NCS Subcommission Paleogene-Neogene

Version for Stratigraphic Commission of Belgium

Authors: Rik Houthuys, Noël Vandenberghe and Johan Matthijs

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Brussels Formation and Members

1 Hierarchical unit name: Zenne Group

2 Type: Formation and Members

3 Name

The Brussels Formation corresponds to a marine sand deposit that is often exposed at Brussels (Bruxelles, Brussel) east of the Zenne river. At the present time, many quasi-permanent outcrops have decayed and no longer provide good exposures. Good temporary exposures are frequently offered in small and large excavations related to infrastructure works and building sites. Dumont (1839) formalized a stratigraphic name already in use at the time, by introducing the "système bruxellien" (see also d'Omalius d'Halloy, 1842). It was defined to incorporate two sedimentary "étages", a lower "sable à grès lustré" and an upper "sable à grès calcarifère". The name “bruxellien” is used on the late 19th century 1:40,000 geological maps of Belgium (Rutot, 1893); those maps were published long before the systematic distinction between litho- and chronostratigraphy was introduced (Hedberg, 1976). The evolution of the precise stratigraphic significance of the term "bruxellien" since its introduction by Dumont (1839) has been reviewed by Steurbaut and Herman (2006). In response to the need of introducing a proper lithostratigraphic term, the names Formatie van Brussel (Dutch) / Formation de Bruxelles (French) were formalized (Geets, 1988, in Maréchal & Laga, 1988) to designate the depositional unit until then commonly named "bruxellien" or "brusseliaan". The late 20th century revisions of the 1:50,000 geological maps of the Flemish Region and 1:25,000 maps of the Walloon Region adopted the new lithostratigraphic terms.

The present definition allows the equivalent names of **Brussels Formation (Brussels Sand)** (English)**, Formatie van Brussel (Zand van Brussel)** (Dutch) and **Formation de Bruxelles (Sable de Bruxelles)** (French), as Brussels, capital of Belgium and Europe, is officially a French and Dutch bilingual city, while its international status has widely promoted the use of the English name.

Extending the name Brussels Sand outside its type area (e.g. Adrichem Boogaert & Kouwe, 1993-1997; De Mulder et al., 2003; Wong et al., 2007) requires to understand that the lithostratigraphic range does not correspond to the description in the reference area in Belgium. Instead, the equivalent unit in The Netherlands forms part of a much more extensive "Laagpakket van de Brusselzanden" of the Dongen Formation, with holostratotype DON-01 trajectory 735-800m. The Dutch Laagpakket incorporates also all the sandy sediments assigned in Belgium to the Vlierzele, Aalter, Lede and Wemmels Sand units.

4 Characterizing Description

4.1 Colour and grain size

The Brussels Formation consists of white to pale yellowish, greenish yellow or greyish green sand. In beds that were originally rich in calcium carbonate and that have decalcified, the colour is now brownish yellow or greenish brown. The grain size varies from fine- to coarse-sized sand. Often, a small fraction of clay and silt is present. When not decalcified, the carbonate is often of clay and silt size.

4.2 Depositional structures

The deposit is often homogenized by bioturbation; in most outcrops, a large-scale internal master bedding slightly dipping to ESE can be recognized. Many outcrops show dm- to several metres thick cross beds. Some beds are faintly wavy laminated to completely structureless. Apart from the latter beds, burrows are common.

The primary depositional structures of the main outcrop area have been grouped and coded into sedimentary facies (Houthuys, 2011, table 1 therein):

- Bf: fine sand homogenized by bioturbation, mottled, some thin to cm-thick mud or marl layers often pierced by biogenic burrows
- Bm: medium sand homogenized by bioturbation, mottled, many biogenic traces
- Bc: coarse sand homogenized by bioturbation, many biogenic traces
- Bx: thin cross beds in fine to medium sand, strongly homogenized by bioturbation
- Xb: 0.2 to 0.3 m thick cross beds with burrows, in medium sand
- X: cross beds between 0.5 and 1.5 m thick, scarce bioturbation, in medium to coarse sand
- M: massive or faintly wavy laminated sand in very well sorted medium to coarse sand (breaching deposits, van den Berg et al., 2017)

The facies had a different label in Houthuys (1990).

