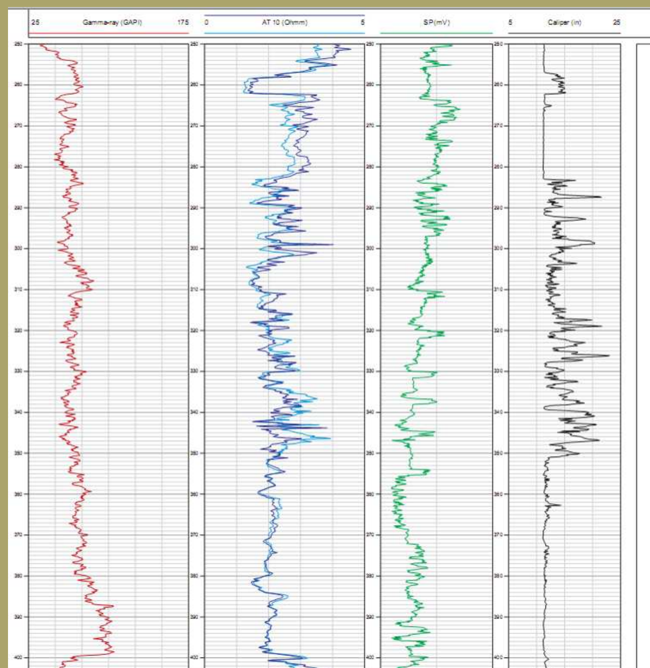
Wellbore integrity in Ypresian clays in Belgium with reference to geophysical well logs



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8.9.2012

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1. Introduction

1.1. Objective of the study

The origin of this study is the observation of borehole breakouts in the Ypresian clay interval of the research boreholes Doel (14E0240 – fig. 1) and Kallo (14E0355 – fig. 2). This behaviour had not been observed when traversing the Boom Clay, meaning that the Boom Clay and Ypresian Clays would possess different geomechanical properties, hence that conclusions on long-term storage of high-level radioactive waste cannot be extended from the well studied Boom Clay to the lesser known Ypresian Clays. Borehole breakouts represent changes in borehole geometry caused by a rotating and down cutting drill bit under normal operating conditions, hence linked to lithological - geotechnical characteristics and the stress regime of the geological formation traversed. Breakouts are observed on the caliper log, registering changes in diameter of the wellbore over restricted vertical intervals. They are mostly caused by washouts, widening the borehole section, rarely by reduction of the wellbore and in that case generally due to swelling of the formation and/or deposition of a clay cake.
By detecting these breakouts, different questions arise :
- Is this a typical log response in the Ypresian clays ?
- Is there a specific geographical or stratigraphical extent ?
- Is it induced by particular drilling methods, hence an artifact ?
- Is there a relation of the breakout with the mineralogy, lithofacies, burial history and formation water ?

A scoping study (see annex 3) conducted by Kris Welkenhuysen (GSB) confirmed that breakouts could be observed in the Ypresian clay interval of other wells, and that this feature is not observed to any comparable extent in the Boom Clay. Borehole breakouts thus are indeed a peculiar feature for the Ypresian Clays (Fig. 3). An overview of the geophysical well logs showed that breakouts were widespread but also quite different between the wells: not always observed, nor over the same stratigraphical interval nor over a comparable vertical section. The complexity in response is such that no clear guideline was found how to tackle the problem. First, boreholes drilled through the Ypresian clays interval has to be screened for caliper anomalies. Then a typology of the breakouts had to be made. Next, a pragmatic iterative approach had to be followed in order to find the factors contributing to the questions raised. Finally, we have to determine if such investigation enables us to find answers to the above questions.

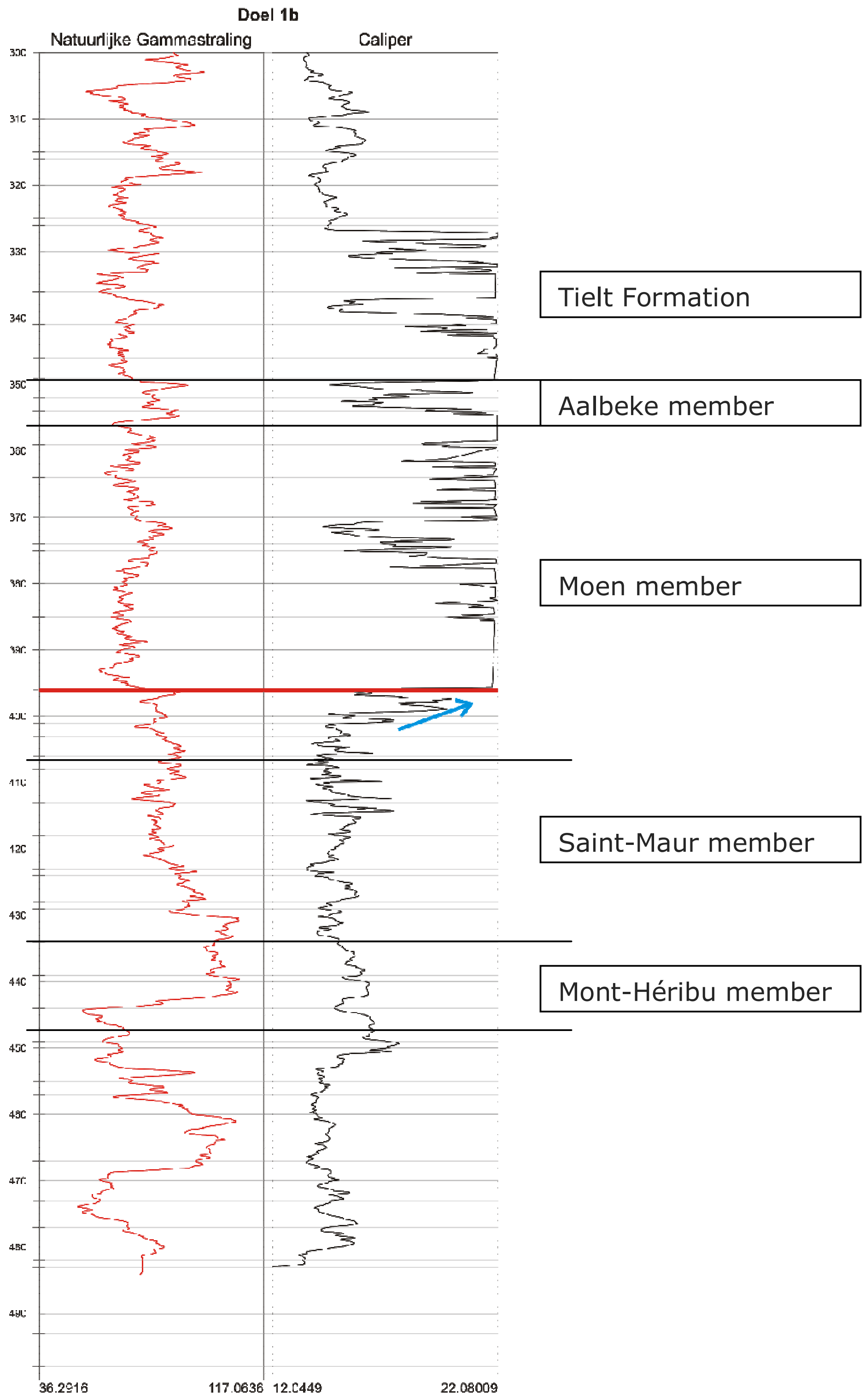


Fig. 1. ONDRAF/NIRAS borehole Doel 1b (14E0240), logplot of caliper vs gamma-ray over the top Thanetian – Ypresian interval showing persistent wash-outs between 325 and 395 m. Horizontal red line = notable increase of caliper value.

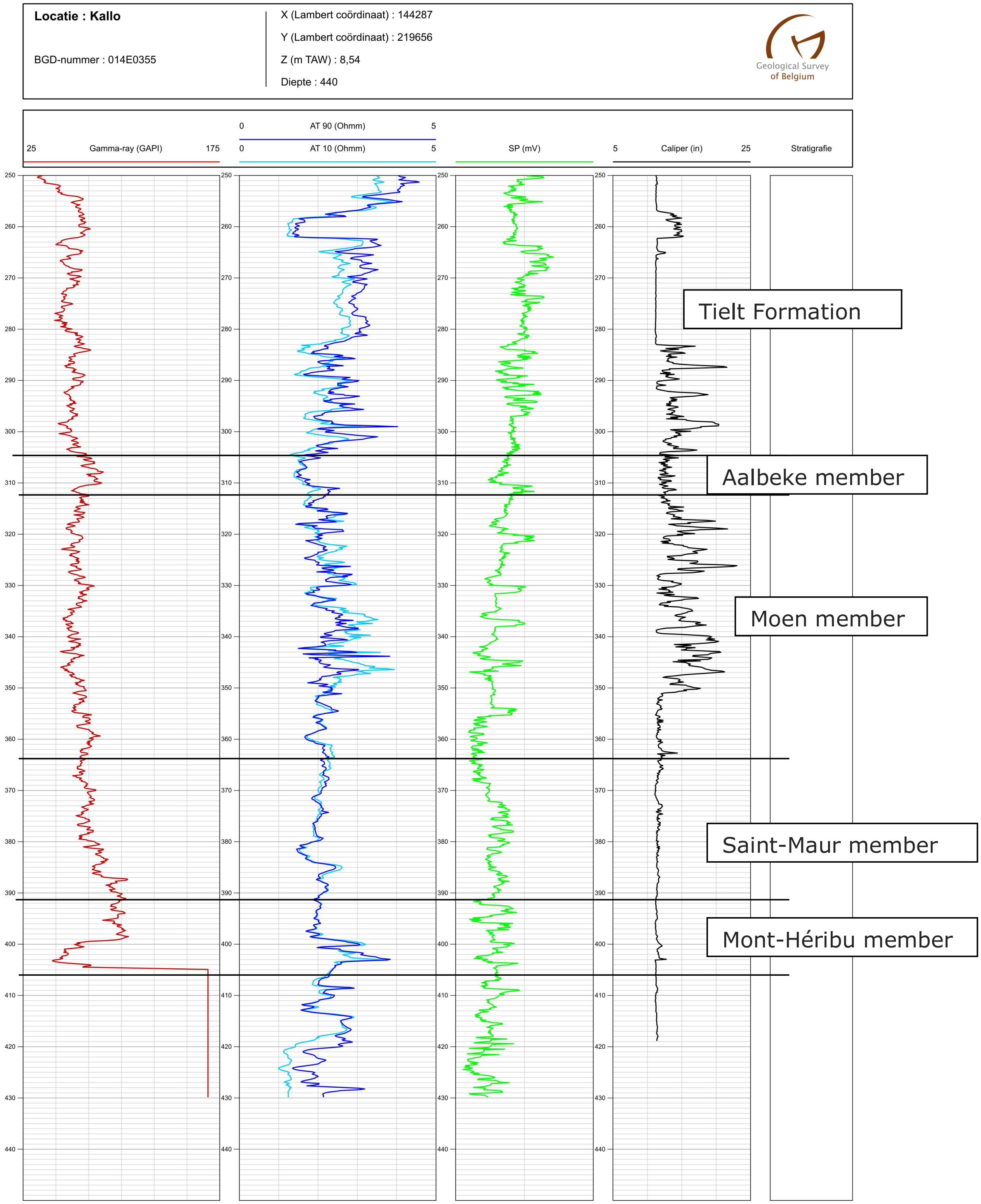


Fig. 2. ONDRAF/NIRAS borehole Kallo (14E0355), logplot with gamma-ray, resistivity, SP and caliper readings versus lithostratigraphical subdivision.

Further in this report we preferentially use the term wash-out instead of breakout. Whereas breakout refers to the phenomenon of modification of the wellbore geometry in response to geomechanical anomalies and by virtue of the term describes phenomena in consolidated strata, washouts are the effect of turbulent mud flow at inappropriate levels compared to the cohesion of the traversed strata. Typically, washouts may be located under the casing shoe, at levels of stationary circulation due to technical problems, over intervals with complex drilling operations (e.g. reaming), or may appear when the mud density is far too high or on the contrary its viscosity is far too low and the wellbore becomes destabilized. In all these cases there is no obvious relationship to geomechanical anomalies. But there are also distinctive patterns in wellbore geometry that appear to be linked to stratigraphy and may indicate different geomechanical properties of the strata affected. These are the anomalies that are the subject of this study.
As in this study erosion of the wellbore occurs in unconsolidated sediments, it is more prudent to use the term washout, which has less tectonic or geomechanical implications.

Fig. 3. Earth Explorer borehole Oostende (GeoDoc 22W0351) showing thick drilling mud and clay balling around rock bit while traversing the Ypresian clays, compared with 'clean' drilling conditions when e.g. traversing the Cretaceous chalks. Erosion of the wellbore in the Ypresian clay interval can be appreciated from the amount of clay flakes coming off the wellbore by action of the reamers.

1.2. Work flow

A first observation was that the borehole washouts are observed in two formations which together comprise the Ypresian clay sequence in Belgium: the Kortrijk and Tielt Formations. In the latter formation, mainly the Kortemark Member is concerned. In this way, the area of investigation is defined by the occurrence of the Kortemark - Kortrijk sequence. To understand if the caliper log anomalies are related to stratigraphy, a concise review of the stratigraphic subdivision, as being deducible from geophysical well logs, was necessary.

The steps leading to the required dataset are analogous to the procedure applied to the human intrusion report (De Ceukelaire et al., 2011) and will be only summarily described here.
Defining the area of investigation based on the outcrop and subcrop areas of Tielt and Kortrijk Formations, derived from previous isohyps mapping.
Inventory of all boreholes drilled in this area. Restrict the borehole dataset in the mapped area to a dataset of boreholes with geophysical well logs.
Selection of well logs intersecting the Ypresian sequence (minimum interval 15 m) including those that cross the top Kortrijk Formation and the top Tielt Formation (either corresponding to base Gentbrugge formation or base Quaternary, as these constitute the mapping boundary layers).
Manual control of the logs and the stratigraphic interpretation, with corrections of the dataset where necessary.

The next task was to create an Excel table with logs with/without caliper. Without caliper means in this case absence of caliper logging in the borehole, no caliper logging over the Ypresian sequence, unreliable quality of the caliper log, or missing data. Only the logs with useful caliper log were retained for further analysis.

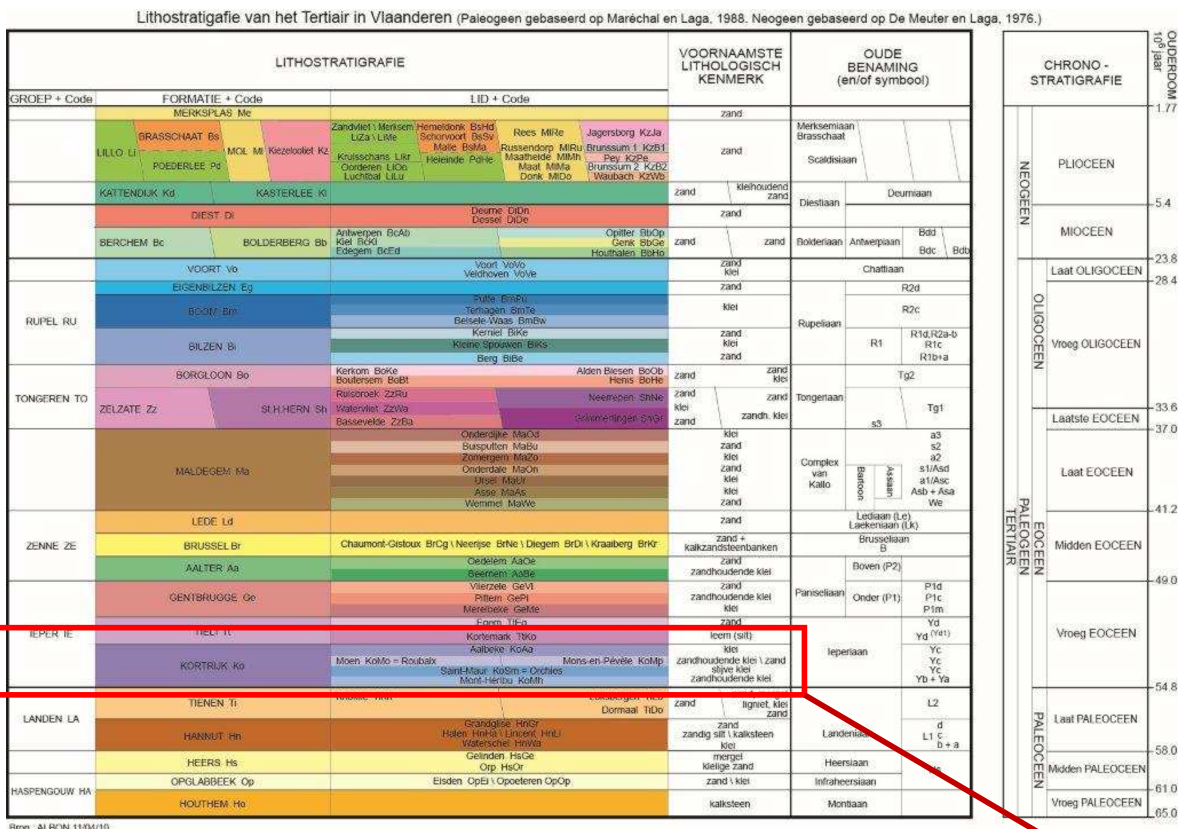
Lastly, a qualitative assessment of the caliper logs was performed to catalog the wash-outs in different types.

1.3. Materials

All possible geophysical well logs over the Ypresian interval were collected. Some of them were already digitized, which makes evaluation more easy. But many were only available as a paper (photo)copy in the archives of the Geological Survey of Belgium. Many logs were digitized by Philippe Van Marcke as part of an inventory conducted for ONDRAF/NIRAS in 2005 but these were selected on different grounds (Van Marcke & Laenen, 2005). Most of the recent logs provided by VMM-afdeling Water also have digital information.
Nevertheless, paper copies of logs prevail. For this exercise, part of them were also digitised.

2. Stratigraphical framework

The lithostratigraphic subdivision adopted here is in conformity with the Lithostratigraphic scale of Belgium published in the Geologica Belgica 2001 volume, used as the reference by the National Commission on Stratigraphy (http://www2.ulg.ac.be/geolsed/GB/SCTert.htm), also used for the new detailed geological maps of Belgium (Table 1). The reference works for the electrical stratigraphy (lithostratigraphy derived from geophysical well logs) are Vandenberghe et al. 1988, De Ceukelaire & Jacobs 1998, Welkenhuysen & De Ceukelaire 2009.



Ieper Groep	Tielt Form.	Kortemark		silt
	Kortrijk Form.	Aalbeke		Clay
		Moen/Roubaix	Mons-en-Pévèle	Silty clay
		Saint-Maur/ Orchies		Clay
		Mont-Héribu		Sandy clay

Table 1. Lithostratigraphic scale of the Tertiairy in Belgium, as used for the geological mapping of Flanders (N. Belgium). The Paleogene formations are based on Maréchal & Laga, 1988 ; the Neogene formations on De Meuter & Laga, 1976.

The Ypresian clay represents the original deposit for naming of the Ypresian chronostratigraphic stage, which is of lower Eocene age (Table 1). This starts with a transgressive event after the probably tectonic uplift at the end of the Thanetian stage, followed by a long period of subsidence, responsible for thepredominantly clayey sediment. The Ypresian clay is composed of a succession of fining upwards and coarsening upwards cycles (or transgressive systems tracts and highstand tracts), grouped into an overall coarsening upward trend. Cyclic grain size variations from clay to silt/fine sand thus are an essential characteristic feature. The sediments in Belgium corresponding to this sequence are grouped in the Ieper Group, composed of the Tielt and Kortrijk Formations. The Ypresian Clay is the more important lower part of this sequence, prior to a rather sudden increase in grain size. Lithostratigraphic boundaries do not correspond to sequence stratigraphic boundaries, however (Vandenberghe et al., 1998) - (Fig. 4). This is part of the problem discussed in this study.

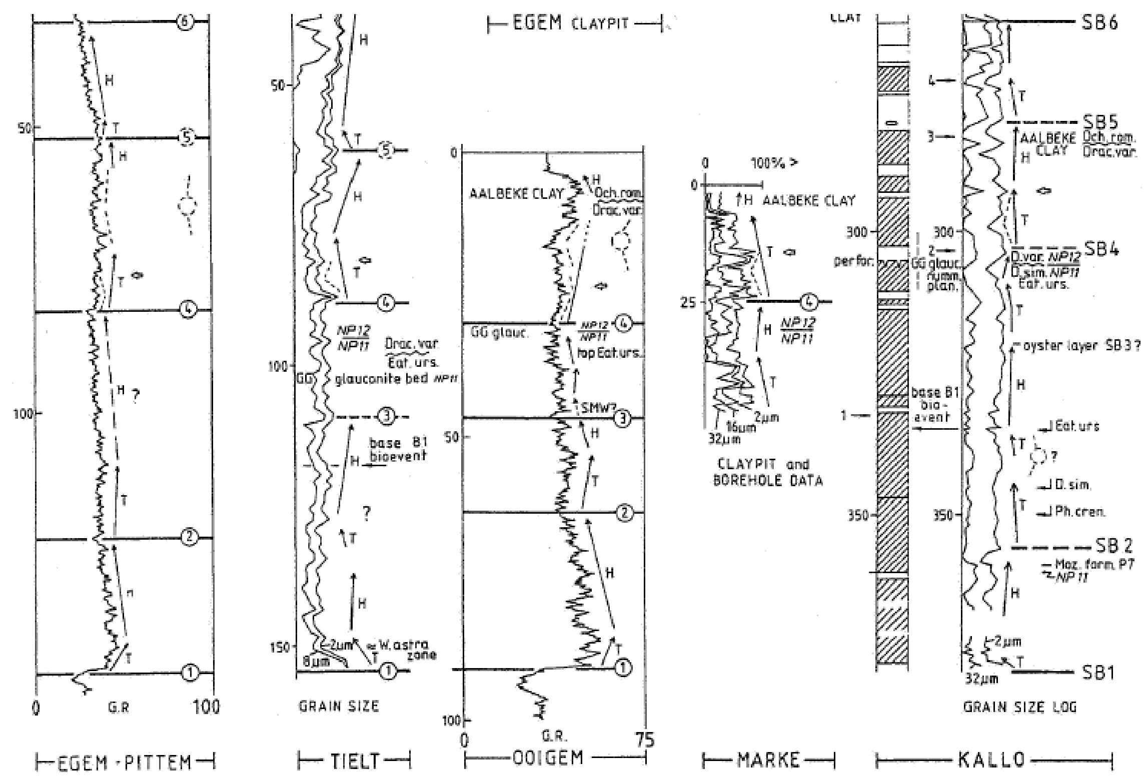


Fig. 4 . Sequence stratigraphy of the Ypresian clay between selected boreholes or clay pits based on gamma ray curves, grain size trends and biostratigraphical constraints. H = highstand, T = transgressive systems tracts, sequence boundaries encircled (from Vandenberghe et al., 1998).

The next paragraphs consist of an overview over the most important characteristics of the different stratigraphical units, into which the Ypresian Clay is formally subdivided (Laga et al., 2001; Laga, 2003). Indeed not many studies have addressed the Ypresian clay by lack of economic interest and of contrasting geological features.

2.1. Tielt Formation

Name: The name has been introduced by Geets (1988b). The formation is defined by boundary stratotypes (Steurbaut, 1998). The lower boundary stratotype is placed at 71 m depth in the Tielt borehole at the base of the Kortemark Mbr. Sheet 21/6 (Wakken). Co-ordinates: x = 76.425, y = 187.55, z = +48 m. The upper boundary is placed at the top of the Egem Mbr in the "Ampe" quarry. Sheet 21/1 (Wingene). Co-ordinates: x = 70.15, y = 190.15, z = +44 m.

General aspect: This marine unit consists in general of a very fine sandy, coarse silt, up-wards there is a transition into very fine sand.
Thickness: more than 50 m in the centre of the outcrop area. It decreases to the south and the east, and probably to the north.
Age: Middle to Late Ypresian.

