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Sediment-petrological study supporting the presence of the Kasterlee Formation in the Heist-op-den-Berg and Beerzel hills, southern Antwerp Campine, Belgium

Jasper VERHAEGEN[1], Rieko ADRIAENS[1], Stephen LOUWYE[2], Noël VANDENBERGHE[1], Koen VOS[1,3]

[1] *Department Earth and Environmental Sciences, Katholieke Universiteit Leuven, Belgium. E-mail: jasper.verhaegen1@gmail.com*
[2] *Research Unit Palaeontology, Ghent University, Belgium.*
[3] *Sibelco Europe, De Zate 1, BE-2480 Dessel*

ABSTRACT. The precise stratigraphic position of the sediments in the Heist-op-den-Berg and Beerzel hills has been under debate for a long time. According to the geological map of Flanders, these deposits are included in the Diest Formation. Reference data for the Diest and Kasterlee Formations are defined and compared to new sediment-petrological data from samples collected in the Heist-op-den-Berg and Beerzel area. This comparative study indicates that the sediments are similar to the Kasterlee Formation. Additionally, a gravel bed observed at the base of the deposits at the Heist-op-den-Berg and Beerzel hills is similar to the basal gravel of the Kasterlee Formation at Olen. The Kasterlee Formation at Heist-op-den-Berg and Beerzel is subdivided into three members. The lithofacies of the lowermost member is comparable to the Diest Formation and is explained through significant reworking. The occurrence of the Kasterlee Formation in the study area implies the formation of a bay or estuary in the late Miocene sea extending towards the south. The curvature in the present base of the Kasterlee Formation and the considerable thinning of the Diest Formation to the south indicates ongoing subsidence of the Campine basin and uplift of the Caledonian Brabant Massif during the late Miocene and Pliocene.

KEYWORDS: Diest Formation, lithostratigraphy, Miocene

1. Introduction

Heist-op-den-Berg and Beerzel (Fig. 1) are located in the south of the Antwerp province and both localities are situated at the southern border of the Antwerp Campine area, which is characterized by its sandy soils. The hills of Heist-op-den-Berg and Beerzel are the highest points of the Antwerp province, with an altitude of respectively 48 m and 51 m above TAW (Belgian ordnance datum). The surrounding landscape is fairly flat, but approximately 10 km to the southeast the hills of the Hageland landscape rise up. The Hageland hills reach altitudes over 100 m and consist mainly of the upper Miocene (Tortonian) Diest Formation. Both studied locations are situated at the southern border of the Campine occurrence of the Diest Formation (Fig. 1). In the Campine area, the Diest Formation mainly occurs in the subsurface. The stratigraphic subdivision and the depositional history of the Diest Formation are discussed in detail by Vandenberghe et al. (2014).

Approximately 11 km to the northeast of both hills, the younger upper Miocene Kasterlee Formation crops out at Olen (Fig. 1). The Kasterlee Formation is mapped to the east all the way to the Roer Valley Graben, while the formation wedges out to the west. The Pliocene Kattendijk Formation occurs in the same geometrical position above the Diest Formation in the Antwerp area (De Meuter & Laga, 1976), and Gulinck (1963) therefore assumed a Pliocene age for the Kasterlee Formation as a lateral equivalent of the Kattendijk Formation. The Kasterlee Formation, however, is devoid of macrofossils and this rendered a precise age assessment difficult. The Pliocene age was generally accepted until Louwye et al. (2007) carried out a dinoflagellate cyst analysis of the glauconitic sands of the Kasterlee Formation at Olen and Dessel. The dinocyst biostratigraphic analysis indicated a late Miocene age for the Kasterlee Formation and deposition in a coastal environment with significant freshwater influx. The temporary outcrop at Olen, only accessible during construction works for the extension of the sluice on the Albert Canal, is the only location where a gravel bed was observed at the base of the Kasterlee Formation (Louwye et al. 2007).

In the 'Symposium sur la stratigraphie du Néogène nordique' (Tavernier & De Heinzelin, 1963) the deposits at Heist-op-den-Berg and Beerzel were regarded as Diest Formation. However, at that time the Kasterlee Formation was considered as a facies within the Diest Formation (Tavernier & De Heinzelin, 1963) and during the same symposium Gulinck (1963) presented a geological map of the Diest Formation on which the top of the hills are mapped as 'Kasterlee facies' or 'Casterlien'. The Kasterlee facies is described as a fine-grained sandy deposit with a low amount of glauconite in contrast to the proper Diest Formation sand by Gulinck (1963). This author also noted the presence of thin clay layers in the Kasterlee facies. According to the new geological map of Flanders (DOV, 2009) the sands of the Diest and Kasterlee Formations are regarded as belonging to two different formations. However, on the geological map Aarschot (1:50 000) the deposits of the Beerzel and Heist-op-den-Berg hills

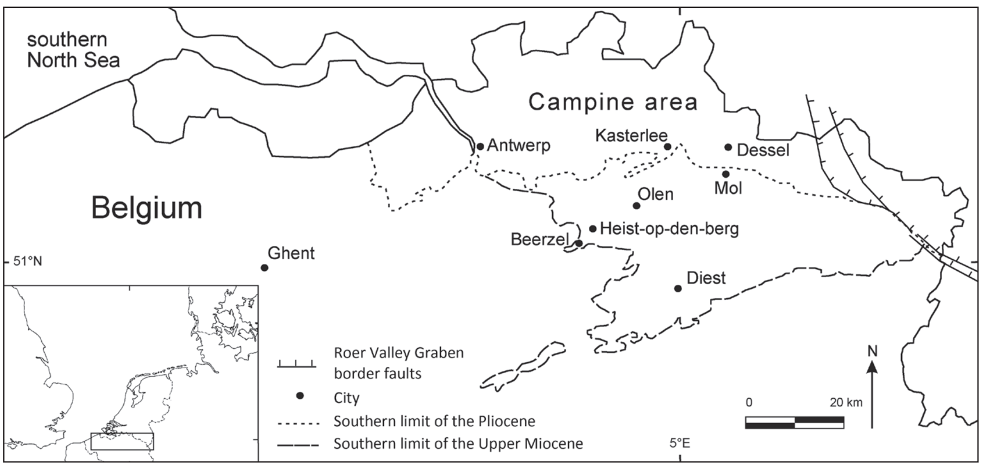

Figure 1. Locations of Heist-op-den-Berg, Beerzel and Olen are given, along with the southern limit of the Upper Miocene and Pliocene.