1990	2011
B	Bf, Bm, Bc, Bx
HB	Bf with horizontal marl layers
XB	Xb
X1, X2, X3	X
H	M

The sedimentary facies can only be recognized in outcrop or on cores. The genesis and paleogeographic relationships between the depositional facies have served to propose a sedimentary model for the Brussels Formation (Houthuys, 2011).

4.3 Base gravel

A base gravel is only found in some parts of the main outcrop and subcrop area, especially in the southeast sectors. It is probably not continuous and may be thicker in erosional base incisions (see below). In the western half and most of the subcropping northern part of the basin, there is generally no base gravel.

4.4 Mineral composition

Quartz grains dominate the deposit. They are mostly well rounded. Locally admixtures of angular grains are present of which it is assumed they are derived from quartzitic Paleozoic subcrops in the eastern part of the Brabant Massif, eroded at the time of the Brussels Sand deposition. The heavy minerals are dominated by ubiquists, mostly tourmaline, then zircon; the parametamorphic group contains typically large pleochroic andalousite grains (Geets et al., 1985). The characteristic composition is largely grain-size determined.

The original deposit is calciferous; the carbonate content is strongly reverse-correlated with grain size, i.e. the finer sized sand beds have higher calcium carbonate contents. The carbonate is mostly very fine grained but also mollusc shells or shell fragments can be preserved. In the outcrop area the sand can be locally or completely decalcified. The colour has then turned to brownish yellow or greenish brown.

Fine-sized pale green glauconite pellets occur in very small quantities throughout the Formation, whenever the fine sand fraction is present; darker and larger glauconite pellets can occur in the coarser-sized sand beds. Such coarse dark glauconite is lacking in the west and south of the outcrop area, even when coarse sand is found. The presence of coarse glauconite is limited to the east and northeast of the occurrence area and there its content tends to increase towards the east (ann. 1). At the base, coarse dark green glauconite is found over a wider area, but also restricted to the eastern part of the basin.

4.5 Lithifications

Occurrence of individual slab- or capriciously shaped cemented zones is a very common aspect of this Formation.

Silicified concretions are so frequent that their presence is almost diagnostic of the Brussels Formation. They are not conclusively diagnostic knowing that, at rare locations inside the Brussels Formation, no concretions are found at all, while on the other hand, concretions are not unique to the Formation (e.g. silicified concretions occur also in the Mont Panisel Member of the Lower Eocene Hyon Formation, but this Member occurs almost exclusively at locations where the Brussels Formation is lacking). In the Brussels Formation, the siliceous concretions are often very irregularly shaped, like hard cores with short stubs, sometimes with separately cemented burrow cores ("grès fistuleux"); but also many decimetres wide and about one decimetre thick, very hard, slab-shaped concretions are common ("grès lustrés"). Sometimes, the concretions are remarkably spherical (this characterizes facies M, see below).

When not decalcified, the finer grained facies of the Brussels Formation often contain carbonate sandstones. They have often been used as construction stone and sometimes have been given specific names (see "Use"). A summary of the Brussels Formation sandstones with a relevant bibliography is given in Dusar et al. (2009).

In decalcified areas, the carbonate sandstones may have completely disintegrated while siliceous sandstones may have turned friable or crumbly or have even decayed into white ghost spots in the matrix of loose, yellowish-brown sand.

In outcrop areas, secondary limonite cementation occurs locally in subhorizontal beds of a few dm thickness, up to several metres thick massive iron-cemented sandstone, such as at Ottenburg, Chaumont-Gistoux, the upper Woluwe Valley and the Sonian Forest (Stainier, 1924) southeast of Brussels and Braine-l'Alleud.

5 Use

Brussels Sand, especially the coarse grained sand, has extensively been and is still being extracted for construction sand (in Flanders: Gullentops, 1996; Broothaers, 2000; in Wallonia: Mignion, 1969).

The irregular 'grès fistuleux' concretions have locally been used for building walls or for decorating wall tops. A remarkable application was their use for building small devotion caves ('pierres de grottes' or 'grotstenen') (Conseil géologique, 1930; Aardkundige Raad, 1932).

