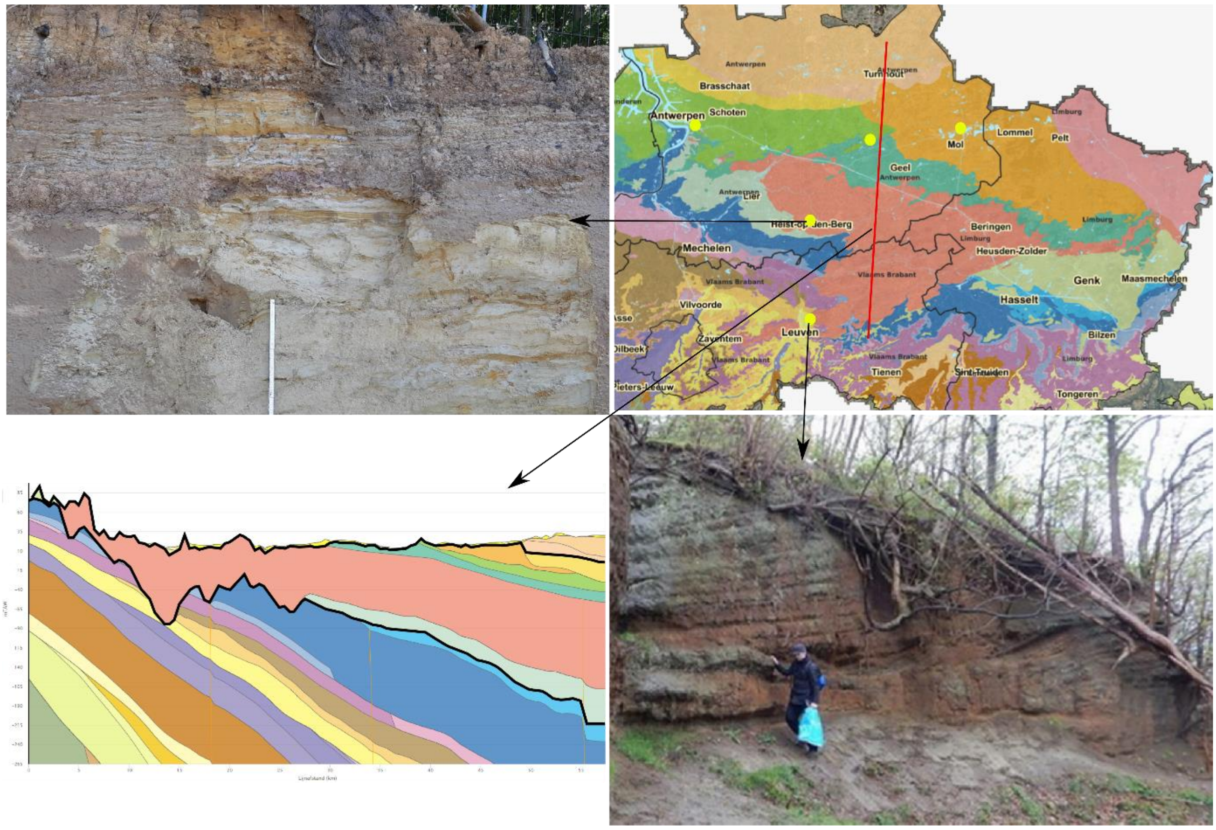
Symposium 'Towards a revised Neogene stratigraphy of Belgium'
19-20 May 2022

Excursion through the Neogene of northern Belgium



Citation

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Content

Introduction

In this excursion in the framework of the symposium on the renewed stratigraphy of the Neogene of Belgium, a selection of outcrops and cores is visited. These provide an overview of the different types of sediment present in the Belgian Neogene. Although the Neogene is a fascinating time period in which important climatic, tectonic and paleogeographic evolutions take place, it is a rather difficult period to showcase in the field. In contrast to the Paleogene of which abundant outcrops occur in the hilly areas of central Belgium, the Neogene sediments mainly occur in the subsurface of the mostly flat area of northeastern Flanders, with the Hageland Hills as a notable exception. As such, good permanent outcrops are few and far between. During this excursion permanent exposures are visited along an approximate south-north transect from Leuven in the Hageland area to Lichtaart in the Campine area (Figure 1). These outcrops are supplemented by cores of the Antwerp city area and the Mol-Dessel area, available in the core repositories of the Geotheek and ESV Euridice. With this combination of cores and outcrops, sediments ranging from the upper Oligocene to the Pliocene and representing distinct sedimentary environments can be observed (Figure 2, Figure 3). The continental Neogene sediments occurring in eastern Limburg, such as the quartz sand of the Opgrimbie Facies and the coarse fluvial sand of the Kiezeloölite Formation are not included in this excursion.

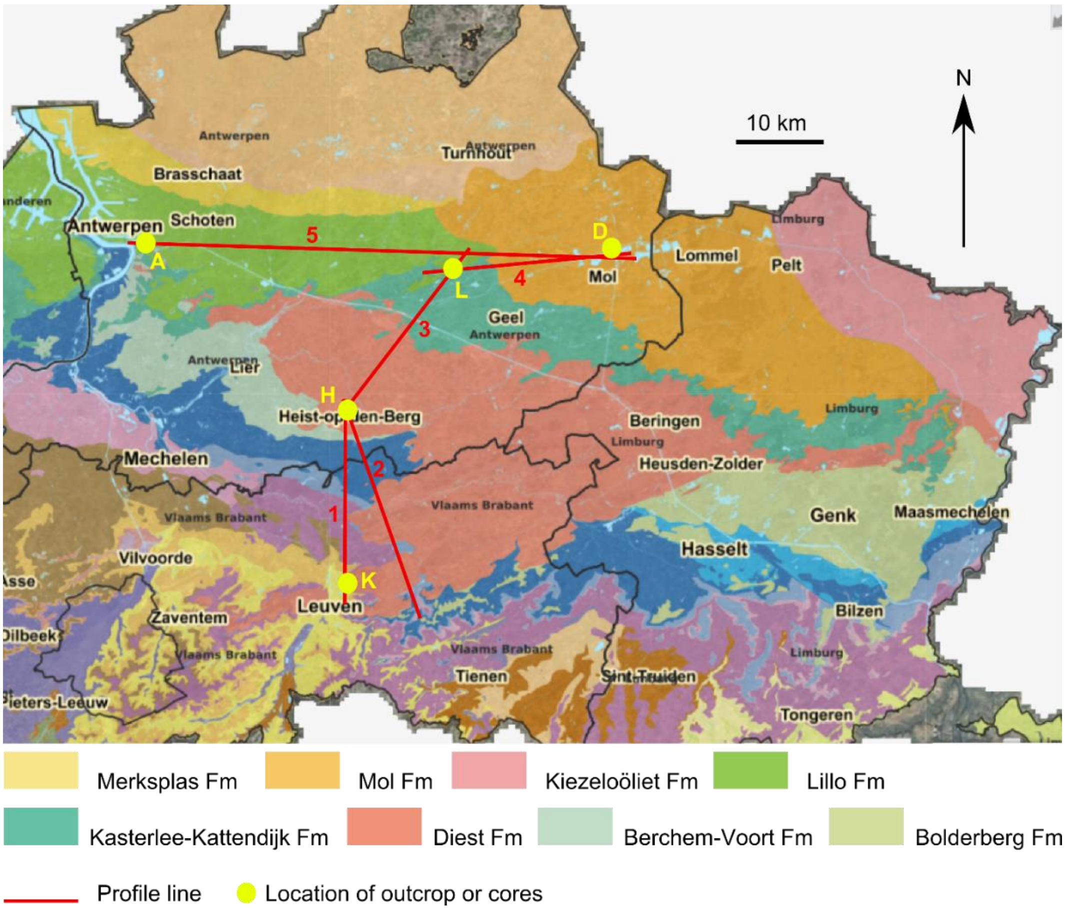


Figure 1. Geological map of eastern Flanders based on the 3D geological model of the Flemish subsurface, G3Dv3.1 (https://www .dov.vlaanderen.be/; Deckers et al., 2019). Legend given for all Neogene units, which mainly occur in the northeastern part of Flanders. Profile lines used in other figures indicated, as well as the location of visited outcrops and drilling locations of cores. A = Antwerp cores drilling site, D = Dessel cores drilling site, H = Heist-op-den-Berg outcrop, K = Kesselberg outcrop, L = Lichtaart outcrop. 1: Figure 16A, 2: Figure 16B, 3: Figure 22, 4: Figure 26A, 5: Figure 26B.

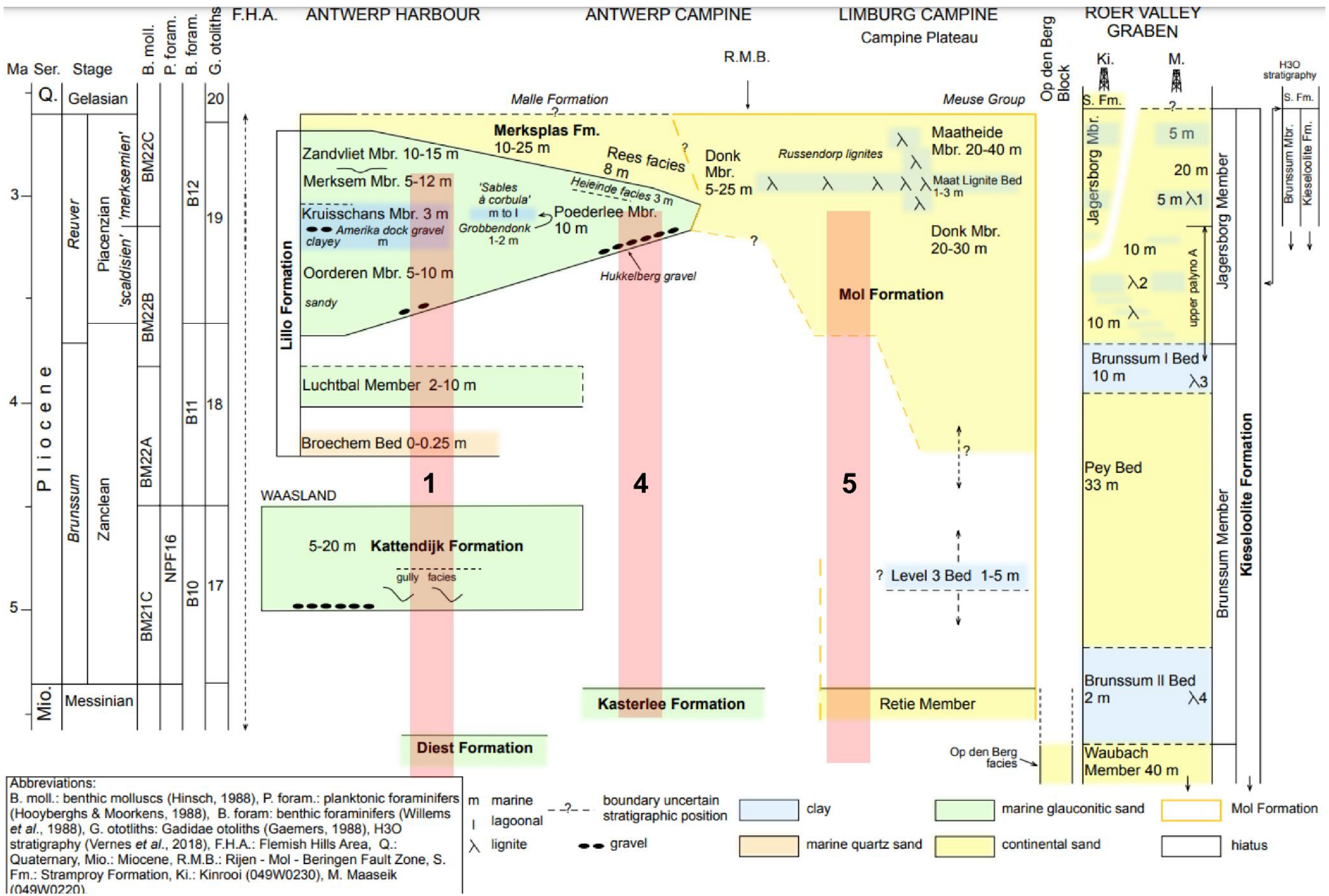
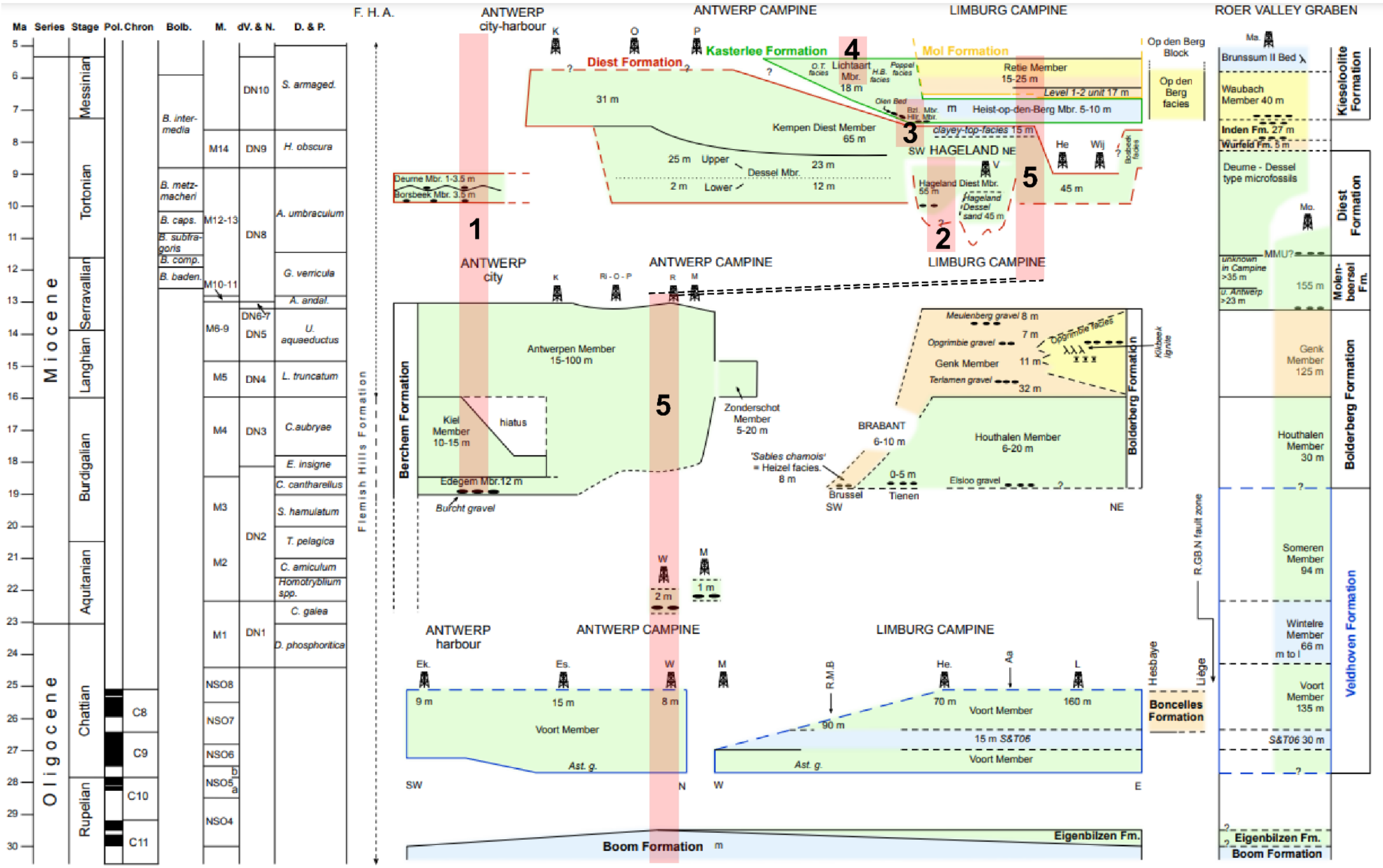


Figure 2. Updated Pliocene stratigraphic table (after Vandenberghe & Louwye, 2020), with stratigraphic situation in red of the outcrops and cores visited during this excursion. 1: Antwerp city cores, 4: Lichtaart, 5: Dessel cores. (Vandenberghe, N. & Louwye, S., 2020. An introduction to the Neogene stratigraphy of northern Belgium: present status. Geologica Belgica, 23/3-4, 97-112)



Abbreviations:
Bzl.: Beerzel, Ek.: Ekeren (015W0142), Es.: Essen (001E0042), Hllr.: Hallaar, He.: Hechtel (047E0192), K.: Kalmthout (006E110), L.: Lommel-2 (032W0409), M.: Mol (031W0221), Ma.: Maaseik (049W0220), Mo.: Molenbeersel (049W0226), O.: Oostmalle (029E0249), P.: Poederlee (030W300), R.: Retie (031W0243), Ri.: Rijkevorsel (016E0153), V.: Veerle (060E0215), W.: Weelde (008E0159), Wij.: Wijshagen (048W0180). A. andal: A. andalousiensis, B. bad.: B. badenensis, B. caps.: B. capsula, D. comp.: B. compressispinosa, R.M.B.: Rijen - Mol - Beringen Fault Zone, R.GB.N.: Reppel - Grote Brogel - Neeroeteren Fault Zone, Aa: Aa Fault Zone, F.H.A.: Flemish Hills Area. O.T. Oud Turnhout, H.B.: Hoge Berg, Pol.: polarity, Bolbof.: Bolboforma biozonation (after King 2016), M.: Munsterman & Brinkhuis (2014) and Van Simaeys et al. (2005) dinocyst biozonations, dV. & N.: de Verteuil & Norris dinocyst biozonation, D. & P.: Dybkjaer & Piasecki (2010) dinocyst biozonation. Boundaries of dinocyst biozonations after Dybkjaer & Piasecki (2010). Ast. g.: Asterigerina guerichi guerichi base, S&T06: Schneider & Thiele unit 06.

Figure 3. Updated Miocene stratigraphic table (after Vandenberghe & Louwye, 2020), with stratigraphic situation in red of the outcrops and cores visited during this excursion. 1: Antwerp city cores, 2: Kesselberg, 3: Heist-op-den-Berg, 4: Lichtaart, 5: Dessel cores.