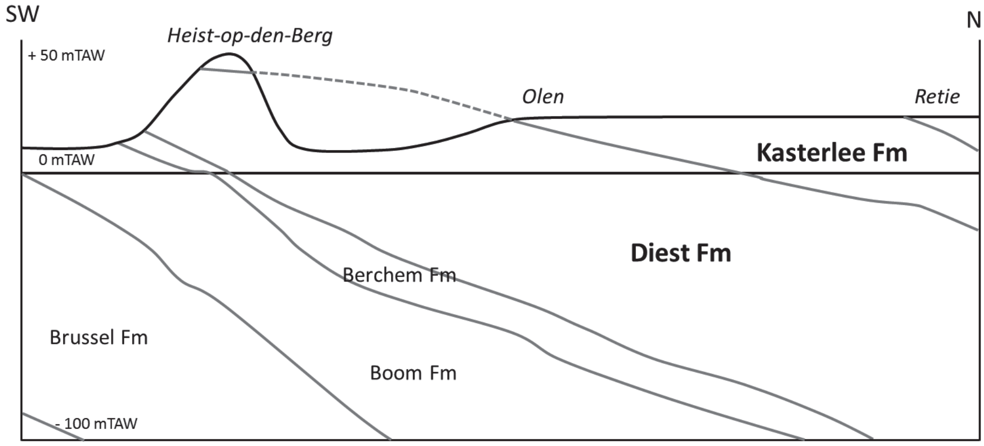

Figure 2. SW-NE profile from Heist-op-den-Berg to Retie, just north of Dessel (see Fig. 1), showing the curved base of the Kasterlee Formation if it occurs on the hill of Heist-op-den-Berg.

are entirely assigned to the Diest Formation (Schiltz et al., 1993). A clayey facies on top of the hills was recognized by Schiltz et al. (1993), but these authors argued that strong variations in grain size and glauconite content with appearance of clay layers at the top of the Diest Formation are not an exception. It was also observed that the occurrence of the Kasterlee Formation at Heist-op-den-Berg and Beerzel would require a considerable thinning of the underlying Diest Formation to the south (Fig. 2). Fobe (1995) placed the presence of the Kasterlee Formation near the summit of the Beerzel and Heist-op-den-Berg hills again under discussion. Based on the sedimentological characteristics of the uppermost layers of the hills, the latter author assigned these deposits to the Kasterlee Formation and proposed a threefold division. Fobe (1995) recognized a first phase of intense reworking of the Diest Formation, which he supposed already stood in relief, followed by the deposition of the Kasterlee Formation in a bay. In a last phase, this bay was partially disconnected from the open marine environment. The bay would have been formed by the incursion of the sea in a river valley between the Diest Hills.

Several problems arise when describing the lithostratigraphy at Heist-op-den-Berg and Beerzel, especially for placing the boundary between the Diest and Kasterlee Formations. A first major problem consists of the strong lithological variations in the upper part of the Diest Formation. The absence of biostratigraphic evidence furthermore poses a problem. Only fairly recently, dinoflagellate cyst biozones were identified in the Diest Formation and Kasterlee Formation (Louwye et al., 2007), yet these are not available for Heist-op-den-Berg and Beerzel since no previous research has been done. Specific stratigraphic markers to correlate the Kasterlee Formation and Diest Formation type areas with the Heist-op-den-Berg and Beerzel hills are not existent and the basal gravel observed at Olen (Louwye et al., 2007), is only observed the first time in the present work.

This paper attempts to define unambiguous parameters to differentiate between the Diest Formation and Kasterlee Formation. These parameters will then be applied to samples from the Heist-op-den-Berg and Beerzel hills. A comparative study of the reference parameters in combination with additional petrographical data from the Heist-op-den-Berg and Beerzel area will be used to assign the deposits to the Diest Formation or Kasterlee Formation. Finally, a hypothesis for the paleogeography and paleotectonics at the time of deposition is presented.

2. Differentiation between the Kasterlee and the Diest Formations

Louwye et al. (2007) investigated the organic-walled palynomorphs (mainly dinoflagellate cysts and acritarchs) from a temporary outcrop at Olen and the ON-Dessel-2 borehole, the sole microfossils identified in the Diest Formation and Kasterlee Formation so far. The palynomorph assemblage of the upper part of the Diest Formation at the Olen outcrop is dominated by the acritarch genus *Cyclopsiella* (> 75 %), whereas the uppermost part of the Diest Formation and the entire Kasterlee Formation are characterized by considerable numbers of *Gramocysta verricula* (Louwye et al., 2007). The occurrence of *Gramocysta verricula* is environmentally controlled and the presence of this species is indicative for shallow marine depositional environments characterized by increased fresh water input through river discharge. The shallow nature of the depositional area is further supported by the occurrence of *Geonettia clineae* in the Kasterlee Formation, a species with a preference for open bay environments with low sediment influx. The S/D ratio (the sporomorph (S) versus marine palynomorph (D) ratio) and the terrestrial component (pollen, spores) are higher in the Kasterlee Formation than in the Diest Formation. *Pediastrum* sp. is a freshwater green alga and its presence is consistently noted in the Kasterlee Formation. The latter species was brought into the shallow marine and near-shore depositional environment via rivers (Louwye et al. 2007). The dinoflagellate cyst diversity and amount per gram of sediment are highest just above the boundary between the Diest Formation and Kasterlee Formation. *Selenopemphix armageddonensis* is present in the Kasterlee Formation in most samples albeit in low abundances. This species has a lowest occurrence in the uppermost Tortonian at 7.45 Ma at mid-latitudes in Northern Hemisphere and a highest occurrence at the top of the Messinian in equatorial regions (Williams et al. 2004). Its range is restricted to the Miocene. The stratigraphic range of *Hystrichosphaeropsis obscura* is as well restricted to the Miocene (Santarelli et al. 1998; Hardenbol et al. 1998), and was recorded in the Olen outcrop in both the Diest and Kasterlee formations. No dinoflagellate cyst species with a post-Miocene lowest occurrence were observed in the Kasterlee Formation (Louwye et al. 2007).

The main petrographic characteristics used by Louwye et al. (2007) for discrimination between the Diest Formation and the Kasterlee Formation are grain size, glauconite content, clay mineralogy and geophysical parameters (resistance, resistivity, natural gamma counts and self potential). According to Louwye et al. (2007) the upper part of the Diest Formation at the Dessel-2 borehole shows a modal grain size of 250-280 µm in contrast to 180 µm for the Kasterlee Formation. The Diest Formation is lithologically characterized as a loosely compacted sand with high glauconite content and a smectite dominated clay mineralogy. The Kasterlee Formation is more compact, has a low glauconite content decreasing upward and the clay fraction is dominated by 10 Å-minerals. An important K-feldspar fraction is present in the Kasterlee Formation (4-5 %). Clay lenses occur in both formations. The boundary between both Formations at Olen is characterized by a coarse quartz fraction, some larger pebbles and a silicified shell fragment (Louwye et al., 2007). The temporary Olen outcrop is the sole location where the boundary is characterized by a distinct base gravel bed.

Supplementary data from Olen (4 collection samples) and the ON-Dessel-2 borehole (7 samples) are given in table 1 and are used as reference values for the Kasterlee Formation and (Campine) Diest Formation. These analyses are done for a PhD in progress by one of the authors (RA). The gravel bed is present at Olen at a depth of approximately 5.2 m below surface (approximately 15 m above TAW). The feldspar and siderite data shown are for the fraction < 32 µm, glauconite data are measured on the fraction > 32 µm. For both sites, the results indicate that plagioclase and siderite are present in the Diest Formation but not in the Kasterlee Formation except for the zone near the basal gravel. K-feldspar does not show significant variations. Glauconite content for the Diest Formation is very variable: for the data given here, it ranges from 21 % to 48 % with lower values for the Olen samples. The glauconite content of the Kasterlee Formation is significantly lower and shows a decrease upwards in the stratigraphic column. It is important to note that the Kasterlee Formation shows Diest Formation characteristics near the boundary between both Formations. Grain-size data indicate there is a significant internal variation in grain size at one location and between different locations for both Formations. The Kasterlee Formation, however, consistently has a smaller grain size than the Diest Formation with values up to 201 µm for the samples measured. The Diest Formation grain sizes range from 201 µm to 311 µm. The Kasterlee Formation also shows much better sorting than the Diest Formation, represented by standard deviation (σ) in table 1.