Carbonate sandstones have been used for building stone across the outcrop area (Dusar et al., 2009). The most characteristic one is the Gobertange sandstone (Stoops & Nijs, 1996; Tordoir, 2000) used in many historic buildings and extracted in the Gete valley (Hoegaarden-Jodoigne area). This stone can be sawn in long, strait slabs. The sawed faces display fine white marl laminae separated by thin glauconiferous fine sand layers. The stratification is often cross cut by glauconiferous sand-filled burrows. Another name commonly used is the Diegem sandstone, a name which is referring to the exploitation area and therefore also contains some sandstone from the Lede Formation where that Formation is present on top of the Brussels Formation and has not been decalcified. This stone is fine-grained, carbonate cemented and more homogenized than the Gobertange sandstone; however, it can also contain fine or thicker marl layers. It is used as rough stone in slabs of about 10-15 cm thickness. A comparable carbonate-cemented sandstone, resembling the Diegem sandstone, occurs in a wide area south of Brussels and in Walloon Brabant, especially near Braine-l'Alleud, Nivelles, Seneffe and Genappe; and locally in a strip-like area near Grez-Doiceau, between Louvain-la-Neuve and Bierbeek, where there are called "grès (calcarifère) bruxellien" or "Brusseliaan kalkzandsteen".

A few characteristic features of Brussels Sand sandstones: a. "Grès fistuleux": cementation has started around cylindrical bioturbation traces. The upper sandstones are individual concretions. In the lower part, closely spaced sandstones have partly merged (Chaumont-Gistoux, Walloon Brabant). b. block type Diegem sandstone. These sandstones often occur in subhorizontal layers of individual but closely spaced blocks (Diegem, Flemish Brabant). c. Gobertange sandstone with typical fine, white laminae (building stone in church, Werchter, Flemish Brabant). Note the difference with the layered Diegem sandstone variety in d. d. layered sandstones found in Diegem sandstone exploitations as testified by their common occurrence mixed with more homogenous Diegem sandstone in buildings in the former exploitation area (building in Nederokkerzeel, Flemish Brabant).

In the southernmost outcrop area, between the Orneau and Sambre rivers, a quarzitic sandstone named "Grès de Fayat" has been quarried as cobble stone. It is an up to 3 m thick silcrete (Rutot, 1987; Michel & Remacle, 2020).

Also iron cemented sandstones have been used for building stones.

Use of building stone in historic and rural constructions provides an indication of where the stone can be found (ann. 2).

The Brussels Formation constitutes, especially in its outcrop area, a very important and productive aquifer (Peeters, 2014). The coarser-grained fills of certain internal erosional troughs have a high hydraulic conductivity, but also the fine grained facies are exploited for drinking water production (e.g., near Braine-l'Alleud). Where it covers sandy or chalk deposits, one merged aquifer is present. In subcrop, the aquifer merges also with the overlying Lede Formation and the sandy members of the Maldegem Formation. Locally near Leuven and Aarschot, incisions at the base of the Diest Formation have removed the former Formations, so that the Brussels Sand aquifer there merges with the Diest Sand aquifer.

6 Occurrence

The Brussels Sand Formation crops out in a strip in Central Belgium, between the Zenne and Gete valleys, in Brabant, NE Hainaut and N Namur, where it fills a 40 km wide complex erosional incision with its long axis oriented SSW-NNE (ann. 1). This erosional incised complex is embedded in a package of conformable Eocene strata that slightly dips to N - NNE where it is buried under younger strata; the erosional incision of the Brussels Formation extends over at least 120 km long. It is found in subcrop in the north of Vlaams-Brabant, the province of Antwerpen and the west of Limburg. In the south, the continuous occurrence of the Formation is replaced by some isolated patches, which extend the outcrop area unto Nalinnes south of the Sambre river. Apart from the central, contiguous area, two remarkable outliers are present inside the Cassel hill and the Mont des Récollets in northern France.

7 Lower boundary

The base of the Formation in its main occurrence area is highly erosive. Erosive channel- or trough-like depressions may lower the base locally by several tens of metres over short distances.

The Brussels Sand body in the Central Belgium erosional complex overlies from south to north and from east to west: Paleozoic rocks, Mesozoic rocks, the Landen Group and the Ieper Group.

In its main occurrence area in Central Belgium, the Brussels Formation occupies geometrically the same stratigraphic position as both the Vlierzele Member (Gentbrugge Formation of the Ieper Group) and the Aalter Formation (Zenne Group). However, Brussels Sand does occur on top of the Aalter sand Formation in the Cassel and Mont des Récollets hills of North France and in the Woensdrecht borehole in the southern Netherlands; both occurrences are located very close to the Belgian border and westwards of the Central Belgian Brussels Sand body. In the Knokke borehole at the coast and in other locations to the west of the Zenne valley, the occurrence of *Nummulites laevigatus* in the base of the Lede Formation is considered as an erosional remnant of the Brussels Sand; therefore Gulinck & Hacquaert (1954) have suggested that the Brussels Sand once covered the area of East and West-Flanders as a thinly developed deposit but was removed before the deposition of the Lede Formation.