Stop 1: Geotheek – cores of the Antwerp city area

J. Verhaegen, K. De Nil, J. Deckers, S. Everaert

Flanders soil and subsurface sample repository (Geotheek)

Adress: Gustaaf Levisstraat 45, 1800 Vilvoorde

An integrated approach is key for the Department of Environment and Spatial Development of the Flemish Government (Departement Omgeving) for a sustainable management of the subsurface, natural resources and available space above and below ground. Subsurface samples or soil samples, collected during often expensive drilling campaigns or during (temporary) excavations inform us directly about the nature and structure of the subsoil. In order to valorise these, the Department manages the 'Geotheek' since 2019. It is the Flemish facility for storage and collection of subsoil and soil samples with reference value. The Geotheek is part of the Flanders Repository site in Vilvoorde (Figure 4). The depot management is linked to the online Soil and Subsoil Database Flanders (Databank Ondergrond Vlaanderen, DOV).

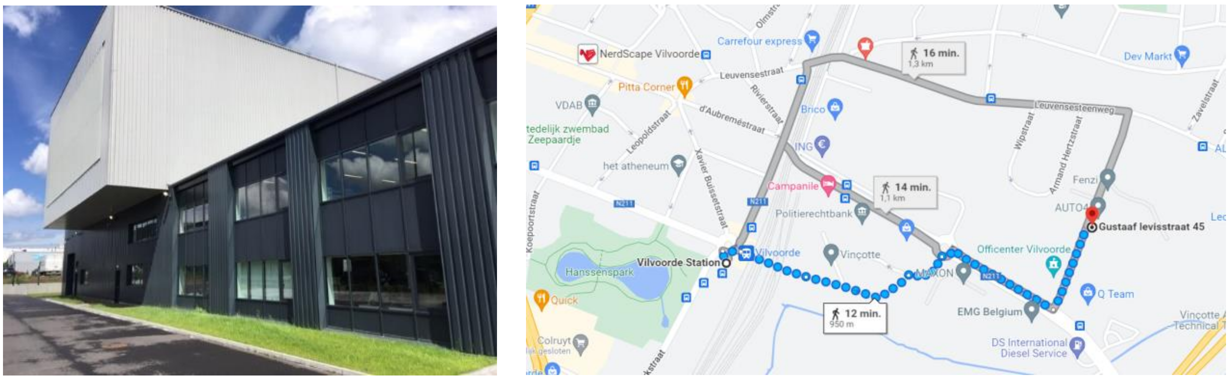


Figure 4. The 'Geotheek' in Vilvoorde, part of Flemish government repository site.

The samples are stored for the long term in appropriate conditions and made accessible to interested parties. The samples can be visually studied on site, but also resampled. The samples are a valuable source for further (scientific) research by the government or third parties and they have an educational value.

There is currently no legal obligation to preserve underground samples, unless it is a condition in the permit. Samples are collected through the Department's own research, through project outsourcing or through networking and collaboration with drilling companies, potentially interesting projects or opportunities in the field. In addition, there is a collaboration with the geotechnical division (Afdeling Geotechniek) of the MOW Department to transfer samples to the Geotheek after finalisation of their projects. The Geotheek is the logical final storage location for all new research in which undisturbed subsoil samples or interesting disturbed subsoil samples are taken in Flanders.

On 01/04/2022, geological samples from the shallow and deep subsurface are available in the Geotheek from 490 locations in Flanders (see Figure 5), together accounting for several thousand individual samples. For now, this mainly concerns:

- Loose sediment samples from drillings commissioned by Department Omgeving, the MOW department, VMM, the Antwerp Port Authority and the Flemish Environmental Planning Agency or third parties.

- Samples from (temporary) outcrops, from own projects or supplied by third parties. They provide a direct view of the nature and location of the geological layers from the subsoil and are therefore a source of high-quality samples.
- Core samples. These are the smallest subgroup of very high-quality samples, originating from the transfer of the deposit of the Royal Belgian Institute of Natural Sciences, from research commissioned by VPO, from drilling by the Geotechnical Department and from drilling companies.

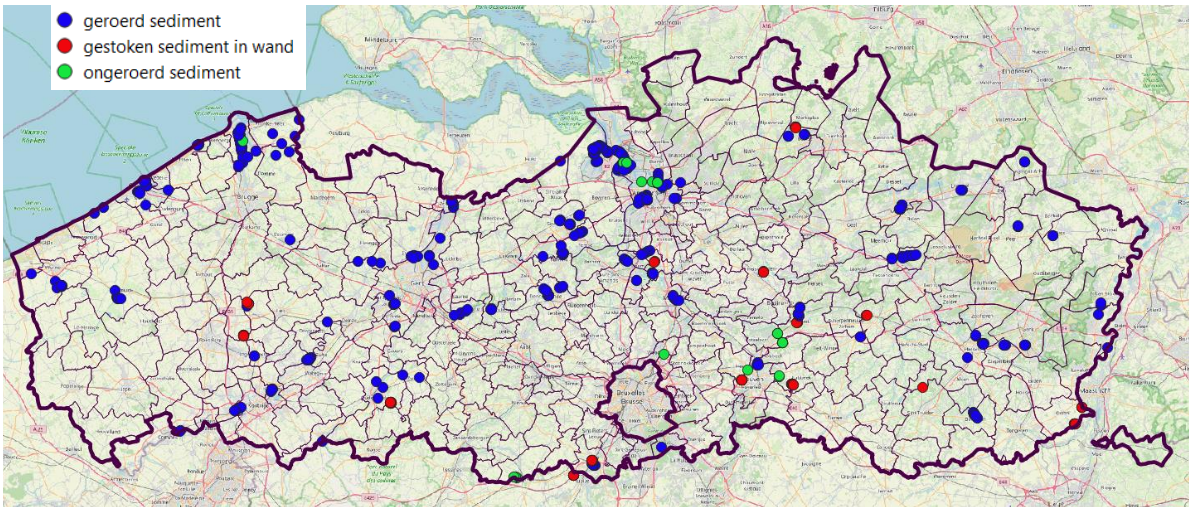


Figure 5. Locations with available samples in the Geotheek, legend based on the type of samples available d.d. 01/04/2022.

Since the majority of the samples comes from the MOW Department, the limited depth of the samples is mainly linked to exploratory drilling for infrastructure works (Figure 6). Exceptions to this are:

- Core sampling in search of mineralisations in the Brabant Massif east of Brussels,
- deep samples from geothermal drilling in Vilvoorde, on the site of the Geotheek,
- deep samples from the 2 geothermal wells in Beerse,
- undisturbed samples from the Port of Zeebrugge

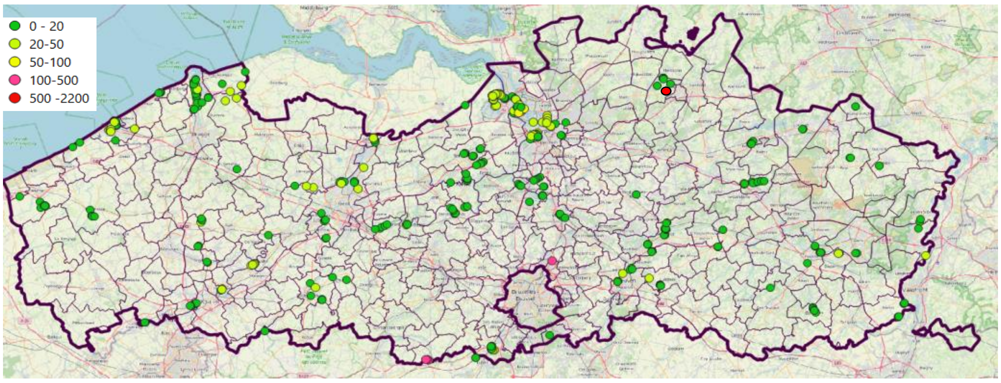


Figure 6. Sample locations in the repository with their maximum depth d.d. 01/04/2022)

In the future, we will focus as much as possible on high-quality, well-documented and examined samples that form as complete a collection as possible of our Flemish subsoil. In this way, the Geotheek will grow into an above-ground library of our Flemish (sub)soil.

Geotheek only accessible upon reservation, contact: Katrien De Nil, katrien.denil@vlaanderen.be

Cores of the Antwerp city area

Neogene units exposed in these cores:

- Lillo Formation – Merksem Member
- Lillo Formation – Kruisschans Member
- in discussion: Lillo Formation – Oorderen Member
- in discussion: Lillo Formation – Luchtbal Member
- Kattendijk Formation
- in discussion: Diest Formation – Deurne Member
- Berchem Formation – Antwerpen Member
- Berchem Formation – Kiel Member
- Berchem Formation – Edegem Member

Geographic situation and relevance of cores

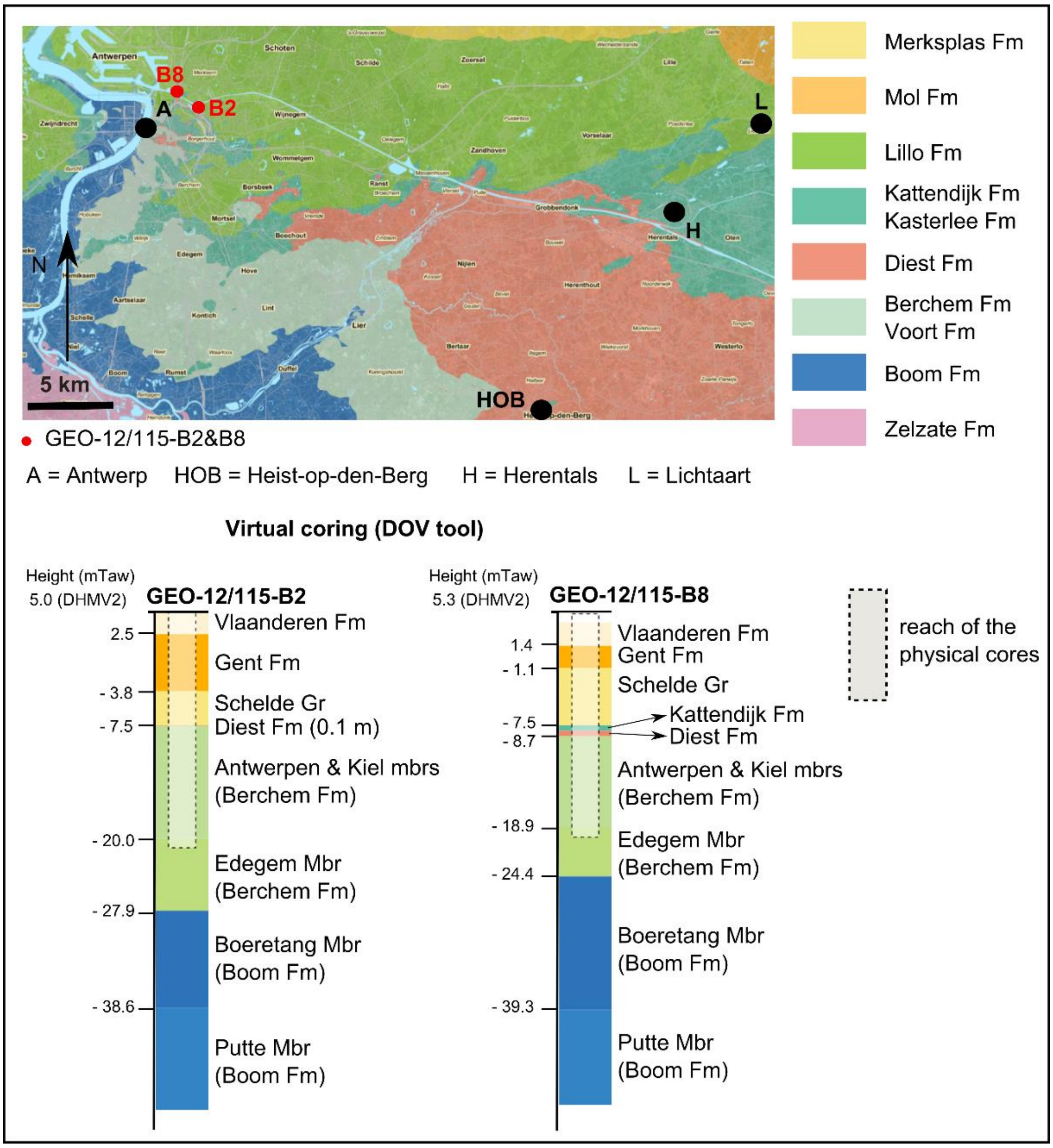


Figure 7. Location of GEO-12/115-B2 & GEO-12/115-B8 boreholes. Geological map and virtual cores based on G3Dv3.1 geological model on dov.vlaanderen.be. The intervals of the physical cores viewed during this excursion are indicated on the virtual cores. In the shallow subsurface model of the Antwerp city and harbour area, the stratigraphy has been refined and the Diest Formation is no longer present at this location, while the Kattendijk Formation is thicker (Van Haren et al., 2021).

The main cores, or more specifically liners, viewed during this excursion are two boreholes (GEO-12/115-B2 & GEO-12/115-B8) drilled for the geotechnical division (Afdeling Geotechniek) of the MOW Department. Drilling sites are located along the Albert Canal and E19 expressway, north of the city of Antwerp, next to the Lobroekdok (GEO-12/115-B2) and the railway (GEO-12/115-B8) (Figure 7). The sampled liners are currently stored at the Geotheek of the Department of Environment, where valuable samples of the Afdeling Geotechniek are stored after the project term has ended.

These boreholes, although only drilled to a depth of 25 m, cross an interesting lithostratigraphic section from the Pliocene Lillo Formation, across the Kattendijk Formation and possibly Diest Formation into the lower to middle Miocene Berchem Formation. As such, they provide a good overview of the Neogene stratigraphy and sedimentology in the Antwerp area, which contrasts nicely with sediments of the Hageland and Campine areas. Additionally, data from lab analyses is available for these liners, collected for internal research by VPO and for a project on the characterization of the Antwerp subsurface by VITO, ordered by VPO. Discrepancies in stratigraphic interpretation between the Virtual Coring, based on the G3Dv3.1 geological model (Deckers et al., 2019), and the borehole interpretations can be partly explained by the position of the boreholes near the edge of the occurrence area of the different Neogene formations, which are often thinly developed, next to the Scheldt river incision (Figure 7). In more recent modelling exercises in the area by van Haren et al. (2021), ordered by VPO, in addition to boreholes, cone penetration tests were integrated which strongly improved the detail of the modelling and knowledge on the stratigraphic position of the Neogene units.

Sediment characterization and stratigraphic interpretation

The detailed lithological descriptions (2013) and accompanying lithostratigraphic interpretations (2019) by M. Dusar are used, available on DOV attached to the boreholes. Based on recent knowledge from outcrops (Everaert et al., 2020) and correlations with nearby CPTs (Deckers & Louwye, 2020; Deckers & Everaert, 2022), alternative lithostratigraphic interpretations by S. Everaert and J. Deckers are also presented here in blue. Because of the complex stratigraphic succession in this area, with Neogene glauconitic sand which is very similar between the different units, and because of ever evolving insights into the Neogene stratigraphy, it is possible that other interpretations are also valid. These descriptions and interpretations are supplemented by data on median grain size, glauconite content and carbon content, collected by VPO (lab analyses carried out by Qmineral) (Figure 8).

GEO-12/115-B2 (https://www.dov.vlaanderen.be/data/boring/2013-170578):
0-5.51 m: Anthropocene to Pleistocene

5.51-8.18 m: Merksem Mbr (Lillo Fm) – Kattendijk Fm
Dark grey silty medium-fine glauconite bearing sand, with $CaCO_3$ and shell fragments.

8.18-8.34 m: Oorderen Mbr (Lillo Fm) – Kattendijk Fm
Dark grey mottled medium-coarse sand, rich in glauconite and shell fragments.

8.34-8.95 m: Deurne Mbr (Diest Fm) – Antwerpen Mbr (Berchem Fm)
Black mottled glauconite-rich medium-coarse heterogenous slightly silty sand, with few shell fragments and bioturbation burrows.

8.95-10.19 m: Deurne Mbr (Diest Fm) – Antwerpen Mbr (Berchem Fm)
Black mottled loosely packed glauconite-rich medium-coarse heterogenous sand, rich in shell fragments and contains Glycymeris shells.

10.19-11.00 m: Deurne Mbr (Diest Fm) – Antwerpen Mbr (Berchem Fm)

Black mottled slightly silty glauconite-rich medium-coarse heterogenous sand, rich in shell fragments and contains Glycymeris shells.

11.00-14.25 m: Antwerpen Mbr (Berchem Fm) – Antwerpen Mbr (Berchem Fm)

Dark grey heterogenous medium-fine glauconite-rich silty sand, bioturbated and containing shell fragments including Glycymeris.

14.25-19.00 m: Antwerpen Mbr (Berchem Fm) – Kiel Mbr (Berchem Fm)

Dark grey to black medium to medium-coarse (coarsening down) glauconite-rich silty sand, bioturbated and containing shell fragments including Glycymeris, which are partly dissolved.

19.00-22.08 m: Kiel Mbr (Berchem Fm) – Kiel Mbr (Berchem Fm)

Dark grey mottled loosely packed medium to medium-coarse silty glauconite-rich sand, with bioturbation burrows, no $CaCO_3$ and very small amount of shell fragments.

22.08-25.00 m: Edegem Mbr (Berchem Fm) – Edegem Mbr (Berchem Fm)

Dark grey medium silty to clayey bioturbated glauconite-rich sand, with fine shell fragments.

GEO-12/115-B8 (https://www.dov.vlaanderen.be/data/boring/2013-170581):
0-5.00 m: Anthropocene to Holocene

5.00-5.70 m: Merksem Mbr (Lillo Fm) – Merksem Mbr (Lillo Fm)

Green grey to brown oxidized, slightly clayey to silty heterogenous mostly medium sand, with little glauconite, rich in $CaCO_3$ and shell fragments.

5.70-8.40 m: Kruisschans Mbr (Lillo Fm) – Kruisschans Mbr (Lillo Fm)

Orange brown clayey sand to sandy clay with shell fragments and glauconite.

8.40-8.73 m: Luchtbal Mbr (Lillo Fm) – Kruisschans Mbr (Lillo Fm)

Grey marly sandy clay with medium fine sand and glauconite, rich in shell fragments up to 5 cm in size and whale bone at the base.