Geographical extension: The northwestern part of Belgium. The formation outcrops in the north of Hainaut, the south and the centre of East- and West-Flanders and the western and southwestern part of Brabant. Outliers occur in the Mons Basin and south of the river Sambre.

The formation is subdivided from bottom to top into the Kortemark Mbr, the Egemkapel Mbr and the Egem Mbr. Because of its clayey nature, only the Kortemark Member is further discussed here.

2.1.1. Kortemark member

Name: The name “Kortemark Silt Member”, derived from the municipality of Kortemark (West-Flanders), was introduced by Steurbaut & Nolf (1986, p. 126). The uppermost clayey part was later described as a separate unit: the Egemkapel Clay (Steurbaut, 1998, p. 114). However, by geological mapping, the Egemkapel Clay has been correlated with the Yd3-layer (Jacobs et al., 1999), hence seen as a part of the Egem member and not of the Kortemark member. Discussion about this topic is going on.

General aspect: This marine deposit consists in the lower part of compact clayey, fine to very fine silt with thick clay lenses. It grades upwards into very fine sand to silt, with sandy and clayey intercalations. Up to seven sequence stratigraphic subunits have been distinguished (Steurbaut, 1998) of which four are exposed in the Kortemark quarry. Macrofossils are rare. Erosive channels occur in the middle of the Kortemark Member (Steurbaut, 1998).

Geographical extension (fig.5): The Kortemark Member is found north of Kortrijk, in the centre and the west of West-Flanders where it is exposed, and probably the central part of East-Flanders, south of Ghent, where the thickness decreases. It is also known from the Kallo and Mol boreholes.

It rests conformably on the Aalbeke Member of the Kortrijk Formation, from which it differs clearly by its silty character. The maximum thickness is 40 m (Tielt borehole – 068E0169). This member occurs in the Doel borehole – 14E0240 at 316 – 347 m depth, in the Kallo borehole – 14E0355 at 289 - 302.5 m.

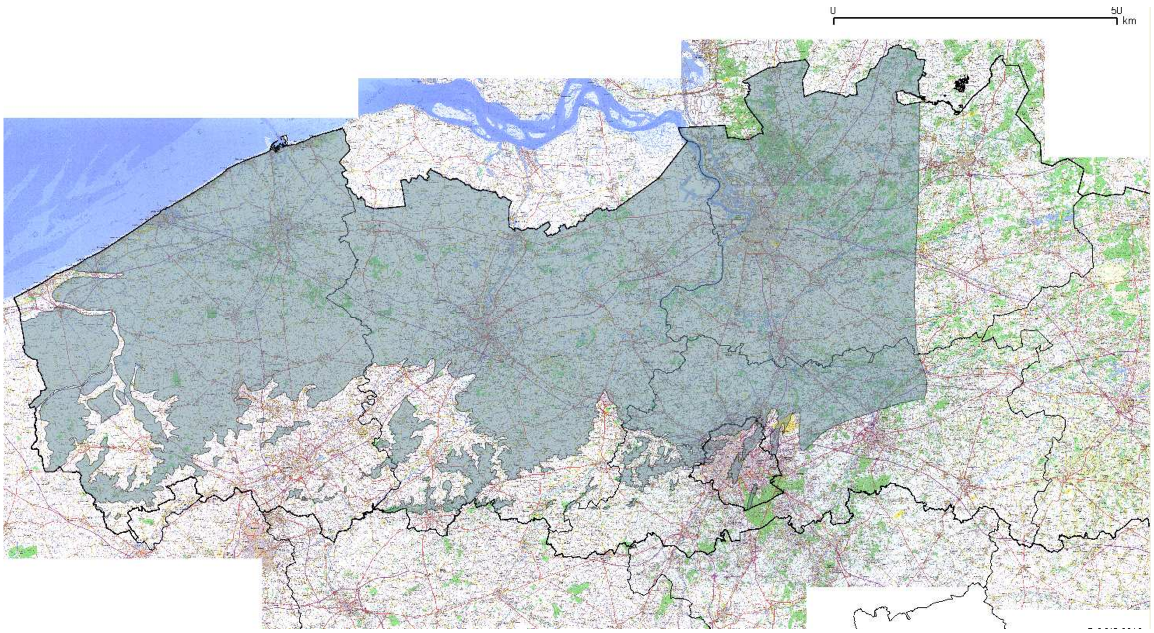


Fig. 5 Distribution map of the Kortemark Member of the Tielt Formation.

Previous names: Geological map 1/40.000 (Conseil géologique, 1909): Ypresian Yc (silty topzone)
Stratigraphic Register (Conseil géologique, 1929, 1932): Lower-Ypresian Y1a (pro .parte).

2.2. Kortrijk Formation

Name: Lyell already introduced the name Kortrijk Clay in 1852 to characterise the clays containing shells and nummulites in the area of Kortrijk. The name was recycled to the status of Formation (Maréchal, 1994, Wouters & Vandenberghe, 1994, Steurbaut, 1998) corresponding to the lower, essentially clayey part of the previous Ieper (Ypres) Formation, which as a consequence, has been elevated to Group status.

General aspect: The Kortrijk Formation is a marine deposit, composed essentially of clayey sediments. The middle part (more or less 65% of the total thickness) can be calcareous. Except for some shell-bearing layers, the Kortrijk Formation is rather poor in macrofossils (for an overview see Steurbaut & Nolf, 1986).
In eastern and southeastern direction the unit becomes gradually more coarse to transform towards Brabant, the Campine and the eastern part of Hainaut into a series of fine sands and clayey sand in which several units can be recognised

(Vorst Sands or Mons-en-Pévèle Sands in Brabant and the Campine, Mons-en-Pévèle in the Mons region and Godarville Sands, Peissant Sands and Morlanwelz Argilite in the Charleroi region; see Steurbaut & Nolf, 1986).
The age is Early Eocene (Ypresian), from the base of Biochron NP 10 to the middle of Biochron NP 12 (Steurbaut, 1998), and is situated between ca 54.8 and ca 51.5 Ma (Berggren et al., 1995).

Geographical extension: The Kortrijk Formation occurs in the western, central and northern parts of the country. The outcrops are located in the north of the province of Hainaut and the south of West-Flanders. The top zone is exposed in the south of East-Flanders; the base is locally seen in the west of 'Brabant Wallon'. Outliers appear in the Mons Basin.
The Formation rests on the Landen Group or locally on Palaeozoic rocks. The Tielt Formation covers the Formation. The under- and overlying units are essentially sandy and are easy to distinguish from the Kortrijk Formation.
The maximum thickness reaches approximately 110 m in the north of West- and East-Flanders, but decreases first slowly, and then rather quickly in eastern direction (Vandenberghe et al., 1991; De Ceukelaire & Jacobs, 1998) – (Fig. 6).

The Kortrijk Formation is subdivided into four members, from top to base :
Aalbeke Member
Moen (Roubaix) Member
Saint-Maur (Orchies) Member
Mont-Héribu Member

2.2.1. Aalbeke Member (KoAa)

Name: De Moor & Geets (1975) proposed the name "Limon argileux d'Aalbeke". The name is derived from the locality Aalbeke, near Kortrijk (West-Flanders). Steurbaut & Nolf (1986, p. 125) described this unit formally for the first time.

General aspect: This marine lithostratigraphic unit is almost entirely composed of very fine silty clay, without any sand fraction. Small irregular shaped pyrite concretions can locally be very abundant. Isolated phosphatic concretions are known from boreholes (e.g. Melle – 70E0183 and Kallo – 27E0148 boreholes) and outcrops. They are common in the Heester clay pit - at the base of the Aalbeke Clay and containing crab or lobster remains (Steurbaut & Nolf, 1986). The top of this Member is bioturbated and infilled by sand from the overlying units.

Geographical extension: The Aalbeke Member is exposed on the hills in the south of West-Flanders (Kortrijk region). It is found in boreholes in East-and West-Flanders. It rests on the Moen/Roubaix Member from which it can be distinguished by its homogeneity and by the sudden increase of the clay fraction and is superimposed by the Tielt Formation. The maximum known thickness (about 20 m) was found in Ieper and Knokke. In the region of Kortrijk the thickness attains roughly 10 m. In Kallo this distinctive unit reaches a thickness of 8 m (302.5 -310 m) and in Doel 6 m (347 – 353 m).

2.2.2. Moen (Roubaix) Member (KoMo)

Name: Gosselet (1874) introduced the unit to distinguish the calcareous heterogeneous silty clays from the under- and overlying non-calcareous stiff clays. Steurbaut & Nolf (1986, p.123) formally described this unit for the first time. The name originates from Roubaix, a town in the northwest of France, at about 10 km NE of Lille. The Moen Member defined by Marechal & Laga (1988) is named after a small village near the town of Kortrijk (West-Flanders). The term Moen is used as a synonym for Roubaix, but boundary beds have not been defined for the latter.

General aspect: This Member is a marine lithostratigraphic unit with a heterogeneous composition. This phenomenon is most evident in the southern part of the depositional area (e.g. the Kortrijk region), where the Member is composed of clayey, coarse silt, in which beds containing up to 10 % of fine and very fine sand appear. In northern direction the heterogeneity decreases and the main texture of the sediment is clayey silt. This unit is calcareous over most of the section and contains moreover different thin compact shell-grit layers and nummulite beds. The Member shows no substantial glauconite enrichment except for one level in the upper part of the Member. This glauconitic bed called 'Lit glauconifère de Tielt' by De Coninck (1973) was encountered in several boreholes in NW-Belgium (Kallo – 27E0148, Tielt - 68E0169, Ooigem – 83E0407, etc.). The top of the Member is bioturbated. The Moen Member was traversed in Kallo – 14E0355 from 310 till 360 m and in Doel – 14E0240 from 353 till 390 m.

Geographical extension: The Moen Member is encountered over NW-France, N-Hainaut, East- and West-Flanders. In south-eastern and eastern direction, this unit passes into the Mons-en-Pévèle Sands. It covers the Saint-Maur Member, from which it differs by its heterogeneity and sandy layers. It is covered by the Aalbeke Member. It is exposed in the north of Hainaut and the south of West-Flanders, where it is 40 m thick. It can be followed in northern direction in boreholes where a thickness of 60 m is attained.

2.2.3. Saint-Maur (Orchies) Member (KoSm)

Name: Gosselet (1874, p. 611) introduced the Orchies Clay to differentiate the stiff and compact clay with sandy base from the underlying Thanetian Ostricourt Sands and the overlying Roubaix Clay or Mons-en-Pévèle Sands. The unit was used in this sense by Steurbaut & Nolf (1986, p. 122). Afterward most authors (Marechal, 1993; Wouters & Vandenberghe, 1994; Steurbaut, 1998) assigned the status of Member to the Mont-Héribu Clay and Orchies Clay. This unit was named after the village of Orchies, located in northern France at about 20 km south-east of Lille. The name St.Maur Member may be a junior synonym for the Orchies Member defined by Marechal & Laga (1988). Nevertheless, as no stratotype has been designed for the Orchies Clay and no provision has been made for the relationship with the Mont-Héribus beds it is not evident to simply exchange the names Orchies for Saint-Maur in the stratigraphic column.

General aspect: This marine lithostratigraphic unit is a homogeneous deposit, mainly consisting of black, bluish or grey very fine silty slightly calcareous clay with a few thin intercalations of coarse silty clay or clayey, very fine silt. Some carbonate nodules and plant debris can be found. Glauconite and volcanic ash layers are encountered at the base (Moorkens et al., 2000).

Geographical extension: The Saint-Maur Member is encountered over the north of Hainaut, East- and West-Flanders, as far as N-France and eastwards over part of Brabant and the province of Antwerp. To the southeast and east, this unit becomes more sandy.
It rests on the Mont-Héribu Member (sensu Welkenhuysen & De Ceukelaire, 2009), from which it can easily be distinguished by the sudden disappearance of the sand fraction or on the Grandglise Member (Hannut Formation) in the north of Hainaut. It is overlain by the Moen Member, or by the Mons-en-Pévèle Sands to the southeast. It is found in northern boreholes (Tielt – 68E0169, Ooigem – 83E0407, Kallo – 27E0148) where the thickness is about de 25 m (Geets, 1990): Kallo – 14E0355 : 370-400 m, Doel – 14E0240 : 390-440 m.

2.2.4. Mont-Héribu Member (KoMh)

Name: Cornet introduced the name Eribus Clay ("Argile de l'Eribus") in 1874 (p. 567). The oldest citation of the locality Eribus in a geological context is by Ortlieb & Chellonneix (1870, p. 168). The unit is named after a hill near Mons (Bergen, Hainaut), and was described as a Member by De Coninck, Geets & Willems (1983, p.98). Steurbaut & Nolf (1986, p. 123) gave this unit the status of layer within the Saint-Maur (Orchies) Member. Although this unit has been retained as a member of the Kortrijk Formation in the lithostratigraphic scale of Belgium, its interpretation and significance, hence place in the stratigraphical table is becoming again a matter for discussion as a result of the ONDRAF/NIRAS exploration activities.

General aspect: The Mont-Héribu Member is a shallow marine deposit, consisting of an alternation of horizontally laminated glauconitic clayey sand, of sandy clays and compact silty clays or clayey silts. Locally burrow traces can be found. The base consists of oxidised and lithified clayey sand with lenses of pure sand.

Geographical extension: The Mont-Héribu Member is probably present in the whole basin in which the Kortrijk Formation is deposited. The Member is about 6 m thick in the Mons Basin. The unit becomes very thin to the centre of the Basin and consists of glauconitic fine-grained sand (approximately 1 m thick in the boreholes of Kallo (27E0148) and Doel (14E0240), 10 cm in the Knokke (11E0138) borehole). The Member crops out in the north of Hainaut and the southwest of Brabant, and in some places in N-France. In Welkenhuysen & De Ceukelaire (2009) the Mont-Héribu Member encompasses the complete more sandy and porous sequence at the base of the Ypresian Clay interval, hence reaches greater thicknesses, compared to the Steurbout & Nolf model.

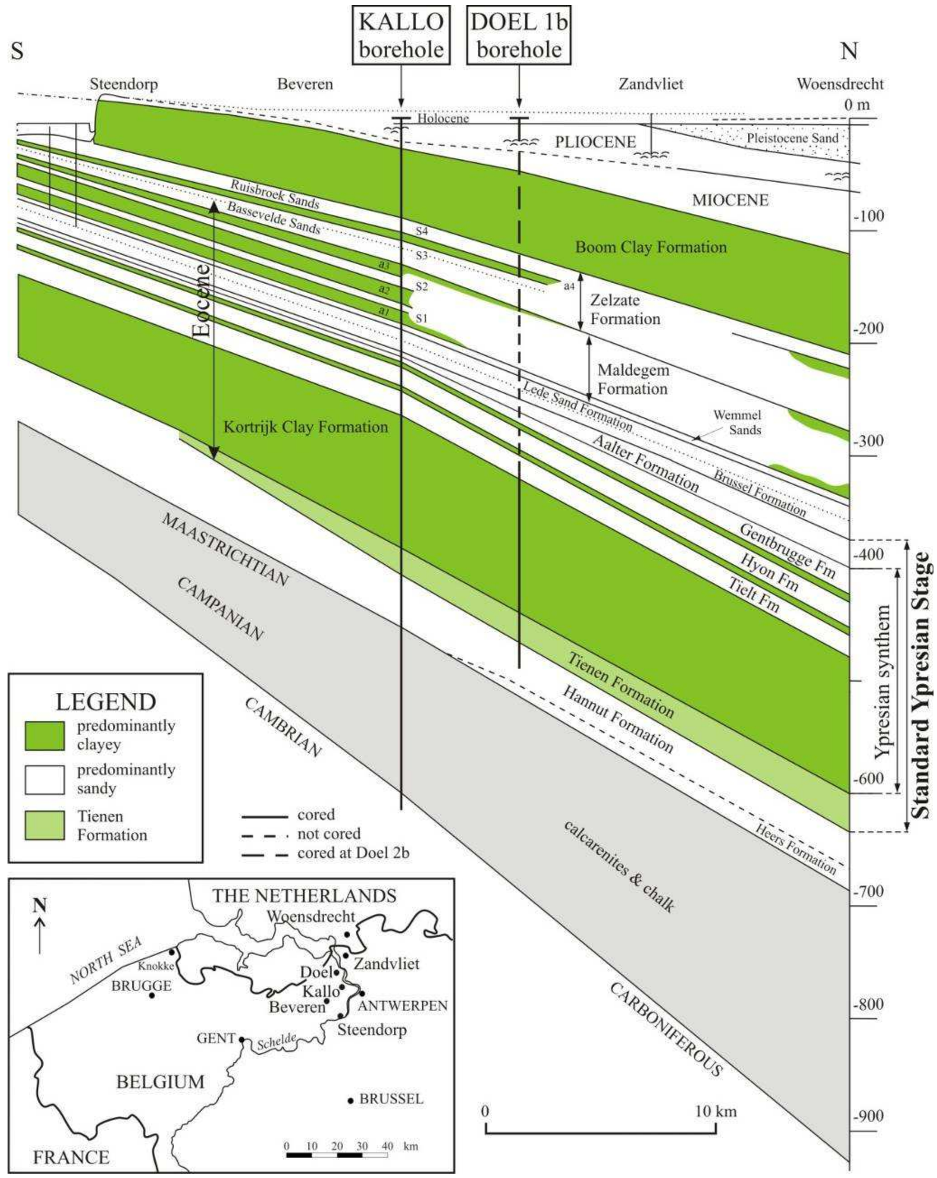


Fig.6. Cross-section through ON-Doel (BGD014E0239-240) and Kallo (BGD027E0148) boreholes, showing relationship between chronostratigraphy and lithostratigraphy (from Steurbaut, 2006).

3. Data acquisition

3.1. Selecting boreholes

The data acquisition porcess was largely similar to a Human Intrusion project (De Ceukelaire et al., 2011). We refer to this report for a more detailed description.

A first step was to make the inventory all boreholes drilled into the Ypresian formations of Belgium, defined by the lower formation boundary of the Kortrijk Formation, obtained by the isohyps project (Vancampenhout, 2005). Only boreholes into the Kortrijk Formation are selected, but boreholes going through the Kortemark Member are also reaching the Kortrijk Formation. Boreholes going into but not through the Kortemark Member will not be selected. Nevertheless, the Kortemark Member is mostly not thick enough to reach a 10 m thick penetration without reaching the Kortrijk clay. This query results in 3011 boreholes (database consultation 12/2010)(Fig. 7).

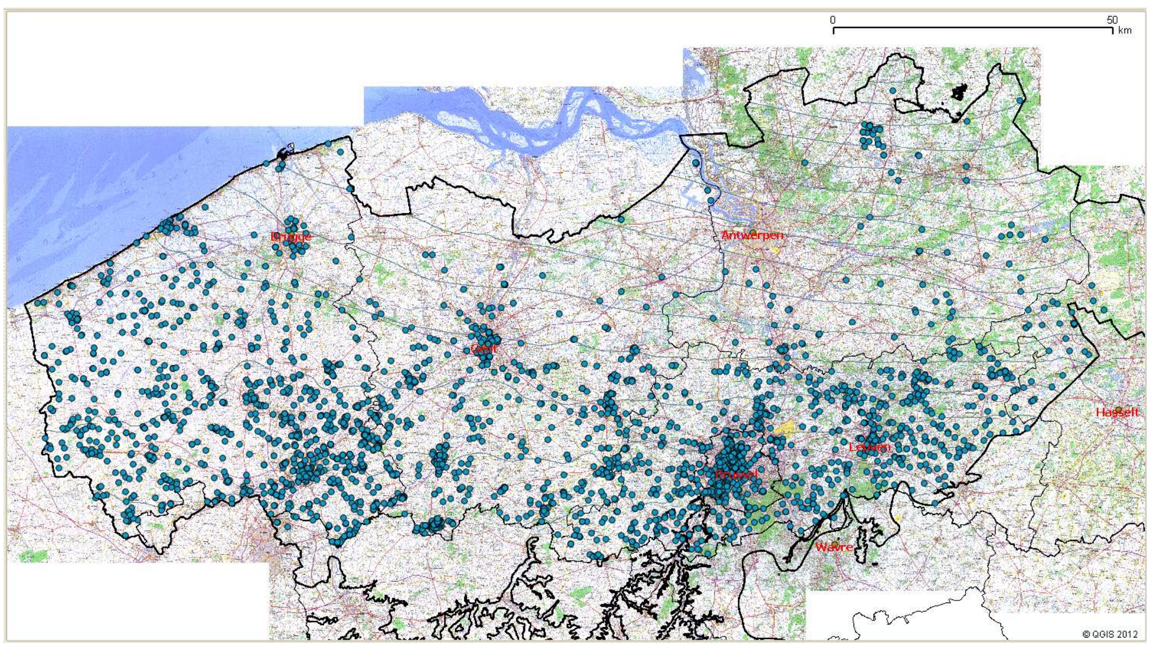


Fig. 7. Map showing boreholes from the GSB archive going into the Ypresian clay. The area of investigation is delimited according to a map of the base of the Kortrijk Formation from the isohypse project 2005.

The next step was to narrow the investigation to those boreholes accompanied with geophysical logs. The resulting dataset contains 662 boreholes, remarkably evenly spread over the subcrop area (Fig. 8).

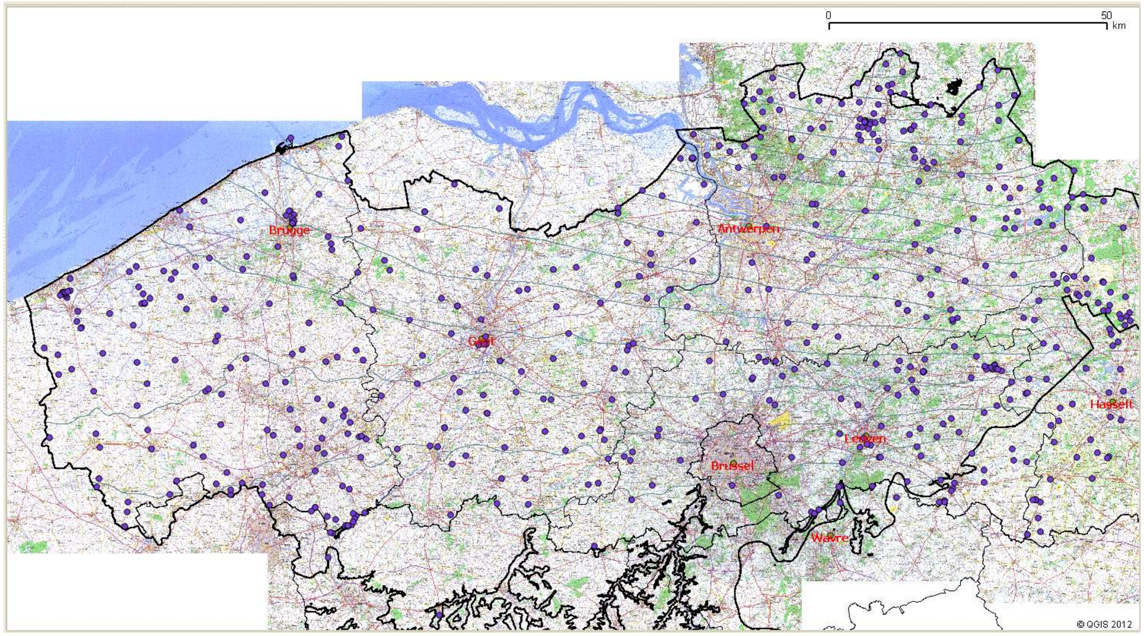


Fig. 8. Map showing boreholes from the GSB archive in the area of interest and logged with geophysical well logs, without specification of the logging tool or the logged interval (662 boreholes).