The thickness in the central Belgium outcrop area is typically 20 to 40 m; locally, where the base has incised strongly into the underlying deposits, over 80 m.

8 Upper boundary

The upper boundary is, in the outcrop area (see Annex 1), a near-planar marine truncation surface formed by the base of the Lede Formation. East of the river Dijle, a marine truncation surface at the base of the Sint-Huibrechts-Hern Formation forms the upper boundary. South of a line Nivelles – Hannut, no covering Paleogene or Neogene formations have been preserved. Due to the present erosive landscape, often a gravel lag and Pleistocene loess cover the formation. In the subsurface it is erosionally covered by the Lede Formation in the west or by the Tongeren Group in the east where the Lede Formation has wedged out

9 Age

Chronostratigraphy, based in particular on nannoplankton analysis, situates the Brussels Formation at the latest Ypresian and the early Lutetian (NP13, mainly NP14a, NP14b) (Herman et al., 2000); the Brussels sand Formation is thus part of biozones that also contain (part of) the Vlierzele Sand Member of the Gentbrugge Formation and the Aalter Formation. A sequence stratigraphic model relating these lithostratigraphic units is given in Vandenberghe et al. (2004). The exact lateral relationship to (nearly) contemporaneous formations remains to be settled.

10 Reference sections

See below, subdivisions.

11 Subdivisions of the Brussels Formation

The Brussels Formation has since the earliest descriptions been perceived as a unity, probably because no clear and extensive internal boundaries were recognized between the base and the top. The sharp quartz sand feel and the omnipresence of silicified concretions have certainly strengthened the sense of unity. Yet at the same time the Formation is characterized by strong lateral and vertical internal variation between a few prominent sand types, of which geologists since the 19th century were well aware (Dumont, 1839; d'Omalius d'Halloy, 1842; Rutot & Van de Broeck, 1883). A good report of the variation is given by Gulinck & Hacquaert (1954) and Gulinck (1963). The transitions between the sand types are usually gradual but locally sometimes abrupt. Informal and more formal subdivisions have been proposed but practice has never followed these proposals as they were not straightforward to apply on available data and in the field and because units may repeat over the vertical. An additional difficulty is that the Formation is difficult to drill due to the presence of hard stone layers or blocks dispersed in the loose sand. Good cores and geophysical logs are rare.

Yet introducing subdivisions offers some advantages. They allow to structure and map observations that share important properties reflecting mode of origin and paleogeography, alteration, use as a raw material, geotechnical and hydrogeological characteristics.

Several properties can be used to organize the subdivision. In practice, the sand type is determined by lithological properties such as colour and grain size, mineralogical properties such as carbonate and glauconite content, sedimentary structures and facies, presence, shape and cementation type of stones.

Previous attempts at defining units or members include informal proposals by Houthuys & Gullentops (1985), Houthuys & Fobe (1988) (adopted by Geets, 2000), Gullentops (1996), and Vandenberghe & Gullentops (2001). Laga et al. (2001) have formally listed the Archennes, Bois de la Houssière, Chaumont-Gistoux, Diegem and Neerijse Member as subdivisions of the Brussels Formation. They tried to reflect some correlation with the sedimentary facies but a satisfying model accommodating the observed variation was not yet available then. The model proposed by Houthuys (2011) provides a robust framework for the sedimentary facies in the main outcrop area. As sediment style determines the distribution of lithological and mineralogical properties, the facies identified are included in the subdivision descriptions given below.

From a re-examination of the available data and of an extensive set of non-published data collected by the first author representing several lithological properties, it appears that grain size is the most robust property on which a lithostratigraphic subdivision can be based. Therefore, the present scheme is based on grain-size characteristics. Other mineralogical and petrographic properties are used as secondary criteria for further detailing sand type encountered in the field. It is observed that the grain-size boundary criteria presented here, that were based on sedimentary facies, also accommodate grain-size classes that can be recognized in Gulinck's (1963) summary of sand facies in the Brussels Formation (see figure below: coarse class represented by curves A, H, M, R, W; medium class by F, U, D; fine class by G, B, C, O).