8.73-13.20 m: Kattendijk Fm – Kattendijk Fm

Grey medium-fine silty glauconite bearing sand, with low $CaCO_3$ content and few shell fragments, coarser and increase in glauconite towards the base.

13.20-14.44 m: Deurne Mbr (Diest Fm) – Antwerpen Mbr (Berchem Fm)

Dark grey coarse glauconite-rich sand, with a low content of shell fragments (mainly Glycymeris).

14.44-15.50 m: Antwerpen Mbr (Berchem Fm) – Antwerpen Mbr (Berchem Fm)

Dark grey to black medium coarse glauconite-rich and clayey sand, with broken shells (Glycymeris) and finer shell fragments.

15.50-22.00 m: Antwerpen Mbr (Berchem Fm) – Kiel Mbr (Berchem Fm)

Dark grey to black medium coarse glauconite-rich well sorted and homogenous sand, with few partly dissolved shell fragments and little to no $CaCO_3$.

22.00-25.00 m: Edegem Mbr (Berchem Fm) – Edegem Mbr (Berchem Fm)

Dark grey medium glauconite-rich silty to slightly clayey sand, with few partly dissolved shell fragments and very low $CaCO_3$ content.

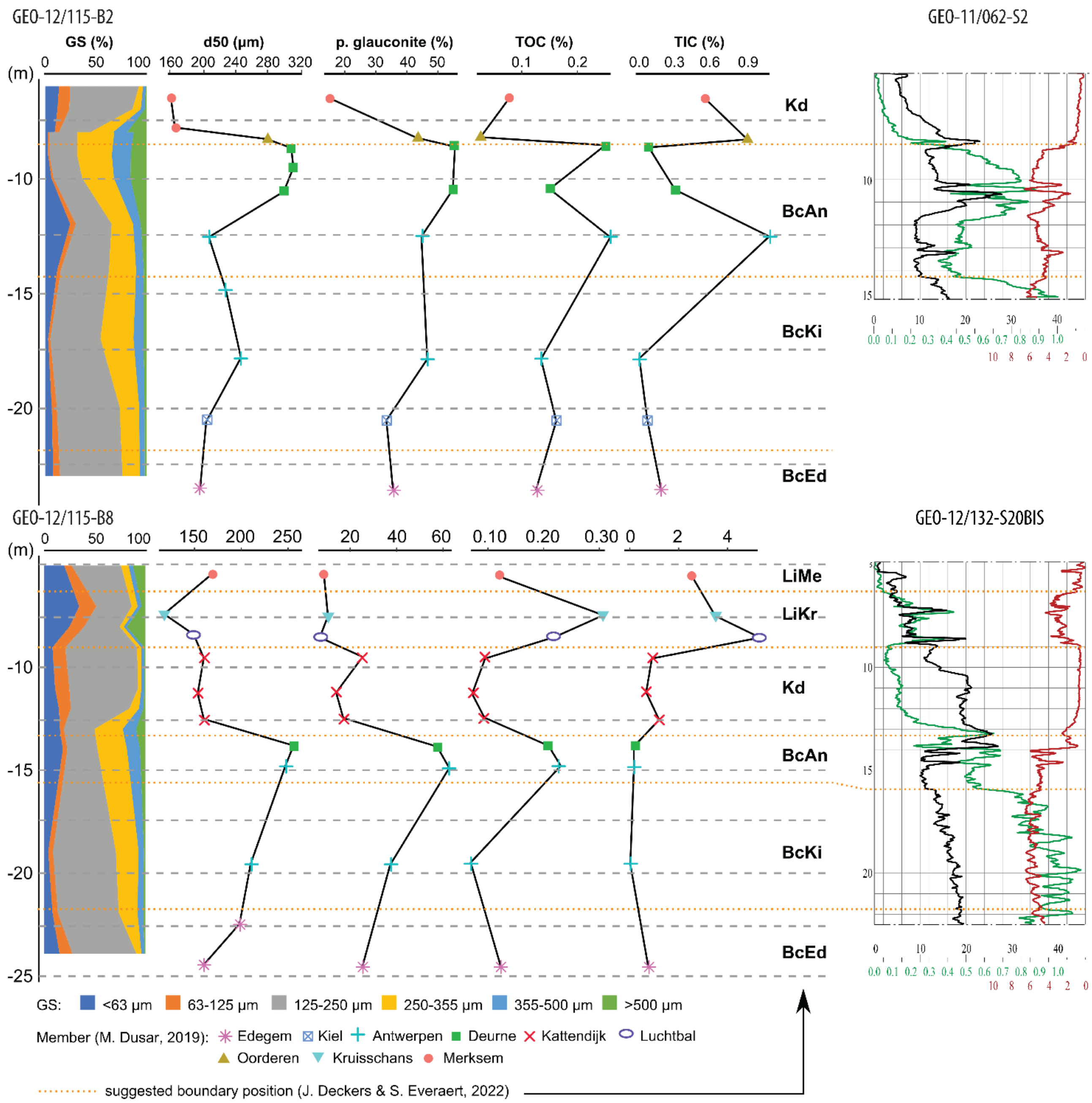


Figure 8. Depth plots of the grain size distribution, median grain size (d50), pelletal glauconite content (> 63 µm fraction), and content organic (TOC) and inorganic (TIC) carbon, of boreholes GEO-12/115-B2 and GEO-12/115-B8. Data from VPO (Vlaams Planbureau voor Omgeving). Depth in m below ground level. Stratigraphic units: LiMe = Merksem Mbr (Lillo Fm), LiKr = Kruisschans Mbr (Lillo Fm), Kd = Kattendijk Fm, BcAn = Antwerpen Mbr (Berchem Fm), BcKi = Kiel Mbr (Berchem Fm), BcEd = Edegem Mbr (Berchem Fm). Correlation added with nearby CPTs GEO-11/036-S2 and GEO-12/132-S20BIS.

Basin correlation

Even over short distances, the lateral continuation of the Neogene units is not straightforward to interpret in boreholes and outcrops. Recently, there have been significant improvements thanks to correlation studies using CPTs (cone penetration tests), which are ubiquitous in the Antwerp city area, and detailed descriptions of temporary outcrops (Everaert et al., 2020; Goolaerts et al., 2020; Deckers & Louwye, 2020; Deckers et al., 2020; Deckers & Everaert, 2022; Deckers & Goolaerts, in press). The CPT profiles by Deckers & Louwye (2020) and Deckers & Everaert (2022) show how the base of the Kattendijk Formation is an important erosional surface which cuts off both the Diest Fm (Deurne Mbr) and Berchem Fm from east to west (Figure 9). Also, a twofold subdivision within the upper part of the Berchem Formation can be interpreted based on both CPT and outcrop interpretations, leading to a revised interpretation of the Antwerpen and Kiel members. For example, when nearby CPTs (GEO-11/062-S2, GEO-12/132-S20BIS) are interpreted (sensu Deckers & Everaert, 2022) and correlated with both boreholes, the boundary between the Kiel and Antwerpen members can be positioned at 14.25 m and 15.50 m in GEO-12/115-B2 and GEO-12/115-B8 respectively (Figure 8). The *'partly dissolved Glycymeris fragments'* mentioned in the lithological description below these depths are congruent with recent observations by Everaert et al. (2020) in a.o. the Argenta outcrop. Towards NE Antwerp, the Kiel Member was found to sporadically contain thin decalcified shells beds between metres of dark grey, very glauconitic, homogenous sand. A similar exercise with CPT correlations was carried out for the Lillo Formation, for which multiple geotechnical units could be defined. These do not everywhere align perfectly with the lithostratigraphic units though, stressing the difficulty of lithostratigraphic interpretations in this area (Deckers et al., 2020; Figure 10). By their modelling work, Van Haren et al. (2021) noticed that the clayey Kruisschans Mbr truncates the underlying Oorderen and Luchtbal mbrs in southern direction across the Port of Antwerp area. Consequently, at the locations of the boreholes south of the Port of Antwerp area, the Oorderen Mbr and possibly even also the Luchtbal Mbr are completely lacking below the Kruisschans Mbr and Kattendijk Fm.

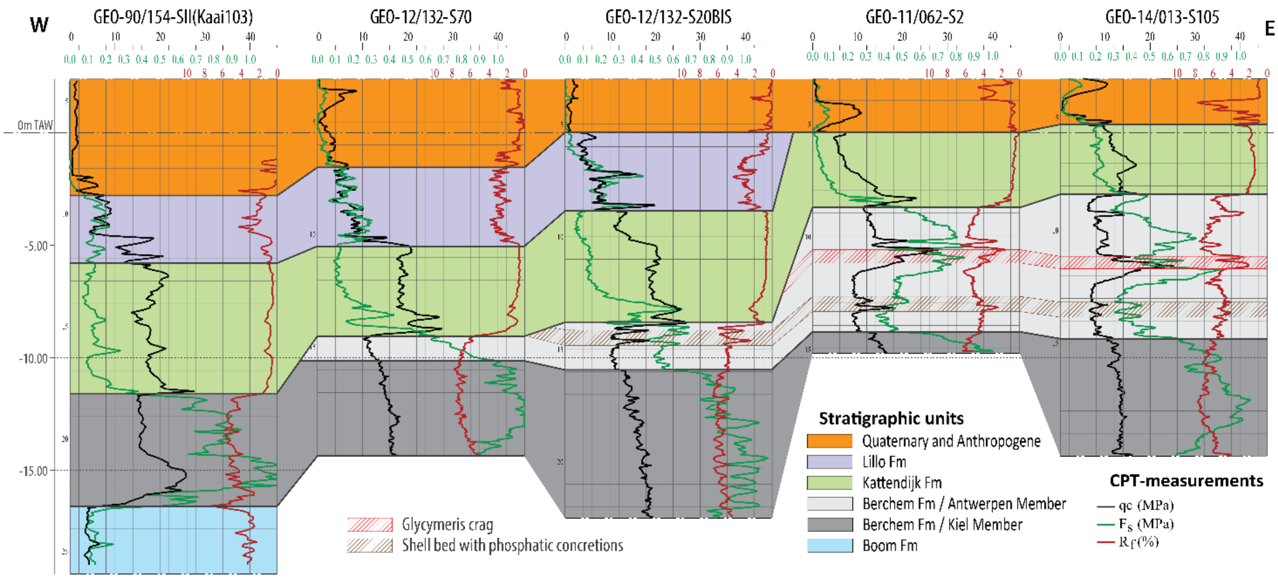


Figure 9. CPT correlation panel north of Antwerp by Deckers & Everaert (2022), with addition of the CPTs used in Figure 8.

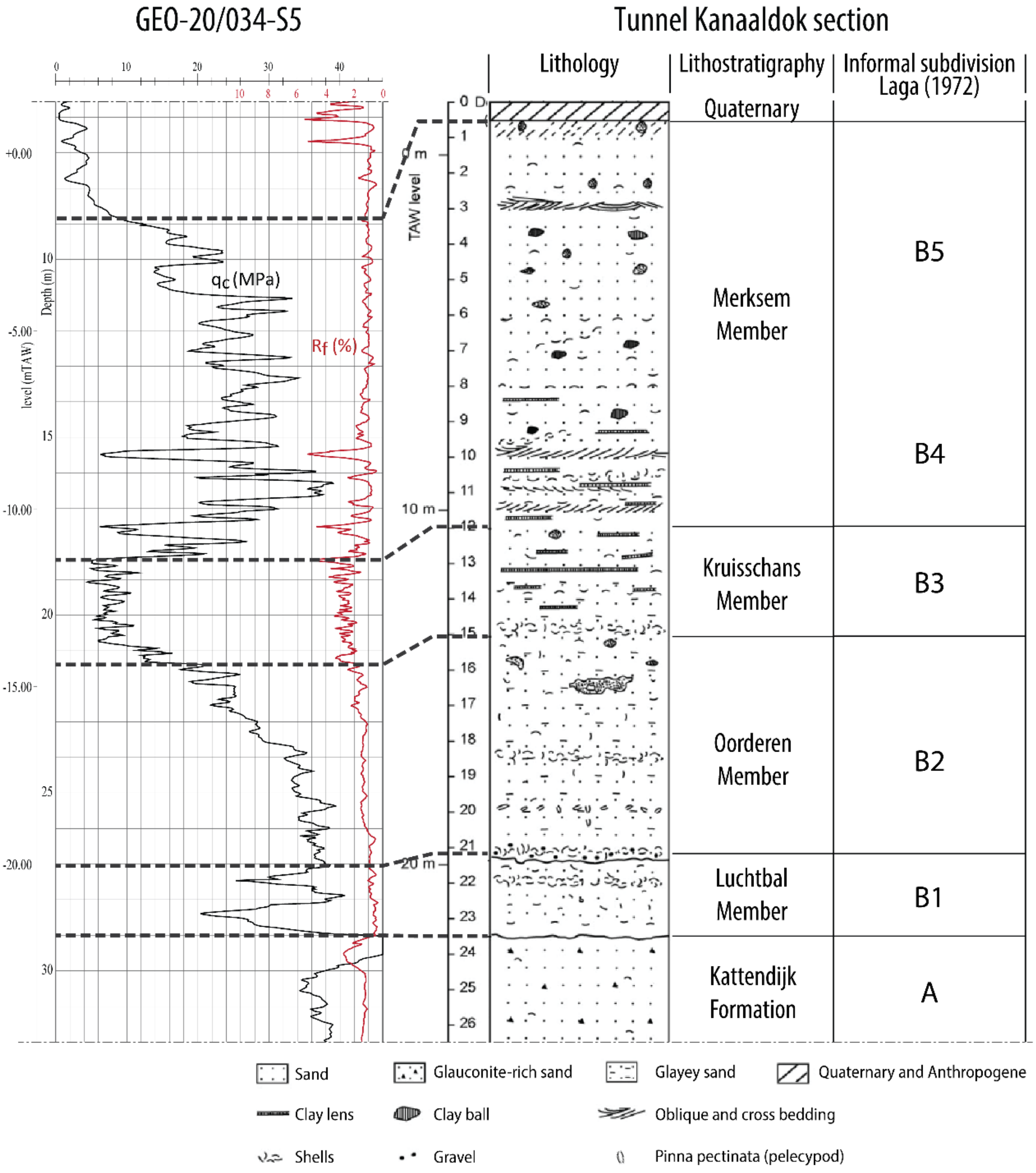


Figure 10. Correlations between a CPT and the temporary outcrop at the Tunnel Kanaaldock as described by Laga (1972; DOV BGD015W0304). Lithostratigraphic and informal boundaries are after Laga (1972). Taken from Deckers et al. (2022).

Further towards the east in the Campine area, the members of the Lillo Formation are laterally replaced to the east by the Poederlee Member. The Kattendijk Formation is laterally replaced to the east by the Kasterlee Formation. These are not coeval units, however, with the Miocene Kasterlee Formation being replaced by the Pliocene Kattendijk Formation. The Deurne Member is overlying the Borsbeek Member in the east of the Antwerp city area, further to the east the members correlate with the Dessel Member and Kempen Diest Member in the Campine area, while to the south the Hageland Diest Member is present. The Edegem, Kiel and Antwerpen members of the Berchem Formation are present in the broader Antwerp city area, while only the Antwerpen Member is also defined in the Campine area. Even further to the southeast, in the Limburg Campine and Hageland areas, these units correlate to the marine to continental Bolderberg Formation.

Key references

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Stop 2: Kesselberg (Leuven)

J. Verhaegen, N. Vandenberghe, R. Houthuys

Neogene units exposed at this location:

- Diest Formation – Hageland Diest Member

Geographic situation and relevance of outcrop

The outcrop is situated on top of the Kesselberg Hill, to the northeast of the city of Leuven. The permanent outcrop can be reached from the street 'Hulsberg' through a walking path in between the streets 'Acaciastraat' and 'Wilgenhof' (Figure 11).

The Kesselberg Hill is one of the many SW-NE elongated hills in the Hageland area, which typically reach heights between 20 and 50 m relative to the surrounding landscape (50-80 mTAW). The outcrop is an old abandoned sand quarry in which the pure white sand of the Kessel-lo Facies underlying the Diest Formation was excavated. The Diest Formation iron sandstone beds were also excavated in the Hageland area as iron ore and as building blocks used in historical buildings.

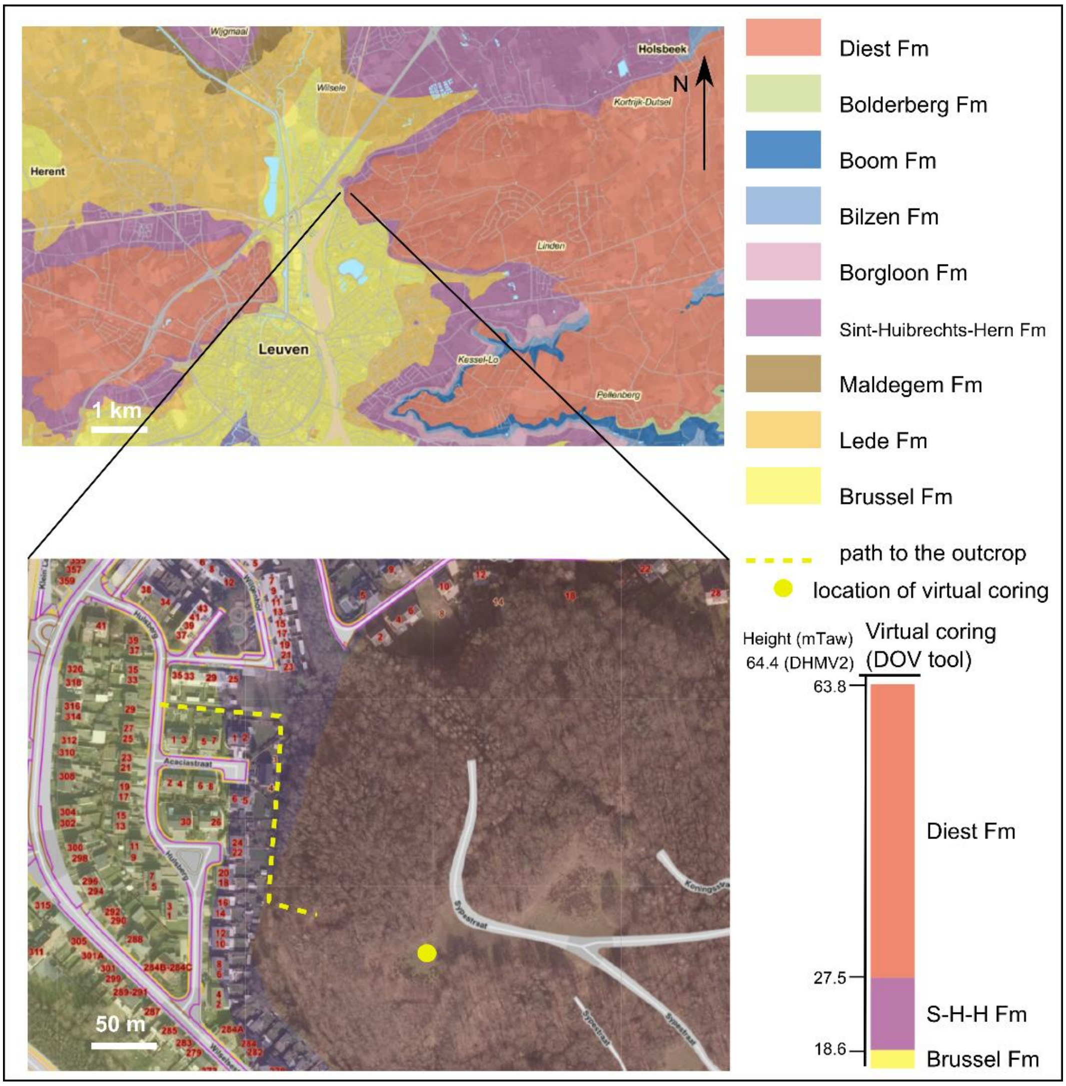

Figure 11. Location of the Kesselberg outcrop. Geological map based on G3Dv3.1 geological model on dov.vlaanderen.be.