To create the map of the boreholes with geophysical well logs in the Ypresian clay, a GIS application was used. The isohypses map of the top of the Kortrijk Formation was compared with the depth of the logs. All logs going deeper than this level were kept, based on the registered logging depth. For the logs in the Tielt Formation, a similar method was followed. In this case, the isohypses of base Gent Formation and base Quaternary in the subcrop area of the Tielt Formation were compared with the logs to create a list of all logs deeper than these levels.

Because geophysical well logs are not always continuous, a manual control of the logs was necessary. The interpretation of this selection was combined with a stratigraphic control and corrections were applied when necessary (Fig. 9).

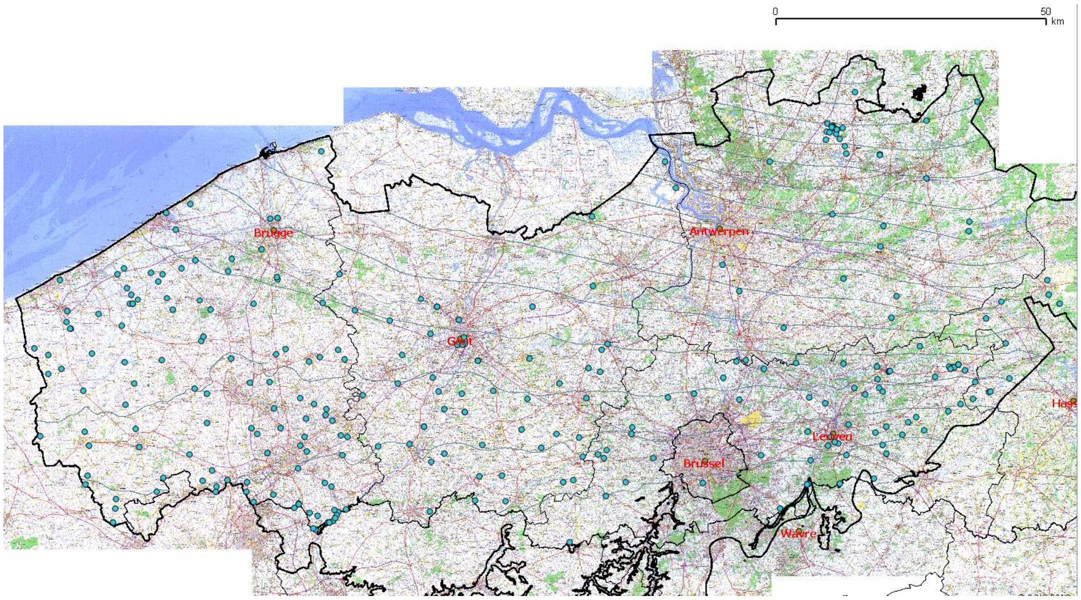


Fig. 9. Map of all logs in the area of interest and penetrating Kortrijk Formation or Kortemark Member for at least 15 m

The aim of the study is to evaluate the caliper anomalies. So the data-set was further restricted to well-logs with a usable caliper data. A final set of 107 wells with useful log information was built (Fig. 10).

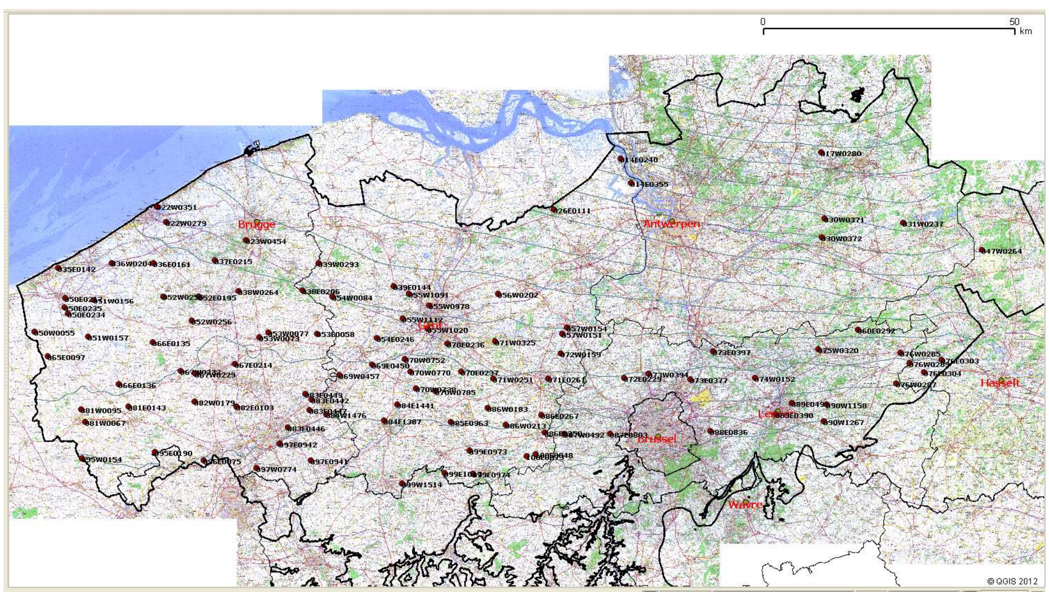


Fig. 10. Overview of boreholes in Ypresian Clay with usable caliper logs (107 boreholes).

3.2. Collecting existing geophysical interpretation data for the Kortrijk Formation

Several publications or sources of unpublished data already made use of the geophysical well logs to make an interpretation of the different members in the Ypresian clays. We selected the most important ones.

3.2.1. Archives GSB

Since the 1980ies, geophysical measurements are performed on a systematic basis and used for the stratigraphical interpretation. Initially, few boreholes were measured in the area of interest. Since the end of the 1990ties much more data has become available. In general, a logged borehole has also a lithological description of cuttings and astratigraphical interpretation. Description and interpretation are incorporated in the archives of the GSB.

3.2.2. Vandenberghe et al. (1988)

This publication displays 7 cross sections, using the gamma ray measurements to make a lithological subdivision of the Kortrijk Formation. 56 boreholes spread over Flanders were used (Fig. 11). Trends in log signature allowed to distinguish 5 horizons and sub-levels, irrespective of the existing stratigraphic subdivisions, which were mostly controlled by paleontological data (Fig. 12). This was the most reliable log interpretation possible for the first phase of geophysical well logs. These were not yet designed for a particular target but mostly applied to shallow water wells, because these form the vast majority of all boreholes drilled (see De Ceukelaire et al., 2011).

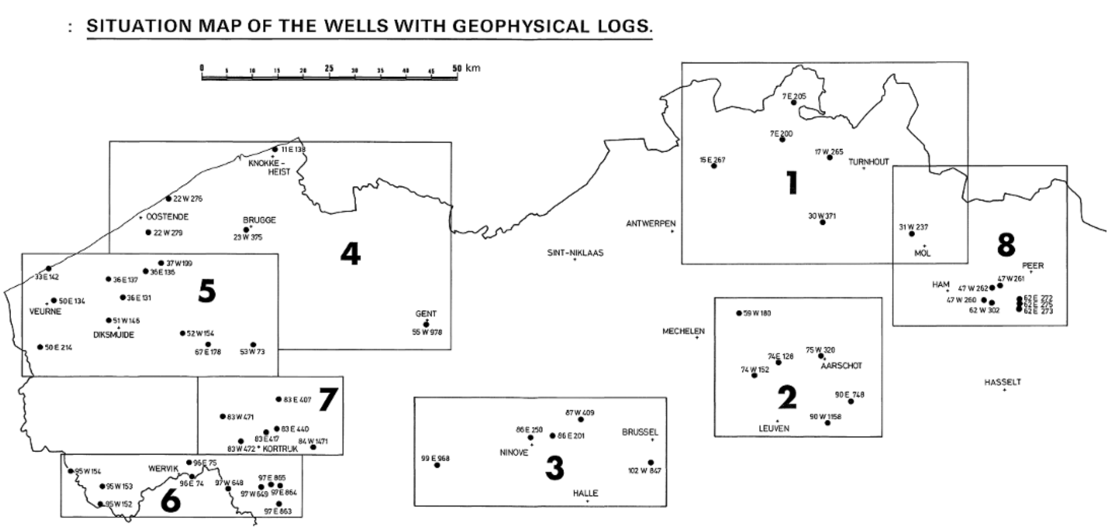


Fig. 11. Map showing location of logged boreholes used in Vandenberghe et al. 1988.

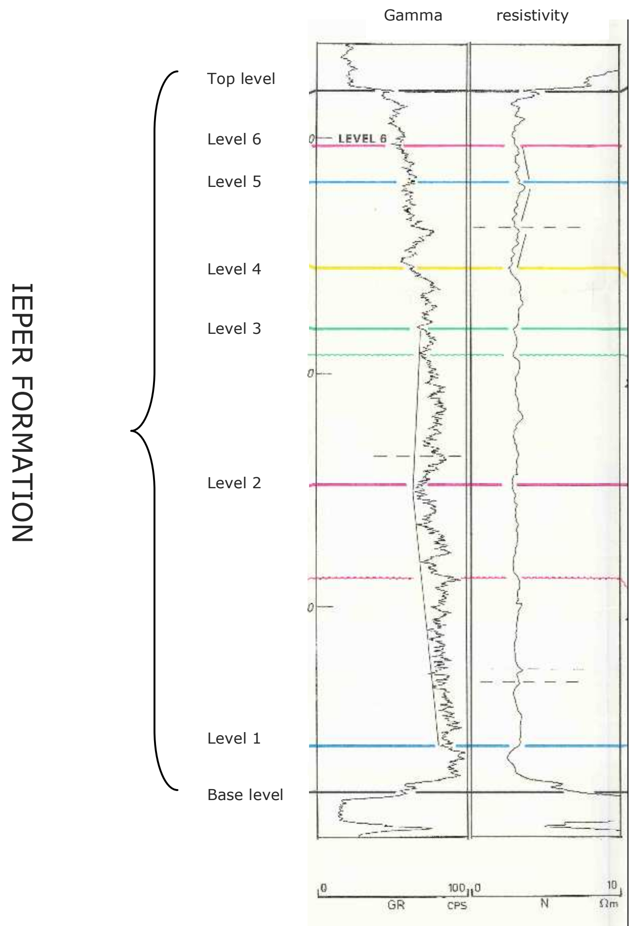


Fig. 12. Example (011E0138-Knokke) of the subdivision according to Vandenberghe et al, 1988.Top level is the top of the Tielt Formation, Base level is the base of the Kortrijk Formation. The different levels within the Kortrijk Formation (1 to 5) are based on gamma-ray and resistivity characteristics.

3.2.3. De Ceukelaire & Jacobs (1998)

This publication deals with geophysical well logs in the western part of Flanders. Contrary to Vandenberghe et al. (1988), resistivity measurements were used from 56 boreholes (Fig. 13). The outcome of a previous study by Bart De Corte (Master thesis, 1994) was also included in this publication. De Corte distinguished 23 boundary beds to subdivide the clay in the province East Flanders. Such detailed subdivision was not possible over a larger area. Nevertheless, good quality resistivity measurements allowed to recognize 7 horizons in practically all wells studied (Fig. 14). As with Vandenberghe et al. (1988), these levels were chosen in function of the log response, irrespective of the existing stratigraphic subdivision and were characterized by different colour marks.

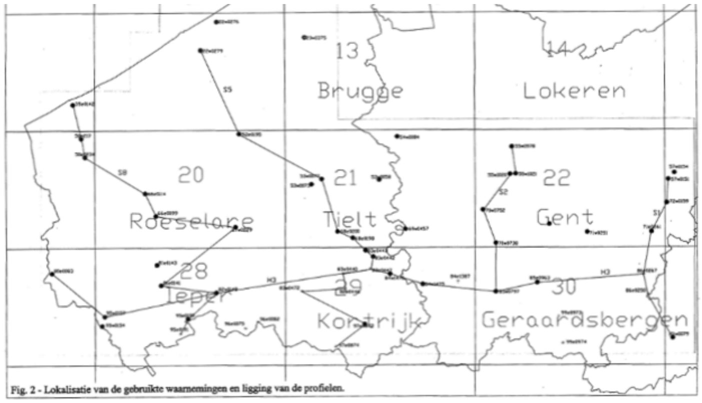


Fig. 13. Localisation of boreholes studied in De Ceukelaire & Jacobs (1998)

a b

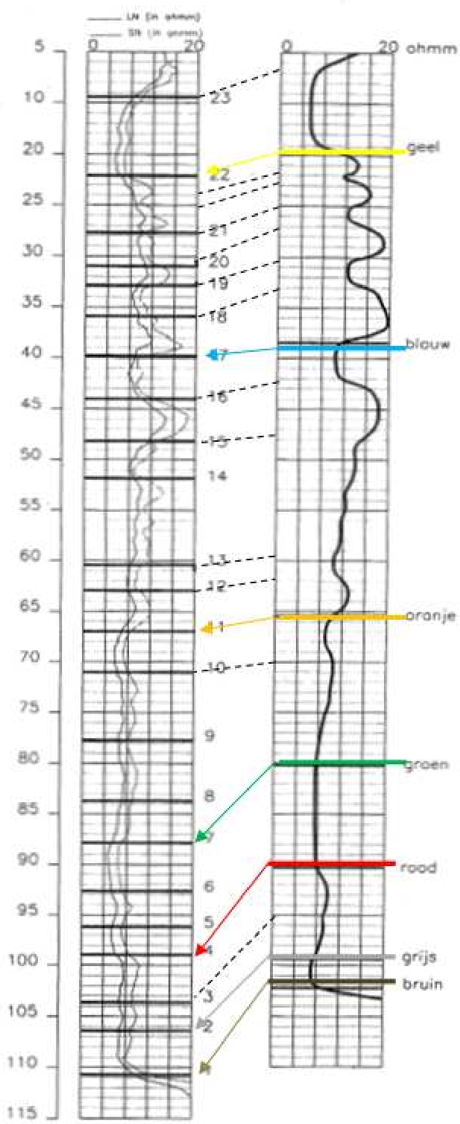


Fig. 14. Example of subdivision of the Kortrijk Formation in De Ceukelaire & Jacobs, 1998. a) Long-normal and short-normal resistivity log showing all levels distinguished in De Corte (1994); b) generic resistivity log showing 7 boundaries, each associated with a colour.

¶

3.2.4. Welkenhuysen & De Ceukelaire (2009)

This publication is an overview of the geophysical well-log properties through the whole Cenozoic (Tertiary) stratigraphical section. Resistivity as well as gamma ray were used. The base set was composed by the new piezometric wells drilled for VMM (Vlaamse Milieu Maatschappij) to create a regional database for monitoring water level and quality. During this drilling campaign conducted in 2005-2006, 51 boreholes have penetrated the Ypresian clays and consequently were used in this study (Fig. 16). Contrary to previous correlation schemes based on electrical stratigraphy, this study made the link between the established lithostratigraphic subdivision, adopted by the Stratigraphic Commission, and its recognition in the geophysical well log signature (Fig. 15).

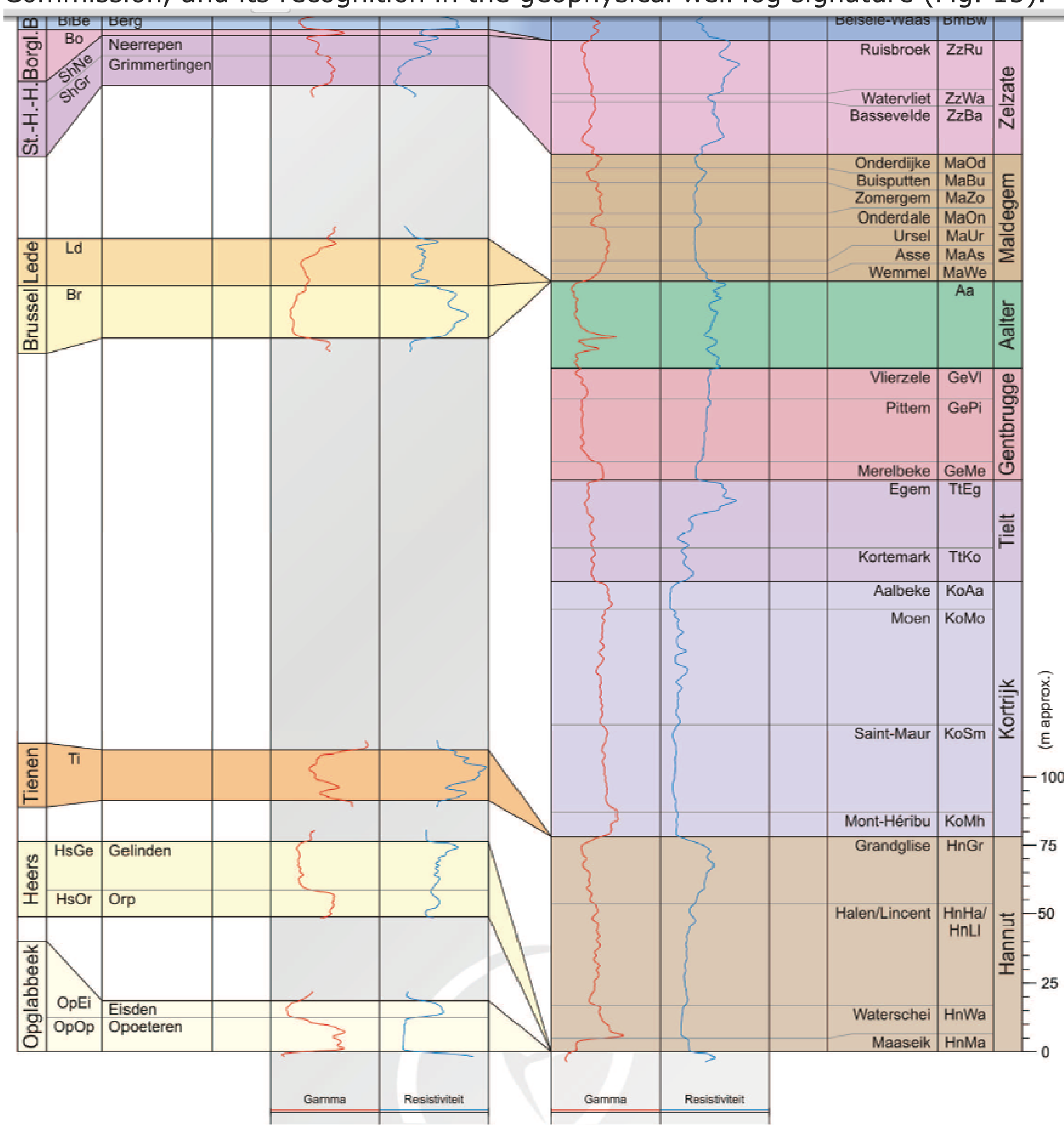


Fig. 15. Stratigraphical subdivision of the Paleogene, based on geophysical well log signature, from Welkenhuysen & De Ceukelaire, 2009.

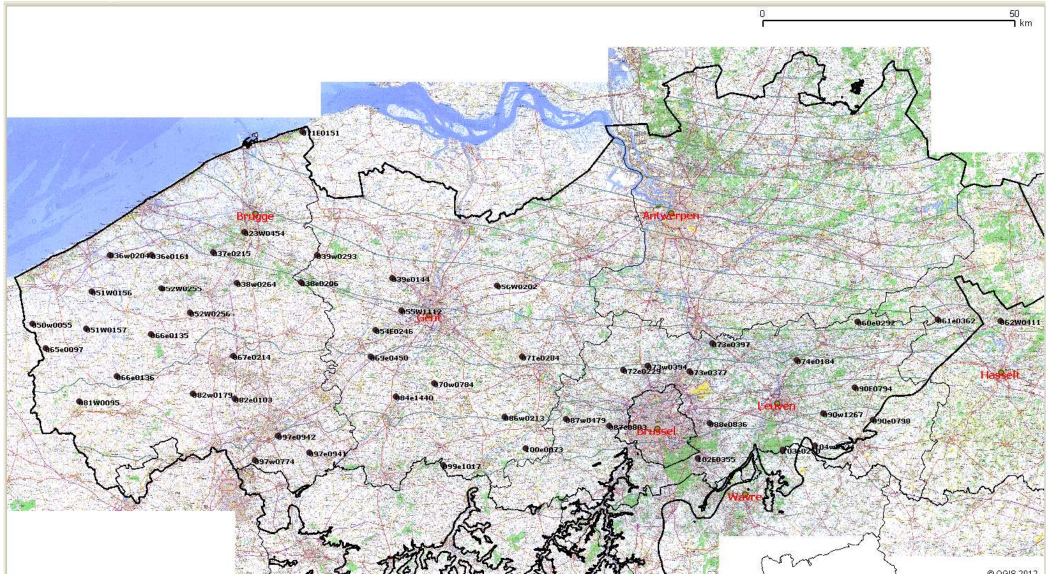


Fig. 16. Location of VMM piezometric wells penetrating the Ypresian clays, set against the isohyps map of the Kortrijk Formation.

The identification of correlation levels, based on integrated log response with control from drill cuttings and comparison with the lithostratigraphic scale is regarded as the best and most practical way to achieve the stratigraphic subdivision in new boreholes. This approach – the establishment of an electrical stratigraphy as proxy for the lithostratigraphical subdivision - is certainly going to be supported by the Stratigraphic Commission. Despite the different approach through the years, a consistent and practical subdivision of the Ypresian clays appears feasible and has been successfully used for compiling the new geological map of Belgium – Flemish region (Table 2).

Table 2. Overview of the different subdivisions used in the three publications discussed (1988, 1998, 2009), completed by granulometric boundaries established by Stephan Geets (1991) and the boundary beds by De Corte (1994).

	VDB 1988	MDC 1998	KW-MDC 2009	SG gran	BDC 1994
Top Kortrijk	Black top level	-		4.1	23
Base Aalbeke	Geel level 4	geel	Aalbeke	3.3	22
					21
					19
	Groen level 3	Blauw			17
					14
Base Moen		Oranje	Moen		11
	Roze Level2	Groen			8
Base SaintMaur		Rood	Saint Maur	3.2	4
	Blue level 1	Grijs			2
Base Kortrijk	Black base level	Bruin	Mont Héribu		1

Note, however, that the member of Mont Héribu used in these studies and on the geological map sheet explanations, consists of the Mont Héribu sand and the stiff clay, which already forms the base of the overlying Saint Maur member. More generally, the boundaries between the lithological units may be drawn differently from pure lithological grounds expressed by geophysical well logs and the biostratigraphically-induced subdivision which introduces the time component in the succession.

3.3. Creating isohypses for the different members

Based on the interpretation of collected data, isohyps map of the different members are constructed (Figs. 17/1 - 6). We refer to the Human intrusion report (De Ceukelaire et al., 2011) for a more thorough discussion of the technical characteristics and interpretation of these isohyps maps.