	K-feldspar	Plagioclase	Siderite	Glauconite	Grain size	
Depth (m)	< 32 µm			> 32 µm	Mode	σ
	ON-Dessel-2					
Kasterlee Fm						
31,15	0.3	0	0	1.2	169.12	93.385
32,7	2	0	0	11	166.58	88.391
33,74	1	0	0	27	162.34	81.74
Diest Fm						
34,95	1	0	0.9	43	255.9	108.522
38,6	1	0.3	1	39	265.9	125.754
41,6	1	0.1	2	48	265.78	166.314
43,05	2	0.3	1	33	200.9	149.113
	Olen					
Kasterlee Fm						
0.5	2	0	0	11	174.09	85.512
4.5	5	1	0.1	26	200.98	98.925
Diest Fm						
8.5	2	0.7	0.4	21	215.53	124.594
12	2	0.3	1	22	311.47	141.246

Table 1. Summarizing table containing reference parameters for the Diest Formation and Kasterlee Formation. K-feldspar, plagioclase, siderite and glauconite data are in wt %. Mode and standard deviation (σ) are in µm. The reference level for the ON-Dessel-2 borehole is 25.45 m above TAW and approximately 20 m above TAW for the Olen outcrop.

3. Local lithostratigraphy of the Kasterlee Formation

The Kasterlee Formation at Heist-op-den-Berg and Beerzel is subdivided into three members by Fobe (1995) (Fig. 3). The base of the supposed Kasterlee Formation lies at approximately 38 m TAW at Heist-op-den-Berg and 40 m TAW at Beerzel. The lowermost member of the Kasterlee Formation is the Hallaar member. This member is defined by Fobe (1995) with a distinct upwards decrease of glauconite content and a poorly developed basal gravel bed (coarse quartz fraction). It was interpreted by this author as a member with intense reworking of the underlying Diest Formation. This reworking is explained as erosion by a river system flowing through the Hageland hills formed in Diest sand, which supposedly already stood in relief. In the 'Fobe-model', the sea level rose and the sea invaded the river valley, creating a bay at Heist-op-den-Berg and Beerzel. In this setting the Beerzel member was deposited. This member consists of very white quartz sand with a much lower glauconite content. On the top of the hills the Heist-op-den-Berg member is found. Glauconite content is again depleted in this member and the boundary with the Beerzel member is defined by the first thick clay layer. Throughout the Heist-op-den-Berg member many clay intercalations are observed. Fobe (1995) interpreted the presence of clay laminae as a deposition in a restricted environment that is partially disconnected from the main Kasterlee Sea basin.

4. Field work and sampling

Samples were taken at Heist-op-den-Berg (4 samples) and Beerzel (2 samples) at locations selected for the objectives of this study (Fig. 3). A search for suitable outcrops was done based on the descriptions by Fobe (1995) and at the relevant topographic heights. Visual inspection of the outcrops allowed to recognize the three members defined by this author and confirmed the proposed lithostratigraphy. All outcrops were first cleaned with a spade to avoid surface contaminations. At Heist-op-den-Berg a sample was taken of the Diest Sands, the Hallaar member, the Beerzel member and the Heist-op-den-Berg member. The sample of the Diest Formation was taken at the base of the 'Holle weg' (Fig. 4). The sample is taken as reference for the Diest Formation and for comparison with the overlying sands. In the field, the sample shows obvious Diest Sand characteristics, i.e. rather coarse grained and a strong green colour due to high glauconite content. The Hallaar member sample was taken along the Kerkhofstraat (Fig. 4). The outcrop is not in a good condition but a colour change from dark green to brown is visible at the boundary with the underlying Diest Sand. The glauconite content of the Hallaar member visibly drops and the grain size decreases. This sample was taken with an Edelman auger to avoid surface effects as much as possible. Along the 'Holle weg' outcrop

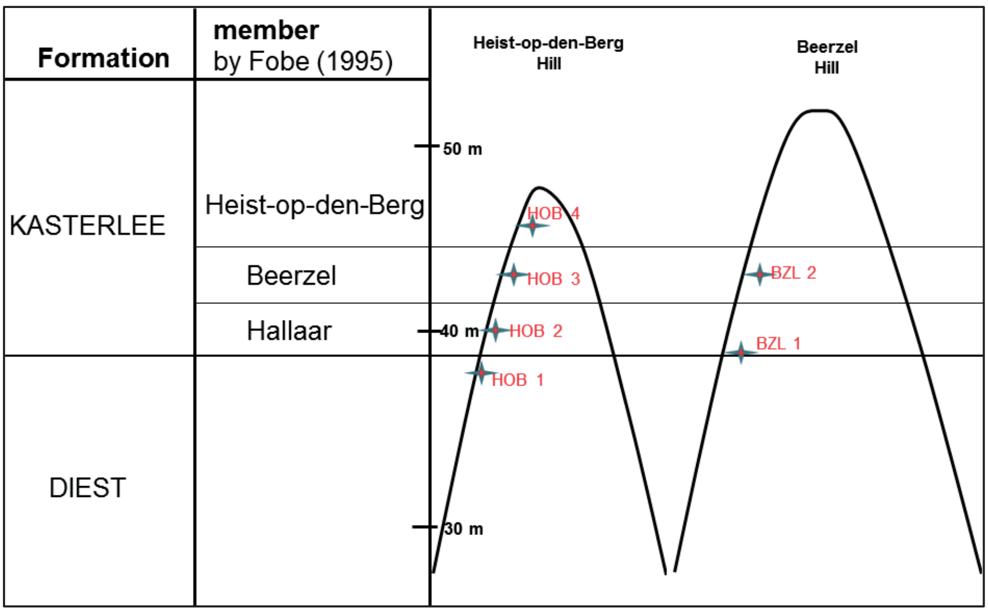

Figure 3. Figure illustrating the stratigraphy of the Heist-op-den-Berg and Beerzel hills as proposed by Fobe (1995). Elevations (m TAW) are indicative. The positions of the samples taken for this research are indicated by the stars (HOB & BZL codes).