This outcrop provides an exceptional view of the large-scale cross stratification present in the Hageland Diest Sand, which has varying orientations with a main NE component. Also the gravel at the base of the Diest Formation is very well developed at this location and the contact with the underlying early Oligocene sediments can be observed, representing a very large hiatus due to erosion.

Sediment characterization

At the base of the outcrop, the white fine-grained and well-sorted sand of the Neerrepen Member (local Kessel-lo facies) of the Sint-Huibrechts-Hern Formation can be observed (Figure 12). This sand dates to the early Oligocene, which means that the hiatus with the overlying Diest Sand spans about 20 million years.

At the Kesselberg outcrop a very well developed gravel at the base of the Diest Formation of more than 20 cm thick is present. The basal gravel is composed of flattened silex pebbles. This gravel is typically found in the lower Oligocene units of the Kerkom Member (Borgloon Fm) and Berg Member (Bilzen Fm) and represents the base Rupelian transgression which also deposits the Boom Clay in this area. As such, the gravel bed is a lag deposit which remained after all overlying Oligocene sediments were eroded in the gullies formed prior to Diest Formation deposition. The contact between the gravel bed and the underlying Neerrepen Sand is very irregular, with the occurrence of pothole structures in which pebbles appear to be ‘bored’ into the underlying white sand (Figure 12).

The Diest Sand above the basal gravel is a medium coarse grained poorly sorted glauconite-rich sand. There appears to be an overall coarsening upwards trend, with a modal grain size varying from 240 µm to 360 µm (Figure 14). The finest sand occurs just above the basal gravel, in a strongly bioturbated and horizontally laminated unit, while the cross-laminated units contain coarser sand (Gullentops, 1963; Verhaegen, 2020). The colour varies from green to brown depending on the amount of oxidation. Strong oxidation has led to the formation of iron sandstone banks near the top of the outcrop (Figure 13).

The iron sandstone banks accentuate the large foreset beds within the Diest Sand near the top of the outcrop, which vary in orientation between north and east (Figure 13). Many bioturbations are visible, easily distinguished by their white colour due to the removal of glauconite. In the iron sandstone banks occasional shell ghosts can be observed.

Figure 12. Photographs of the contact between the Hageland Diest Sand and the underlying white Kessel-lo Sand. The well-developed basal gravel with silex pebbles is clearly visible as well as the apparent pothole structures infiltrating the underlying white sand. The many white spots visible in the Diest Sand above the basal gravel are caused by the removal of glauconite in bioturbations. (photographs from excursion report by Verhoeve D. & Wouters K., 1968)

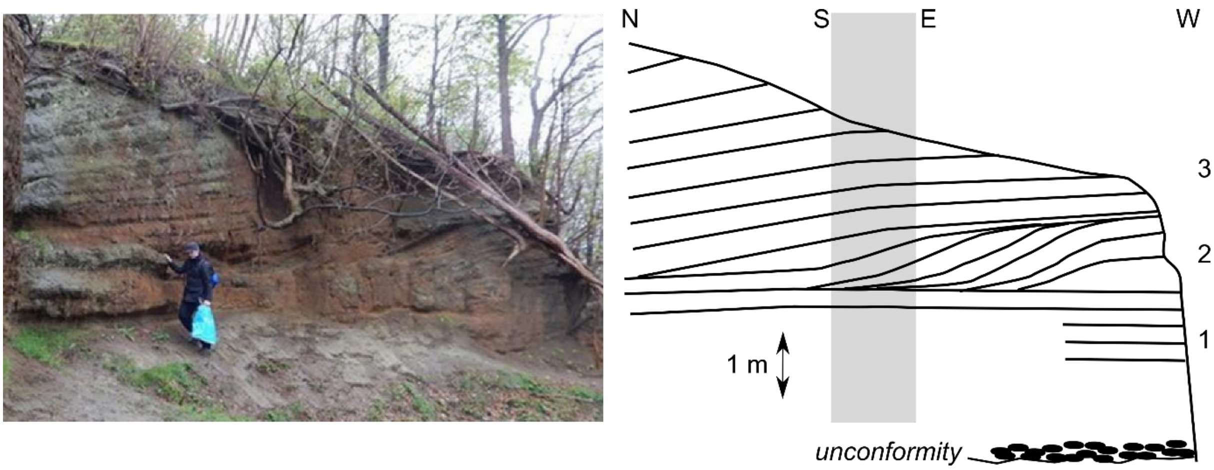

Figure 13. Sketch of the large-scale sedimentary structures visible in the Kesselberg outcrop, with the distinction of three sequences. (adapted from PhD thesis of Verhaegen, J., 2019)

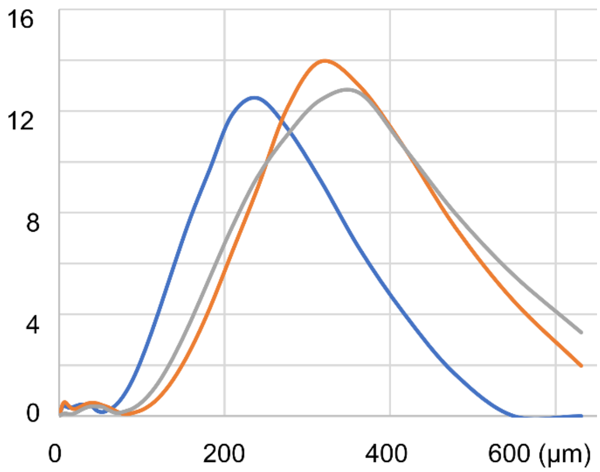

Figure 14. Grain size distribution of three samples taken from the Kesselberg outcrop. Blue curve: sequence 1 of Figure 13. Orange curve: sequence 2 of Figure 13. Grey curve: sequence 3 of Figure 13. Data from Verhaegen (2020).

Basin correlation

The orientation of the Hageland gully, the elongation of the Hageland Hills and the dip of the crossbeds within the Hageland Diest Sand all point to a flow direction towards the northeast, towards the Roer Valley Graben. Dinoflagellate cyst biostratigraphy allows the recognition of biozones in the Diest Formation in the Campine area. Although no dinoflagellate cysts or other microfossils are present in the bulk of the Hageland Diest Sand, a basal fine-grained unit observed in the northern Hageland Veerle borehole, resembling the Campine Dessel Member, has a DN8 (early Tortonian) biozone. The Hageland Diest Sand is all interpreted as part of DN8, as the sediments with the younger DN9 and DN10 zones which occur in the Campine area have a completely different progradation orientation (towards the south and west) and appear to onlap onto the Hageland Diest Sand (Figure 15). The Hageland Diest Sand may correlate to the lower part of the Dessel Member in the Campine area and the Deurne Member in the Antwerp area, in which similar though smaller scale gullies and foresets were observed (Goolaerts et al., 2020).

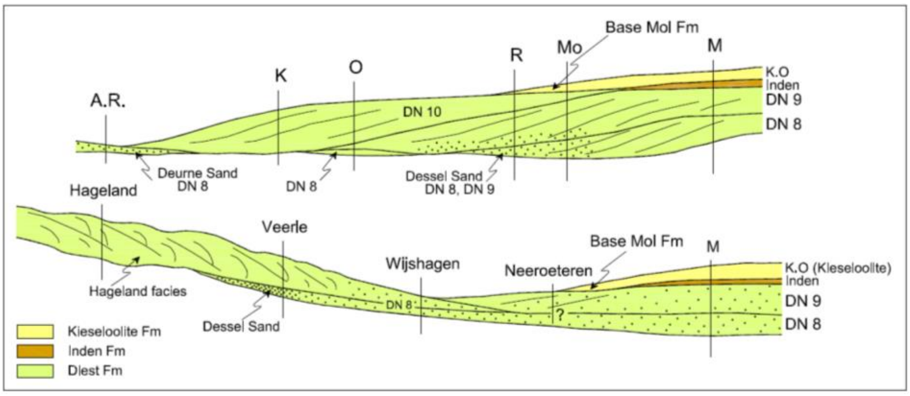

Figure 15. A northern (top) and southern (bottom) E-W section showing the correlation of the Diest Sand across the Campine and Hageland areas based on dinoflagellate cyst biostratigraphy (Vandenberghe et al., 2014).

Depositional model

Different models have been proposed to explain the deposition and related paleogeography of the Diest Formation and no final conclusion has yet been reached. The different options are discussed in detail in Houthuys et al. (2020).

Gullentops (1957) linked the Hageland hills to the tidal sandbanks currently present in the English Channel. As such Gullentops inferred a narrow marine seaway to the English Channel, across the area of the Flemish Hills, in which strong tidal currents would have scoured the deep Hageland gully and led to the northeast progradation of the Hageland sandbanks. A sudden drop in sealevel would have caused the emersion of the hills, which were preserved due to rapid oxidation and the formation of iron sandstone in the tops of the hills.

Houthuys (2014) rather proposes a model similar to the Brussels Formation for the deposition of the Diest Formation. In this model, the gradual N-S lateral infill of a large marine tidal embayment caused the incision and infill of the Hageland gully. In this model, the incision and subsequent infill are closely related and part of the same process. No connection to the English Channel, through the Flemish Hills, is inferred in this model.

Alternatively, the large incisions at the base of the Diest Formation may have been initially formed due to river erosion during a time of uplift of the Brabant Massif and coeval subsidence of the Roer Valley Graben, as a local expression of the Mid Miocene Unconformity. The incisions were further deepened and widened by tidal currents during sea level rise (Vandenberghe et al., 2014). During transgression the fine basal Dessel Sand filled up the incision, after which during highstand the tidal sandbanks prograded to the northeast.

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Profile Kesselberg – Heist-op-den-Berg

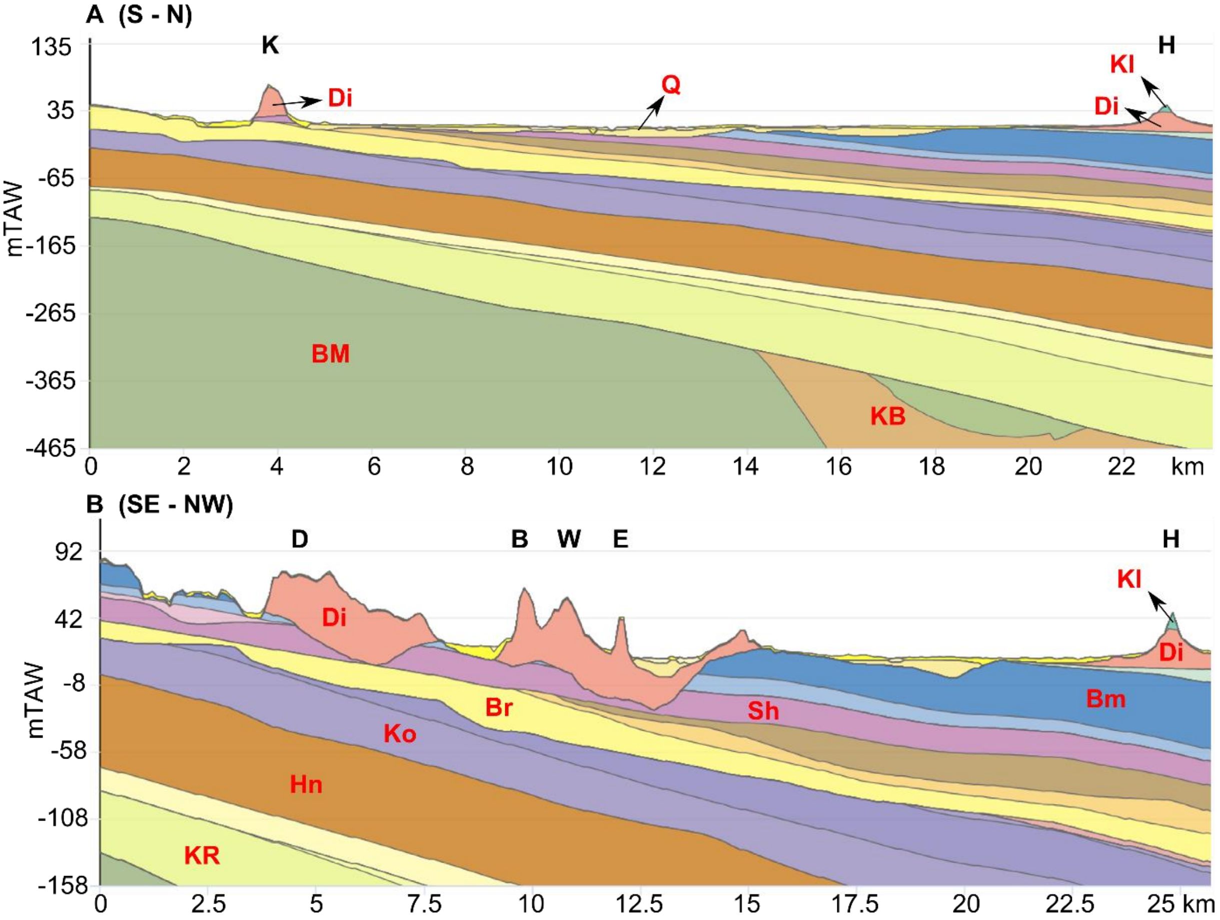

Figure 16. Profiles through the 3D geological model of the Flemish subsurface, G3Dv3.1 (https://www .dov.vlaanderen.be/; Deckers et al., 2019). (A) south-north profile from the Kesselberg (Leuven) to Heist-op-den-Berg, profile line 1 on Figure 1. (B) southeast-northwest profile from Lubbeek (east of Leuven) to Heist-op-den-Berg, profile line 2 on Figure 1. K = Kesselberg (Leuven), H = Heist-op-den-Berg, D = Dunberg (Lubbeek), B = Beninksberg (east side, Holsbeek), W = Wijngaardberg (east side, Aarschot), E = Eikelberg (Aarschot). Q = Quaternary deposits of the Schelde Group, Arenberg/Stokkem fms, Gent Fm, in the rivervalleys of Dijle, Demer and Nete. Kl = Kasterlee Fm, Di = Diest Fm, Bm = Boom Fm, Sh = Sint-Huibrecht-Hern Fm, Br = Brussel Fm, Ko = Kortrijk Fm, Hn = Hannut Fm, KR = Cretaceous formations, KB = Campine Basin (Devonian – Carboniferous), BM = Brabant Massif (Cambrian – Silurian).

From the Kesselberg near Leuven to Heist-op-den-Berg we leave the Hageland Hills behind and enter the Campine area. In a straight line, the Kesselberg is the last hill in between both points (Figure 16A). In between is a very flat area which was incised by rivers in the Quaternary and is currently filled by Quaternary fluvial and eolian sediments. The rivervalleys of the Dijle, Demer and Grote Nete are crossed between the Kesselberg and Heist-op-den-Berg. In relation to the deeper subsurface, the lower Paleozoic Brabant Massif is left behind for the edge of the upper Paleozoic Campine Basin (Figure 16A). The road (along the highway E314) does not take a straight line, however, and does cross some Hageland Hills along the first SW-NE section, before turning to the NW in Aarschot (Figure 16B). The area of the hills Beninksberg, Wijngaardberg and Eikelberg is crossed, which pose a significant relief along the road, of WSW-ENE oriented hills. Below the surface, the Diest Formation strongly incises into older sediments, up to the lower Oligocene Sint-Huibrechts-Hern Formation (Figure 16B).

