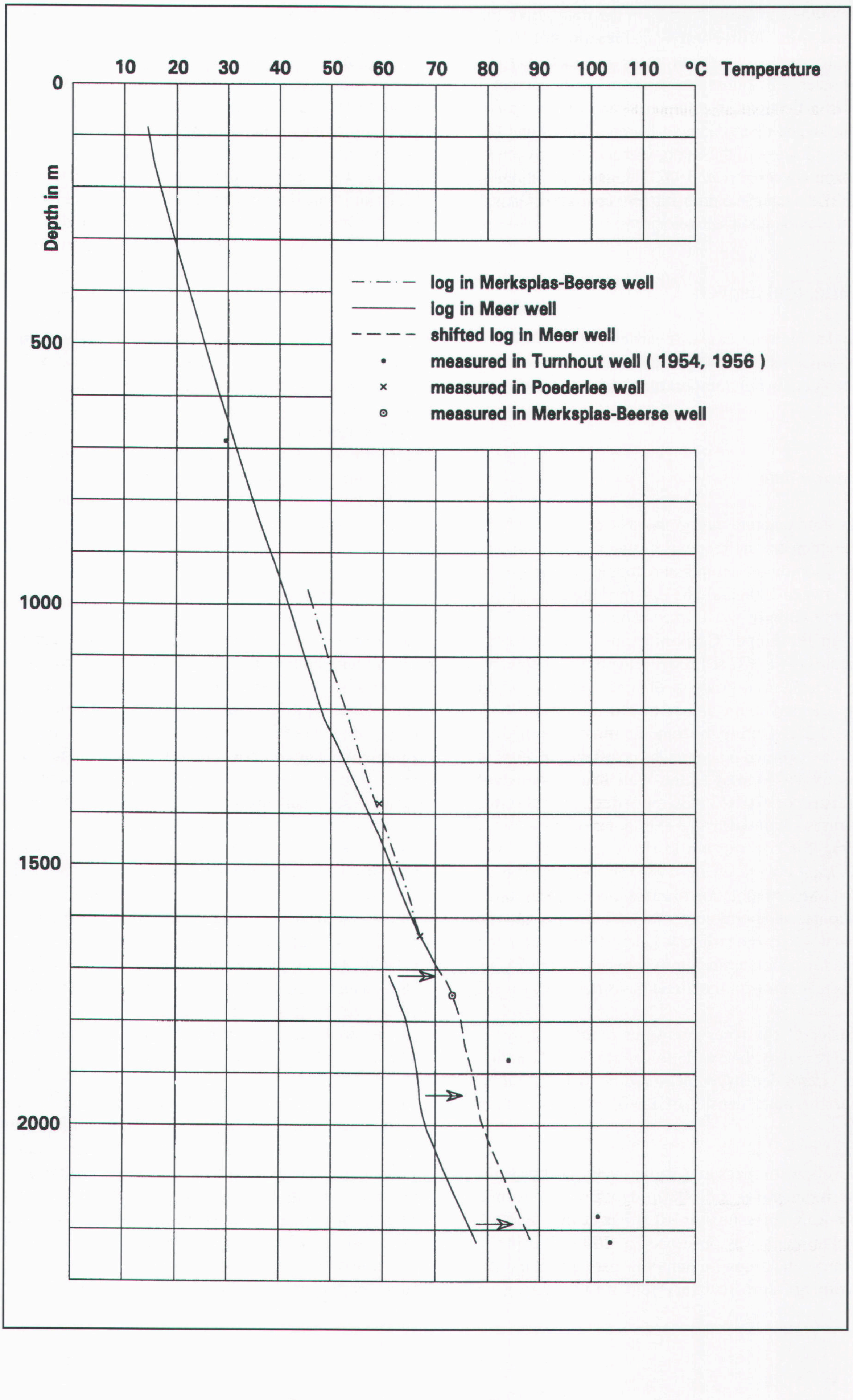


Figure 7. Selected reliable thermal measurements in the Merksplas-Beerse, the Turnhout and the Poederlee wells in the area. The shift of the continuous log recorded in the lower part of the Meer well is justified as the well is clearly cooled by the drilling operation and the shift links this cooled continuous log to a more equilibrated continuous log ending at about 1700 m depth.

4.3. The semi doublet concept

In order to reduce the investment costs of a full doublet where the produced water is reinjected in the same formation, a loop was tested between the deep production well and a second shallower injection well. This well was drilled at a distance of 132 m from the first well down to the Upper Cretaceous chalk arenite reservoir at 800 m. Such a system is called a semi-doublet. The productivity of the chalk is 4 m^3/h/bar. Pore size is large attaining 30 µm with interconnecting pore radii of 0.1 µm. A test semi-doublet loop, connecting production and injection well, was successfully tested for a period of three weeks at 75 m^3/h. Injection well head pressure diminished from 23 bar down to 19 bar during testing. The permeability determined during the brine injection is about 0.26 darcy (Lie and Vandenberghe, 1988). The thermal power available is about 3.2 MW.