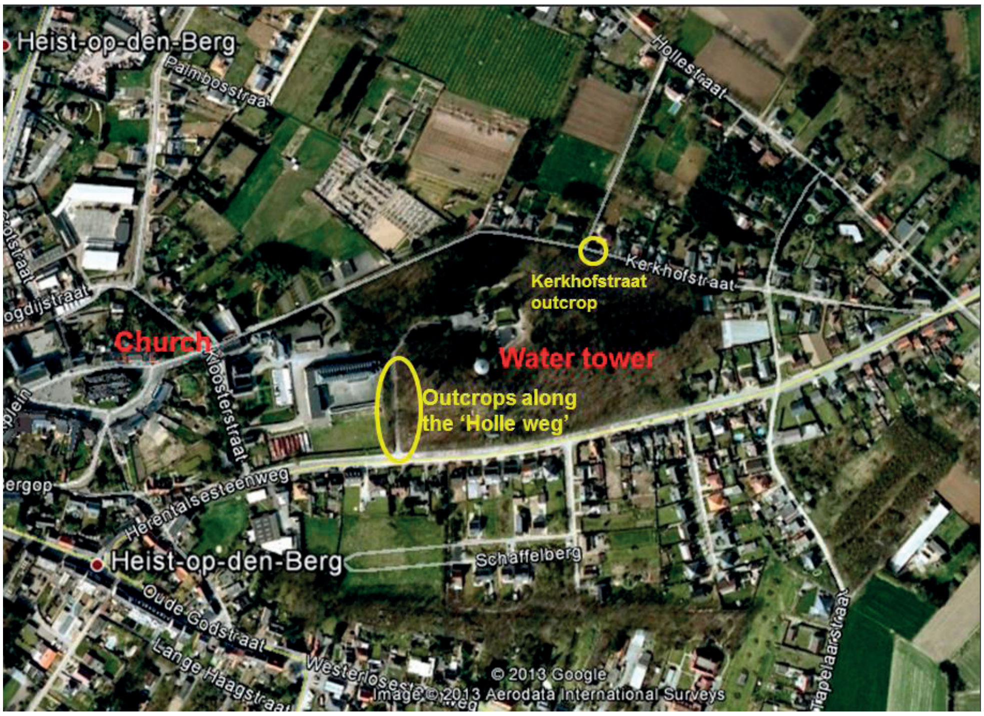

Figure 4. Location map showing the position of the outcrops at Heist-op-den-Berg. The Church and the water tower are indicated as reference points.

samples were also taken of the Beerzel member and the Heist-op-den-Berg member. The Beerzel member is distinguishable by its white colour and finer grain size. The Heist-op-den-Berg member at the top of the outcrop consists of a browner sand with several clay intercalations. In this member several iron concretions were observed, discussed in section 6. The sand sample was again taken with an Edelman auger.

At the Beerzel hill another two samples were taken, one of the Hallaar member and one of the Beerzel member. The Diest Sands are not readily observable here making it impossible to take a sample. The two samples were taken behind 'De Schoenberg' along the Heistse Steenweg (Fig. 5). Both samples at this outcrop were taken with the Edelman auger. The sample of the Hallaar member probably lies at the base of the member because a basal gravel was found here which is further discussed in section 6; the sand shows a green colour – not brown oxidized as in Heist-op-den-Berg – and rather coarse grain size. In the field, the Beerzel member is again distinguished by its whiter colour. At this outcrop, a layer was observed above the Beerzel member which has a high concentration of up to 10 cm large iron concretions (section 6).

As gravel was observed near the base of the Hallaar member during sampling at the Beerzel hill, the contact between the Diest Sand and the Hallaar member at the Heist-op-den-Berg hill was reinvestigated and the presence of a gravel could also be established in this hill (section 6.). Although the sampling site was contaminated with construction waste, care was taken to retrieve gravel only from the undisturbed green sand.

For dinoflagellate cyst analysis, a separate sample set was taken from all stratigraphic units present in the two hills using an Edelman auger in order to avoid near surface alteration as much as possible.

5. Analysis results

The different analyses carried out on the samples are glauconite content determination, grain-size analysis, XRD analysis, shape analysis and dinoflagellate cyst analysis. At the start of the procedure all the samples were wet-sieved on 1 mm because larger grains block the Franz Isodynamic Separator used for glauconite separation and are outside the measuring range of the

Figure 5. Location map showing the position of the outcrop at Beerzel. The tavern 'Beerzel Berg' is indicated as reference point.

Malvern Laser set-up used for grain-size analysis. Only in the Hallaar Member sample of the Beerzel hill a significant fraction >1 mm was separated. Before measurements were carried out the samples were also wet-sieved on 38 µm, separating a smaller fraction containing the fines from a larger fraction containing the bulk of the quartz and glauconite grains.

5.1. Glauconite content

For this analysis the Franz Isodynamic Separator was used which is based on the paramagnetic properties of glauconite. This separation is done on the fraction larger than 38 µm. The supply power used for the glauconite separation is 0.5 – 0.6 A. The front angle is fixed at 20° and the side angle can range from 15 to 20°, sloping away from the operator (Adriaens, 2009). The results of this analysis are shown in table 2.

Glauconite content	Heist-op-den-Berg	Beerzel
Heist-op-den-Berg mbr	0.55%	/
Beerzel mbr	1.31%	2.21%
Hallaar mbr	11.5%	27.31%
Diest Fm	49.82%	/

Table 2. Glauconite content of the samples investigated in wt %.

Glauconite content decreases upward in stratigraphic order from a maximum in the Diest Formation to very low values in the Heist-op-den-Berg member. The high glauconite content of the Diest Formation sample is conform the reference value (Fig. 1). The Hallaar member has a glauconite content higher than the reference values of the Kasterlee Formation. The higher value of the sample from the Beerzel hill compared to the Heist-op-den-Berg hill sample is explained by the position of the former on, or nearby, the boundary with the Diest Formation as indicated by the gravel found in the sample. The low glauconite content of the Beerzel and Heist-op-den-Berg members are in agreement with the observed color and glauconite estimates in the field.

5.2. Grain-size analysis

These measurements were carried out using laser diffraction (Malvern, 2014). For each sample, measurements were done on the > 38 µm fraction of the total sample, the separated glauconite grains and the remaining mainly quartz grains (rest fraction). No major pretreatment of the samples was done to avoid the desintegration of glauconite grains. The samples were only placed in some water and shaken to loosen the grains. This minimal pretreatment may cause a bias towards coarser grain sizes, due to the presence of iron cements and possibly some organic matter yet a full quantitative investigation of the sediments is not the aim of this research. The results are accurate enough for comparing and differentiating the different lithological units. Results expressed by modal size and standard deviation are presented in table 3.

The sample of the Diest Formation is much coarser grained than the other samples and is poorly sorted. The values measured for this sample match the reference values of the Diest Formation. The total sample of the Hallaar member of the Heist-op-den-Berg hill has a bimodal grain-size distribution. The finest modus is comparable to the Kasterlee Formation reference value, while the second modus is much coarser grained (675 µm) and probably represents the "weakly developed basal gravel" described by Fobe (1995). This coarse fraction is also present in the Diest Formation sand, at lower volume% (Fig. 6). The Beerzel hill sample of the Hallaar member shows only one modus and poor sorting, yet in this sample a visible basal gravel with flints up to 2 cm in diameter was observed. At this location, the sample was taken closer to (or on) the boundary with the Diest Formation. The Beerzel and

Grain size	Heist-op-den-Berg		Beerzel	
	Mode	*σ*	*Mode*	*σ*
Heist-op-den-Berg mbr				
Total	196.49	57.257	/	/
Rest fraction	199.5	55.612	/	/
Glauconite fraction	/	/	/	/
Beerzel mbr				
Total	198.62	51.752	200.51	59.648
Rest fraction	202.07	54.779	199.3	56.81
Glauconite fraction	169.33	38.548	221.02	149.503
Hallaar mbr				
Total	203.98 *	201.523 *	265.72	160.192
Rest fraction	218.55	176.382	220.47	150.817
Glauconite fraction	372.25	160.925	307	167.024
Diest Formation				
Total	375.54	179.595	/	/
Rest fraction	454.59	185.088	/	/
Glauconite fraction	415.49	197.196	/	/

Table 3. Results of the grain-size analysis with modal grain size and standard deviation (σ) in µm. The Hallaar member sample of Heist-op-den-Berg (*) shows 2 modes, the second at 674.83 µm, explaining the large σ. Results are shown for the glauconite fraction, rest (mainly quartz) fraction and the total samples.