Stop 3: Heist-op-den-Berg

J. Verhaegen

Neogene units exposed at this location:

- Kasterlee Formation – Heist-op-den-Berg Member
- Kasterlee Formation – Beerzel Member
- Kasterlee Formation – Hallaar Member
- Kasterlee Formation – Olen Gravel
- Diest Formation

Geographic situation and relevance of outcrop

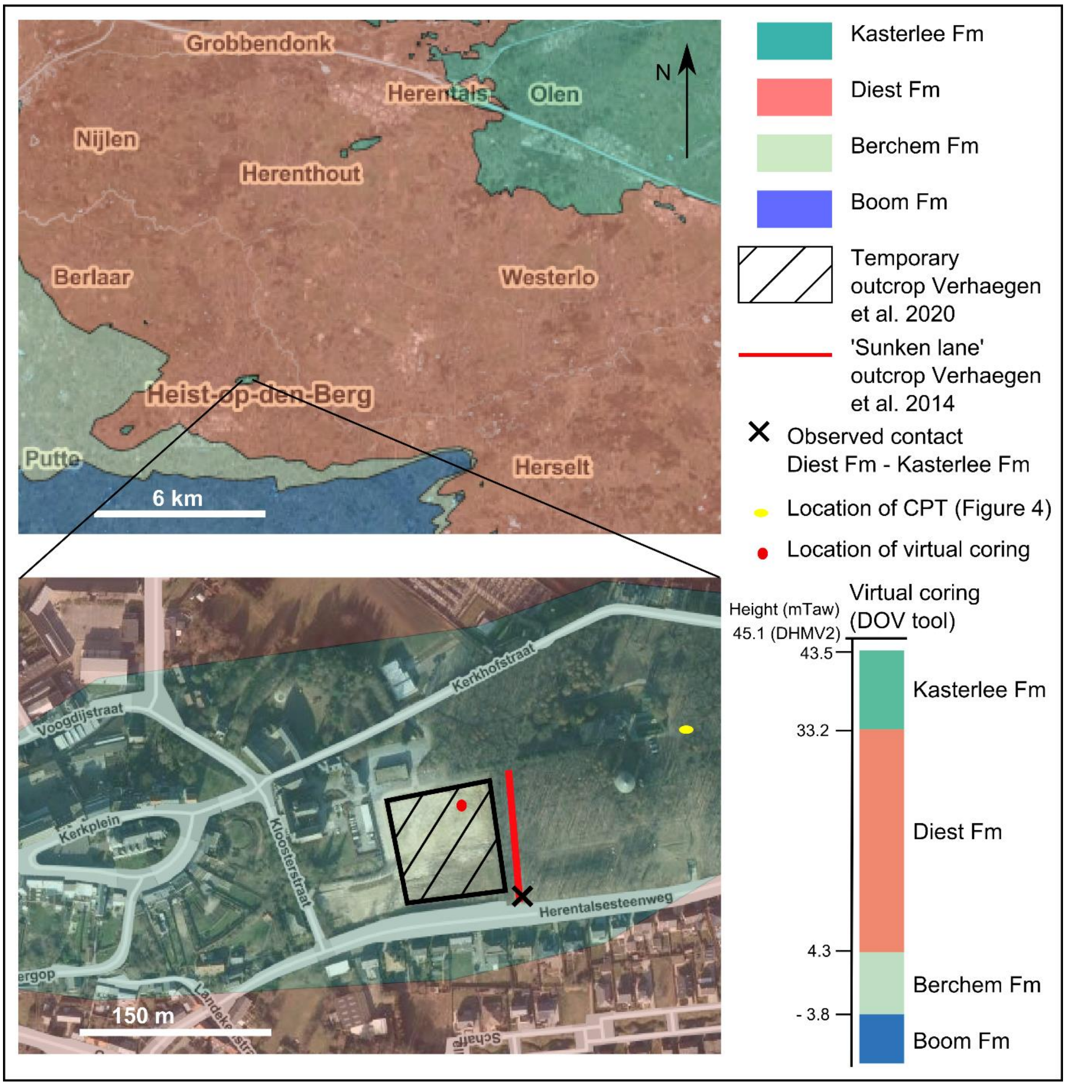

Figure 17. Location of the Heist-op-den-Berg outcrop. In red the sunken lane is indicated where a permanent exposure is present. The indicated temporary outcrop was described by Verhaegen et al. (2020). Geological map based on G3Dv3.1 geological model on dov.vlaanderen.be. Modified from Verhaegen et al. (2020).

The outcrop is situated on top of the hill of Heist-op-den-Berg, in the south of the province of Antwerp. The Heist-op-den-Berg hill has an altitude of 48 m, making it the second highest point of the Antwerp province, second to the nearby Beerzel hill (51 m) which has a similar geology. A permanent exposure is present along a sunken lane connecting the main road (Herentalsesteenweg) to the top of the hill where the water tower is located (Figure 17). The roadside is largely overgrown, so small sections must be dug out to observe the geology.

The peculiar geology of the Heist-op-den-Berg hill was already noted by Van den Broeck (1882), yet the exact stratigraphic position of the sediments remained uncertain for a long time. Recent advances place the top sediments of the hill firmly in the Kasterlee Formation, mainly due to the observation of the Olen Gravel by Verhaegen et al. (2014). The outcrop is now a type section of the Hallaar, Beerzel and Heist-op-den-Berg members of the Kasterlee Formation, which are also present towards the north in the subsurface.

Litholog and sediment characterization

Along the sunken lane, a complete section is present from the top of the Diest Formation to the top of the Kasterlee Formation, including the Hallaar, Beerzel and Heist-op-den-Berg members (Figure 18). Pictures of the different units are available in Verhaegen et al. (2020) and of the gravel in Verhaegen et al. (2014).

The Diest Formation can be easily distinguished based on its coarser grain size, high glauconite content and related dark green color, yet significant clay content. This is confirmed by the measured grain size distribution, which shows a d10 of only 0.8 µm and a coarse mode of 430 µm (Figure 19).

Near the base, the Hallaar Member is a poorly sorted brown clayey sand with a significant amount of glauconite and the disperse occurrence of a basal gravel. The gravel is described and illustrated in detail by Verhaegen et al. (2014), and consists of rounded and flattened flint pebbles often with a weathered and spotted surface, coarse angular and rounded to flattened quartz grains, and white powdery altered silex fragments. The glauconite content decreases from base to top. The Hallaar Member varies in color from green to brown depending on the amount of oxidation, which varies across the exposure. It has a mottled appearance due to the occurrence of greener reduced clayey pockets within the brownish oxidized more sandy matrix. The transitional nature of the Hallaar Member is apparent based on the grain size distribution with two modes, one coarse mode at 430 µm due to reworking of Diest Sand, and a finer mode at 140 µm (Figure 19).

The transition to the Beerzel Member can be observed by the disappearance of the brownish green mottled character of the Hallaar Member towards a yellowish white more homogenous fine well-sorted sand poor in clay. The Beerzel Member has a very consistent modal grain size between 185 and 205 µm (Figure 19). Some irregular layers of brownish oxidized sand occur. Even though the boundary between the Beerzel Member and overlying Heist-op-den-Berg Member can be placed at the base of the first purple clay layer, the top of the Beerzel Member also includes some very thin clay laminae accentuated by later limonite precipitation.

The Heist-op-den-Berg Member consists of an alternation of well-sorted fine yellow brownish sand and grey to purple clay intercalations which vary in thickness from one to ten centimeter. The boundary between the Beerzel Member and Heist-op-den-Berg Member can be placed at the base of the first purple clay layer which is at least 10 cm thick. The next thick purple clay layer occurs 80 cm above the basal layer, with in between an intercalation of many thinner grey clay and sand layers. The sand layers have a very similar grain size distribution to the Beerzel Member (Figure 19). The top part of the Heist-op-den-Berg Member observed in outcrop consists mainly of fine brownish sand with fewer clay intercalations. At the top of the hill, the Heist-op-den-Berg Member is possibly up to 3.6 m thick, based on the interpretation of a nearby CPT log (Verhaegen et al., 2020, Fig. 9).

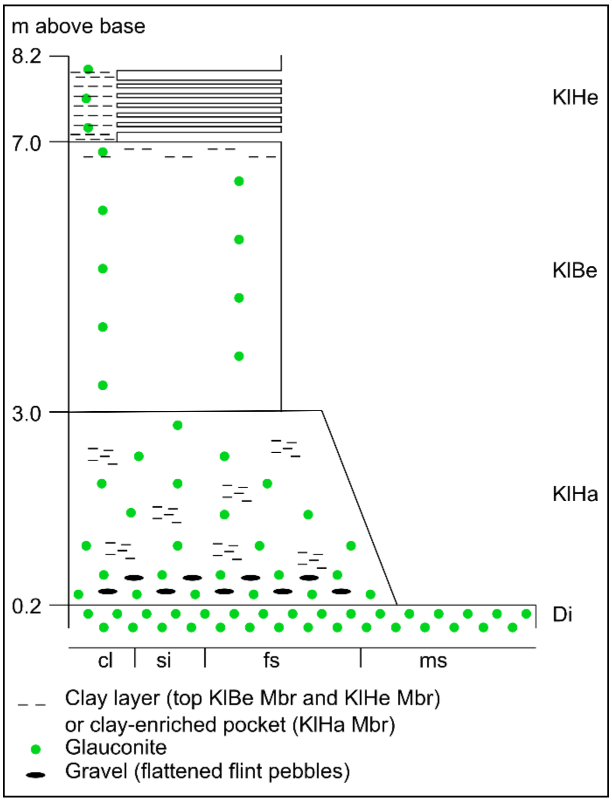

Figure 18. Litholog by Verhaegen et al. (2020) of the top the Heist-op-den-Berg hill, at the temporary exposure described by Verhaegen et al. (2020), right next to the permanent outcrops along the sunken lane. Di = Diest Formation, KlHa = Hallaar Member, KlBe = Beerzel Member, KlHe = Heist-op-den-Berg Member.

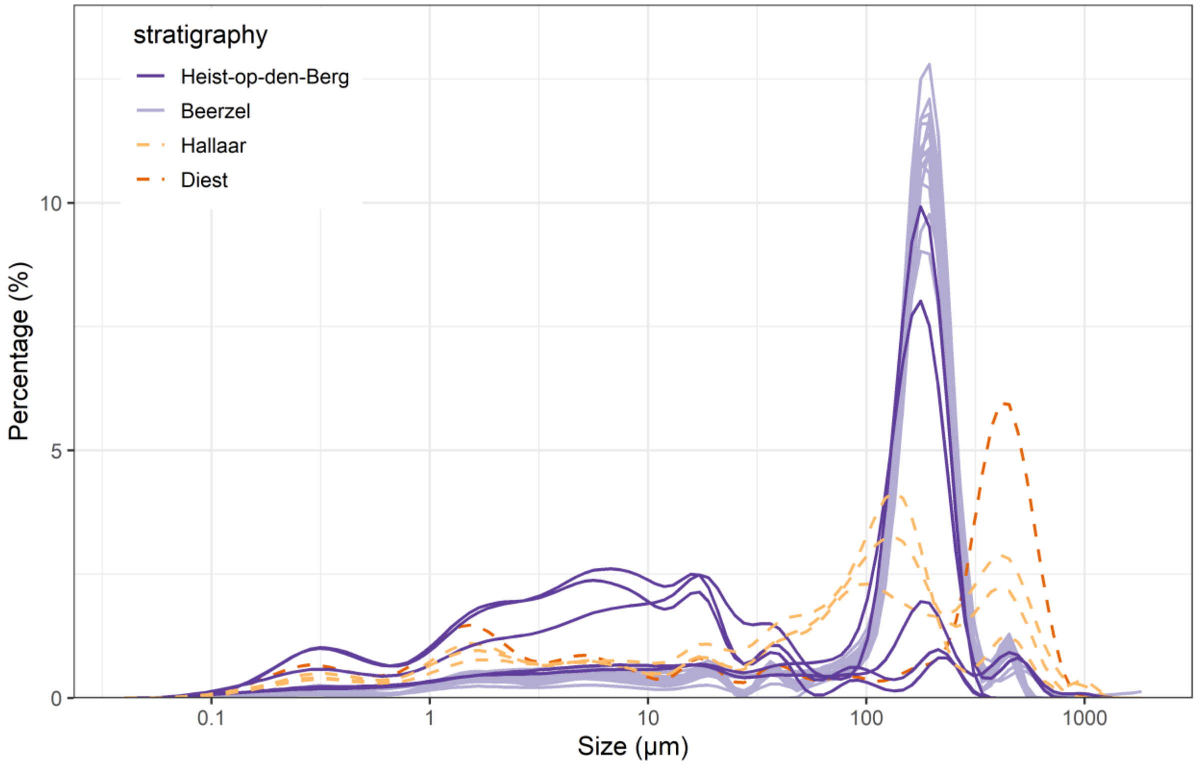

Figure 19. Grain size distribution of samples collected along the described section of the Heist-op-den-Berg hill, by Verhaegen et al. (2020).

Basin correlation

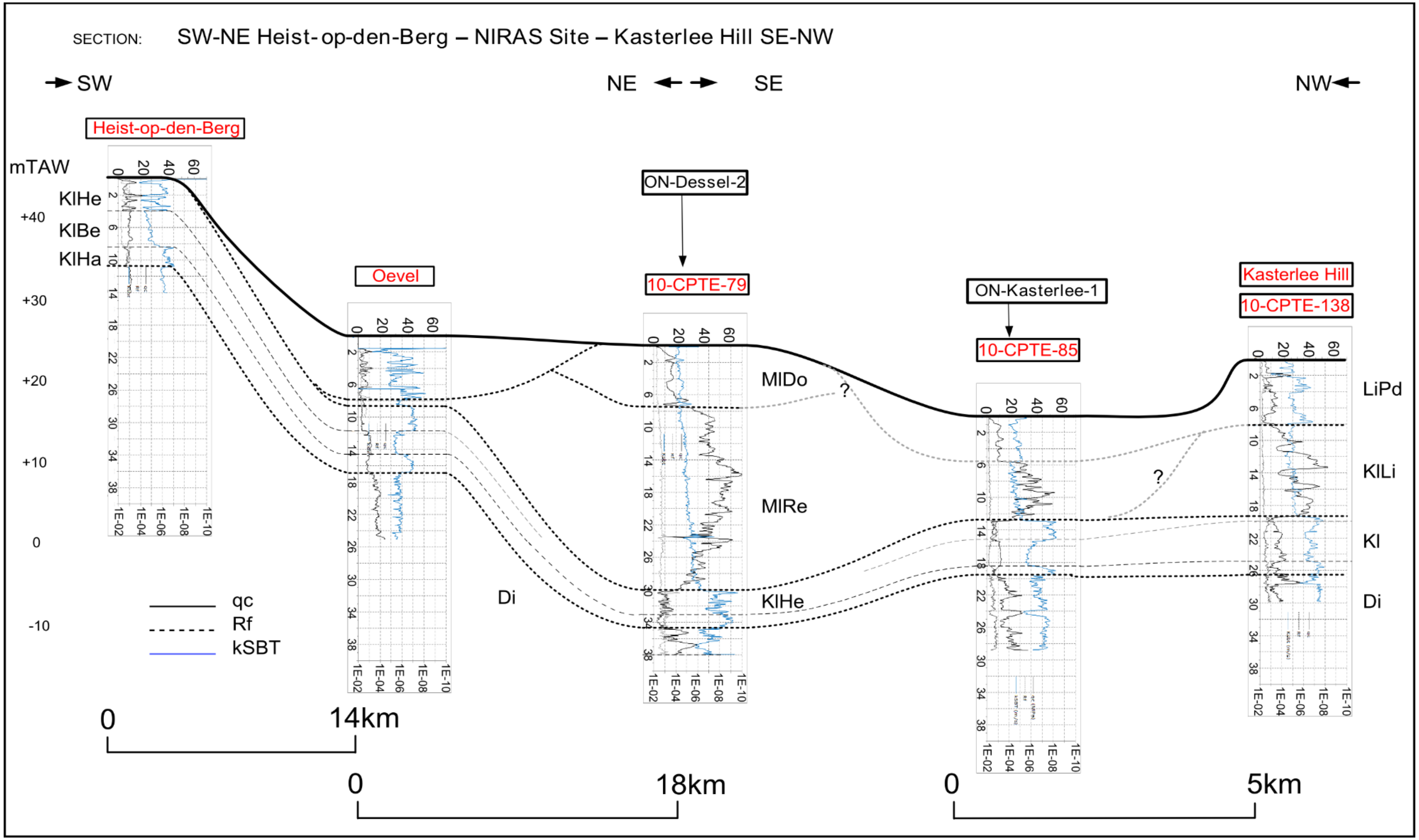

Figure 20. Correlation of the Heist-op-den-Berg hill type section towards the northeastern Mol-Dessel area and towards the Kasterlee hill type section, using CPT log signature. Profile line on Figure 21. Di = Diest Formation, Kl = Kasterlee Formation, KlHa = Hallaar Member, KlBe = Beerzel Member, KlHe = Heist-op-den-Berg Member, KlLi = Lichtaart Member, MlRe = Retie Member (Mol Fm), MlDo = Donk Member (Mol Fm), LiPd = Poederlee Member (Lillo Fm). Profile indicated on map of Figure 21. Modified from Verhaegen et al. (2020).

Using a CPT log correlation along a SW-NE transect, the observed units at the Heist-op-den-Berg hill can be correlated to the subsurface geology of the Mol-Dessel area and to the Kasterlee-Lichtaart ridge, where the Kasterlee Formation was initially defined (Figure 20). This correlation shows that the Hallaar and Heist-op-den-Berg members can be correlated across the basin. The Heist-op-den-Berg Member was described in the Mol-Dessel area as the 'clayey Kasterlee Formation' by Vandenberghe et al. (2020). The Beerzel Member does not occur continuously, but its presence can be inferred at Oevel/Olen and Kasterlee. The members defined at Heist-op-den-Berg occur beneath the 'typical Kasterlee Formation', now Lichtaart Member, observed in the Kasterlee-Lichtaart ridge outcrops. In the Mol-Dessel area the Lichtaart Member is replaced by the Retie Member ('Kasterlee-sensu-Gulinck' in Vandenberghe et al., 2020) of the Mol Formation, which directly overlies the Heist-op-den-Berg Member in that area.

Depositional model

The boundary between the Diest and Kasterlee formations is interpreted as a wave-ravinement surface, formed during a renewed transgression. The underlying Diest Sand was eroded and reworked into the Hallaar Member, which explains its transitional characteristics.