5. Conclusions

The Cenozoic and Mesozoic stratigraphy was established from the mud logs and geophysical wireline logs. The bottom of the Upper Cretaceous consists of 40 m of smectitic marls of the Vaals Formation (966 m to 1005 m). This is followed by Westphalian A Coal Measures to 1297, the Andenne Formation (Kinderscoutian, Marsdenian and Yeadonian) to 1614 m and the Chokier Formation (Alportian-Arnsbergian) which is characterised by high natural gamma radiation. The Upper/Lower Carboniferous boundary is difficult to establish because the base of the Namurian already contains limestone intervals, while the top of the Dinantian is a partly dolomitised and shaly limestone with karstic morphology into which parts of the Chokier shale were deposited.

Wireline logs were used to analyse the lithology and the natural fracture distribution which correlated closely to the stratigraphic interpretation of the nearby cored Turnhout deep well. The draping of the Namurian shale over the Dinantian paleokarst relief, indicated by the dipmeter log, appears to be the best indicator of the important time hiatus between the top of the Dinantian and the base of the Namurian deposits. The boundary is put at 1630 m. Anomalous high vitrinite reflectivities occur in an interval between about 1400-1500 m and 1650 m, probably related to the presence of the high heat-producing radioactive shales of the Chokier Formation. Fracture identification analysis based on dipmeter logs as well as the drilling Rate of Penetration (ROP) identified two fractured reservoirs in the top of the Dinantian: from 1630 to 1656 at the top and between 1739 and 1747 at the bottom.

These two fractured and karstic reservoir sections are associated with the presence of siliciclastics and dolomite in contrast to the massive limestones in the Dinantian. This association points to a relationship with the uplift of the Brabant Massif axis during the Sudetic compressional phase of the Varistic deformation.

The reservoir water is a sodium chloride brine (140 gr/liter TDS) with sulphate and bicarbonate and minor silicate anions. Ra^{226} and Rn^{222} is related to the presence of the radioactive shales. Reservoir water density is a 1,064 gr/cm^3 at 70°C. The reservoir pressure measured at 1608 m depth is 161,9 bar. The geothermal pumping and injection tests show a productivity index of 5.4 m^3/h/bar and an injectivity index of about 3.7 m^3/h/bar. Permeability is estimated from build-up curves and is in the range of 2 to 3D, but the calculated skin pressure loss is very high. Acid treatment did not significantly improve the skin. The radius of influence was calculated to be between 5 and 6 km but observation in the DZH5 and 9 wells at the Distrigas gas storage site of Loenhout-Wuustwezel, at 9 and 9.5 km distance, did show small pressure effects suggesting an even larger regional permeability than was obtained from the well testing data.

While drilling the two reservoir intervals, traces of methane were recorded which increased considerably during post-drilling circulation. A standard Drill Stem Test, with nitrogen-lift and downhole sampling could not demonstrate the presence of free gas at the reservoir level. Therefore solution gas is interpreted from the downhole samples, with the bubble point corresponding to depth levels between 277 m and 127 m. The GLR determined is around 1, but lower values are obtained during the geothermal testing probably due to high solubility of CO_2, the main component of the gas. Laboratory analysis of the downhole samples show a gas composition of about 90% CO_2 4-5% CH_4 and 5-6% N_2. Methane and nitrogen contents appear higher in analyses from gases taken at the separator during geothermal testing, again due to the higher solubility of the CO_2 in the reservoir water. Small contents of other gases such as H_2 O_2 and He have been reported in some analyses. Calculations show that the actually measured reservoir water composition is approximately in equilibrium with limestone. Although the origin of the gases is not completely clear the composition is not unlike some Upper Carboniferous gas reservoirs in Northwest Europe. This is corroborated by similar $^{13}C/^{12}C$ values in methane. Isotopic carbon values of the CO_2 and CH_4 are different but are probably caused by fractionation. It is suggested that the gases have migrated from the deeper lying Upper Carboniferous north of the Hoogstraten fault.

The Merksplas-Beerse production well has been completed as a semi-doublet by an injection well in the shallower Cretaceous chalk arenite. However, the semi-doublet was not put into operation for non-technical reasons. Future geothermal development in the Campine area will have to take into account the special composition of the reservoir water, the relative low productivity and low reservoir pressure, and the irregular distribution of the karst void distribution.

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