Heist-op-den-Berg member samples have a finer grain size with good sorting (Fig. 6), compatible with the Kasterlee Formation. The glauconites of the Diest Formation are finer grained than the rest fraction, while the glauconites are coarser than the rest fraction in the Hallaar member and have a grain-size distribution very comparable to Diest Formation glauconites (Fig. 7). The glauconites of the Beerzel member sample from Beerzel show anomalous values, i.e. higher than the rest fraction and with poor sorting.

5.3. XRD analysis

Feldspar content is determined using XRD analysis on the > 38 µm fraction. The samples are mixed with 10% of an internal standard (ZnO) after which they are wet milled with a McCrone micronizing Mill. The samples are subsequently loaded into the sample-holders using a side-loading technique to minimize any preferred orientation (Środoń et al., 2001). Although most of the glauconite present in this fraction was already separated in a previous step, a small amount of finer grained glauconite remains in most samples. The results, given in table 4, are recalculated without the residual glauconite.

XRD fr > 38 µm	Heist-op-den-Berg	Beerzel
Heist-op-den-Berg mbr		
Total Feldspar	4%	/
K-feldspar	100%	/
Plagioclase	0%	/
Beerzel mbr		
Total Feldspar	/	3.6%
K-feldspar	/	100%
Plagioclase	/	0%
Hallaar mbr		
Total Feldspar	4.7%	5.6%
K-feldspar	89%	84%
Plagioclase	11%	16%
Diest Fm		
Total Feldspar	2.5%	/
K-feldspar	92%	/
Plagioclase	8%	/

Table 4. Percentage of feldspar in the different samples and percentage of K-feldspar and Plagioclase within the feldspar fraction.

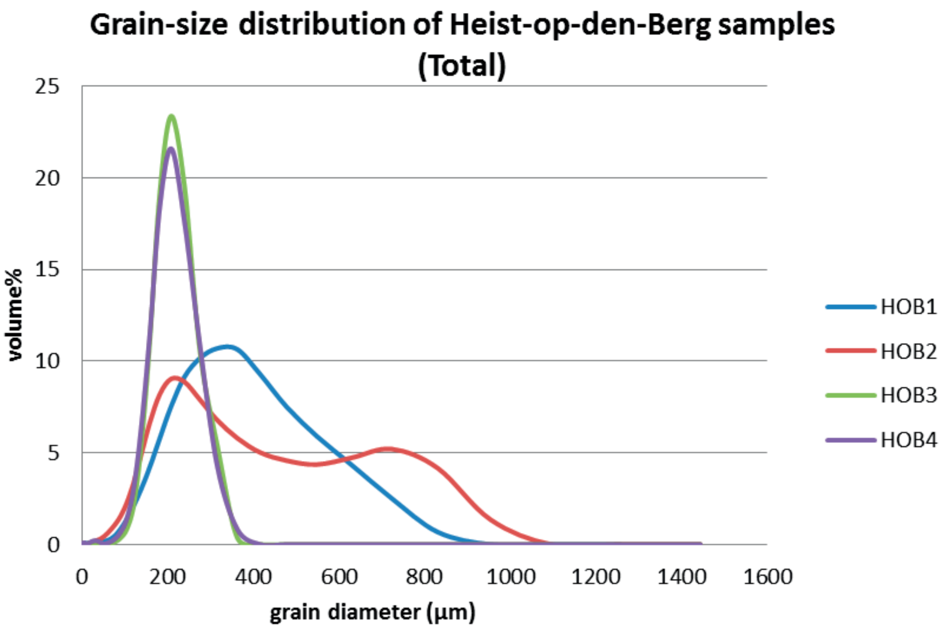

Figure 6. Grain-size distributions of all the Heist-op-den-Berg samples. Measurements are on the total samples. Samples from the 2 upper members (HOB3 & HOB4) show a fine and well sorted grain-size distribution, similar to the Kasterlee Formation. The Hallaar member sample (HOB2) has a bimodal distribution due to reworking from the coarser grained Diest Formation (HOB1). Values are reliable up to 890 µm.

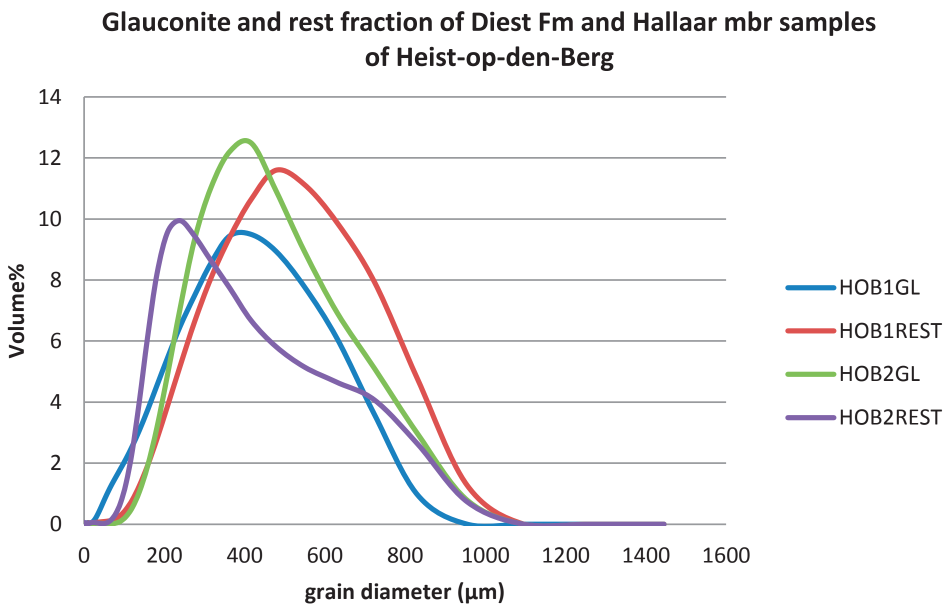

Figure 7. Grain-size distributions of the glauconite fraction and rest fraction for samples HOB1 (Diest Fm – Heist-op-den-Berg) and HOB2 (Hallaar mbr – Heist-op-den-Berg). Note the resemblance between the glauconite fractions of both samples. Values are reliable up to 890 µm.

The results for the Heist-op-den-Berg member and Beerzel member show an absence of plagioclase. The Hallaar member has a larger amount of total feldspar and a significant presence of plagioclase. The Diest Formation sample shows a somewhat smaller feldspar fraction and also a slightly smaller proportion of plagioclase than the Hallaar member samples.

5.4. Shape analysis

The grain shape of the samples was analyzed by a Camsizer, which is a dynamic, digital image analysis technique returning quantitative values for both grain size and shape (Miller & Henderson, 2010). The Camsizer parameters can be correlated to the qualitative values of sphericity and roundness defined by Krumbein & Sloss (1963). Results are shown in table 5 for the glauconite fraction and the rest fraction. The rest fraction does not show a distinction between the different samples based on the shape analysis. In the glauconite fraction, however, obvious shape differences between the samples can be observed. The Diest Sand sample (HOB1) and the Hallaar member sample of Heist-op-den-Berg (HOB2) have the highest sphericity values. Sphericity is lower in the Beerzel member sample of Heist-op-den-Berg

Shape	Heist-op-den-Berg		Beerzel	
	Sphericity	Roundness	Sphericity	Roundness
Heist-op-den-Berg mbr				
Rest fraction	0.67	0.46	/	/
Glauconite fraction	0.64	0.67	/	/
Beerzel mbr				
Rest fraction	0.66	0.46	0.67	0.46
Glauconite fraction	0.65	0.69	0.69	0.64
Hallaar mbr				
Rest fraction	0.67	0.45	0.67	0.43
Glauconite fraction	0.71	0.63	0.69	0.59
Diest Fm				
Rest fraction	0.67	0.46	/	/
Glauconite fraction	0.71	0.56	/	/

Table 5. Results of the shape analysis. Parameters sphericity and roundness are given on a scale from 0 to 1. These values are reliable up to 2 decimals.