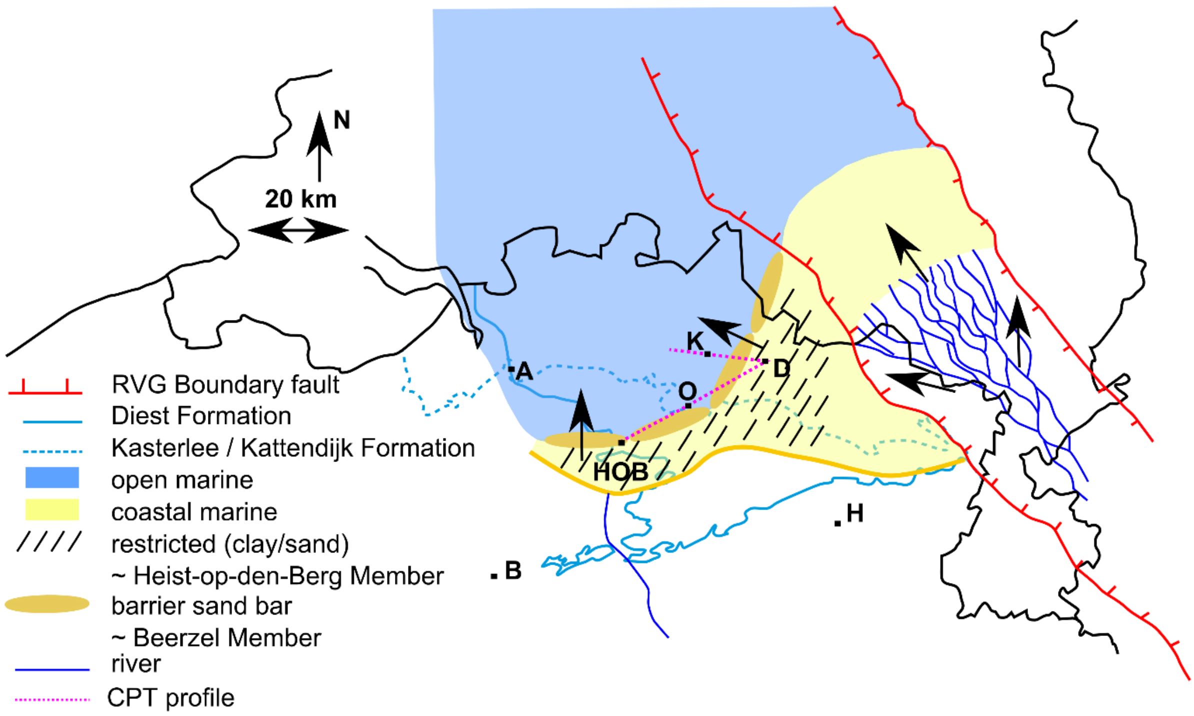

Figure 21. Paleogeographic model of the deposition of the Kasterlee Formation units described at Heist-op-den-Berg (Verhaegen et al., 2020). CPT profile refers to Figure 20. A = Antwerp, B = Brussels, D = Dessel, H = Hasselt, HOB = Heist-op-den-Berg, K = Kasterlee, O = Oevel.

The homogenous well-sorted fine sand of the Beerzel Member is interpreted as a barrier sand bar. The Heist-op-den-Berg Member then represents the related shallow lagoon (Figure 21). Due to a regression, the Heist-op-den-Berg Member progrades onto the Beerzel Member, as we observe it at the Heist-op-den-Berg hill. The Mol-Dessel area was always in the back-barrier lagoonal position, explaining the absence of the Beerzel Member.

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Profile Heist-op-den-Berg – Lichtaart

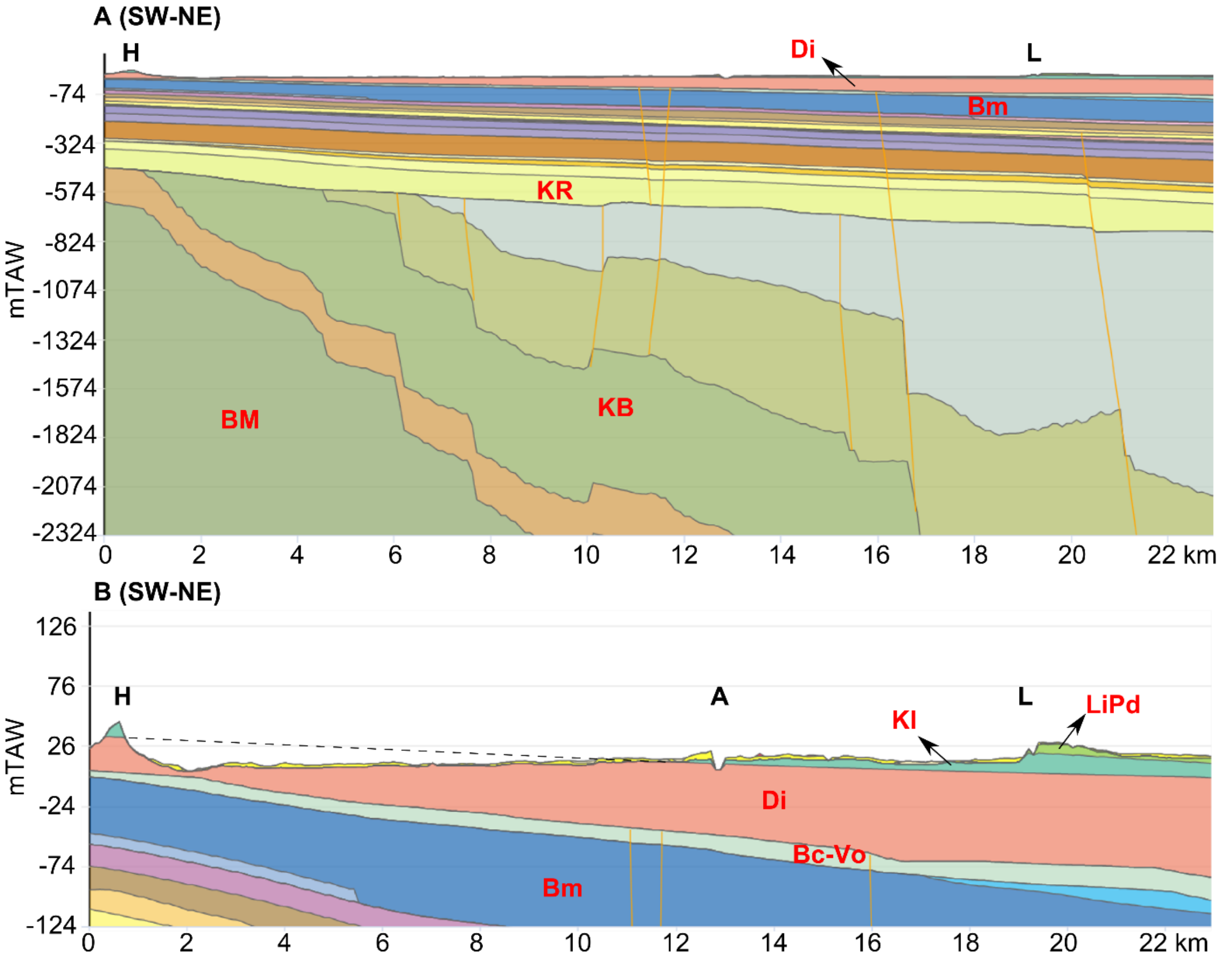

Figure 22. Profiles through the 3D geological model of the Flemish subsurface, G3Dv3.1 (https://www .dov.vlaanderen.be/; Deckers et al., 2019). Southwest-northeast profile from Heist-op-den-Berg to Lichtaart, profile line 3 on Figure 1. (A) deep profile. (B) shallow profile, dotted line shows the continuation of the base of the Kasterlee Formation from the edge of the subcrop area to the outcrop at Heist-op-den-Berg. H = Heist-op-den-Berg, L = Lichtaart, A = Albert Canal near Herentals-Olen, LiPd = Poederlee Mbr (Lillo Fm), Kl = Kasterlee Fm, Di = Diest Fm, Bc-Vo = Berchem Fm and Voort Fm, Bm = Boom Fm, KR = Cretaceous formations, KB = Campine Basin (Devonian – Carboniferous), BM = Brabant Massif (Cambrian – Silurian).

A southwest-northeast transect between Heist-op-den-Berg and Lichtaart shows that the lower Paleozoic Brabant Massif is definitively left behind and the upper Paleozoic Campine Basin strongly increases in thickness up to almost three kilometers (Figure 22A). The Kasterlee Formation which occurs near the top of Heist-op-den-Berg is eroded away north of the hill in the valley of the Grote Nete (Figure 22B). It reappears in the Olen-Herentals area near the Albert Canal, where the Olen Gravel Bed was initially described. A straight line following the base of the Kasterlee Formation connects both outcrop points. The thinning of the Miocene Diest Formation from 75 to 30 m in southwards direction is likely at least partly caused by the erosive nature of the basal surface of the Kasterlee Formation. At Lichtaart, the Lichtaart-Kasterlee hill ridge is present just north of the Kleine Nete valley, where the Kasterlee Formation is overlain by the Poederlee Member of the Lillo Formation.

Stop 4: Lichtaart

J. Verhaegen, N. Vandenberghe, R. Houthuys, R. Adriaens

Neogene units exposed at this location:

- Lillo Formation – Poederlee Member
- Lillo Formation – Hukkelberg Gravel
- Kasterlee Formation – Lichtaart Member – Hoge Berg Facies

Geographic situation and relevance of outcrop

This outcrop is located in Lichtaart, Kasterlee, just north of the crossroads between the 'Olensteenweg' and 'Herentalsesteenweg' (N123). It can be accessed through a walking path starting from the 'Coolsweg' (Figure 23). The outcrop is an abandoned sand quarry on the southern steep flank of the 'Kempense Heuvelrug', a SW-NE elongated hill ridge or cuesta in the area of Herentals-Kasterlee. The top of the cuesta lies at approximately 30 mTAW, which is a significant relief compared to the surrounding flat Campine area.

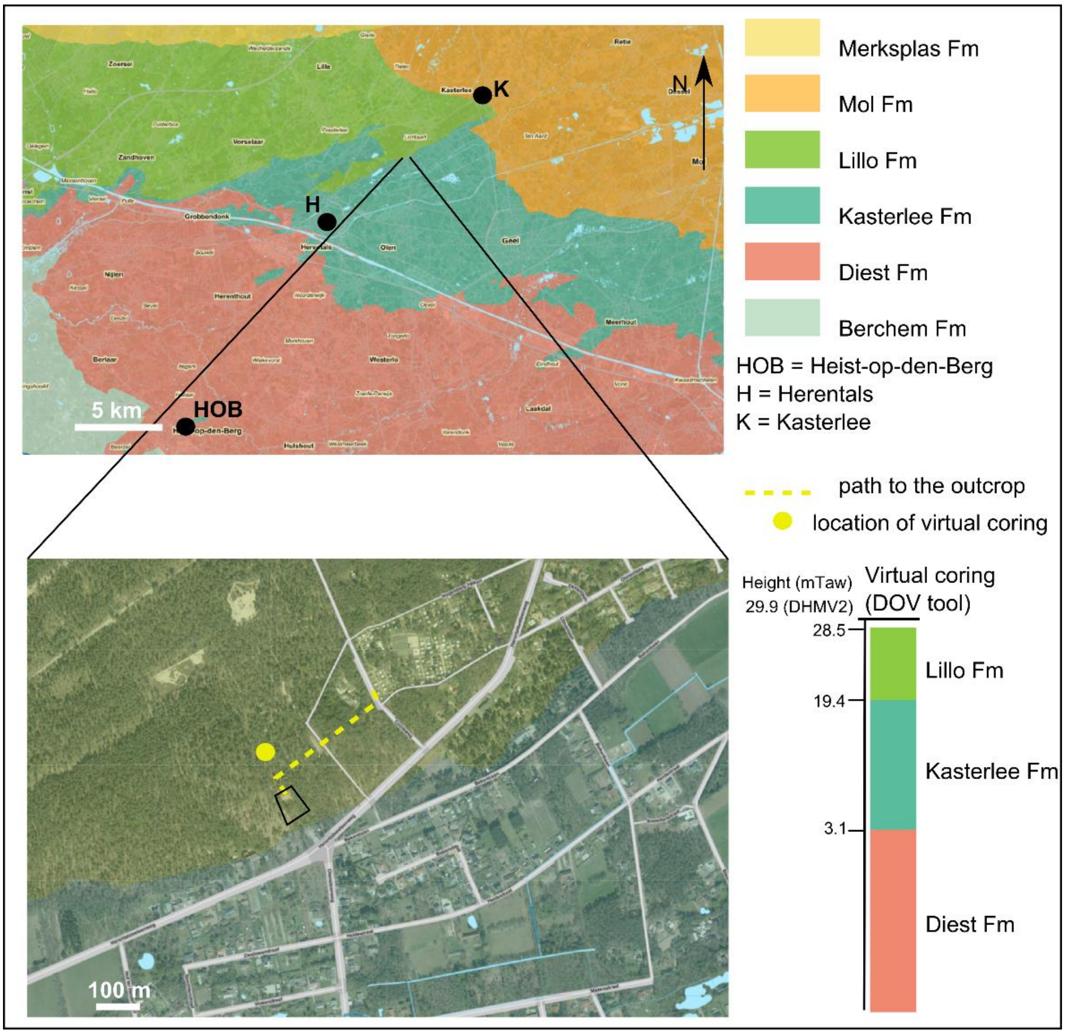

Figure 23. Location of the abandoned quarry outcrop along the southern edge of the Herentals-Lichtaart-Kasterlee hill ridge. Geological map based on G3Dv3.1 geological model on dov.vlaanderen.be.

This outcrop is one of the last remaining large outcrops in the Lichtaart hill ridge, which have been described in the past and which are a reference location for the contact between the Kasterlee

Formation and Poederlee Member, with the characteristic Hukkelberg Gravel. Gullentops & Huyghebaert (1999) already advocated for the preservation of this outcrop as National reserve for its high scientific interest.

Sediment characterization

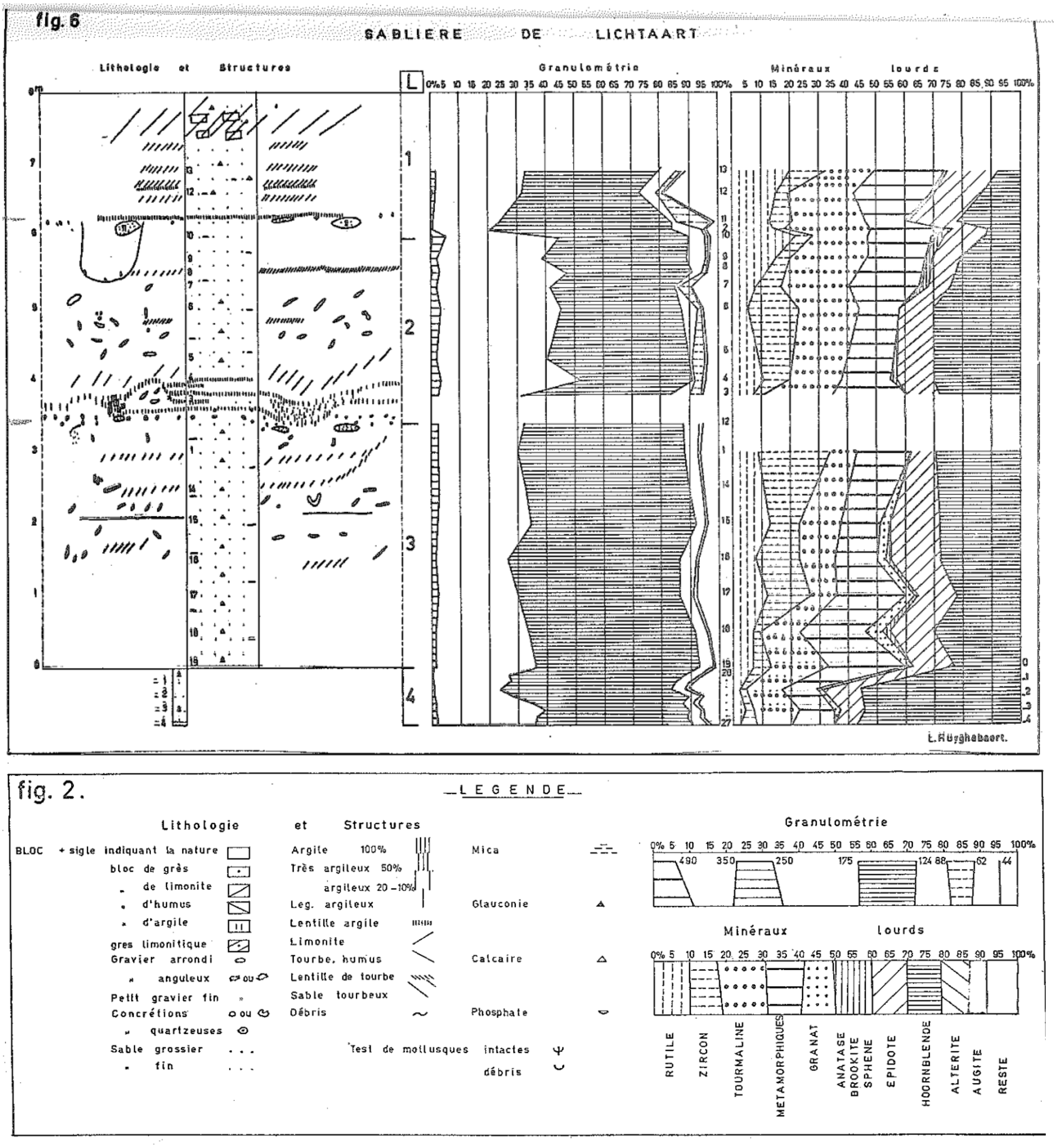

Figure 24. Litholog, granulometry and heavy mineral log of this outcrop, from Gullentops (1963).

This outcrop was described and analyzed, and incorporated into the excursion by Gullentops (1963) (Figure 24). A vertical section of 8 m was described, and additionally a hand boring of 3.5 m was made.

The sand in this outcrop is fine-grained, slightly glauconitic (max. 5 %) and very well-sorted with most grains in the range 124-250 µm (Figure 24) and a modal grain size of 160-170 µm (Gullentops & Huyghebaert, 1999). Bioturbations, devoid of glauconite, are present. There is no distinct difference between the sand of the Kasterlee Formation and Lillo Formation, even though a significant hiatus is present between both.

These units are separated by the Hukkelberg Gravel, which occurs 3.5 m above the base of the outcrop and has a thickness of up to 20 cm (Figure 24). The largest pebbles in this gravel reach a diameter of about 1.5 cm. It can be characterized by the large abundance (~ 50 %) of very well rounded and flattened discoid quartz granules. Other elements such as silex pebbles, rolled iron crust fragments (supposedly of eroded Diest Fm) and weathered silex fragments are present as well (Gulinck, 1960). Partly hardened blocks of Mol Formation type white sand can also be observed at the base of the Poederlee Member.

Just above the gravel, irregular and discontinuous fine clay layers (several cm) are present. A second minor gravel layer is present 6.2 m above the base of the outcrop, in which ravinations up to 60 cm deep are present. Near the top of the outcrop ferruginous sandstone occurs, which is up to 2 m thick along the top of the cuesta. At the base of the sandstone fossil moulds have been observed in the past (Geets, 1962).