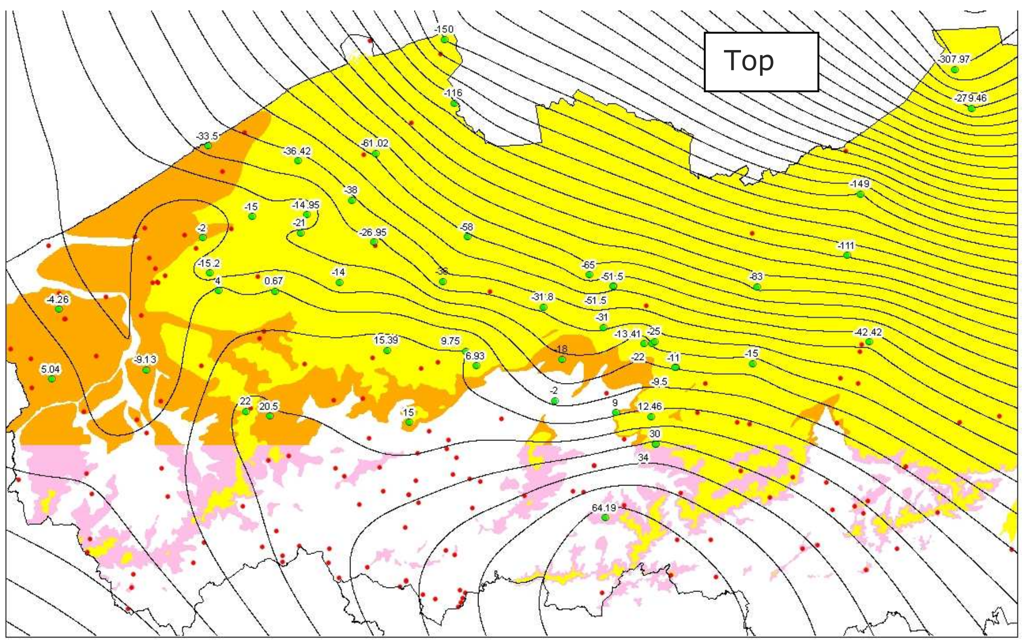


Fig. 17/1. Isohyps map of the top of the Kortemark member (Tielt Formation)

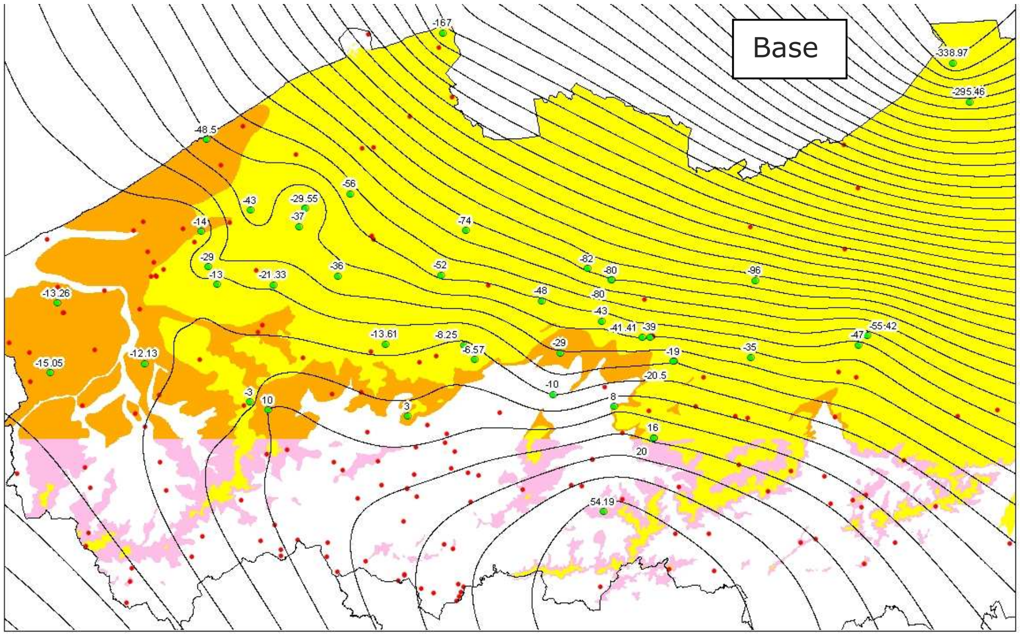


Fig. 17/2. Isohyps map of the base of the Kortemark member (Tielt Formation)

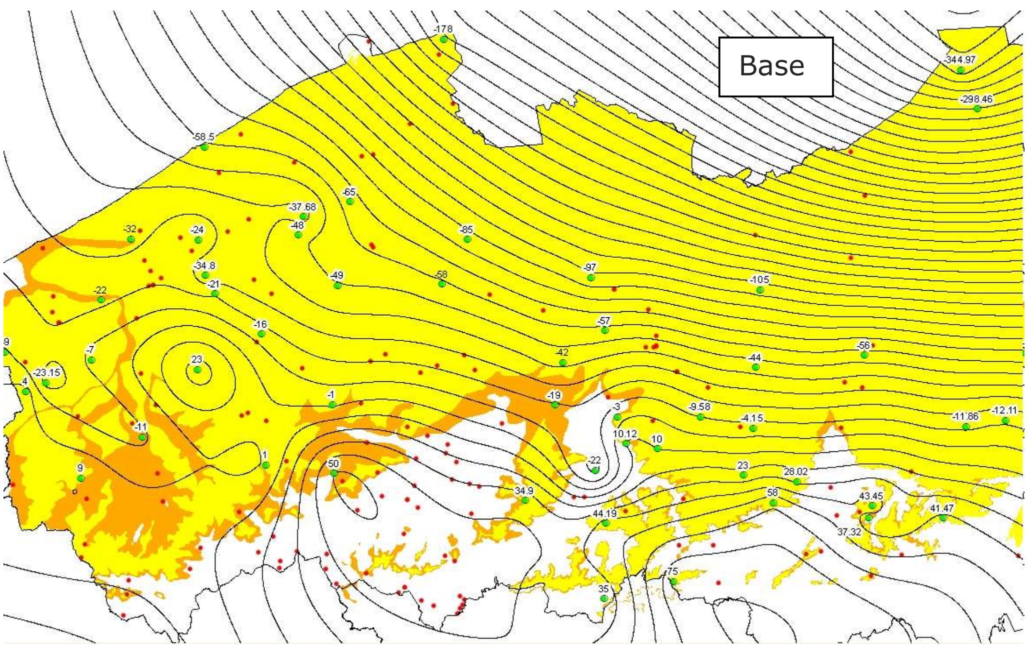


Fig. 17/3. Isohyps map of the base of the Aalbeke member (Kortrijk Formation)

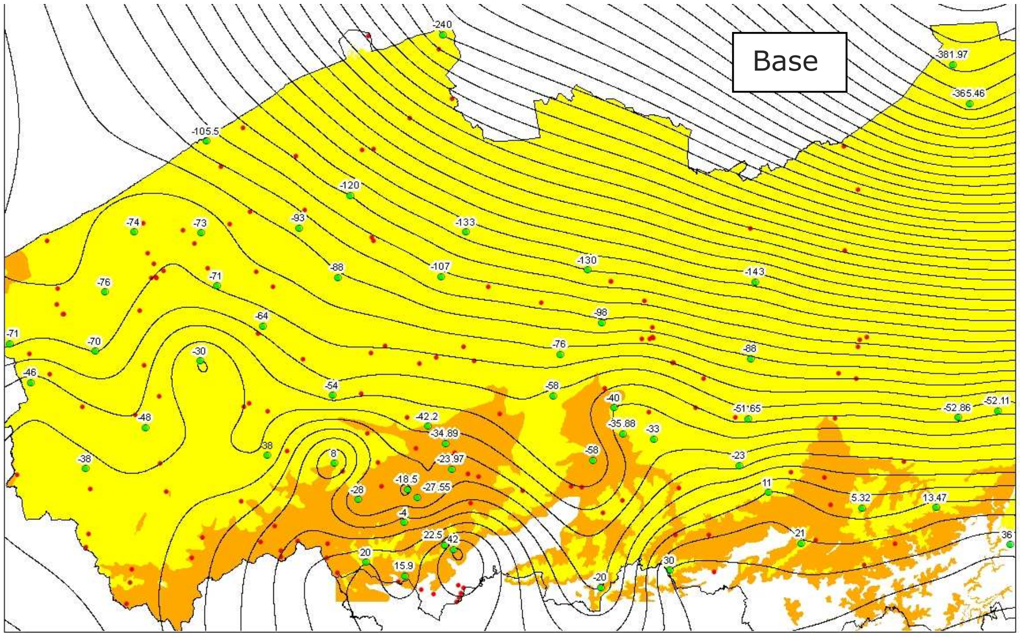


Fig. 17/4. Isohyps map of the base of the Moen member (Kortrijk Formation)

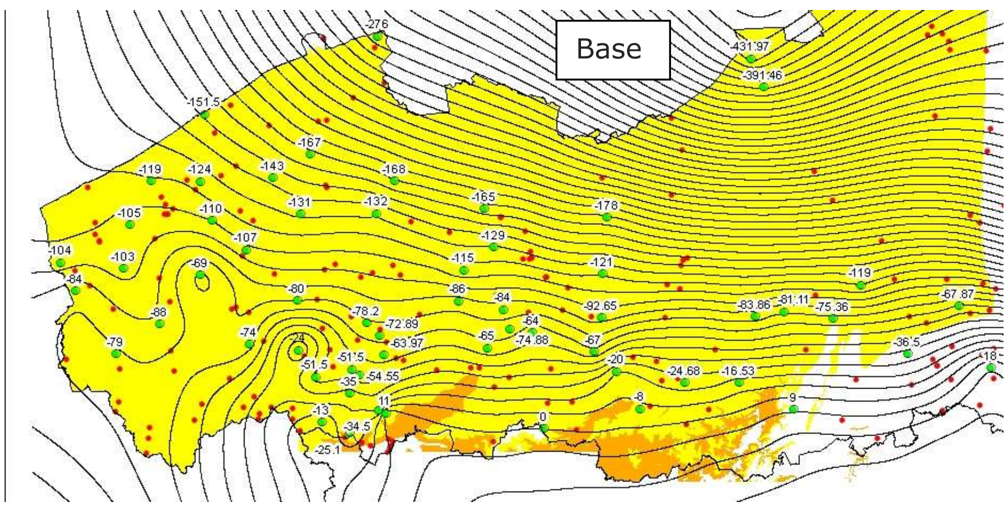


Fig. 17/5. Isohyps map of the base of the Saint-Maur member (Kortrijk Formation)

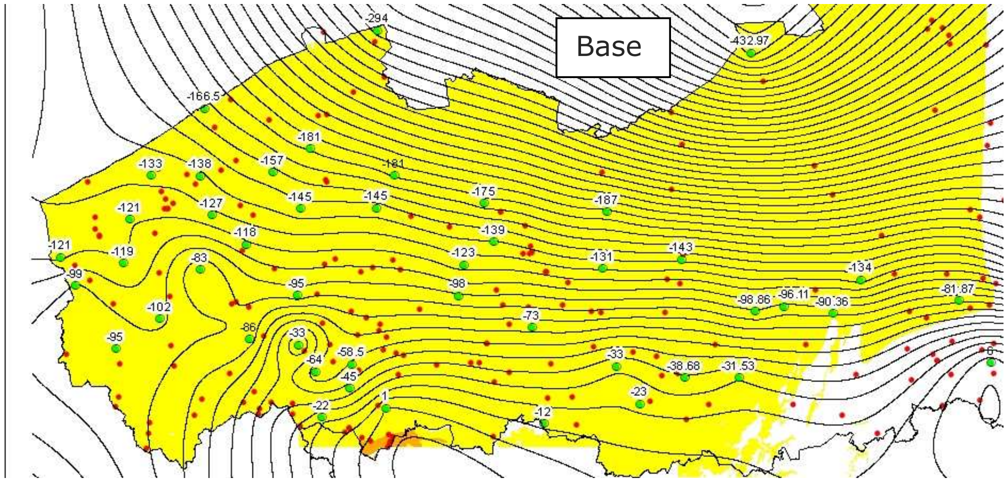


Fig. 17/6. Isohyps map of the base of the Mont-Héribu member (Kortrijk Formation)

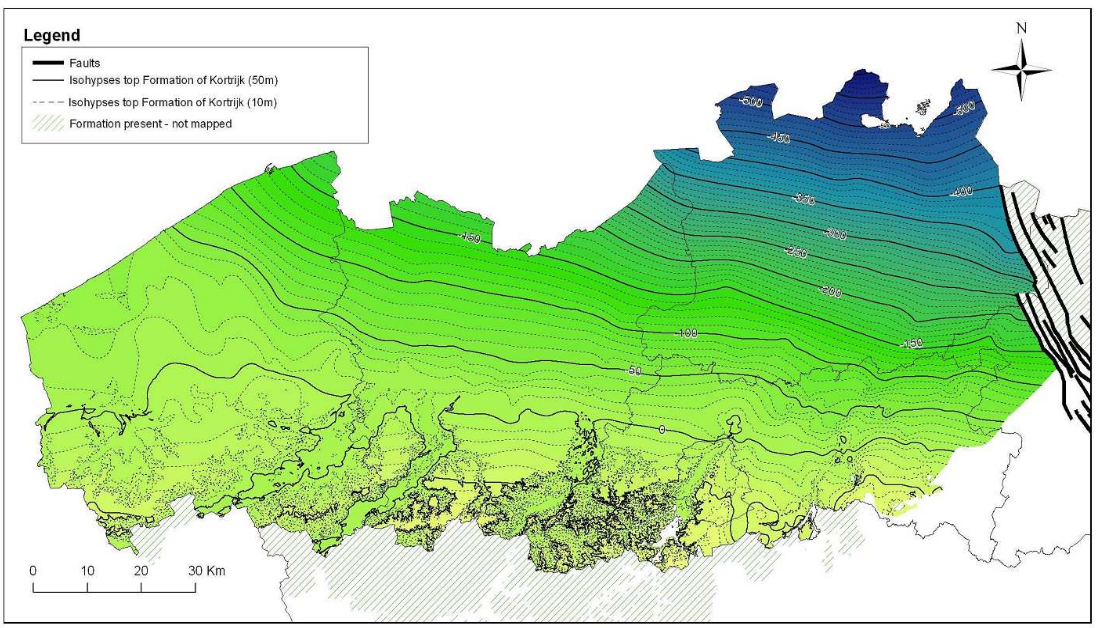


Fig. 17/7. Isohyps map of top Kortrijk Formation (from deconvolution of isohyps maps of base of overlying formations).

4. Caliper log anomalies

4.1. The problematic interpretation and use of caliper logs

In the absence of well-structured digital data, caliper log anomalies were defined on the printed graphs. This method has some constraints and problems. Data quality is not uniform; the generally used 1-arm caliper is subject to mechanical failure or erratic registration. The response from a multiple arm caliper is difficult to compare with a one-arm caliper, which is the standard in most water wells or piezometric wells. Logs with blocky, unnatural caliper log signature were not considered. Large anomalies may be cut off on the paper graphs. Photocopies are not always very clear and sometimes incomplete. The most important problem is the great variety of used scales, which could not be standardized without digitalization.

Another problem is that technical data on drilling conditions is generally missing, so some anomalies may be induced by poor drilling conditions or technial incidents, independent of the stratigraphic level in which they occur. This may partly explain why some caliper anomalies are present in one borehole and not in an adjoining borehole with very geological similar conditions. Negative drilling conditions may include 'mud balling' of the drill bit by clay deposit, reducing the capacity of the drill bit to maintain the rate of penetration and cut a regular wellbore, and increase of the circulating mud density (Fig. 3). Anomalies created this way may extend over an appreciable part of the Ypresian clay interval. They will not be very distinctive and were not considered. On the other hand, wash outs below a casing shoe are easily recognized. As they are not particularly connected to the stratigraphical interval concerned, they stayed out of scope as well.

By taking into account all these concerns, by comparing the logs and taking into account the different problems, "typical" caliper log anomalies could be characterized, leading to the possibility to describe a typology of caliper log anomalies in the Ypresian clay (Fig. 18, example Earth Explorer). However, it should be borne in mind that caliper log anomalies in the Ypresian clays interval are not necessary represented by a herin defined 'typical' response. It should be borne in mind that differences in scale, hence of importance of the observed anomalies, are underestimated in this comparison and that there are boreholes in which anomalies are too weakly expressed to be discerned.

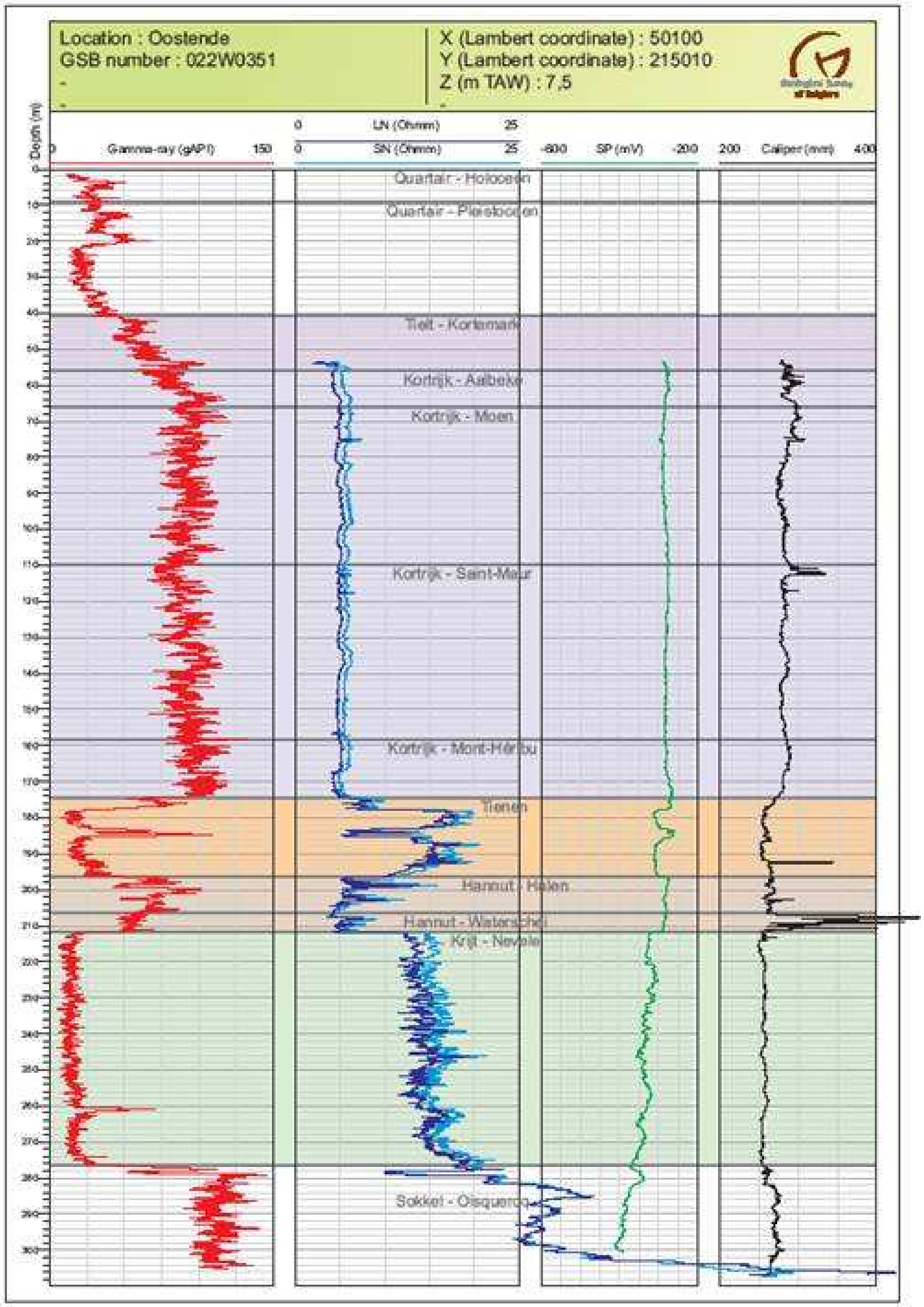


Fig. 18. Borehole Earth Explorer Oostende (GeoDoc 022W0351). Example of washouts over the Ypresian clay section, showing different problems (caliper, right column): a large spike at the Moen – Saint Maur transition, and spalling over the whole Ypresian section (compare to fig. 3).

4.2. Typology of the caliper log anomalies

The well logs are subdivided in several groups according to the visual appearance of the caliper log anomaly.

4.2.1. The case of the ON Doel and Kallo boreholes

The deviation of the caliper in borehole 014E0240 increases sharply starting at 395 m depth moving upwards (fig. 19). This is about 50 m above the base of the Kortrijk Formation. This transition correlates with a decrease of the gamma-ray. This boundary is interpreted as being positioned a few meters above the base of the Moen Member. The Kallo borehole presents a similar caliper graph, resulting in a significant increase of caliper value a few meters above the boundary between the Saint-Maur and Moen members.

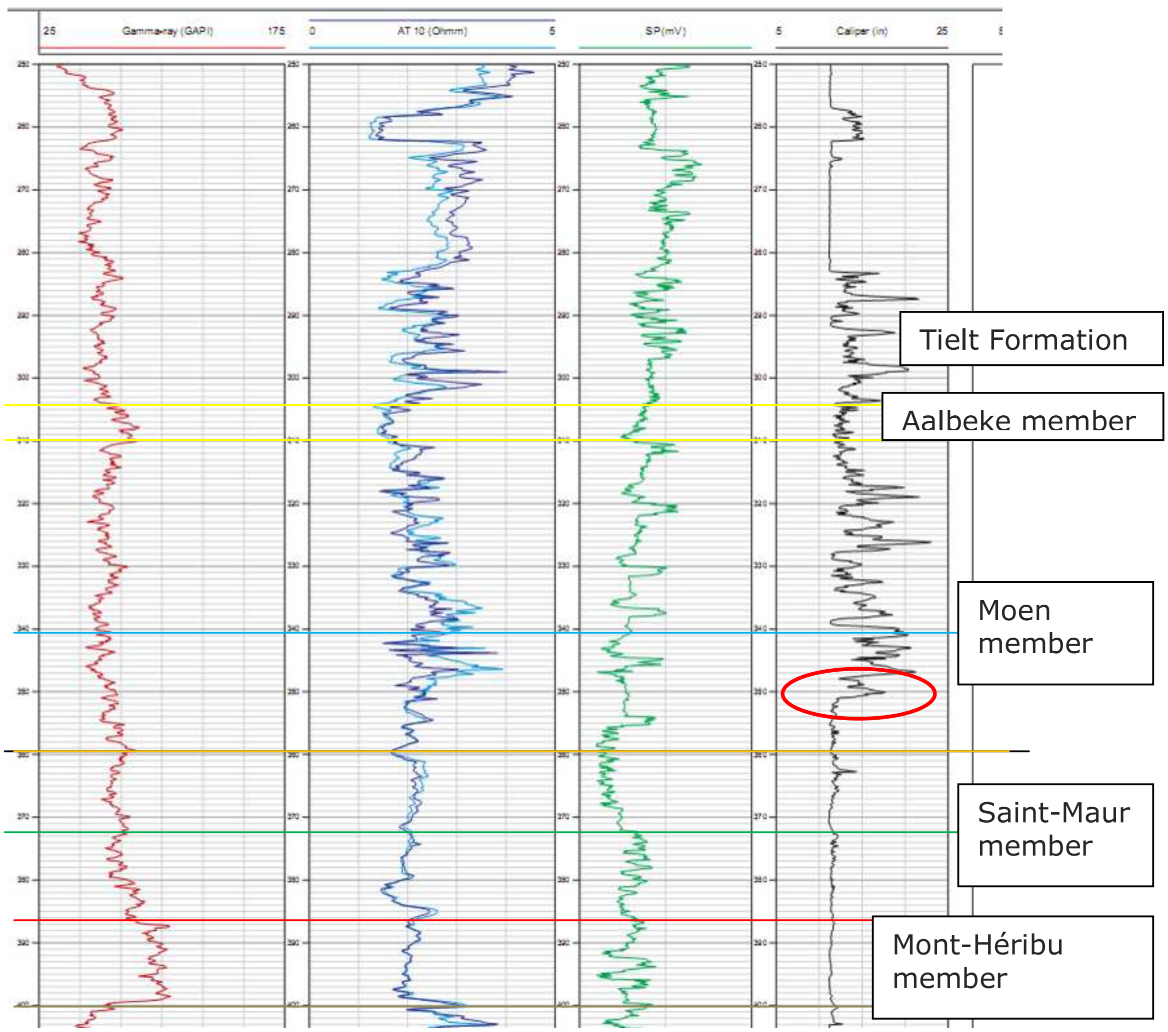


Fig. 19. A large increase of the diameter above the transition from a more silty to a more clayey deposit. Example of ON-Kallo – 14E0355. The coloured lines refer to the subdivision of the Kortrijk formation in De Ceukelaire & Jacobs (1998).

4.2.2. Extensive washouts in the silty top of the Ypresian clays (Kortemark Member)

This is a widespread type of anomaly which is moreover similar to the washouts observed in the loose Upper Landen sands immediately below the Ypresian Clay interval (Fig. 20).