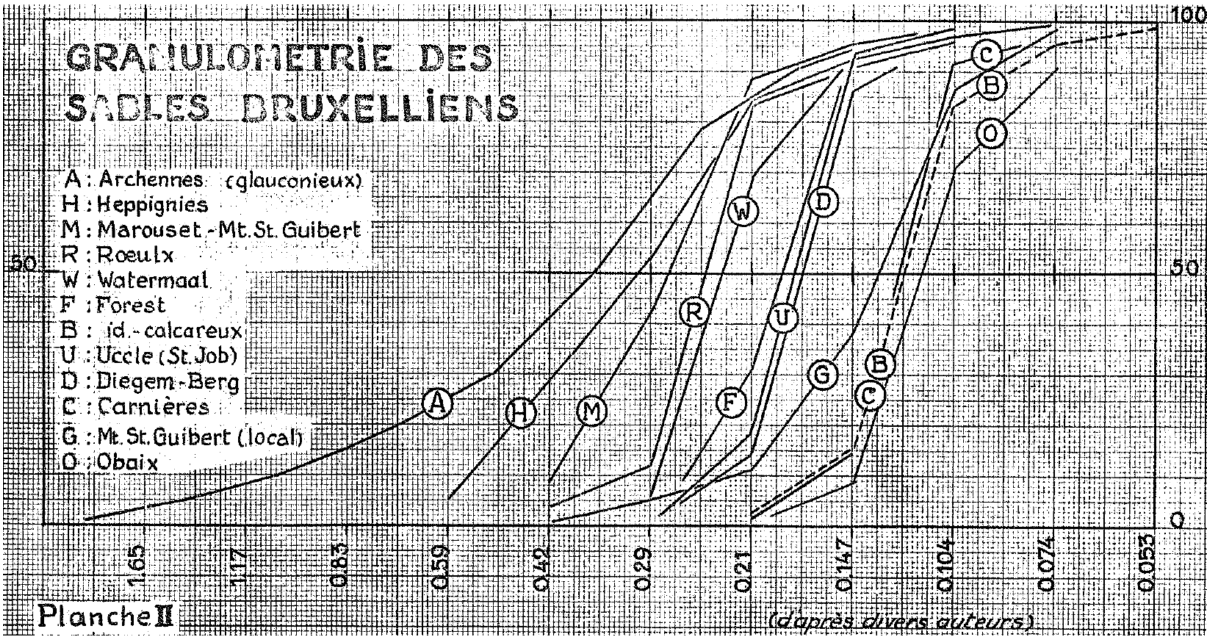


Planche II from Gulinck (1963). Grain size in mm on X-axis, cumulative weight percentage on Y-axis.

Below the Description of the grain-size based members in par. 12, a procedure is presented in par. 13 that allows to obtain objective and systematic descriptions of field observations and to accord them to the proper subdivision. It furthermore allows to evaluate existing records in terms of the new Members and lithostratigraphic facies, and the development of a database with uniform records of new observations across the different regions of Belgium.

12 Description of the proposed formal Members

The Members have been defined so that they can easily be identified and serve for practical purposes. They only distinguish between fine, medium and coarse sand. In view of the often gradual transitions of sand types inside the Brussels Formation, instead of using sharp grain-size boundaries, diffuse grain-size boundaries have been used to define the Members. The interpreter can thus evaluate the overall vertical and lateral grain size evolution and incorporate small intercalations of another grain-size class in the encompassing unit. It is intended that this will allow the attribution to one Member of relatively large outcrops or long borehole sections.

Gradual transitions between the Members often occur. In these cases, there is a freedom of interpretation where to exactly place the bounding surface between the Members. The definition that uses a grain-size range for the boundaries instead of an exactly set grain size, allows flexible application of the grain-size criterion so that identification of Members with meaningful volumes is possible. Due to the grain-size based definition of the Members and the complex internal arrangement of beds inside the Brussels Formation, they constitute no genetically meaningful geometric relation (i.e. sedimentary time surfaces will systematically cross-cut unit boundaries).

12.1 Machelen Member: fine sand

Very fine to fine sand. The central grain size value (mode or median) is **finer than 150-175 µm**. The Member contains a subdominant admixture (much less than 2%) of very fine, light green glauconite pellets.

Calcareous facies

In its original appearance (i.e., not decalcified), the sand is white to pale yellow, the carbonate content is higher than 15% and consists of fine mud. Carbonate content may locally reach high values, even exceeding 50%. The sand is fully or partially bioturbated and may contain very fine to cm-scale marly mud laminae. Macrofossils may be present.