(HOB3) and the lowest in the Heist-op-den-Berg member sample (HOB4). The Hallaar member and Beerzel member samples of Beerzel (BZl1 & BZL2) have sphericity values slightly lower than the highest values. The values range between 0.71 (HOB1 & HOB2) and 0.64 (HOB4) on a scale from 0 to 1. Roundness values show the opposite relation and have a larger total range. Roundness increases (or angularity decreases) upwards in the stratigraphic column. The lowest value, 0.56, is obtained in the Diest Sands (HOB1) and the highest value, 0.69, is recorded in the Beerzel member sample of Heist-op-den-Berg (HOB3). The values obtained with the shape analysis show differences between both locations. It should again be stressed that clear patterns can only be observed for the glauconite fraction. This shape analysis can only be used as a complementary tool to the other analysis conducted due to the limited differences and the lack of a reference data set. To confirm the validity of the Camsizer results, a visual assessment with a binocular of the glauconite grains of the Diest Formation and Beerzel member samples from Heist-op-den-Berg was conducted. These samples were chosen for their strongly contrasting values of sphericity and roundness. This visual assessment reveals that the Diest Formation glauconites have a botryoidal habit whereas the glauconites of the Beerzel member have a smooth, flattened surface.

5.5. Dinoflagellate cyst analysis

A palynological maceration of the Diest Formation and the Kasterlee Formation at Heist-op-den-Berg and Beerzel yielded negative results. No organic-walled palynomorphs or any other organic material was recovered. A thorough post-depositional oxidation, possibly caused by percolating water, can be held responsible for the complete degradation of the organic material. This phenomenon is certainly not unique, and has been observed in other Neogene outcrops in the Campine area.

6. Base gravel and iron concretions

A gravel was observed at or near the base of the Hallaar member. The gravel from the Beerzel hill location was concentrated by sieving the sample over a 1 mm screen. The gravel is diffusively present in the member, not as a concentrated layer. Several components can be separated. Most apparent are the flints up to 2 cm in diameter, which are relatively flattened and show a spotted patina (Fig. 8). The majority of the gravel consists of large quartz grains which can be split into angular grains (Fig. 9) and more rounded, flattened ones, 1 to 5 mm in diameter (Fig. 10). Some fragments of altered silex are present, recognizable by their white color and powdery surface (Fig. 11). Also some iron crusts up to 1.5 cm are present in the basal gravel, which have rounded corners (Fig. 12). In the Hallaar member of Heist-op-den-Berg the flat and spotted patina flints were also found. The pebbles at Heist-op-den-Berg are larger (up to 4 cm diameter) than at Beerzel and they have a weathered, etched surface (Fig. 13). A distinct gravel bed at the base of the Kasterlee Formation is only known from the temporary Olen outcrop (Louwye et al., 2007). A collection sample from this gravel was investigated and compared to the gravel found at Beerzel and Heist-op-den-Berg.

Although no exact sieving was applied when sampling the base gravel at Olen, the same components as in the gravel collected at Beerzel can be recognized, except for the iron fragments. Quite specific are the characteristic pale grey flints with black spots observed at all three locations. 16 out of 40 flints from the Olen sample show this specific patina and similar specimens were also found at Beerzel and Heist-op-den-Berg (Fig. 8).

Iron fragments present in the basal gravel from Beerzel appear to have a weathered and somewhat rounded surface. This is in contrast with the Hallaar member sample from Heist-op-den-Berg (Kerkhofstraat outcrop) and observations made in the other members, where the iron fragments have a smooth and angular surface (Fig. 12).

As mentioned in section 4, a layer was observed on top of the Beerzel member at 'De Schoenberg' in Beerzel with a high concentration of iron concretions. These iron concretions vary in size from a few cm up to 10 cm. A lot of these concretions show a very smooth, polished surface (Fig. 14). Several iron concretions were also observed in the Heist-op-den-Berg member at Heist-op-den-Berg, but they lack the polished surface and are present throughout the member, not concentrated.

7. Discussion

7.1. The Kasterlee Formation at Heist-op-den-Berg and Beerzel

Although the small number of samples analyzed cannot yet provide final results, the consistency of the results from the different analyses is instructive. All sedimentological properties analyzed show a distinction between the uppermost sediments of the Heist-op-den-Berg and Beerzel hills and the underlying Diest sand, with in between both a unit with mixed properties. New evidence to place these uppermost layers in another formation is the occurrence of a gravel bed at the base of the mixed properties unit. The gravel bed was observed at both locations. The strong resemblance between this gravel and the gravel observed at the base of the Kasterlee Formation at Olen is an indication that the top layers of the Heist-op-den-Berg and Beerzel hills logically belong to the Kasterlee Formation. A more quantitative analysis of the gravel would be useful but the outcrop at Olen was only temporary and no longer accessible.

The Hallaar member can be interpreted as a member with substantial reworking, which is also suggested by Fobe (1995). The first indication is the intermediate glauconite content between the reference values of the Diest Formation and the Kasterlee Formation indicating a substantial amount of glauconite could be the result of reworking from the Diest Formation. The grain-size analysis of the Hallaar member shows a bimodal distribution for the Heist-op-den-Berg sample. The fine mode can be correlated to the Kasterlee Formation and the coarse fraction can be interpreted as a poorly developed base gravel mixed with a concentration of coarser Diest sand. The grain-size distribution of the glauconite also strongly suggests reworking of the glauconites from the Diest Formation since the glauconites of the Hallaar member are larger than the rest fraction and very similar in size to the glauconites of

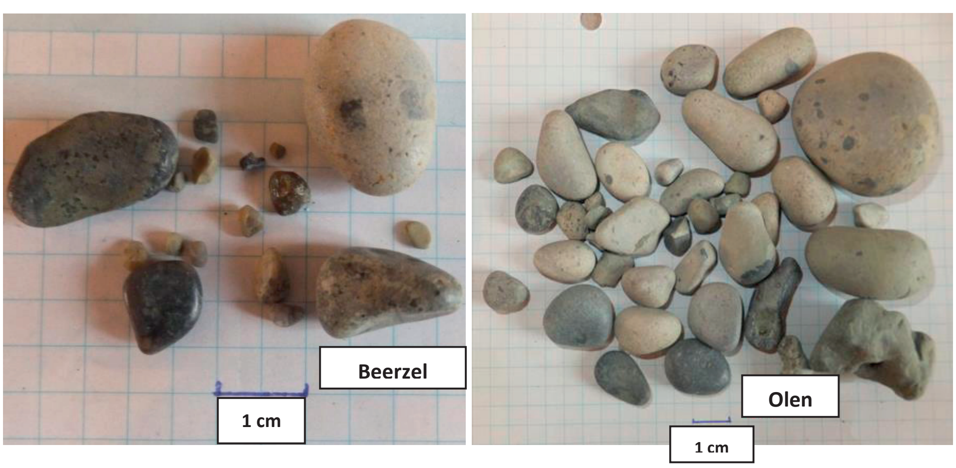

Figure 8. These pictures show the flints with spotted patina present both in the basal gravel at Beerzel and Olen. The flints are the characteristic element of the basal graval.