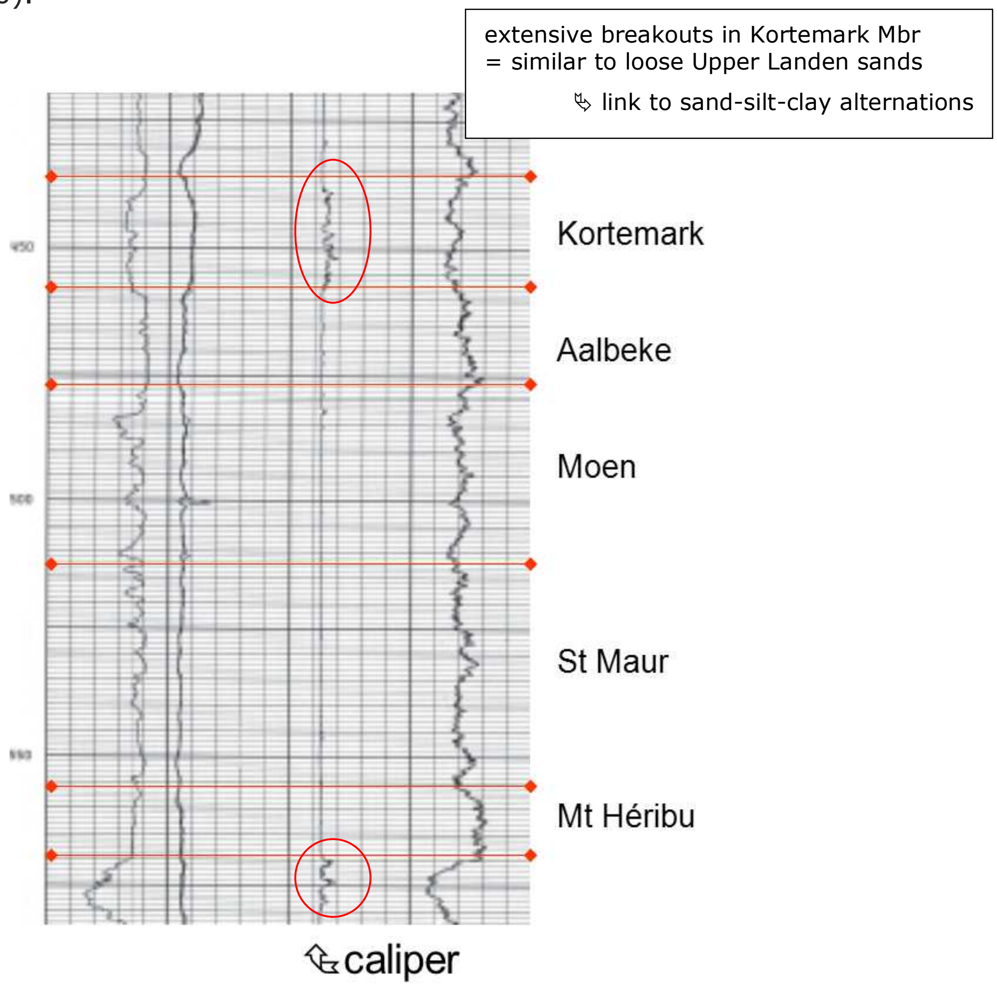


Fig. 21. Extensive and similar wash outs observed on the caliper in the Kortemark Member (Tielt Formation) and the Upper Landen, the latter being composed of loose sands (example: borehole 017W0280).

In this case there is a clear link to sand-silt-clay alternations, whereby beds composed of coarse silt to very fine sand without clay admixture correspond to the most easily erodible granulometric class (cf. Hjulström diagram, Fig. 21).

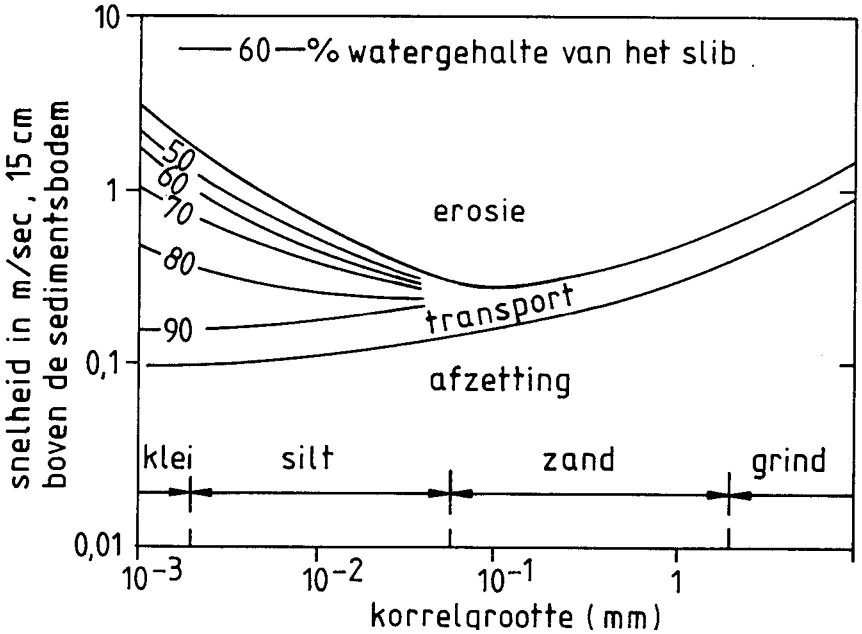


Fig. 21. Hjulström diagram showing relation between erodibility in function of water energy and grain size, with maximum erodibility at the silt-sand transition (from Vandenberghe & Laga, 1991).

4.2.3. Logs with an increase of the diameter above the base of the transition from stiff clay to silty clay layers

A really large increase of the diameter was observed in the base of the Moen member in the boreholes Doel and Kallo (14E0240 and 14E0355) – see also 4.2.1. An anomaly on the same scale was not observed in other boreholes. Its unique nature thus may be due to different drilling conditions in the scientific exploration boreholes, compared to standard water wells. Nevertheless, some other boreholes also have an anomaly at the base of Moen, but of minor extent.

4.2.4. Logs with an increase of diameter from middle stiff-clay to nearly the top of silty-clay layers (across the boundary between the St.-Maur – Moen Members)

Some logs have a clearly higher diameter starting already some meters in the stiff clay to nearly the top of the silty-clay layers. Scale variations can be mentioned, leading to a spiky signature of the caliper log. In fact, an increase of the diameter above the base of the transition stiff clay – silty clay layers is observed (Fig. 22).
The response of the caliper log must be considered meaningful, and shows that the lithological distinction between the different members of the Kortrijk Formation may be very small to non-existent and/or geographically variable.

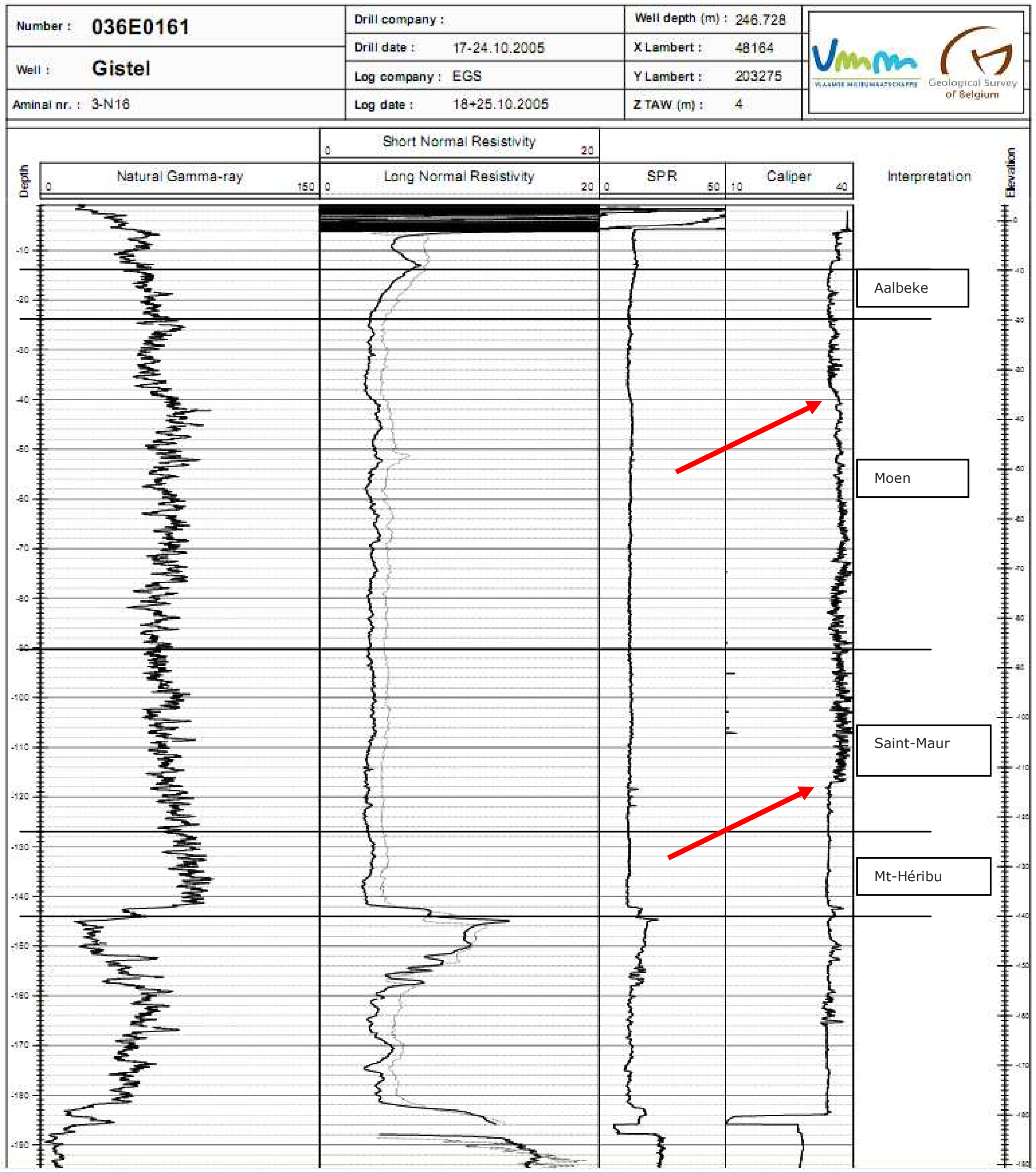


Fig. 22. An increase of diameter from middle Moen till middle or end Saint-Maur. Example : Gistel – 036E0161

4.2.5. Logs with a peak at the transition bedded clay-silt member – stiff clay member

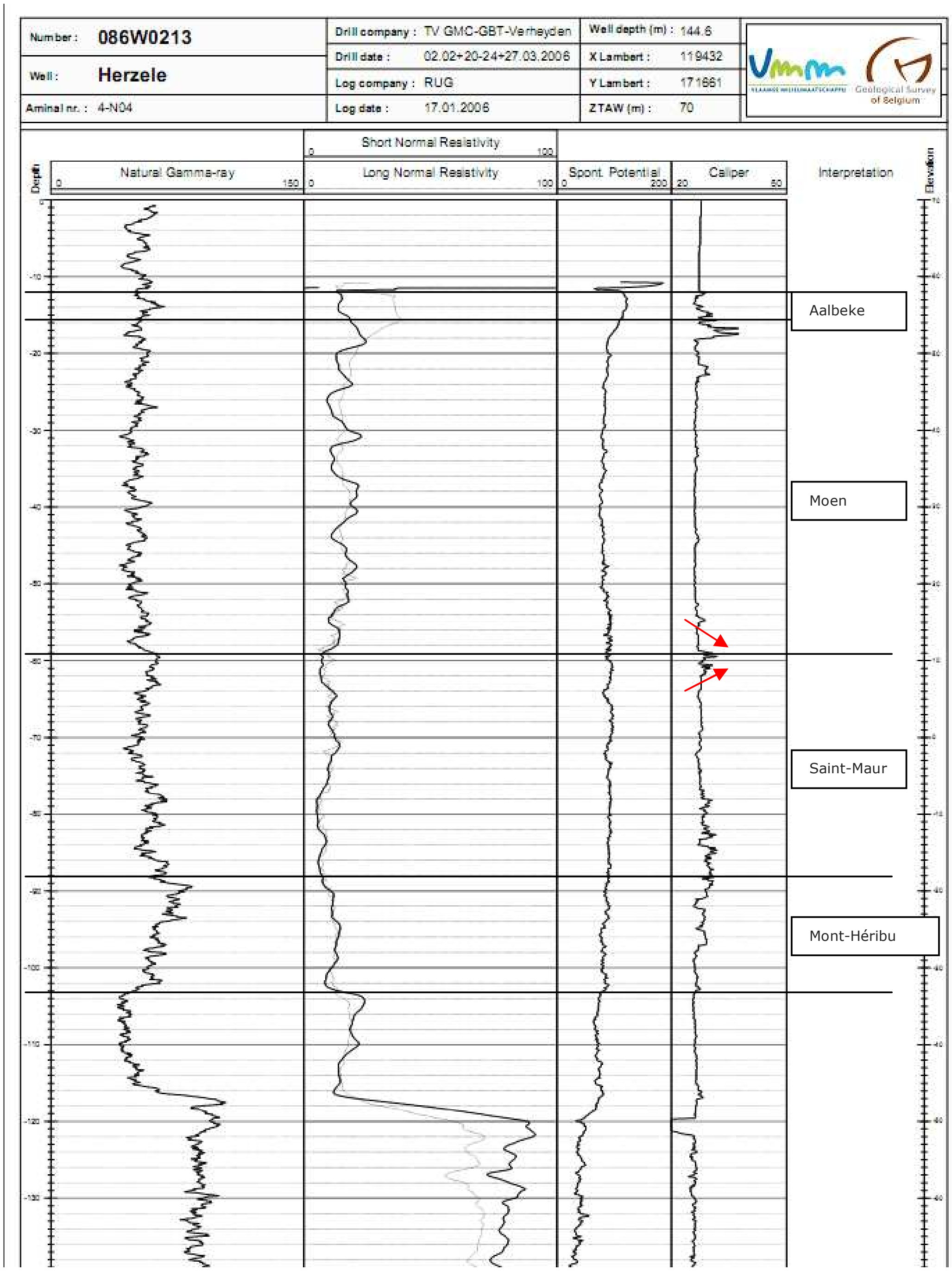


Fig 23. A small peak at the transition from Saint-Maur Member, rich in stiff clay, to Moen Member, rich in clay-silt alternations. Example : Herzele - 086W0213

In several cases, there is a narrow peak on the transition clay-silt to stiff clay. In this example we also notice a break-out on the base of stiff clay layer (Fig. 23).

4.2.6. Decrease of diameter

A decrease of the diameter is a more exceptional case (Fig. 24). In case of a negative spike, one might think of an artefact. However, the phenomenon seems to be genuine and may be due to clay swelling and borehole instability or to deposition of a thick mud cake. The observed decrease is important and without obvious explanation. This decrease of diameter appears in the silt-clay layers as well as in the stiff clay layers. It is plausible that workover or reaming of the borehole, normally performed before a logging operation, will temporarily bring the wellbore diameter into gauge and that, therefore, this phenomenon of collapsing borehole diameter is underestimated from well log registration (see for example the large amount of clay slabs sliced off the walls of Earth Explorer borehole in Oostende, apparently without appreciable widening of the diameter). Although the phenomenon. It may be related to the proven presence of swelling clay minerals in the Ypresian Clay sequence.

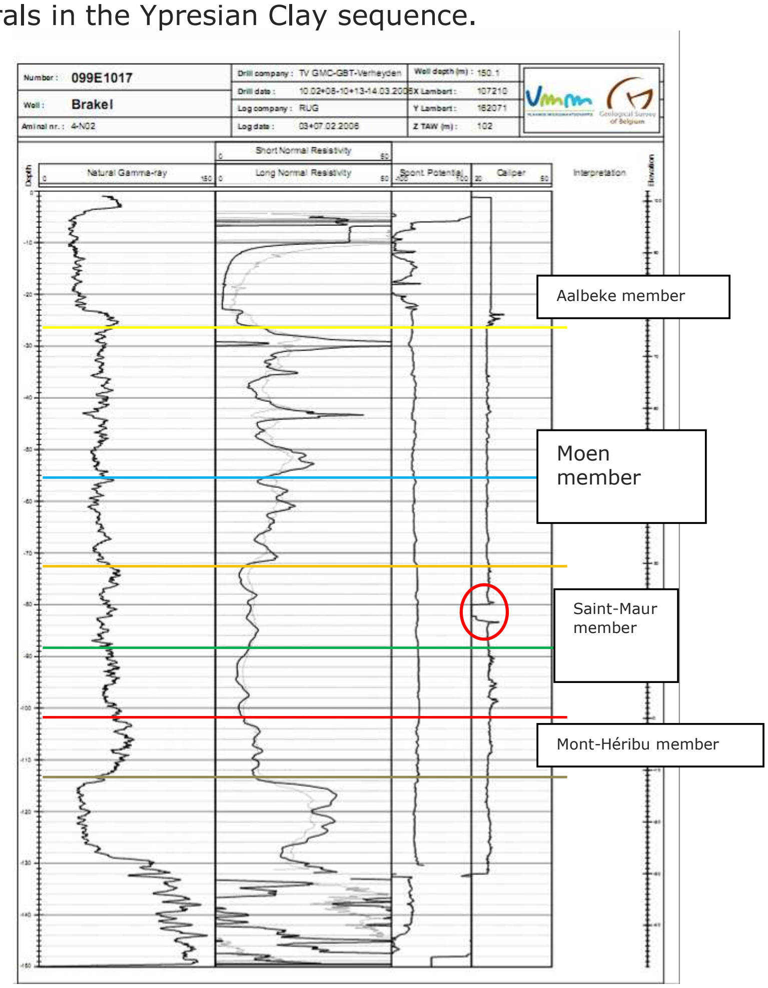


Fig. 24. A large decrease of the diameter below depth of 80 m in the Saint-Maur Member. Example : borehole Brakel – 099E1017.

4.3. Preliminary conclusions

Caliper log anomalies are enhanced by the very fine sand to clay granulometric changes, which is so typical for the Ypresian Clay interval. Particularly, layered sand/silt – clay successions or contacts with stiff clay are preferred places for washouts, because of the high erodibility of the fine sand to silt (Fig. 21). Classification of the caliper log anomalies is very complex and not always straightforward.

It is of great importance to realize that the anomalies presented here are qualitative, because of scale problems. There is not only a maximum cut-off imposed by the movement of the caliper arm, but also a resolution imposed by the calibration of the mechanical tool. Strong visual differences in scale and data quality can give another impression, making a certain log signature appear as an anomaly or not.
Plotting the different typologies on a map gives a random geographic distribution, no pattern can be discerned (cf §4.7). So there is no connotation to paleogeographic differences nor to regional affinities of the drilling companies.

A possible explanation for the random distribution of anomalies when plotted against the stratigraphic level concerned is the low differentiation of the sediment content of the Ypresian clay. Lateral facies changes may be as important as variations according to the vertical succession.

4.4. Note on the poor discrimination between the Moen and St.- Maur members of the Kortrijk Formation with respect to caliper readings

It has been observed that the principal cause for abrupt changes in borehole diameter is the transition between (loose) sand/silt and (stiff) clay. The more silt interlayerings the more levels prone to erosion in a borehole (Fig. 20). The St.-Maur Member is distinguished from the Moen Member by its higher clay and lower silt content, hence it was expected that washouts would be less important in this lithological unit, which apparently is not the case. A possible explanation of this apparent paradox could be the carbonate content which contributes to a better cohesion of the sediment. The upper, more silty part of the Kortrijk Formation often is calcareous, which could effectively suppress the tendency towards washouts and reduce the caliper anomalies in the Moen member. However, the transition from decalcified to calcareous sediment does not coincide with the St.-Maur – Moen boundary but generally occurs earlier, within the St.-Maur Member. Although the carbonate content may contribute to reducing the differences between both stratigraphic units, it cannot explain the greater tendency to washouts in the St.-Maur Member. Other reasons must be invoked.

The lithostratigraphical approach apparently is too rude to explain tendencies and typology of washouts. It is at the bed-to-bed level that lithological changes occur and that washouts are initiated. These may be below the resolution level for most geophysical well logs, but not for the Formation Microscanner (FMS) Tool. One such measurement has been executed for ONDRAF/NIRAS in a borehole for the Loenhout gas storage project (province of Antwerp, between the cities of Antwerp and Turnhout)-(Table 3 – fig. 25). The borehole studied is located in an area where the Ypresian Clay sequence is already becoming more sandy, but the overall sedimentary sequence and sedimentological characteristics remain typical for the basin (Table 4). This is supported by the lithology observed in a cored interval at 547 – 555,80 m: Silty clay, fossiliferous, with dispersed pyrite; increasingly laminated at mm-scale towards base.

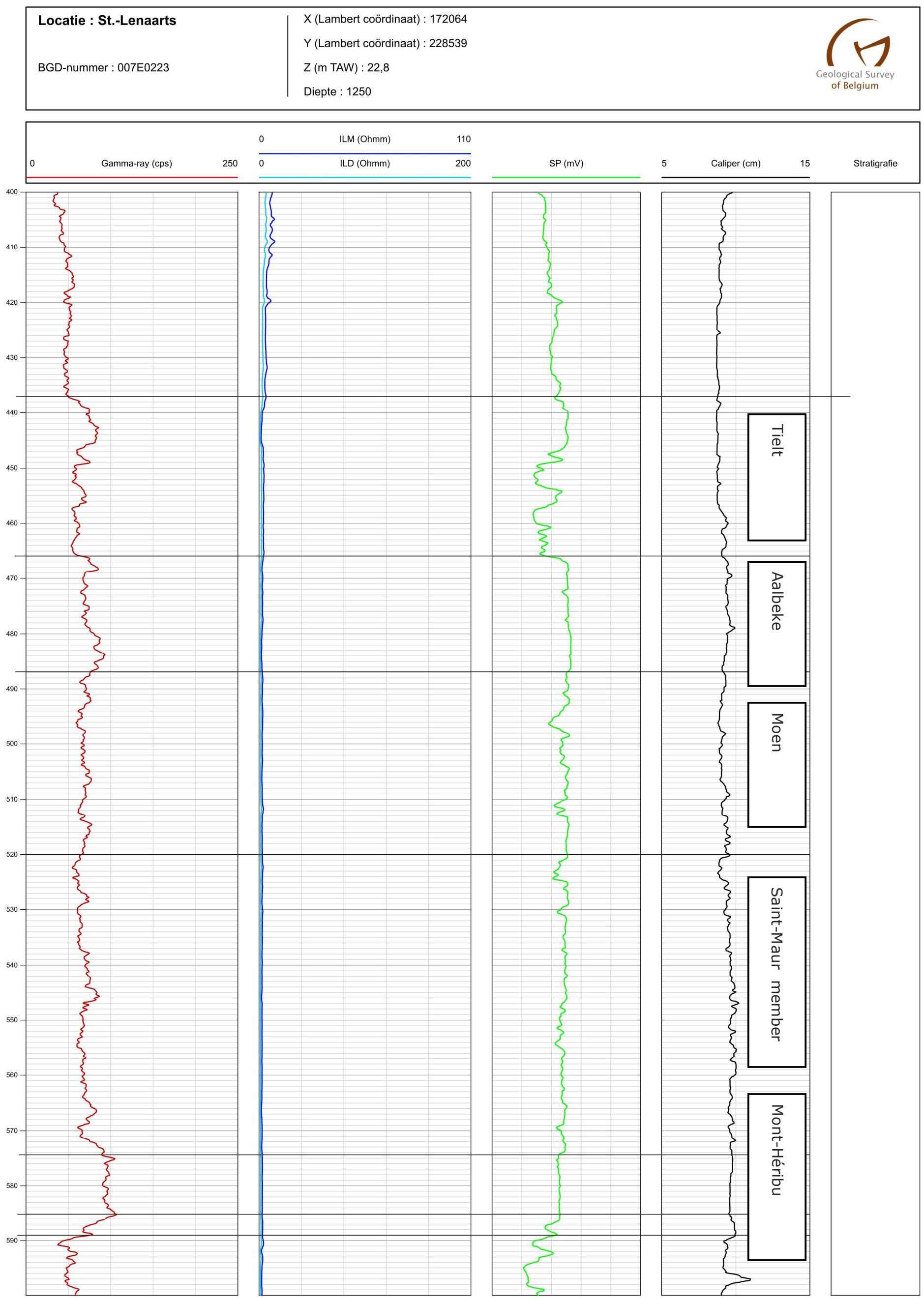


Fig. 25. Logplot over the Kortrijk Formation – DZH15, St.-Lenaarts (007E0223) with caliper (thin black line at right and lithostratigraphical interpretation.