The heavy mineral composition of the sediments shows a mixed signal with a significant amount of northern 'marine' minerals (hornblende, epidote, 30-50 %) yet also a large amount of southern 'continental' minerals (tourmaline, parametamorphics, 25-50 %) (Figure 24). The southern signature increases towards the top. Most striking is the exceptionally high hornblende content (> 50 %) in the hand boring at the base of the section, in the Lichtaart Member (Figure 24; Gullentops, 1963).

Basin correlation

In this outcrop the Hoge Berg Facies of the Lichtaart Member occurs, which is a facies with a limited amount of glauconite (max. 5 %). Towards the north, in the Turnhout area, the Oud-Turnhout Facies occurs, in which glauconite percentages of 30 % are measured.

The Lichtaart Member, visible in the outcrop below the Hukkelberg gravel, correlates to the east with the Retie Member of the Mol Formation (previous 'Kasterlee-sensu-Gulinck'). Although a gradual transition between the Lichtaart Member (Kasterlee Fm) and the Retie Mbr (Mol Fm) is proposed in the Neogene-2020 review such relation is not yet proven and an erosional boundary is still not excluded (Figure 25; Vandenberghe et al., 2020).

The Pliocene Kattendijk Formation occurs laterally from the Kasterlee Formation towards the west. In the past this geometric lateral relationship was the main argument to chronostratigraphically equate both formations, until dinocyst biostratigraphy showed the Kasterlee Fm to be late Miocene in contrast to the Pliocene calcareous fossils bearing Kattendijk Fm.

Based on CPT logs, the Hallaar, Beerzel and Heist-op-den-Berg members which are recognized in the southern and eastern occurrence area of the Kasterlee Formation are present below the Lichtaart Member at Kasterlee (Vandenberghe et al., 2020).

Based on the mollusk fauna, the Poederlee Member (previous Poederlee Formation) which occurs above the Hukkelberg Gravel was correlated with the Merksem and Kruisschans members of the Lillo Formation in the Antwerp area, previously named the 'Scaldisian' (De Heinzelin, 1955; Geets, 1962).

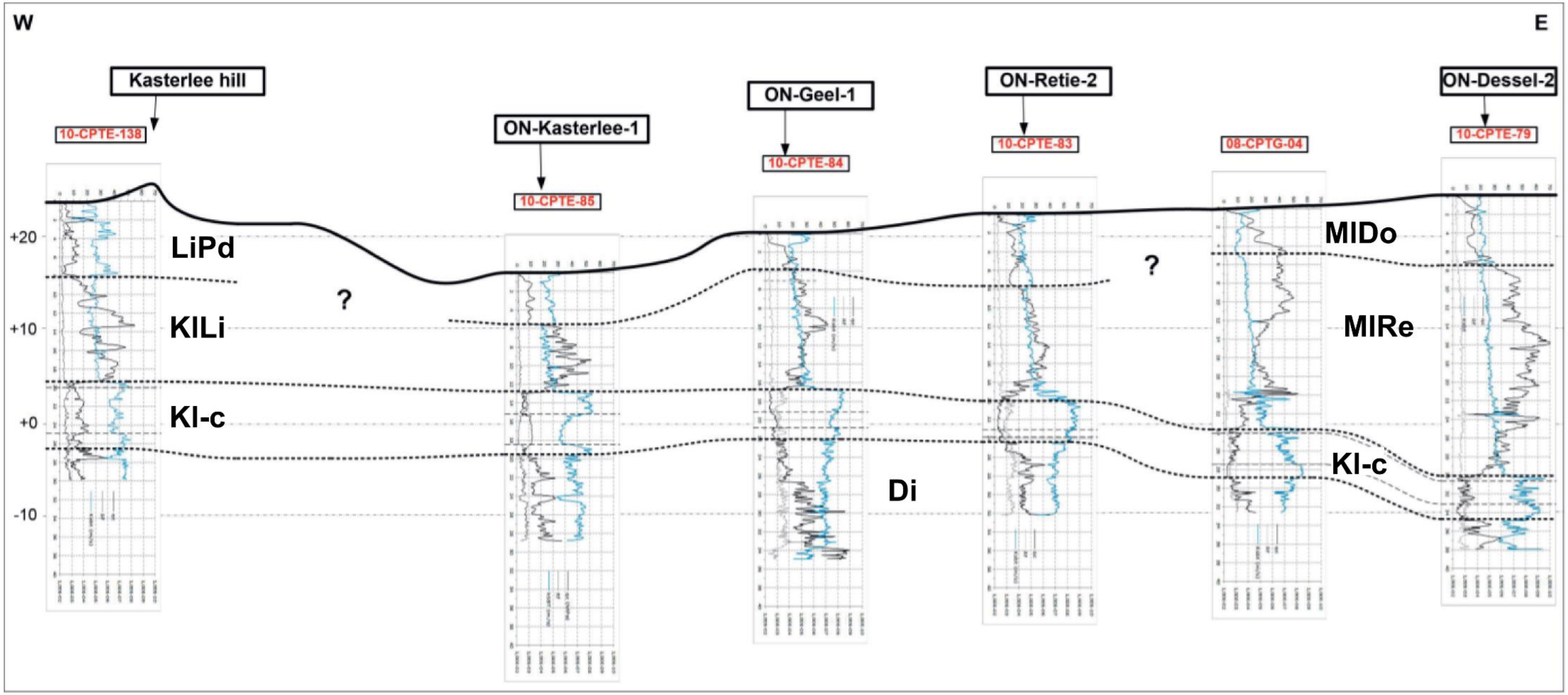

Figure 25. Correlation of the Kasterlee-Lichtaart hill towards the eastern Mol-Dessel area, using CPT log signature. Di = Diest Formation, Kl-c = Hallaar, Beerzel and Heist-op-den-Berg members (Kasterlee Fm), KlLi = Lichtaart Member (Kasterlee Fm), MlRe = Retie Member (Mol Fm), MlDo = Donk Member (Mol Fm), LiPd = Poederlee Member (Lillo Fm). Figure adapted from Vandenberghe et al. (2020).

Depositional model

The sediments observed in this outcrop were deposited in a shallow marine environment with rather low wave energy (Gullentops & Hyghebaert, 1999). The Hukkelberg Gravel represents a hiatus of more than one million years and was itself deposited in a beach environment. The discoid shape of the quartz pebbles point to long shore transport over a large distance, most likely from west to east, ultimately derived from England (Gullentops & Huyghebaert, 1999). The clay laminae above the gravel point to deposition in beach pools with a limited tidal influence. Due to transgression the sand above is again deposited in a shallow marine environment, until the second gravel layer which either represents a storm event or a short regressive phase with beach conditions. In the top of the outcrop transgression resumes with mollusc-bearing sand deposited in the upper wave platform (Gullentops & Huyghebaert, 1999). Alternatively the mix of sedimentary structures in the Poederlee Member may point to the infill of an erosive gully.

The increase in southern heavy minerals towards the top of the section indicates the arrival of the continental Mol Sand to the east. The exceptional hornblende content in the Lichtaart Member is explained as a local chaff effect by winnowing during long-shore transport (Gullentops & Huyghebaert, 1999). Geets (1962) interprets this anomaly as the result of a local chance occurrence of amphibolite fragments in the Hukkelberg Gravel.

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Profile Lichtaart – Dessel

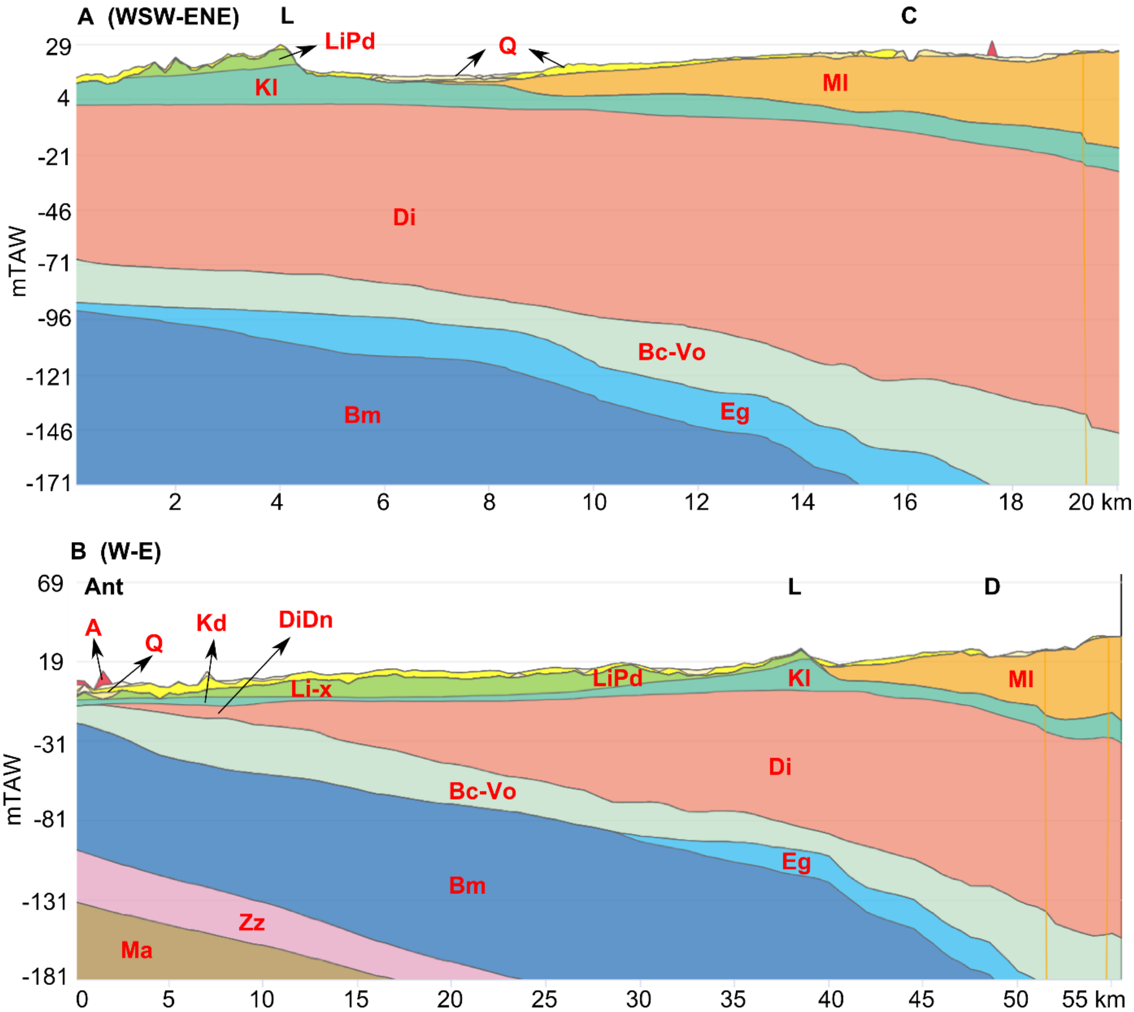

Figure 26. Profiles through the 3D geological model of the Flemish subsurface, G3Dv3.1 (https://www .dov.vlaanderen.be/; Deckers et al., 2019) (A) westsouthwest-eastnortheast profile from the Lichtaart hill ridge to the Mol-Dessel area, profile line 4 on Figure 1. (B) west-east profile from the city of Antwerp to the Mol-Dessel area, profile line 5 on Figure 1. Ant = Antwerp, L = Lichtaart hill ridge, C = Canal Bocholt-Herentals next to the ESV Euridice site and the location of the ON-Dessel-2 and ON-Dessel-5 corings, D = Dessel near to the ESV Euridice site and the location of the ON-Dessel-2 and ON-Dessel-5 corings. A = Anthropogene, Q = Quaternary deposits of the Schelde Group, Arenberg/Stokkem fms, Gent Fm and Vlaanderen Fm, in the rivervalley of the Kleine Nete, the Aa and the Scheldt, Ml = Mol Fm, LiPd = Poederlee Mbr (Lillo Fm), Li-x = other members of the Lillo Fm in the Antwerp area, Kd = Kattendijk Fm, Kl = Kasterlee Fm, Di = Diest Fm, DiDn = Deurne Mbr (Diest Fm) in Antwerp area, Bc-Vo = Berchem Fm and Voort Fm, Eg = Eigenbilzen Fm, Bm = Boom Fm, Zz = Zelzate Fm, Ma = Maldegem Fm.

From Lichtaart to the Mol-Dessel area, near the site of ESV Euridice, the Kleine Nete valley is crossed just east of the Lichtaart-Kasterlee hill ridge. East of the valley, there is a marked decrease in the thickness of the Kasterlee Formation, which appears to be partly laterally replaced by the overlying Mol Formation (Figure 26A). This demonstrates the apparent lateral evolution from the shallow marine Lichtaart Member and Poederlee Member in the Lichtaart hill to the continental Mol Formation towards the east, as the Roer Valley Graben comes closer by. The Diest Formation and Berchem Formation significantly increase in thickness towards the east. A profile towards the west, to the city of Antwerp where the cores of stop 1 were drilled, shows the marked decrease in thickness of the Diest Formation, which is cut off by the overlying Pliocene Kattendijk Formation (Figure 26B). Further to the west, the lower Miocene Berchem Formation and even the Oligocene Boom clay are cut off as well. Near Antwerp, the increased thickness of the Quaternary in the Scheldt river valley, as well as the occurrence of a large amount of Anthropogene sediment is apparent.

Stop 5: ESV Euridice core repository – Dessel cores

J. Verhaegen, R. Adriaens, N. Vandenberghe

Neogene units exposed in these cores:

- Mol Formation – Donk Member
- Mol Formation – Retie Member
- Kasterlee Formation – Heist-op-den-Berg Member
- Kasterlee Formation – Hallaar Member
- Diest Formation – Kempen Diest Member
- Diest Formation – Dessel Member
- Berchem Formation – Antwerpen Member

Geographic situation and relevance of cores

The cores shown during this excursion are ON-Dessel-2 and ON-Dessel-5. Both cores were drilled by ONDRAF/NIRAS, which is the organization in charge of nuclear waste management. Much research has been done on geological nuclear waste disposal in the Boom Clay in this area, which occurs beneath the Neogene units discussed during this excursion. This research is done by ONDRAF/NIRAS and SCK-CEN, the Belgian Nuclear Research Center, and the cores are stored at the repository of ESV Euridice, which is the economical partnership between both institutions. Both cores were drilled on the site of ONDRAF/NIRAS, Belgoprocess, in Dessel at a distance of 350 m from each other and less than 2 km from the core repository where they are currently stored (Figure 27).

These cores are very important for Neogene research as both cores combined provide a complete section from lower Miocene to Pliocene with Voort Formation (Oligo-Miocene boundary) to Diest Formation in ON-Dessel-5 and Diest Formation to Mol Formation in ON-Dessel-2 (Figure 27). Many of the current interpretations of the Neogene of the Campine area rely on research from these cores, which are of very good quality, including granulometry, clay mineralogy, heavy mineral composition, biostratigraphy and borehole logging data.

Sediment characterization

The sedimentary succession is discussed based on the boundaries suggested in this guide, following the most recent insights. Many data are available for these cores, which aide in the interpretation of the stratigraphic units (Figure 28, Figure 29). For the ON-Dessel-5 core, the lithological differences between the units are very subtle and the boundaries remain uncertain. Different interpretations have been given over recent years, which is why intervals are indicated in which the boundaries are present, as well as a suggested boundary position (Figure 29). For the ON-Dessel-2 core as well, multiple interpretations have been proposed in the past, yet the lithological differences are more pronounced and the interpretations of Vandenberghe et al. (2020) can be followed with more confidence.

ON-Dessel-2:

0-3 m: Quaternary

3-8 m: Donk Mbr (Mol Fm)

Coarse white quartz sand. Heavy mineral composition is dominated by southern continental minerals. Clay mineral content very rich in kaolinite.
Base at the transition from fine to coarse sand.

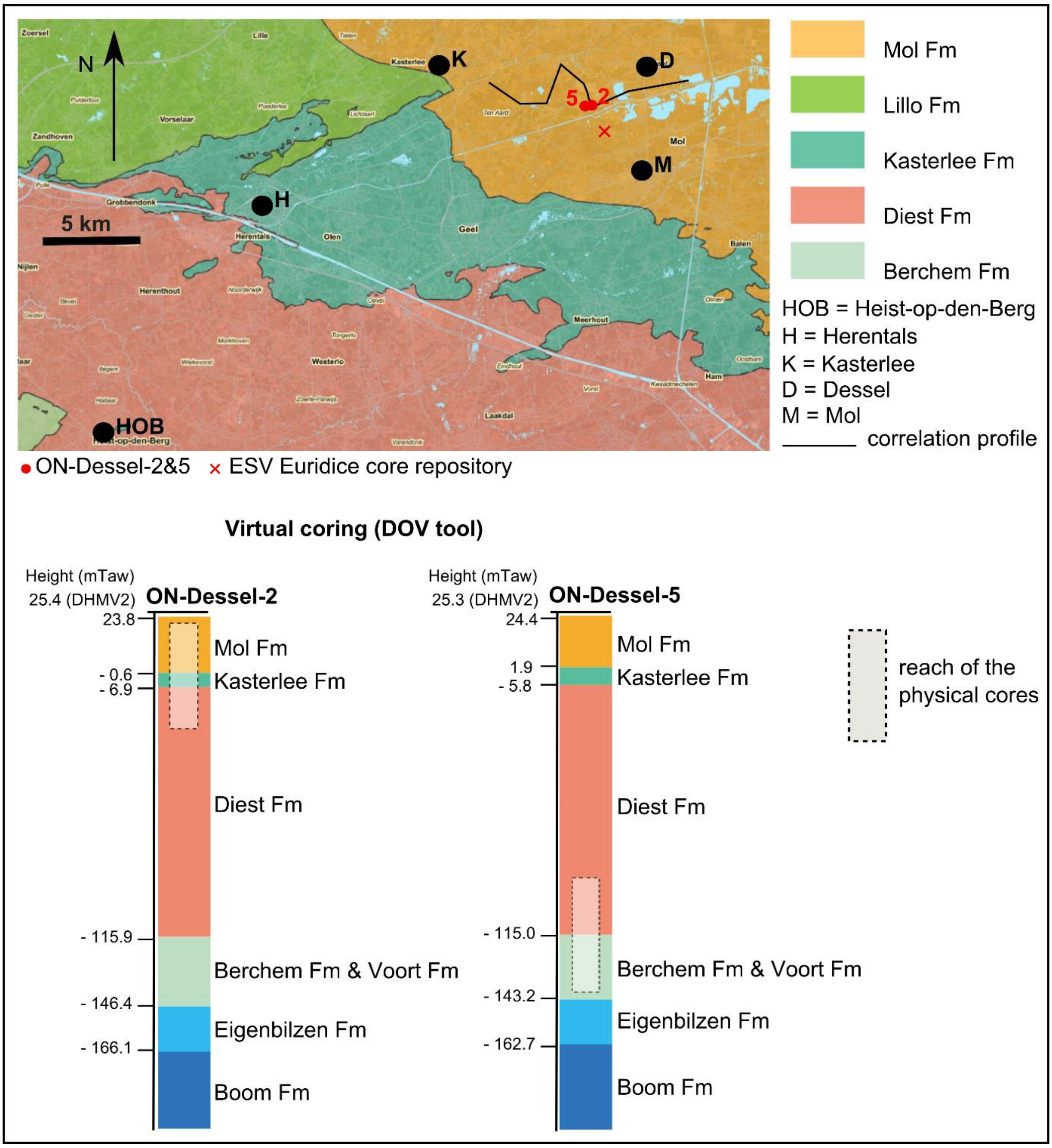

Figure 27. Location of ON-Dessel-2 and ON-Dessel-5 cores. Geological map based on G3Dv3.1 geological model on dov.vlaanderen.be. The interval of the physical cores viewed during this excursion are indicated on the virtual cores. Correlation profile refers to Figure 30.