Figure 9. Pictures of the angular quartz grains present both in the basal gravel at Beerzel and Olen.

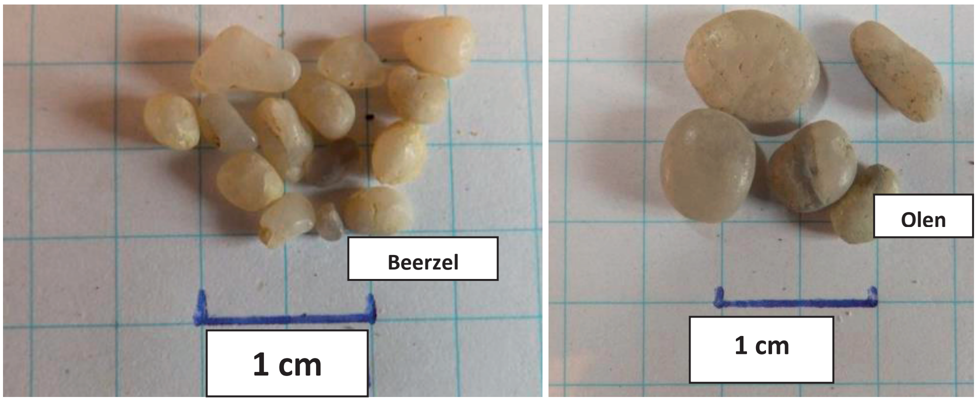

Figure 10. Pictures of the rounded quartz grains present both in the basal gravel at Beerzel and Olen.

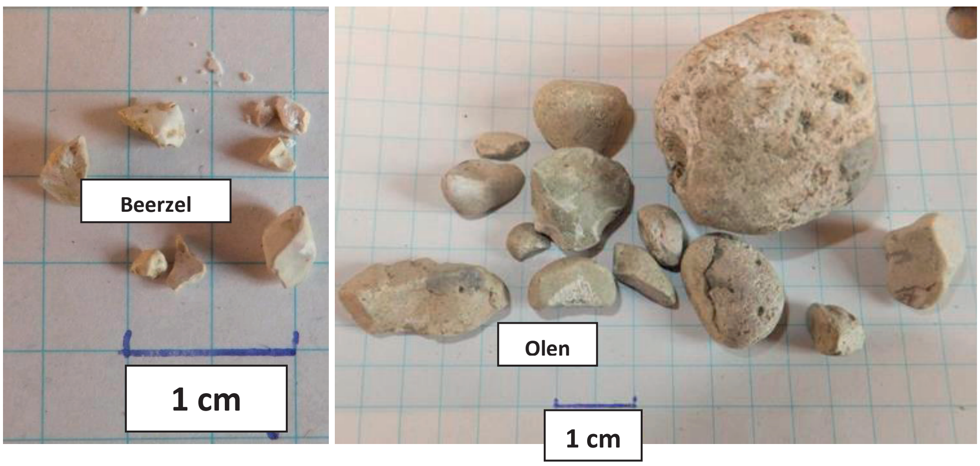

Figure 11. Pictures of the altered silex fragments present both in the base gravel at Beerzel and Olen.

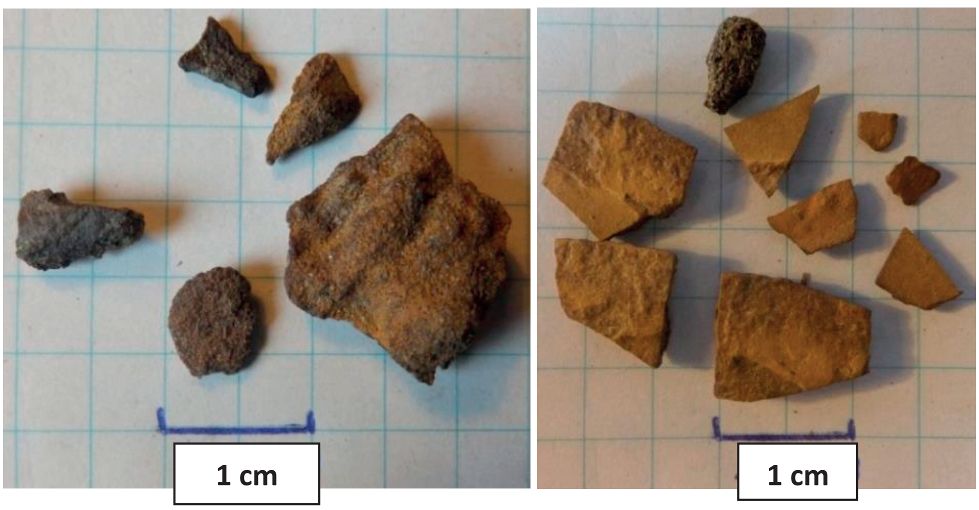

Figure 12. Pictures of iron crust fragments present in the basal gravel at Beerzel (to the left) and in the upper Hallaar member from Heist-op-den-Berg (to the right). The iron crust fragments from the basal gravel show a more rounded and weathered surface which could indicate reworking from older Diest Formation iron crusts.

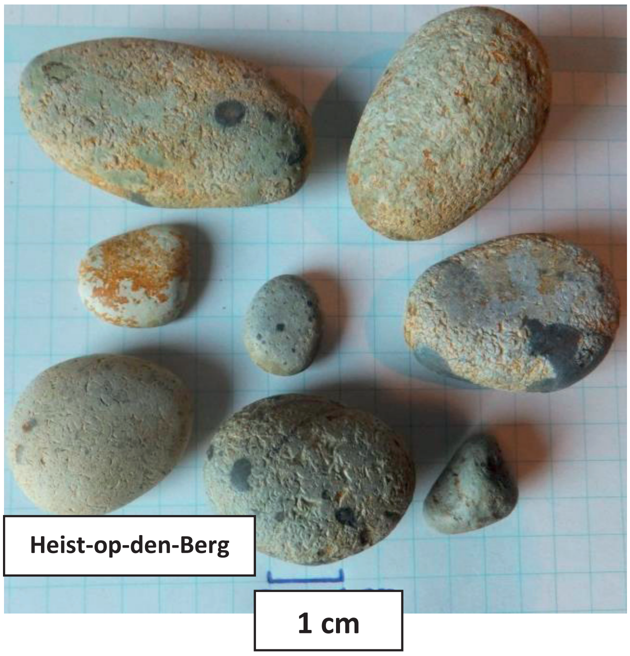

Figure 13. Picture of the flints found at the Heist-op-den-Berg 'Holle weg' outcrop. The flints show the same characteristic spotted patina as the flints from Beerzel and Olen.