Table 3. Stratigraphy of borehole 7E0223 (DZH15), St.-Lenaarts (Lambert x 172063, y 228544).

Z	23,63 m
Top Tielt Fm	437 m
Base Tielt Fm	466 m
Base Aalbeke Mbr sl	487 m (base of peak values in gamma ray)
Base Moen Mbr	520 m (dip in gamma ray)
Base St. Maur Mbr ss	574,50 m (sensu Welkenhuysen & De Ceukelaire, 2009)
Top Mt. Héribu Mbr	585,50 m (base Saint-Maur sensu Steurbaut, 1986)
Base Kortrijk Fm	589 m
Base Tertiary	689 m (vertical inclination 0.20°)

Correlation of borehole DZH15 is based on gamma ray and density logs as no resistivity log is available. However, the quality of the logs makes interpretation interesting and rather independent from other correlations which are largely determined by the resistivity signature. Remarkable observations are that higher gamma ray intervals do not necessarily correspond to stiff clay layers but may be due to glauconiferous sand-bearing intervals.

From this investigation it can be concluded that sand – clay dominated intervals alternate at metric scale, but that sand – clay alternations at bed level occur at centimetric to millimetric scale. This means that there are ample contacts where erosion can be initiated. Wash-outs then result from the cumulative effect of closely spaced erosion levels. This is the case in the Saint-Maur Member as well asin theMoen Member.

Table 4. Lithological succession based on Formation Microscanner of the Ypresian Clays sequence in borehole 7E0223 (DZH15), St.-Lenaarts. Note that the sand/silt content (poorly differentiated) from resistivity logs seems to be overestimated compared to visual inspection.

Lithology	Base in m
Clayey sand to silt, bioturbated	439,50
Clay, bedded	442
Clayey silt, with cm-clay layers	447
Sand, with thicker clay layers	454
Clayey silt becoming more sandy,rare cm-clay layers	466
transition to massive clay	467
stiff clay	469
silty clay, bioturbated	472
clayey silt, bioturbated, with sandy top, alternating with silty clay in 50 cm intervals	478
stiff clay, bioturbated	487
clayey silt, bitoturbated, thin sand laminae	488,20
silty sand	489
silty clay, bioturbated	490,25
silt to sand	491

silty clay, bioturbated	492,70
grading into bedded sand-silt-clay	493,25
silty sand with cm-clay layers	497,20
alternation of 50 cm thick layers of silty-clayey sand with cm- to dc- silty clay, bedded or bioturbated	506,10
massive bioturbated clay to silty clay	508,25
silty clay, bioturbated, with cm-sandy layers	510
silty sand, bioturbated	511,40
sand-clay alternation, decimetric-bedded	513
silty clay, bioturbated, with dc-stiff clay layers and rare sand layers	519,75
grading into clayey silt with cm-sand layers	521,40
silty sand, bedded, with silty clay layers, pure sand at base	524,75
silty clay, bioturbated	525,75
silty sand to more pure sand, bedded	526,40
massive clayey silt to silty clay	529,40
silty to clayey sand, with dc-pure sand layers	530,80
clayey sand, bioturbated, with decimetric silty clay intrcalations	535,50
silty clay with up to 40 cm thick sand layers with erosive base	537,60
silty clay grading into clayey silt with fossils	540,25
massive silty to sandy clay, disturbed	546,50
bedded alternation between sand and silty clay, with decimetric stiff clay layers	547,90
silty clay with dispersed fossils	549,25
grading into clayey silt with clay base	551,10
clayey sand – silty clay thick-bedded alternation, with fossils	554,50
silty clay to massive clay, bioturbated, with sand laminae	563
grading into massive pure clay	567,50
grading into more bioturbated clay	569
clayey sand to silt, decimetric clay layers and thin sand laminae	571,50
grading into massive clay, bioturbated	574,50
silty clay to clayey silt, bioturbated, with cm-thick sand layers	582,50
stiff clay – silty clay – clayey sand in disturbed decimetric alternation	586,50
sand to clayey sand in disturbed layers, with clay clasts at the base	589

4.5 How absolute are the Ypresian wash outs?

Washouts are not unique for the Ypresian clay interval. Rather they were unexpected and therefore cause for concern, despite that they may be weakly expressed compared to some much stronger washouts, observed e.g. in thick bodies of uncohesive sands. As an example, washouts over the Ypresian clay interval in borehole 7E0223 (DZH15) – (Fig; 25) are weak in comparison to the stronger but irregular caliper peaks in the Brussel Formation and top Landen Group. The Ypresian washouts in this well are not really corresponding to marker anomalies and their interpretation is subject to caution. The caliper log presents some irregularities in the lower 10 m of the Tielt Formation (assumed Kortemark Mbr but interpreted as Egem Mbr in the original borehole report). These slight irregularities resume in the upper part of the Moen Mbr, with an increase from 540 m onwards to a relative maximum until 560 m from where it stabilises. In fact the baseline caliper registration seems to present a drift towards a larger borehole size from the top of the Tielt Fm till the base of the Kortrijk Fm. Below the base of the Kortrijk Fm the pattern switches from narrow gauge to peaks, representing a large washout in the top of the Landen Group. This gradual increase in borehole diameter over the clay interval seems curious. It may be due to a balling effect of the clay around the rock bit, thereby increasing its size. We refer to the images from the Earth Explorer borehole in Oostende to visualize this effect (Fig.3).

A comparison with the Boom Clay interval in the same borehole 7E0223 (DZH15) indicates that the Boom Clay has overall a similar sand – silt – clay composition but differs in possessing thicker pure clay layers and more gradual lithological transitions. Moreover, the silty base of the Boom Clay (Belsele-Waas Member) displays stronger variations in borehole geometry than the Ypresian Clays interval, without therefore becoming outstanding anomalous.

4.6. New approach

The seemingly disappointing result of this investigation could be the result of the rather rough qualitative approach. Collecting original digital data was unfortunately not possible, but might not have solved inherent problems of scale or resolution. In view of the rather unusable results, the stratigraphical interpretation of the well logs was repeated in more detail, based on the 1998 colour subdivision scheme (De Ceukelaire & Jacobs, 1998), but also taking in account the different spikes in resistivity (numbered from 1 till 6) within the Moen member (Fig. 26). In some boreholes, the boundary between the Moen and Saint-Maur Members (brown just below 6) had to be corrected, applying this method.
After stratigraphic adjustment the anomalies of the caliper were then connected with the spike number of the resistivity log. For each anomaly, a minimal description was prepared e.g. anomaly of 3 cm width over 5 m length. (Table in annex 1)

A newly introduced indicator is the relative importance of the anomaly with reference to the lithostratigraphy, whether the average caliper width is greater or lower in the Moen member than in the Saint-Maur member.

In order to apply these semi-quantitative calculations, an estimation was made of the borehole diameter in the anomalous zones compared to the drill bit size, thus regular minimal diameter, based on data from the paper graphic logs.

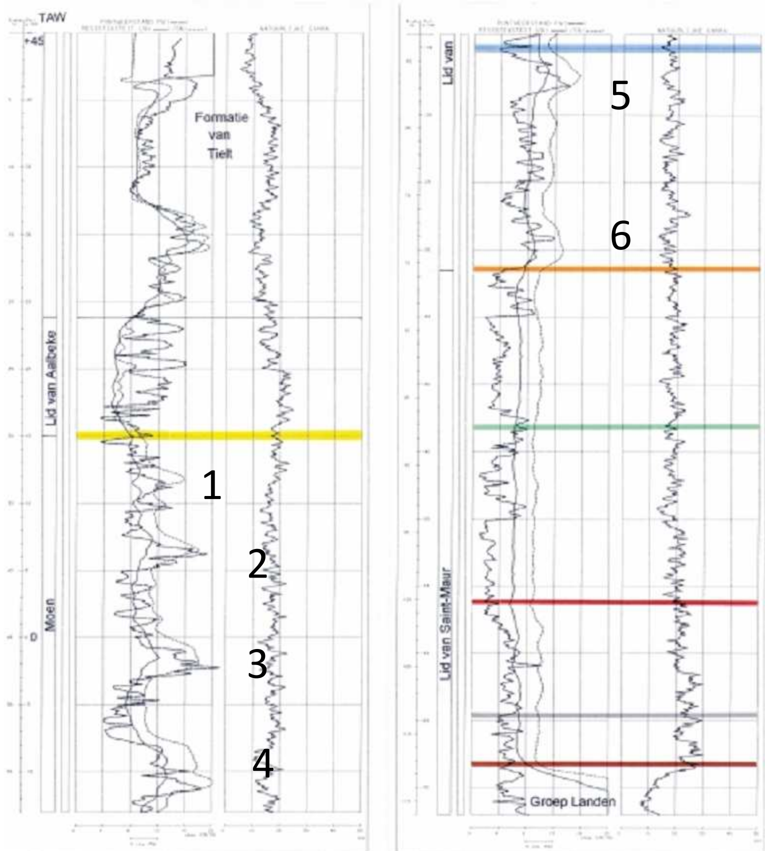


Fig. 16 - Boorgatmeting te Wortegem-Petegem met indeling van de Formatie van Kortrijk.

Fig 26 – An example (borehole Wortegem – Petegem, 084W01475) of the subdivision of the silty clay layers (Moen) based on different spikes (numbered from 1 till 6) from De Ceukelaire & Jacobs, 1998.

4.7. Results

In the first place we had expected a larger caliper anomaly value in the more silty sediments attributed to the Moen Member. This is in fact not what has been observed (Table in annex 1). In the majority of the cases both members have approximatively the same average caliper value. There are even less cases where the caliper value in the Moen member is larger than in the Saint-Maur member than vice-versa (Fig. 27). This means that the lithological difference between the members of the Kortrijk Formation is overrated (cf § 4.4), or that there are factors which inhibit the erodibility of the very fine sand/silt-rich layers, e.g. its carbonate content, which however does not vary in accordance with the lithostratigraphic boundaries.

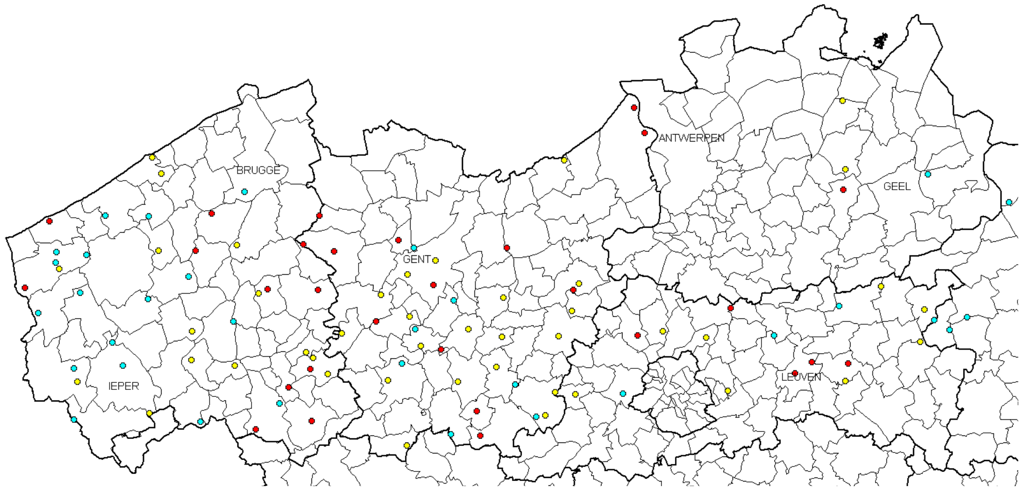


Fig. 27 - Location map of boreholes with indication of the relation Moen / Saint-Maur members on caliper logs. Red = Moen wider wash-outs than Saint-Maur (29 boreholes), yellow = no difference between Moen and Saint-Maur (43 boreholes); blue = Moen smaller washouts than Saint-Maur (32 boreholes).

To have a closer look, different maps were made to find some systematics in the different anomalies. Some anomalies were grouped, so that only 3 categories were left for compiling the maps. First, a group called top of the Ypresian (Fig. 29), starting at the top of the Ypresian until middle of the Moen member, including peak 4. Second, a group starting below peak 4 and going to the Moen/Saint-Maur boundary (Fig. 30). Third, a group with anomalies in the lower half of the Saint-Maur member, including Mont-Héribu (Fig. 31). Finally, we recall that only 10 logs do not display any visible anomaly (Fig. 28). In any case and whatever the explanation, there does not appear any geographical trend from this analysis: the anomaly distribution remains random (Figs. 32-35).

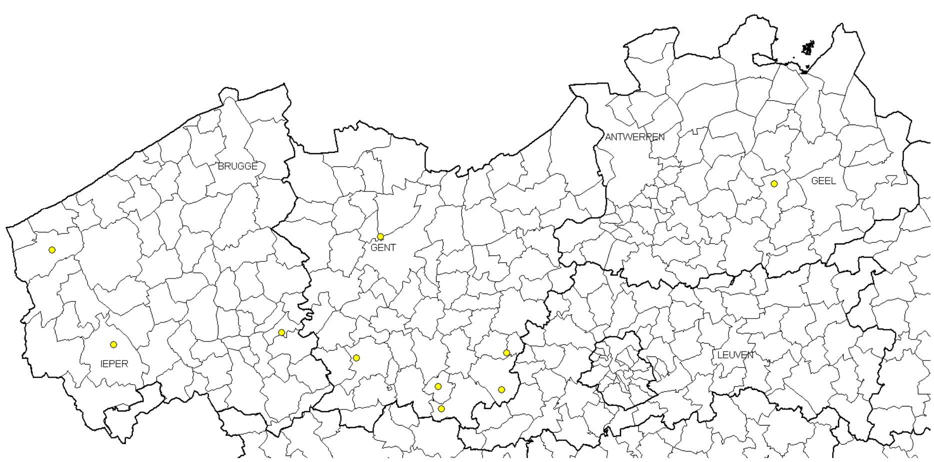


Fig. 28. Logs with no visible anomalies.

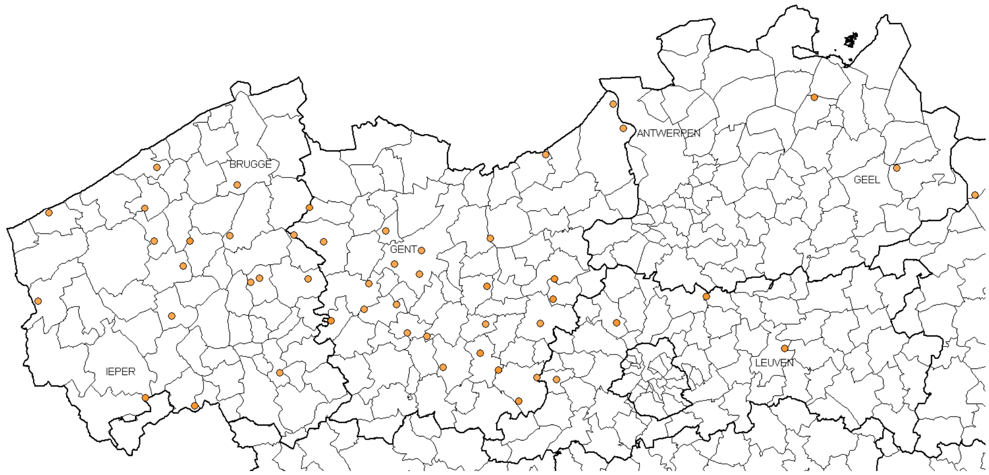


Fig.29. Logs with one or more anomalies in the upper part of the Ypresian clay.

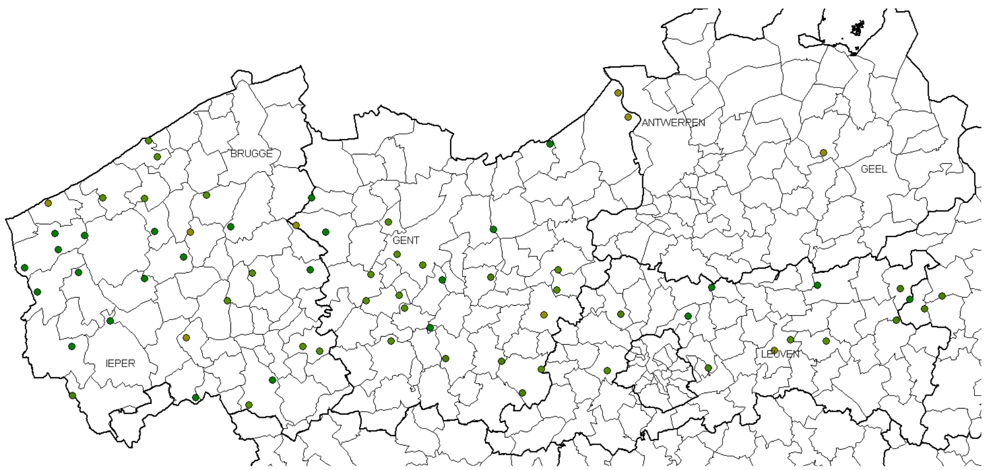


Fig.30. Logs with one or more anomalies in the middle of the Ypresian clay.

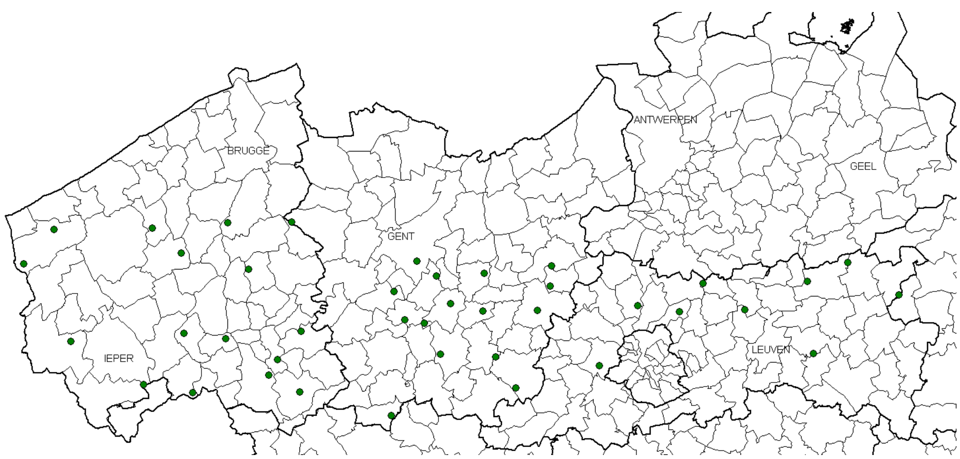


Fig. 31. Logs with one or more anomalies in the lower part of the Ypresian clay.

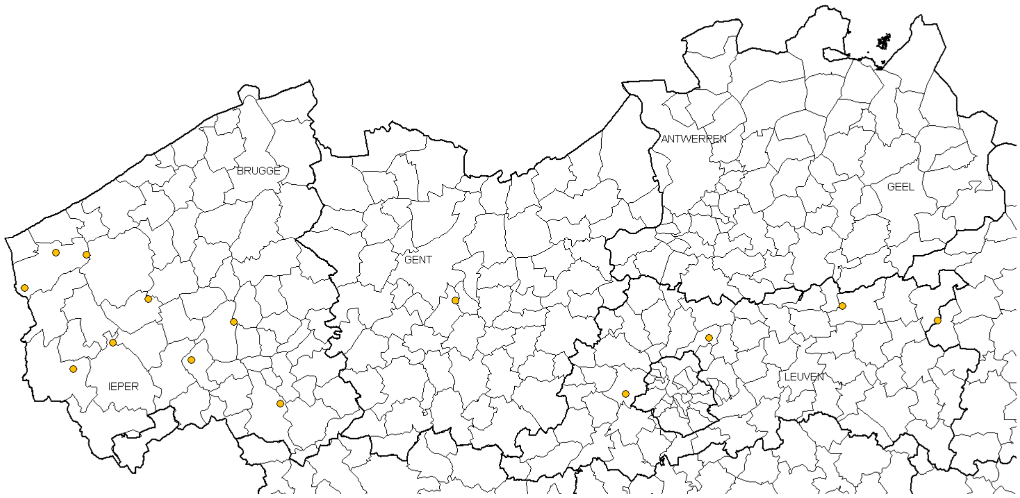


Fig. 32. Logs with anomalies only in the middle and the lower part of the Ypresian clay.

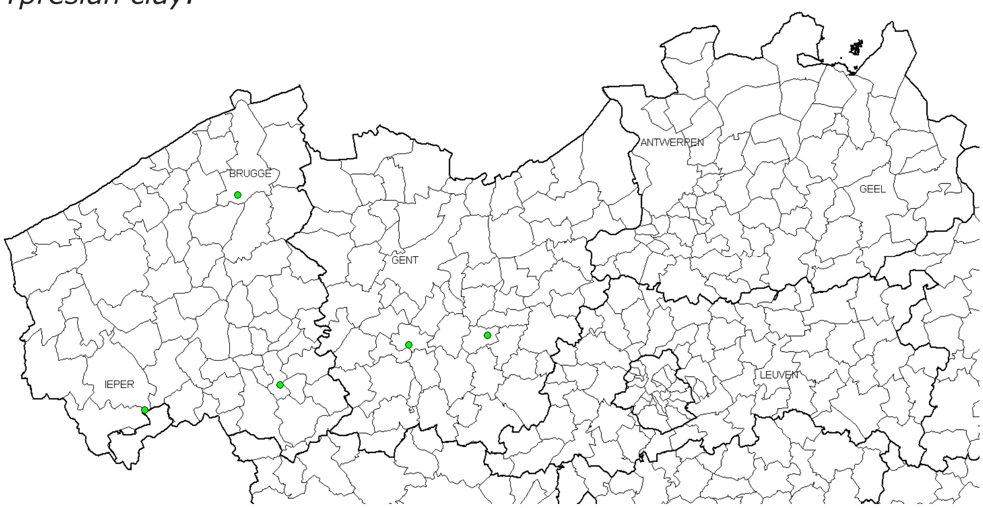


Fig. 33. Logs with anomalies only in the upper and in the lower part of the Ypresian clay.

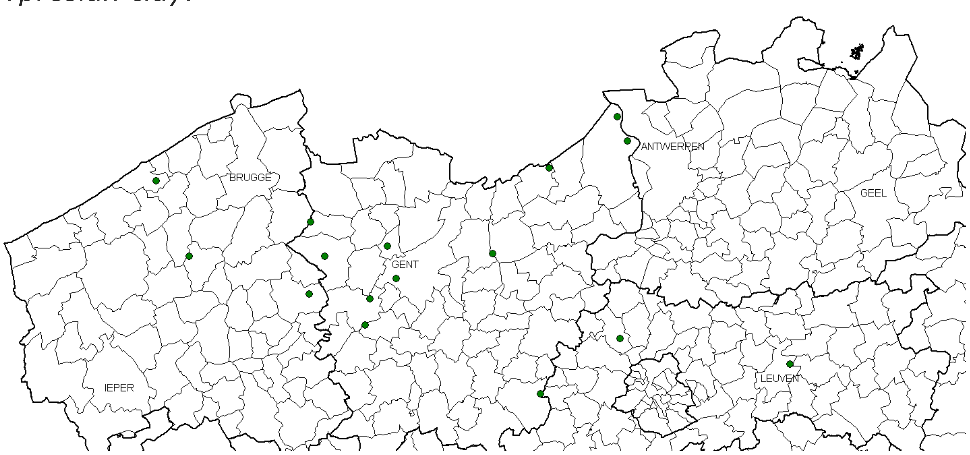


Fig. 34. Logs with anomalies only in the upper and in the middle part of the Ypresian clay.