In flush wells, this facies is easily recognized by the white colour of the flushing fluid. In outcrop, it is easily recognized by the fact that on touching the fingers are stained white.

Presence of calcareous sandstones

In this Member, subhorizontal, ca. 1 to 2 dm thick stone beds, cemented by carbonate and by some opal (Fobe, 1986), are common. The stone beds have a high total carbonate content, even up to 80%, that occurs as cement, as marly laminations, as fossils and as rounded bioclast grains that are mixed with the quartz grains (Dusar et al., 2009, p. 242 & 330). When they occur, often several such subhorizontal sandstone beds are found over the vertical profile, separated by 0.5 to 1 m of uncemented sand. These carbonate sandstones have in the past been used as building stones (ann. 2). At the historic type locality, Brussels and its immediate surroundings, this unit is predominantly found near the top of the Formation (Dumont, 1839; Rutot & Van den Broeck, 1883). In the area NE of Brussels, the sandstone is called "Diegem sandstone", in the area between Tienen and Jodoigne, the "Gobertange sandstone" is found, while in the wide area around Braine-l'Alleud and Nivelles, a similar stone called "grès calcareux du Bruxellien" (the name of "central Brabant sandstone" is proposed here) occurs. The Diegem sandstone mostly represents stone from the Brussels Formation but also partially from the Lede Formation sandstone, where it is found on top of the Brussels Formation. The stone layers in both formations have a similar aspect but Lede stones have less well sorted quartz grains, may contain 1-2 mm quartz grains and have more varied fossil remains. The Gobertange sandstone has in the 19th and first half of the 20th century been quarried and exported as building stone on an almost industrial scale (Tordoir, 2000). This stone is characterized by very thin white marl laminae perforated by burrows, filled with glauconite-rich medium to coarse sand. South and southeast of Brussels, in the wide area around Braine-l'Alleud and Nivelles, and locally around Grez-Doiceau (ann. 2), carbonate sandstones are found, which have an aspect very similar to the Diegem sandstone though in this area some layers attain a thickness of over 3 dm and the proportion of medium sand may be higher. Local variants may be found, e.g. finely laminated calcareous sandstone at Rood Klooster/Rouge Cloître (Oudergem/Auderghem).

Presence of siliceous sandstones

Capriciously shaped, hard, often small (at most 1 dm) siliceous concretions ("grès fistuleux" and "pierres de grottes") are frequent in this facies; in fact, their presence is a diagnostic for separating it from surrounding, similar strata such as the Lede Formation. In calcareous facies, the siliceous concretions may contain carbonate elements.

Decalcified facies

The Member is often decalcified. Decalcification caused a change in colour: it is yellowish or greenish brown due to the fact that non soluble grains such as fine-grained glauconite are concentrated and grains are limonite coated. Decalcification is found only in the outcrop area and there tends to occur primarily near the flanks of the valleys (geomorphology) and near the surface (vadose zone). Decalcification fronts are generally very sharp and may form capricious surfaces. Decalcification is caused by dissolution of carbonates in permeating water. The process is recent (related to the present landscape evolution) and is still ongoing.

Calcareous (lower right) and decalcified (upper left) facies of the Machelen Member. Note sharp and capricious shape of interface surface.. Note disintegrated carbonate sandstone in middle of photo. Construction site in Diegem, 16/02/2022. Tool is 40 cm long.

As it is decalcified, the facies no longer contains carbonate cemented sandstones and the chalcedony cemented concretions have turned brittle. In outcrop, the occurrence of capricious brittle siliceous sandstones or ghosts provides a good diagnostic.

An important consequence of this superficial weathering is that the sand becomes undercompacted and loses nearly all compressional strength. The alteration depth is in the metric scale but may exceed 10 m and its distribution is erratic. Recording the alteration is of great importance for geotechnical applications.

Correspondence with the sedimentary facies (Houthuys, 2011) :

This Member contains sedimentary facies Bf and Bx (Houthuys, 2011), but primary structures are obscured or completely erased due to decalcification.