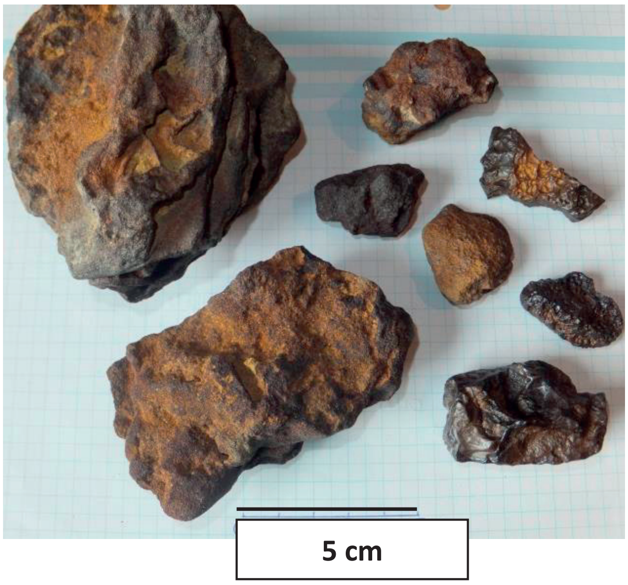

Figure 14. Picture of the iron concretions found in the concentrated layer at Beerzel. The concretions to the right clearly have a polished surface.

the Diest Formation, which are smaller than its rest fraction. The glauconite content and the grain-size distributions of the Beerzel and Heist-op-den-Berg members total samples are very similar to the Kasterlee Formation reference data (Table 1). The XRD analysis reveals the near absence of plagioclase in the Beerzel and Heist-op-den-Berg members but the presence of K-feldspar, which again correlates to the Kasterlee Formation reference parameters. The presence of plagioclase in the Hallaar member can be expected by reworking of plagioclase from the underlying Diest Formation. The shape analysis of glauconite grains showed more indications of reworking for the glauconite fraction. The glauconites of the Diest Formation have the highest sphericity and lowest roundness values, explained by their original botryoidal habit. The values for the Hallaar member are similar to those of the Diest Formation due to reworking of the Diest glauconites into the Hallaar member.

7.2. Palaeogeographic and palaeotectonic implications

The absence of a basal gravel bed in the main outcrop area of the Kasterlee Formation to the north can be explained by the deepening of the depositional basin in that direction. The gravel was deposited in a marginal marine setting of a late Miocene sea in the area of Heist-op-den-Berg, Beerzel and Olen. Iron crust fragments are common in all the described units except for the Beerzel member. In the basal gravel, however, they seem to show a rounded and weathered surface instead of apparently broken fragments with smooth surfaces. This could be interpreted as the reworking of already existing iron crusts in the top of exposed Diest sands. The implication would be that the Diest sands already stood in relief and were iron cemented when the Kasterlee Formation was deposited. At Heist-op-den-Berg, several iron concretions were observed dispersed throughout the Heist-op-den-Berg member with a rough granular surface. At Beerzel, a layer was observed on top of the Beerzel member at the surface (no Heist-op-den-Berg member present), with a high concentration of these iron concretions. Many of these iron concretions show a polished surface. The polished surface of the iron concretions is explained by sand blasting of the concretions, in a Quaternary periglacial desert on an erosion pavement after the Heist-op-den-Berg member was removed. Apparently iron crust formation in the glauconitic sands is a common and rapid phenomenon; in the sections studied it is interpreted to have formed both in the top of the Diest Formation after this unit was exposed and in the top of the Kasterlee Formation. In addition, similar iron cementation is also known from the Pliocene Poederlee Formation to the north of Olen.

The presence of the Kasterlee Formation at Heist-op-den-Berg and Beerzel implies that the late Miocene sea would have formed a bay or estuary as proposed by Fobe (1995) (Fig. 15). The Diest Formation characteristics of the Hallaar member are the result of erosion and reworking of the Diest Formation by the transgression of the late Miocene sea and by rivers draining the landscape to the south. Interpreting the 1:50 000 geological maps (DOV, 2009), during the Pliocene, the Kasterlee Formation was eroded and subsequently covered by the sands of the Mol Formation in the east, the sands of the Poederlee Formation in the center and the sands of the Kattendijk Formation in the west. The absence of the Kasterlee Formation to the west of Kasterlee is explained either by the shape of the Kasterlee bay or by the erosion as a consequence of the early Pliocene transgression which even eroded the underlying lower Miocene Berchem Formation. The presence of the Kasterlee Formation on top of the Beerzel and Heist-op-den-Berg hills results in a curved trace of the southern limit of the Kasterlee Formation on the geological map and in a considerable thinning of the Diest Formation to the south (Fig. 2). The implication of this stratigraphic thinning is that during the deposition of the sands of the Diest Formation, the Campine area to the north was markedly subsiding relative to the Brabant area, which is underlain by an old Caledonian block. The curvature in the base of the Kasterlee Formation and its dip to the north shows that this differential subsidence in the Campine area continued during the Pliocene.

8. Conclusion

The deposits at the top of the hills of Heist-op-den-Berg and Beerzel are interpreted here to belong to the Kasterlee Formation. The glauconite content, grain size and feldspar content show a good correlation between the Beerzel and Heist-op-den-Berg members, sensu Fobe (1995), and the Kasterlee Formation reference data. This conclusion confirms the interpretation by Gulinck (1963) and requires a review of the 1:50 000 geological map sheet Aarschot. The Hallaar member is interpreted as a member with significant reworking of the Diest Formation. In the region of Heist-op-den-Berg, the boundary between the Diest Formation and the Kasterlee Formation is defined by a gravel rich zone characterized by spotted patina flints. The late Miocene sea formed a bay or estuary in the Heist-op-den-Berg and Beerzel area and deposited the Kasterlee Formation. During the Pliocene transgression, part of the Kasterlee Formation was eroded and laterally replaced to the west by the Kattendijk Formation.

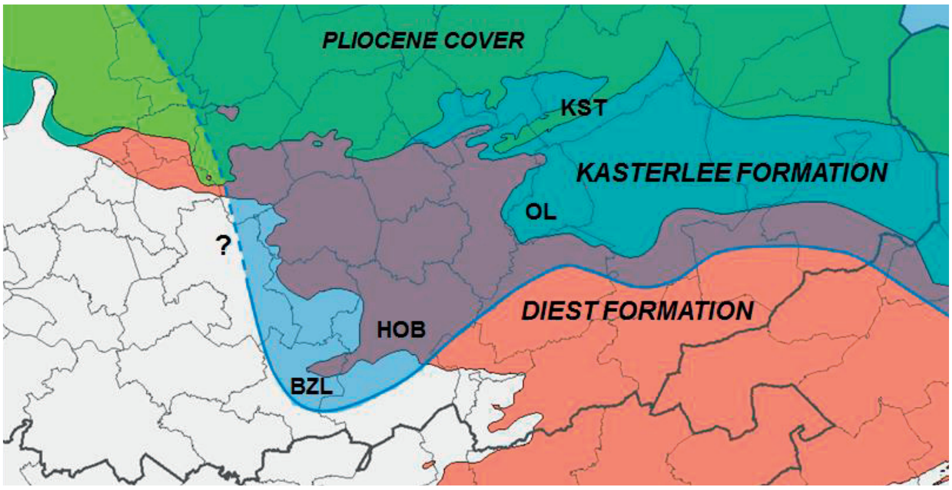

Figure 15. Palaeogeographic map of the Kasterlee Sea (in blue), with the current occurrence of Diest Formation, Kasterlee Formation and Pliocene cover (after DOV, 2009). BZL = Beerzel, HOB = Heist-op-den-Berg, OL = Olen, KST = Kasterlee.

Weathered and rounded reworked iron crusts at the base of Kasterlee Formation deposits suggest that the Diest Formation already stood in relief during the late Miocene. The presence of the Kasterlee Formation in the Heist-op-den-Berg and Beerzel hills confirms the ongoing differential tectonics of the subsiding Campine basin and uplifting Caledonian Brabant Massif during the late Miocene and Pliocene.

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