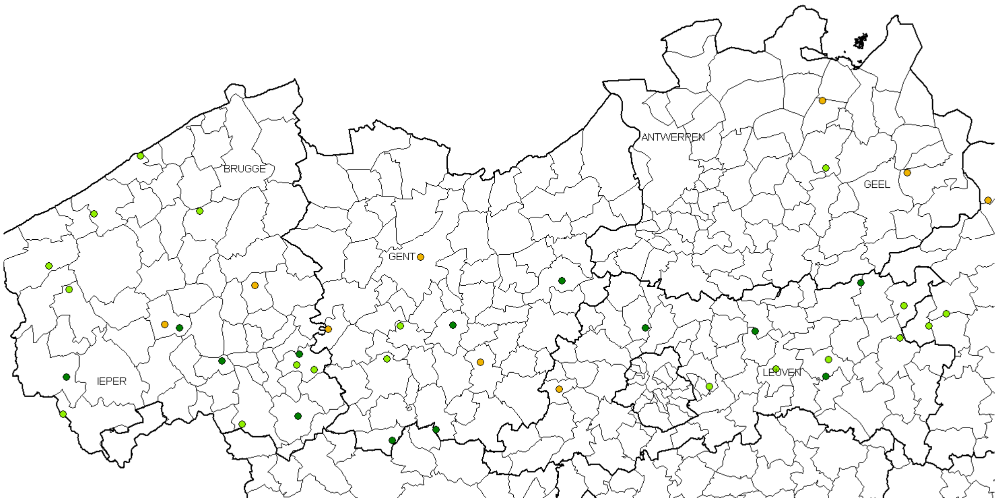


Fig. 35. Logs with anomalies only in the middle part (light green) or anomalies only in the lower part (dark green).

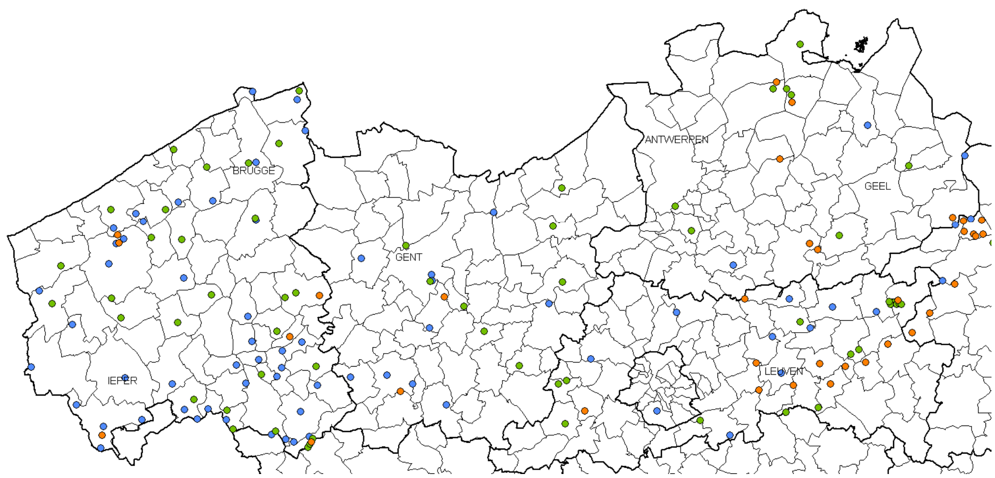


Fig. 36. Overview of the logs which are not usable because of no information (orange); no caliper value (blue) or no interpretation possible (green)

5. Conclusions

When plotting the different anomalies, even with this more detailed interpretation, no clear geographical pattern emerged. For the moment we cannot derive very useful conclusions from the observations about regular patterns in caliper anomalies. As a result this study does not yield predictive value for the behaviour of boreholes to be drilled on new sites, or delineation of geographical exclusion zones with high geomechanical irregularity.

The characteristic caliper anomalies observed in the ON-Doel and ON-Kallo boreholes are not seen in other cases on the same scale. There is no stratigraphical explanation for these caliper anomalies. They are probably drilling-induced, probably by the drilling method leading to frequent reaming of the wellbore, or may be by the drilling mud out of balance with the increased salinity of the formation water.

This study however indicates that geophysical well logs are useful for interpreting the Ypresian clay (compare fig. 10 to fig. 36 for the geographical distribution of boreholes with useful caliper log compared to the logged boreholes which did not allow caliper study). The current stratigraphical scheme appears to be too rude for a geomechanical interpretation of the caliper anomalies but cross-correlation of characteristic patterns in the log signature (e.g. the 6 peaks used in this study) allow comparisons across the basin. Currently, problems of scale and graphical representation pose limits to the interpretation. Digitized data are necessary to compare and evaluate the results of the logging in (semi)-quantitative means. It is therefore recommended to continue the digitization of all logs covering the Ypresian clay interval into LAS files. Nevertheless, poor logging data cannot change into good ones. The quality of logs is irregular, both due to the lack of economic interest in the rather impervious Ypresian strata and to different standards used by the logging companies. A standardised logging procedure with attention to high resolution data is a must for exploiting the full potential of geophysical well logs. This comes at a limited cost for the well owner or operator but the logging companies must be qualified and agree to operate on this basis. This could be a task for the regional authorities in refining permit conditions.

Logging anomalies are not only induced by lithology but also by drilling practice. It is obvious that technical incidents while drilling must have an impact on the regularity of the wellbore and cause some of the spurious anomalies observed. Technical reports are rarely available. In fact for this study they were limited to the ONDRAF/NIRAS exploration wells and to the Distrigaz well DZH15. It cannot be expected that borehole operators will communicate about drilling incidents without any compulsory reason to do so. However, at least the geological exploration wells and/or to wells drilled under supervision or on behalf of the authorities (e.g. the piezometric wells) should provide information not only on the well architecture and emplacement of piezometers but also on unforeseen events, if not as a special report, then at least as copies of daily drilling reports by the drilling companies, to be made available for this type of investigation.

Finally, a refinement of the lithostratigraphic subdivision, with boundary conditions based on geophysical well logs is recommended. Currently, there is no rule for recognition of the lithostratigraphical boundaries in well logs. This must be formalised within the framework of the National Commission for Stratigraphy.

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7. Annexes

7.1. Distribution of caliper anomalies in the boreholes studied

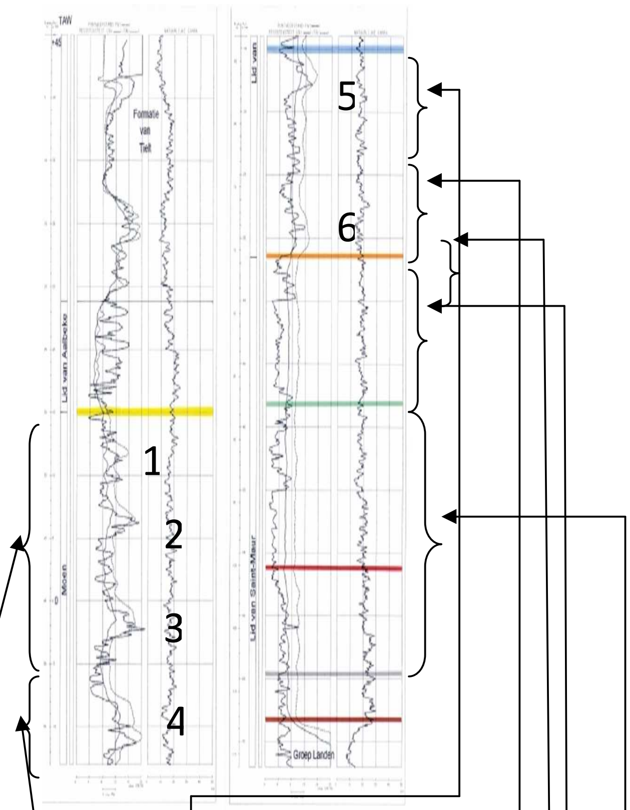


Fig. 16 - Boorgatmeting te Wortegem-Petegem met indeling van de Formatie van Kortrijk.

BGDnr	Purpose of drilling	diam	Top anomaly	Anomaly at peek 4	Anomaly at peek 5	Anomaly at peek 6	Anomaly at boundary	Anomaly at top of Saint-Maur	Anomaly at base of Saint-Maur	Value in Moen vs value in Sm
014E0240	PM	14	x	x	-8					x
014E0355	VKG	26	x	x	-8					x
017W0280	VKG	22	1 m x 5 ?							22
022W0279	WWG	26	5 m x 2 ?	1 m x 1 ?		5 m x 3 ?				27
022W0351	SEISM	26				3 m x 50 mm				28
023W0454	PM	26	6 m x 5	4 m x 4						32 vs 40
026E0111	PM	22		4 m x ?				2 m x ? + 5		
030W0371	GAS	?			1 m x hoog					
030W0372	WWG	24								15 vs 13
031W0314	VKB	24				2 m x 2.5 cm			18 m x 1 cm	24 vs 25
031W0237	VKN	?		3 m x ?						
035E0142	VKB	26		15 x 5	zie 4					30 vs 28
036E0161	PM	26		sprong 3 m	14 m x 1	4 m x 2				26 vs 28
036W0204	PM	26				4 m x 2				35 vs 37
037E0215	PM	34				2 m x 3				35 vs 34
038E0206	PM	26	1 m x 3.5	16 m x 3	idem				15 m x 2	26 vs 25
038W0264	PM	36		6 m x 2	2 m x 3	8 m x 2		6 m x 2	20 m x 2	36 vs 35
039E0144	PM	27		sprong 2 m	idem	idem				29 vs 27
039W0293	PM	26	10 m x 1		sprong 3 m	idem		idem x 6 m		27 vs 26
047W0264	VKS	20		1 m x 1						1 m x 1
050E0217	WWG	32			3 m x 2	4 m x 3		6 m x 5	7 m x 3	33 vs 34
050E0234	PM	26						1 m x -15		26

050E0235	PM	24								25 vs 28
050W0055	PM	21				sprong - 1		sprong+0.5	sprong - 0.5	22 vs 21
051W0156	PM	32						sprong + 2		34 vs 36
051W0157	PM	32						sprong + 2		34 vs 36
052E0195	PM	20.5	8 m x 2		0.5 m x 2					20.7 vs 20.
052W0255	PM	35		sprong + 2	blijft	2 m x 1		sprong - 2	sprong + 2	37
052W0256	PM	32		sprong +2	blijft	blijft		sprong -2	sprong +2	37 vs 38
053E0058	PM	32		5 m x 2	4 m x 3	10 m x 3		8 m x -2		32 vs 30
053W0073	WWM	35		2 m x 1	2 m x 5	2 m x 3			8 m x 3	35
053W0077	PM	25		3 m x - 10						28 vs 25
054E0246	PM	30		10 m x 2		2 m x 1				32
054W0084	PM	27		sprong + 2	blijft	blijft		sprong -2		32 vs 28
055W0978	WWG	35		2 m x 8						35
055W1020	PM	22		13 m x +2	6 m x + 1	2 m x 2			sprong - 2	25 vs 24
055W1091	PM	18.5								20 vs 22
055W1112	PM	27	sprong -2	2 m x 2		2 m x 0.5				27
056W0202	PM	27		sprong -1		3 m x 3		14 m x 3		29 vs 27
057W0151	WWG	35	15 m x 1			3 m x 2			2 m x 3	37 vs 35
057W0154	PM	28								29
060E0292	PM	24							0.5 m x 0.5	24
065E0097	PM	32	8 m x 1	8 m x 1				sprong + 2		32 vs 34
066E0135	PM	32				5 m x 2		sprong + 2		32 vs 35
066E0136	PM	35				1 m x 6		sprong + 2		36 vs 38
067E0214	PM	34			3 m x 3	3 m x 3				34 vs 35
067W0229	PM	?								
067W0232	PM		x	x						
069E0450	PM	32		sprong - 3		4 m x 2				33 vs 32
069W0457	PM	26	10 m x +2							26
070E0236	WWM	??						5 m x ?	12 m x ?	
070E0237	PM	26							4 m x -15	26
070W0738	WWG	33		1 m x 8					sprong + 3	33
070W0752	PM	26	6 m x +4	5 m x +2	2 m x +2	2 m x +2			10 m x +5	28
070W0770	PM	24				1 m x 5				23 vs 24
070W0785	PM	26	4 m x 5	4 m x 5	6 m x 4			12 m x 4	10 m x 2	30 vs 26
071E0261	WWM	24	4 m x 3	4 m x 3	3 m x 2				sprong + 2	24
071W0251	PM	24	10 m x 2	5 m x 1					sprong +2	24
071W0325	PM	27	4 m x 2				2 m x 5		sprong +2	27
072E0229	PM	27	1 m x 1				4 m x 5			30 vs 28
072W0159	PM	??	12 m x 2 ?			2 m x 2?			8 m x 3?	
073E0377	PM	27				2 m x 1		1m x 1	2 m x 2	27
073E0397	PM	22	10 m x 1			sprong -1		sprong -1	sprong +1	24 vs 22
073W0394	PM	28							2 m x 1	28
074W0152	WWK	22							sprong +2	22 vs 23
075W0320	WWM	27			4 m x 2			6 m x +2	2 m x 1	27 vs 28
076E0303	PM	24					3 m x 6			24 vs 26
076E0304	PM	24					1 m x 4			24 vs 25
076W0285	WWG	34					2 m x 2			34
076W0287	WWK	18					1 m x 1			18
076W0289	WWG	26						6 m x 2	3 m x 2	26 vs 28
081E0143	PM	22								22 vs 23
081W0067	WWG	24								24
081W0095	PM	34				6 m x 5		sprong +5	sprong +5	26 vs 28
082E0103	PM	34							5 m x 2	35
082W0179	PM	34			3 m x 5				5 m x 2	35
083E0442	WWM	27							3 m x 2	40
083E0443	PM	25								25
083E0446	VKB	24		4 m x 2					8 m x 1	26 vs 25
083E0447		24				1 m x 1				26 vs 25
084E1387	WWM	34								34
084E1441	PM	24				2 m x 8				25 vs 28
084W1476	PM	28				1 m x 3				28
085E0963	PM	??	10 m x ?	3 m x ?			3 m x ?		8 m x ?	
086E0250	WWM	24		1 m x 1		1 m x 1				24
086E0267	PM	24								
086W0183	PM	22	3 m x -8							22
086W0213	PM	26	2 m x 3				4 m x 4		12 m x 4	26 vs 32
087E0803	PM	12				sprong +2			sprong -2	12 vs 14
087W0492	PM	28		4 m x 3						28
088E0836	PM	10					3 m x 2			
089E0390	WWG	21			5 m x 1					22 vs 21
089E0492	WWG	58	11 m x 2		3 m x -1	1 m x 2				62 vs 58
090W1158	WWK	18				6 m x 1				19 vs 18
090W1267	PM	28							3 m x 1	28
095E0190	PM	24	11 m x 3						6 m x 1	25
095W0154	WWM	18					3 m x 2			18 vs 19

096E0075	WWG	18	9 m x 3			2 m x 3		4 m x 3	6 m x 3	18 vs 20
097E0941	PM	34							sprong - 3	38 vs 35
097E0942	PM	34						4 m x 8	2 m x 4	38 vs 39
097W0774	PM	34			sprong -4	sprong -2				40 vs 34
099E0973	PM	??								??
099E0974	PM	26								29 vs 27
099E1017	PM	26								26 vs 28
099W1514	PM	18							4 m x 1	19
100E0048	PM	18								18
100E0073	PM	26	2 m x 2		2 m x 1		5 m x 2		12 m x 2	26 vs 28

Legend : PM = piezometric well; WWx = water well, VKx = exploration borehole

7.2. Overview of the used boreholes

Opdracht	bgdnr	jaar	doel	x	y	z	diepte
NIRAS Doel	014E0240	1998	PM	142240	224444	8.03	688.00
NIRAS On-Kallo-1	014E0355	2008	VKG	144287	219656	8.54	440.00
boring Merksplas	017W0280	1987	VKG	182012	225742	30.00	800.00
Weverij	022W0279	1984	WWG	51900	211891	2.50	376.00
ALBON	022W0351	2008	SEISM	50100	215010	7.50	307.00
MVG - AfdelingWater 3-N25	023W0454	2006	PM	67784	208344	11.00	253.00
aminal	026E0111	1999	PM	128880	214425	3.00	505.82
Distrigaz en BGD	030W0371	1984	GAS	182667	212654	15.50	1685.80
Stad Herentals	030W0372	1988	WWG	182179	208801	16.01	692.00
NIRAS MOL 1	031W0314	1997	VKB	200191	211651	24.88	572.5
SCK	031W0237	1975	VKN	198400	211725	24.50	577.00
BGD-SGB	035E0142	1979	VKB	30409	202711	6.55	270.30
MVG - AfdelingWater 3-N16	036E0161	2005	PM	49392	203709	4.00	252.00
MVG - AfdelingWater 3-N20	036W0204	2005	PM	41083	203807	1.00	265.00
MVG - AfdelingWater 3-N23	037E0215	2006	PM	61517	204301	14.00	259.00
MVG - AfdelingWater 4-N26	038E0206	2006	PM	79027	198332	22.00	297.00
MVG - AfdelingWater 3-N10A	038W0264	2005	PM	66286	198186	20.00	275.00
MVG - AfdelingWater 4-N22A	039E0144	2005	PM	97161	199116	8.00	277.00
MVG - AfdelingWater 4-N25	039W0293	2005	PM	82118	203791	12.00	287.00
BGD-SGB	047W0264	1986	VKS	213939	206366	46.00	1504.00
N.V. SANTENS industrieterrein	050E0217	1986	WWG	31766	196824	2.50	174.00
AMINAL	050E0234	1994	PM	32365	193675	3.36	138.00
aminal	050E0235	1999	PM	31635	194905	4.74	252.00
MVG - AfdelingWater 3-N15A	050W0055	2005	PM	25786	190028	5.00	140.00
MVG - AfdelingWater 3-N19A	051W0156	2005	PM	37522	196391	4.00	267.00
MVG - AfdelingWater 3-N07	051W0157	2005	PM	36365	189086	3.00	256.00
aminal	052E0195	1991	PM	58332	197127	26.67	254.00
MVG - AfdelingWater 3-N11	052W0255	2005	PM	51330	197169	21.00	240.00
MVG - AfdelingWater 3-N21	052W0256	2006	PM	57008	192209	18.00	237.00
Aminal	053E0058	1994	PM	81840	189700	28.75	267.00
Clarysse Weverij	053W0073	1983	WWM	70440	188940	35.50	244.00
Aminal	053W0077	1992	PM	72176	189840	37.39	241.50
MVG - AfdelingWater 4-N09A	054E0246	2005	PM	93778	188743	10.00	147.00
AROL, Aalter	054W0084	1990	PM	84918	197042	17.98	173.00
De Nieuwe Molens	055W0978	1986	WWG	104230	195300	8.00	319.00
AROL, Gent	055W1020	1990	PM	103904	190630	10.59	163.00
aminal	055W1091	1999	PM	100115	197715	5.00	194.00
MVG - AfdelingWater 4-N24A	055W1112	2005	PM	98905	192666	10.00	228.50
MVG - AfdelingWater 4-N21	056W0202	2005	PM	117867	197644	5.00	280.00
fabriek	057W0151	1989	WWG	130548	189689	5.00	288.00
AROL, Dendermonde zwembad	057W0154	1990	PM	131606	190824	4.58	218.00
MVG - AfdelingWater 2-N22	060E0292	2005	PM	189381	190395	19.00	300.00
MVG - AfdelingWater 3-N14	065E0097	2005	PM	28356	185241	18.00	281.00
MVG - AfdelingWater 3-N12	066E0135	2005	PM	49287	187923	40.00	260.00
MVG - AfdelingWater 3-N22	066E0136	2005	PM	42522	179666	8.00	235.00