Reference section:

Problematic, not permanently exposed. Building sites near Diegem and in Braine-l'Alleud often show the calcareous facies of this Member. The Waversesteenweg entrance to the RBINS museum at Brussels (Lambert 72 X 150546, Y 169493, outcrop from about 61 to 70 m TAW) also showed this facies, but the exposure is now walled up. It would make a meaningful stratotype. An alternative could be the Hussompont sandpit west of Jodoigne (X 183440, Y 158190, outcrop from about 87.5 to 104 m TAW), but at present, access to the site is difficult to obtain. The abandoned sand extraction pit at Waterloo in the Soignes Forest, situated between the R0 and the N5b (Chaussée de Tervuren), X 152955, Y 155810, shows the decalcified facies of this Member but the outcrop would need to be refreshed.

12.2 Neerijse Member: medium sand

White to pale yellow, when glauconiferous greenish yellow, medium sand. The **grain size central value** is **comprised between a lower value range of 150 to 175 µm and an upper value range of 250 to 300 µm**. The **carbonate content** (if not decalcified) **is between 2 and 15%**; most of this is fine mud. Micro- and macrofossils are often present. Commonly, the sand is moderately sorted and a fraction of fine sand is present. In that case, always a small admixture (much less than 2%) of very fine, light green glauconite pellets is found.

This unit has low to medium dark glauconite content facies. In certain areas, a gradually increasing admixture of coarser, dark green to blackish coloured glauconite pellets has been observed (ann. 1).

The dominant primary sedimentary structure is parallel master bedding, inclined at a small angle and dipping to ESE. The master beds show a gradually decreasing slope near the bottom of the Formation. Thin and thicker, up to 1 m thick, cross beds occur and are incorporated in the master fill style. Sometimes they constitute stacks of cross beds. The cross beds have a (very) dominant foreset dip to NNE, with rare occurrences of dips to SSW, and numerous mud drapes testifying to tidal currents. In numerous outcrops, the sand is strongly homogenized due to bioturbation. Between the opposites of relatively non-bioturbated cross beds and completely homogenized beds, all possible grades of increasing bioturbation occur. Locally, faintly wavy to structureless bedding is present in sharply bounded packages.

In most cases, numerous siliceous concretions are present, varying from capriciously shaped "grès fistuleux" (including "pierres de grottes") to slab-shaped "grès lustrés". They tend to be very hard and make drilling and excavating difficult. In structureless facies, siliceous stones are rare and often spherical, to absent. No carbonate stone beds occur.

In places where this Member has been decalcified, the Member remains identifiable by its grain size. Decalcification brings about a change in colour: it has turned yellow, brownish yellow or greenish brown due to the fact that non soluble grains such as glauconite are concentrated and grains are limonite coated. Often, local limonite cementation has occurred during or following decalcification. Decalcification is found only in the outcrop area and in this case tends to occur primarily near the flanks of the valleys (geomorphology) and near the surface (vadose zone). Decalcification fronts are generally sharp and may form capricious surfaces.

In the decalcified facies of the Unit, the chalcedony cemented concretions have turned more or less brittle.

Correspondence with the sedimentary facies (Houthuys, 2011)

This Member nearly exclusively contains sedimentary facies Bm, Bx, Xb and furthermore may show facies X and M (Houthuys, 2011).

Reference section

De Kock sandpit in Ganzemansstraat, Neerijse (X 167320, Y 167360, lower and middle part of sandpit face, approximately from about 45 to 60 m TAW).

Note: the upper part, from about 60 to 70 m TAW, in the Neerijse sandpit is the decalcified facies of the Machelen Member. In the immediate vicinity of this reference section, both the calcareous facies of the Machelen Member and the Bierbeek Member have been found in outcrop.

12.3 Bierbeek Member: coarse sand

White to pale yellow, when glauconiferous greyish green, medium-coarse to coarse sand. The **grain size central value** is comprised **between a lower value range of 250 to 300 µm and an upper value range of 400 to 500 µm**; the coarsest grains have an angular shape. In a small area in the southeast of the basin, around Eghezée, central values in the order of 1 to 2 mm are found; this very coarse facies is also included in this Member. In some boreholes, a bed of similar very coarse sand is found at or near the base of the Formation, e.g. at Bierbeek and Scherpenheuvel. Such coarse, angular grains can be found admixed in the medium to coarse sand of the thick cross beds of this Member at some locations. **Carbonate content** (if not decalcified) is very low, **below 2%**, and consists of fossil remnants. This unit can have well, moderately or poorly sorted facies. A bipolar grain size distribution is often present in the sedimentary facies X.