8-29 m: Retie Mbr (Mol Fm)

Greyish to white fine quartz sand. Towards the base the sediment has a slightly greenish colour which mainly becomes visible in borehole fluid, yet no glauconite is visibly present. Heavy mineral composition is dominated by southern continental minerals, including an important andalusite fraction. Clay mineral content rich in kaolinite.

Base at the transition from green sand with clay to greyish white sand.

29.2-32.2 m: Heist-op-den-Berg Mbr (Kasterlee Fm)

An alternation of fine green glauconite bearing sand layers with grey to purple clay layers. Increased content of southern continental heavy minerals and kaolinite compared to underlying Diest Sand. Base at the start of the clay to fine sand alternation.

32.2-34.4 m: Hallaar Mbr (Kasterlee Fm)

Medium fine green clayey glauconite bearing sand with clay. Zone of reworking of underlying Diest Sand, with transitional characteristics.

34.4-52 m: Kempen Diest Mbr (Diest Fm)

Green poorly sorted medium sand, with a large glauconite content and a significant fine fraction. At the top, a clayey top facies occurs as well as an interval with a significant fraction of Fe-vermiculite clay. Smectite is an important clay mineral in contrast to overlying units.
In the sand itself, clay sized glauconite is dominant.

ON-Dessel-5:

85-110 m: Kempen Diest Mbr (Diest Fm)

Green poorly sorted medium coarse sand, with a large glauconite content. Contains a lot of clay-sized glauconite. The northern marine heavy minerals are much more prominent compared to the top of the formation and overlying units.
Base at the transition to fine sand.

110-141.6 m: Dessel Mbr (Diest Fm)

Fine green glauconite bearing well sorted sand, with an upper non calcareous and a lower calcareous section. An approximate 50/50 split between northern and southern heavy minerals. Clay mineralogy characterized by illite/smectite and smectite.
Base at a layer containing coarser quartz grains.

141.6-148 m: Berchem Fm

Medium fine dark green sand with an increased fine fraction, very rich in glauconite and containing shell fragments. A significant increase in the proportion of northern marine heavy minerals occurs in this unit. Illite/smectite and smectite dominated clay mineralogy.
Base at a dip in resistivity values and at the base of a peak in gamma values, and based on regional correlation constraining the thickness of the Voort Fm.

148-165 m: Voort Fm

Fine to very fine grey green glauconite bearing sand with shell fragments. Heavy mineral composition dominated by northern marine heavy minerals. Illite/smectite and smectite clay mineralogy.

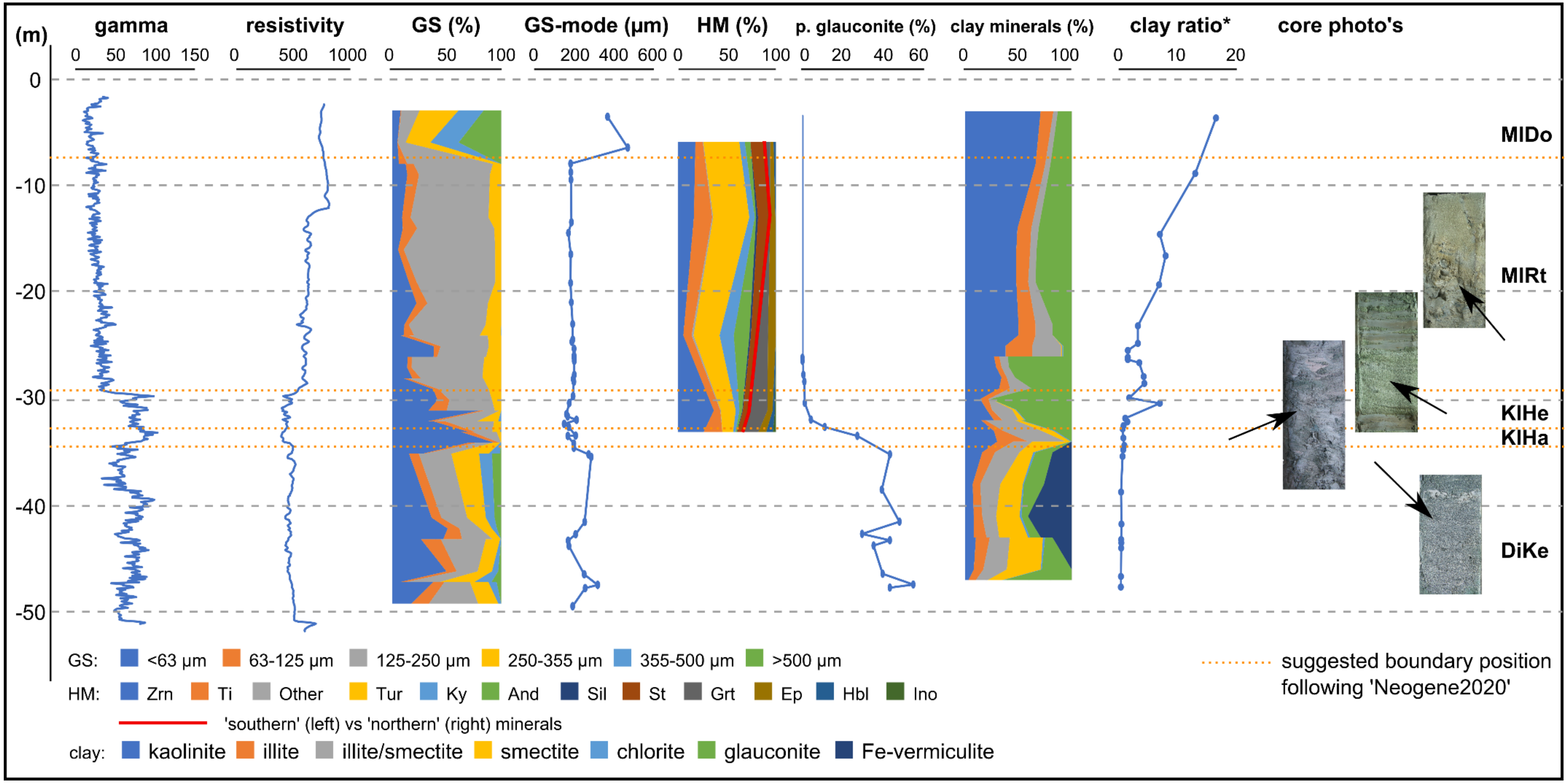

Figure 28. Data of the ON-Dessel-2 core. Geophysical well log data from Wouters & Schiltz (2011). Grain size data from Adriaens (2015, 2020) and Verhaegen (2019, 2020). Heavy mineral data from Verhaegen (2019, 2020). Glauconite and clay mineral data from Adriaens (2015, 2020). (m) in meter below ground level. GS = grain size distribution. HM = heavy mineral composition. P. glauconite = pelletal glauconite (fraction > 63 µm). Clay mineralogy in fraction < 2 µm. clay ratio = kaolinite / (illite/smectite + smectite). Heavy minerals: Zrn = zircon, Ti = titanium group minerals, other = rest group, Tur = tourmaline, Ky = kyanite, And = andalusite, Sil = sillimanite, St = staurolite, Grt = garnet, Ep = epidote, Hbl = hornblende, Ino = other inosilicates. Stratigraphic units: MlDo = Donk Mbr (Mol Fm), MlRt = Retie Mbr (Mol Fm), KlHe = Heist-op-den-Berg Mbr (Kasterlee Fm), KlHa = Hallaar Mbr (Kasterlee Fm), DiKe = Kempen Diest Mbr (Diest Fm).*

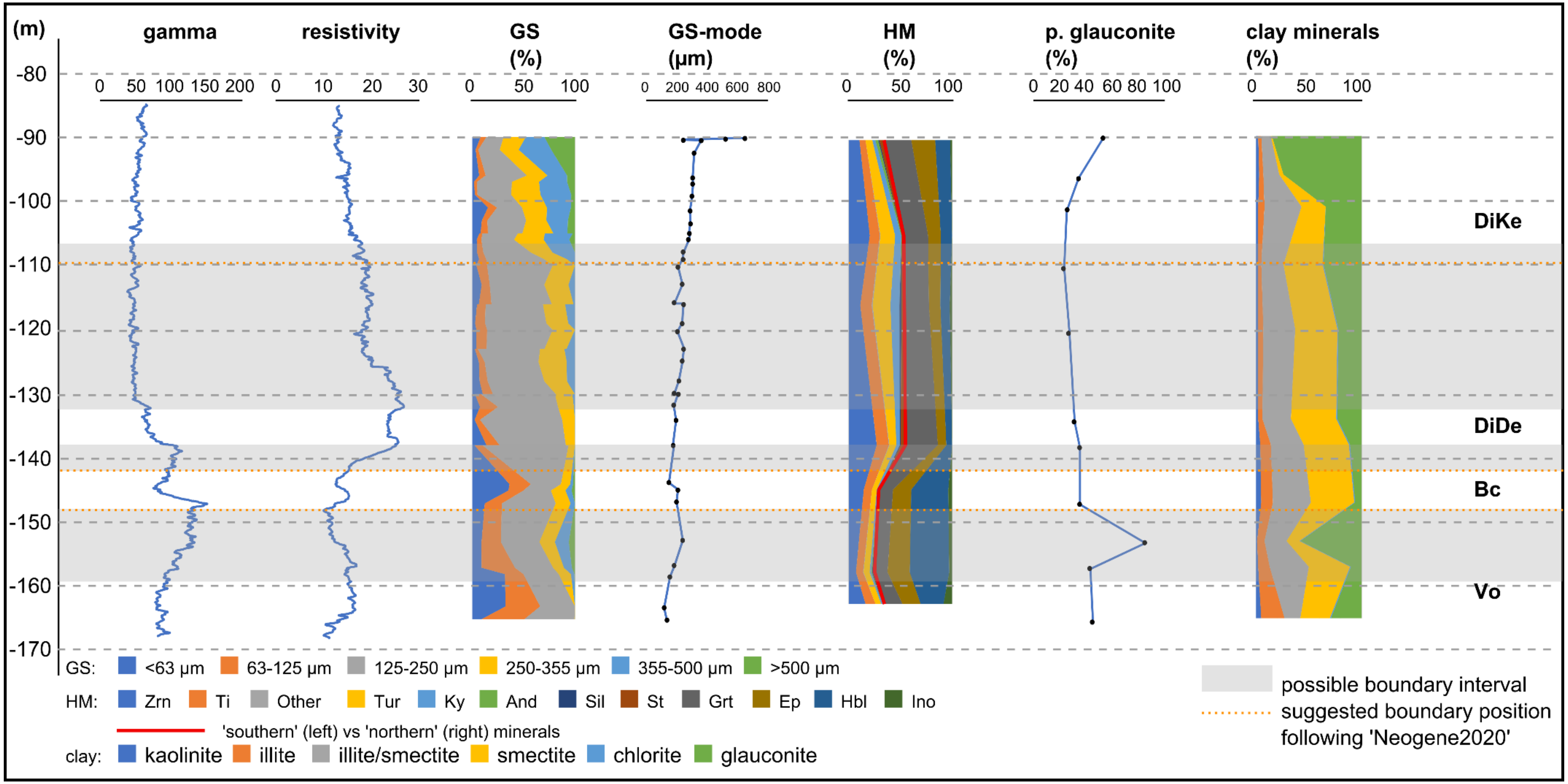

Figure 29. Data of the ON-Dessel-5 core. Geophysical well log data from Wouters & Schiltz (2011). Grain size data from Adriaens (2015, 2020) and Verhaegen (2019, 2020). Heavy mineral data from Verhaegen (2019, 2020). Glauconite and clay mineral data from Adriaens (2015, 2020). (m) in meter below ground level. GS = grain size distribution. HM = heavy mineral composition. P. glauconite = pelletal glauconite (fraction > 63 µm). Clay mineralogy in fraction < 2 µm. Heavy minerals: Zrn = zircon, Ti = titanium group minerals, other = rest group, Tur = tourmaline, Ky = kyanite, And = andalusite, Sil = sillimanite, St = staurolite, Grt = garnet, Ep = epidote, Hbl = hornblende, Ino = other inosilicates. Stratigraphic units: DiKe = Kempen Diest Mbr (Diest Fm), DiDe = Dessel Mbr (Diest Fm), Bc = Berchem Fm, Vo = Voort Fm.

Basin correlation

In the Mol-Dessel Campine area, many boreholes are present with well log data and analytical data such as shown for ON-Dessel-2 and ON-Dessel-5. Between those cores, correlation can be made based on the most recent insights (Figure 30; Vandenberghe et al., 2020).

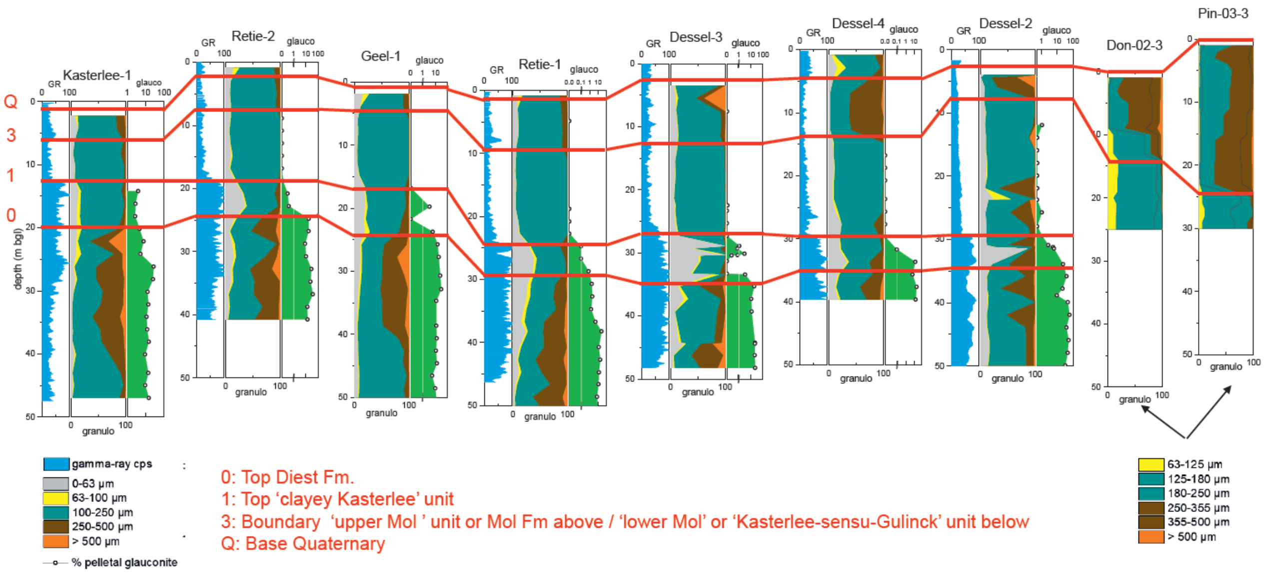

Figure 30. Correlation between cores of the Mol-Dessel area, including ON-Dessel-2. Location indicated on Figure 27. 'clayey Kasterlee' unit = Heist-op-den-Berg Mbr (Kasterlee Fm). 'lower Mol' or 'Kasterlee-sensu-Gulinck' unit = Retie Mbr (Mol Fm), 'upper Mol' unit = Donk Mbr (Mol Fm). Vandenberghe et al. (2020).

To the west, to Antwerp, there is an overall shift to more distal marine sediments. The Antwerpen Member of the Berchem Formation can be followed towards Antwerp but is there underlain by the Edegem and Kiel members, while the Voort Formation does not reach that far. The Diest Formation is progressively younger towards the west, as evidenced by the dinoflagellate cyst biozonation, indicating a large scale progradation. The youngest Diest Formation sediments west of Kasterlee are coeval with the Kasterlee Formation. In the Antwerp city area, the local lower Tortonian Deurne Member occurs, coeval to the Campine basal Dessel Member. The Kasterlee Formation is laterally replaced by the Pliocene Kattendijk Formation. The Mol Formation is laterally replaced by the Poederlee Member of the Lillo Formation and further west by the Merksem and Kruisschans members.

To the south, the Hallaar and Heist-op-den-Berg members of the Kasterlee Formation are better developed, in the Olen – Heist-op-den-Berg area, and the Beerzel Member occurs in between. The Kempen Diest Member is lateral to the Hageland Diest Member in the south, which is older. South of the Hageland incision, the Berchem Formation is replaced by the lateral and coeval Bolderberg Formation, with marine to continental sediments.

To the east, towards the Roer Valley Graben, the Mol Formation is lateral to the Upper Waubach Member and overlying units of the Kieseloölite Formation (Louwye & Vandenberghe, 2020). The Diest Formation is lateral to the Lower Waubach Member (or Inden Formation) and Diessen Formation. The Berchem Formation is lateral to the Groote Heide Formation.

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