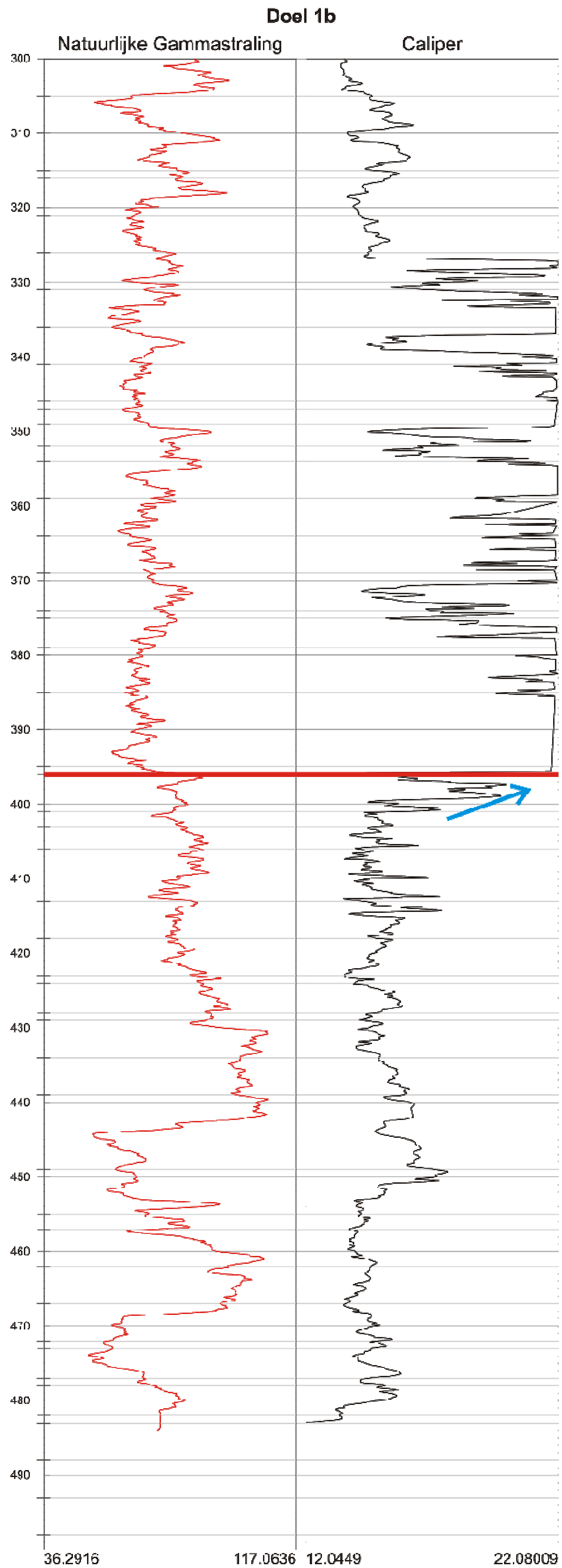
MVG - AfdelingWater 3-N06	067E0214	2005	PM	65643	183636	23.00	201.00
AMINAL, Min. Vl. Gemeenschap	067W0229	1992	PM	57652	181724	25.00	248.00
AMINAL	067W0232	1994	PM	54735	182300	44.00	22.00
MVG - AfdelingWater 4-N08A	069E0450	2005	PM	92868	183585	12.00	189.60
AROL, Olsene	069W0457	1989	PM	86383	181411	11.00	111.00
RUG-LTG	070E0236	1989	WWM	107750	187675	10.00	143.00
AROL, Oosterzele	070E0237	1990	PM	110512	182146	52.42	155.00
Christiana bronnen	070W0738	1988	WWG	101495	178903	24.12	134.00
AROL, Eke	070W0752	1989	PM	99311	184597	11.98	146.00
aminal	070W0770	1999	PM	100405	182125	14.00	140.60
MVG - AfdelingWater 4-N07A	070W0785	2005	PM	105342	178259	62.00	151.00
Slachthuis Verbiest, Aalst	071E0261	1988	WWM	127749	180821	10.00	260.00
AROL, Oordegem	071W0251	1990	PM	116915	180765	38.35	205.10
MVG - AfdelingWater 4-N23A	071W0325	2005	PM	117253	188164	15.00	220.00
MVG - AfdelingWater 2-N13	072E0229	2006	PM	142885	180944	66.14	234.00
AROL, Wieze	072W0159	1990	PM	130325	185708	10.77	145.00
MVG - AfdelingWater 2-N05	073E0377	2004	PM	156065	180588	16.64	152.00
MVG - AfdelingWater 2-N10	073E0397	2004	PM	160635	186224	9.00	209.00
MVG - AfdelingWater 2-N04	073W0394	2005	PM	147744	181731	49.89	183.00
prive	074W0152	1985	WWK	168928	180974	17.00	110.00
slachthuis tessenderlo	075W0320	1985	WWM	181415	186655	11.00	172.00
aminal	076E0303	1996	PM	205920	184474	23.65	258.00
AMINAL	076E0304	1996	PM	202500	182050	43.00	208.00
stad	076W0285	1983	WWG	197758	185946	35.00	350.35
prive	076W0287	1986	WWK	196913	179745	57.50	120.00
fabriek	076W0289	1988	WWG	199606	183851	40.00	158.00
AMINAL	081E0143	1994	PM	44420	175250	13.41	259.20
Tex Works	081W0067	1986	WWG	35798	172147	29.00	665.00
MVG - AfdelingWater 3-N13A	081W0095	2005	PM	35076	174644	30.00	246.90
MVG - AfdelingWater 3-N09	082E0103	2006	PM	65878	175277	67.00	270.00
MVG - AfdelingWater 3-N05	082W0179	2005	PM	57586	176243	34.00	226.00
Primeur	083E0442	1989	WWM	80810	176630	12.50	254.00
AMINAL	083E0443	1994	PM	79530	177710	15.11	206.00
BGD-SGB	083E0446	1994	VKB	76145	171100	14.45	178.00
BGD-SGB VLA 92 3.1	083E0447	1994		80360	174560	16.03	10.26
Mitec	084E1387	1986	WWM	95124	172422	22.50	457.00
MVG - AfdelingWater 4-N06B	084E1441	2005	PM	97768	175647	23.00	127.00
aminal, Waregem	084W1476	1994	PM	83680	173680	17.00	246.00
Arol, Sint-Goriks-Oudenhove	085E0963	1990	PM	108479	172199	35.78	140.75
Dender-Aluminium	086E0250	1975	WWM	127160	170150	12.00	114.00
AROL, Iddergem - AROL	086E0267	1990	PM	126425	173524	24.01	126.30
aminal, Herzele	086W0183	1999	PM	115820	175015	65.00	164.60
MVG - AfdelingWater 4-N04	086W0213	2006	PM	119432	171661	70.00	160.00
MVG - AfdelingWater 2-N20	087E0803	2006	PM	140132	169814	59.47	125.00
MVG-AfdelingWater	087W0492	2006	PM	131015	169794	47.32	123.00
MVG - AfdelingWater 2-N06	088E0836	2005	PM	160078	170389	79.14	130.00
fabriek	089E0390	1989	WWG	173027	173733	25.00	58.00
VMW	089E0492	1992	WWG	176179	175953	25.44	182.00
prive	090W1158	1985	WWK	183154	175619	50.00	85.00
MVG - AfdelingWater 2-N26	090W1267	2006	PM	182597	172286	80.00	165.00
Aminal, Hollebeke	095E0190	1991	PM	49620	166191	24.82	202.00
Alti Flora	095W0154	1985	WWM	35185	164987	102.50	170.00
NMW	096E0075	1985	WWG	59339	164552	17.50	228.91
MVG - AfdelingWater 3-N02A	097E0941	2005	PM	80604	164632	60.00	160.00
MVG - AfdelingWater 3-N03	097E0942	2005	PM	74473	167959	28.00	157.00
MVG - AfdelingWater 3-N01A	097W0774	2005	PM	69827	163094	52.00	176.00
Arol , St Maria Lierde	099E0973	1990	PM	112156	166527	35.09	63.00
Arol, Goeferdinge - AROL	099E0974	1990	PM	112829	161914	35.53	61.00
MVG - AfdelingWater 4-N02	099E1017	2006	PM	107210	162071	102.00	146.00
aminal, Ronse	099W1514	1999	PM	98785	159970	65.00	105.30
aminal, Denderwindeke	100E0048	1999	PM	125305	165795	56.00	95.50

7.3. Initial Scoping study. Caliperuitwijking boring van Doel

De afwijking op de calipermeting (boorgatdiameter) van de boring van Doel 1B (014E0240) neemt sterk toe vanaf ongeveer 395m diepte naar boven toe (Fig. 1); dit is op ongeveer 50m van de basis van de Formatie van Kortrijk. Deze overgang komt overeen met een daling in de gammastraling. Deze grens wordt geïnterpreteerd als de basis van het Lid van Moen van de Formatie van Kortrijk. Al vanaf een 25 meter dieper zijn er enkele pieken in de calipermeting zichtbaar (in het Lid van Saint-Maur).

In verschillende boringen van de boorcampagne van VMM – afdeling Water uit 2005-2006 is dit fenomeen eveneens waar te nemen.
Een eerste reeks van 20 boringen (Tabel 1; Fig. 2) vertoont vanaf ergens tussen de basis en midden van het Lid van Saint-Maur tot ongeveer de top van het Lid van Moen in de Formatie van Kortrijk een positieve uitwijking van de caliper (voorbeeld boring BGD036E0161, Fig. 3).
Een tweede reeks van 4 boringen (Tabel 2; Fig. 2) vertoont onder de basis van het Lid van Moen een korte piek in de calipermeting (voorbeeld boring BGD086W0213, Fig. 4).
Deze caliperuitwijking komt overeen met een verzanding van de klei. Naar boven toe begint er een afwisseling van siltige/zandige kleilagen met meer vaste kleilagen. Deze afwisseling is ook zichtbaar in de resistiviteitsmeting (hoge waardes voor zandige lagen, lage voor klei) en de natuurlijke gammastraling (lage waardes voor zandige lagen, hoge voor klei).

Kris Welkenhuysen
19-05-2009


Doel 1b
Natuurlijke Gammastraling
Caliper
300
310
320
330
340
350
360
370
380
390
400
410
420
430
440
450
460
470
480
490
36.2916
117.0636
12.0449
22.08009

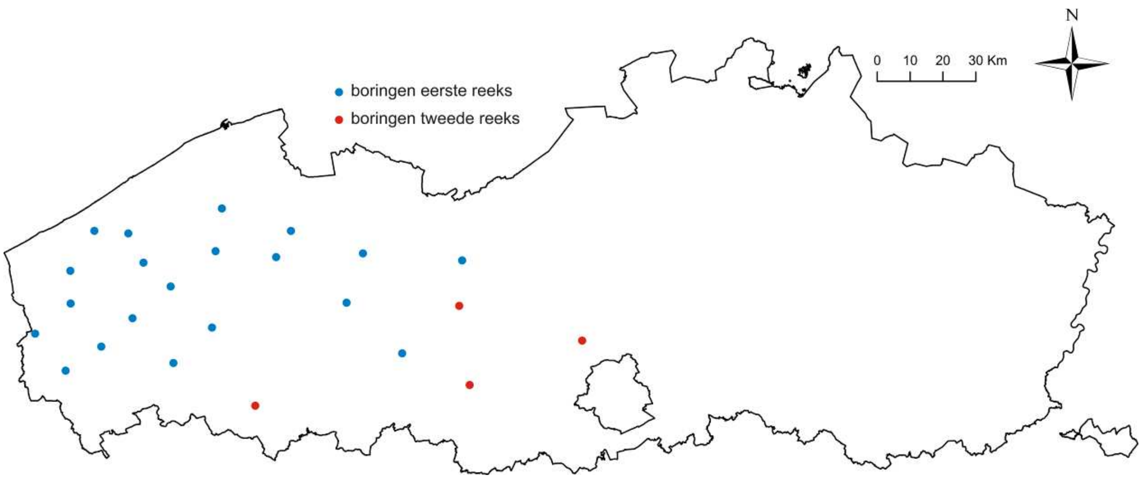
Figuur 1

Tabel 1

BGD-nummer
023W0454
036E0161
036W0204
038E0206
038W0264
039E0144
039W0293
051W0156
051W0157
052W0255
052W0256
054E0246
056W0202
065E0097
066E0135
066E0136
067E0214
070W0785
081W0095
082W0179

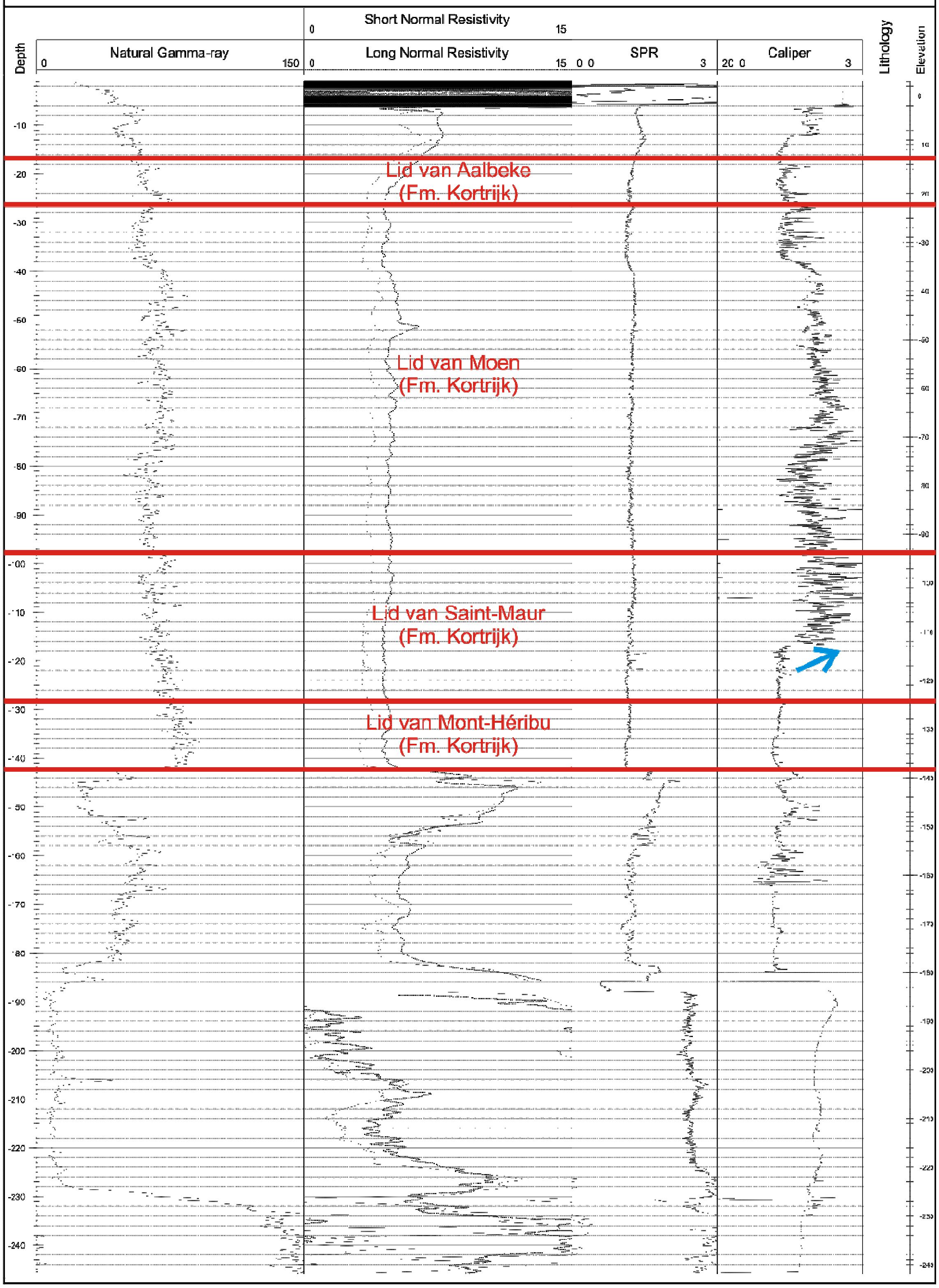
Tabel 2

BGD-nummer
071W0325
072E0229
086W0213
097E0942

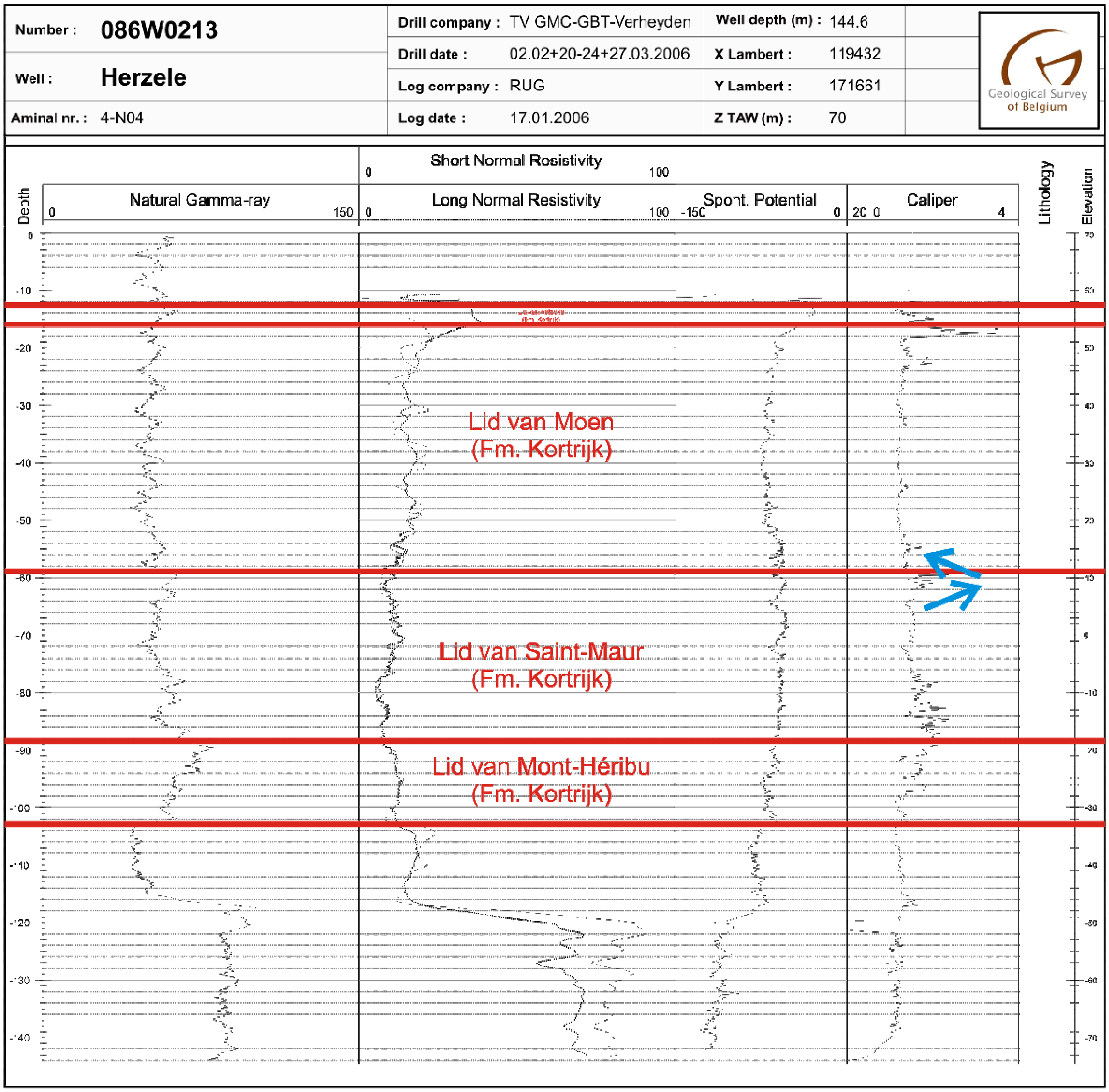


Figuur 2

Number :	036E0161	Drill company :		Well depth (m) :	246.728	Geological Survey of Belgium
Well :	Gistel	Drill date :	17-24.10.2005	X Lambert :	48164	
		Log company :	EGS	Y Lambert :	203275	
Aminal nr. :	3-N16	Log date :	18+25.10.2005	Z TAW (m) :	4	



Figuur 3

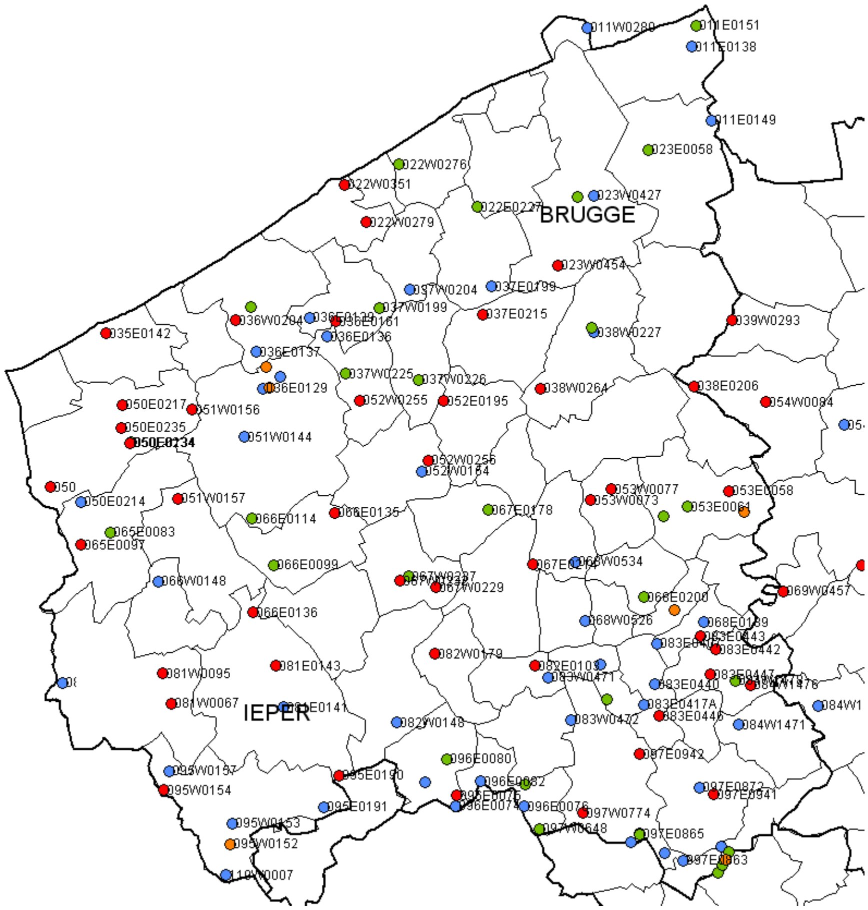


Figuur 4

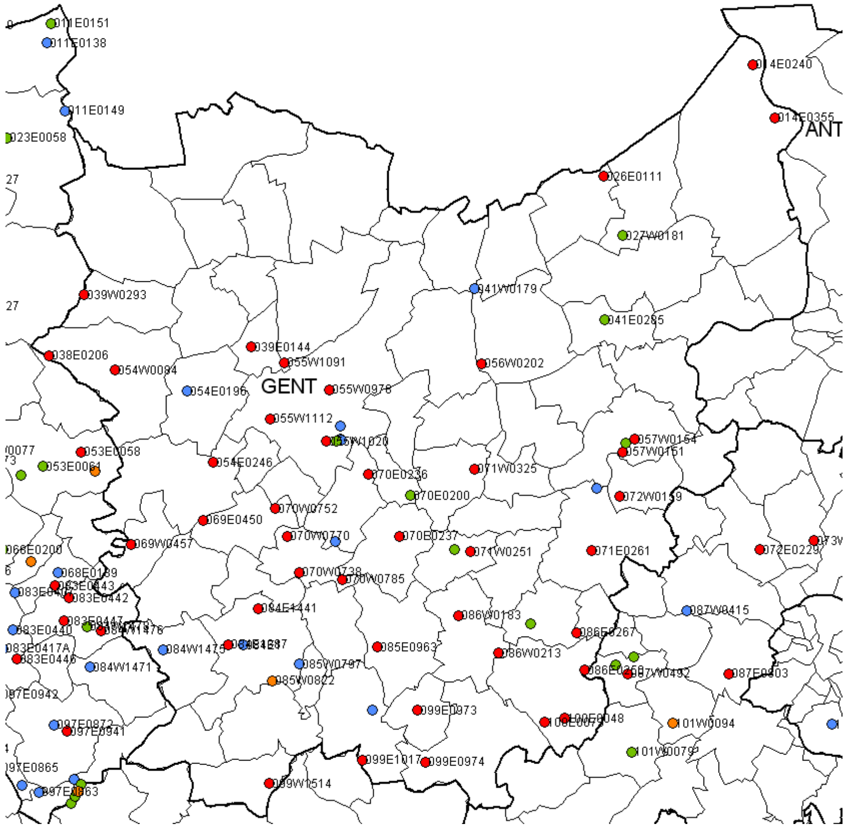
Opmerking :

Een nieuwe versie van figuur 3 is verwerkt op pagina 33; een nieuwere versie van figuur 4 is terug te vinden op pagina 34.

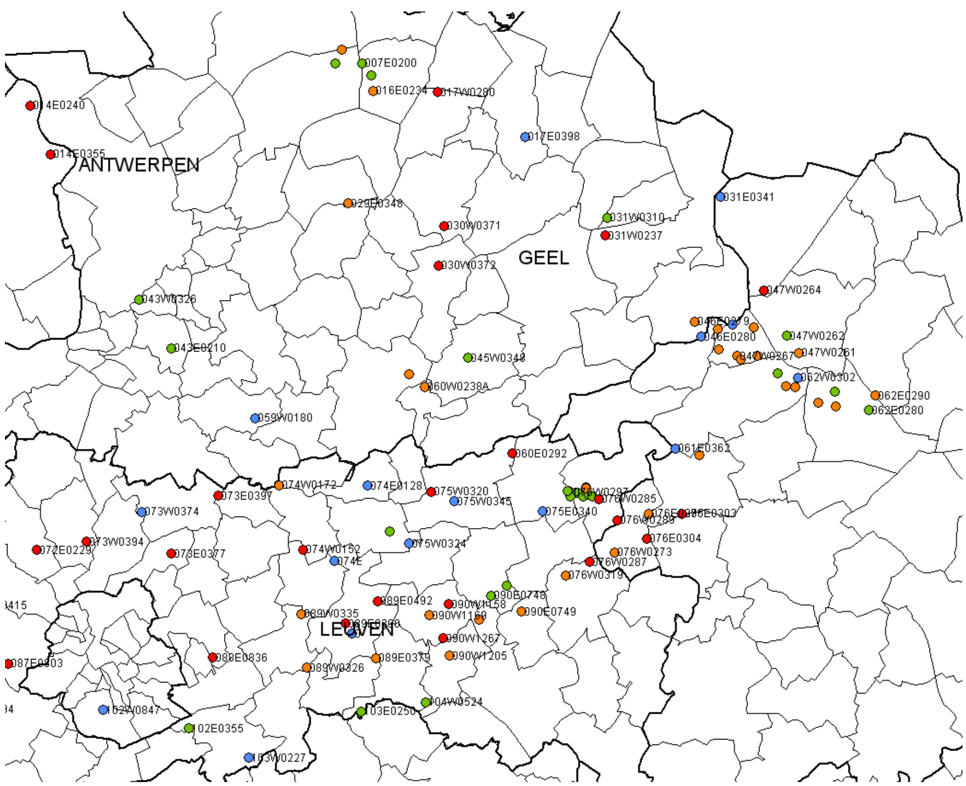
7.4. Location of the logged boreholes with GSB (GeoDoc) number



Province of West-Flanders



Province of East-Flanders



Provinces of Antwerp, Vlaams-Brabant and Limburg