If a fraction of fine sand is present, a small admixture (much less than 2%) of very fine, light green glauconite pellets is always found. The Bierbeek Member may either contain a considerable admixture (from 5 to up to about 30%) of coarse dark green to blackish glauconite pellets (this tends to be the case in the east of the basin) or it can be devoid of such glauconite (in the west and southeast of the basin).

The cementations have different shapes and sizes and are of the type with chalcedony to microquartz cement; also their content may vary. Very well-sorted beds tend to have low numbers of siliceous concretions; beds with mud laminae like in the bottomsets of cross-beds tend to have higher contents of siliceous concretions. Locally mud layers may be marly, but they are then often silicified.

Because of the low original carbonate content, decalcification doesn't alter the aspect of this unit much. Limonite cementations are only found in decalcified occurrences of the unit.

Correspondence with the sedimentary facies (Houthuys, 2011)

This Member exclusively contains facies Bc and is furthermore often shows facies M, Xb and X (Houthuys, 2011). The coarsest occurrences are in facies X.

Reference section

Godts sandpit, Builoogstraat, Bierbeek (X 176760, Y170650; the exposed section from about 48 to 63 m TAW and the approximately 50 m below it, known from boreholes, that fills an internal erosion trough).

12.4 The facies M (Houthuys, 2011)

The facies M ("massive sand"), described and interpreted as a turbidite deposit related to breaching, a special type of slope failure (van den Berg et al., 2002; Houthuys, 2011; van den Berg et al., 2017), is a particular facies of the Brussels Formation, arranged in both conformable wedge-shaped and highly erosional canyon-shaped beds of varying volume, with bed thicknesses ranging from only a few dm to over 10 m. The facies represents the result of the transfer of relatively coarse shore sand towards deeper parts of the Brussels Embayment, due to breaching. It has only been observed as sand without dark, coarse glauconite. In a sandpit in Ottenburg, a lense of white massive sand was incised in glauconite-rich, cross bedded sand. The facies is, as far as known, restricted to the central area of the Brussels Sand basin where incisions at the base occur (ann. 3). Several instances of facies M may repeat over the vertical direction. The facies M consists of well sorted massive sand lacking clearly developed sedimentary structures, lacking a fine mud fraction, lacking carbonate cemented stones and lacking bioturbations; in non-decalcified locations, shells may occur as concentrated shell beds. The richest fossil sites are probably related to such concentrated beds. Siliceous concretions in this facies may be remarkably ellipsoidal to spherical in shape. They occur much less frequently than in the other facies. Due to this composition, it is a type of Brussels Sand much sought for exploitation.

This facies is included in the Bierbeek and Neerijse Members. As it can only be recognized in outcrop or undisturbed cores, no separate bed or Member has been defined for it. Due to its intricate interweaving in the fabric of the Brussels Sand, it has no specific lithostratigraphic status. If recognized, its occurrence should be reported in the properties of an outcrop or borehole.

12.5 Summary of Member properties

The Members are defined based on the grain size.

Property	**Machelen Member**	**Neerijse Member**	**Bierbeek Member**
Lower grain-size value range (quartz grains)	(around 100 µm)	150 – 175 µm	250 – 300 µm
Upper grain-size value range (quartz grains)	150 – 175 µm	250 – 300 µm	(500, locally over 1000 µm)

Once the Member has been identified and given its name Machelen, Neerijse or Bierbeek, its supplementary properties can be used to further specify a facies. Examples are:

- Machelen Member, facies with Gobertange stone
- Neerijse Member, decalcified, glauconitic facies with platy siliceous stones
- Bierbeek Member, siliceous platy stone facies with sedimentary facies Bc
- Neerijse Member with sedimentary facies M and with thick ironstones

The supplementary properties are:

Property	**Machelen Member**	**Neerijse Member**	**Bierbeek Member**
$CaCO_3$ content in original undecalcified Member	> 15%	> 2% and < 15%	< 2%
Decalcified facies of Member	strong colour difference w.r.t. non-decalcified facies; $CaCO_3$ cemented stone beds dissolved; siliceous concretions are decomposed or turned brittle	mild colour difference; siliceous concretions turned brittle	close resemblance to non-decalcified facies
Facies of Member containing dark green coarse glauconite pellets	rare or missing (a fraction typically below 1% of pale green glauconite is always present)	facies exists	facies exists
Calcareous sandstones	Usually present in carbonate facies, according to area: NE of Brussels: Diegem Sst. From Brussels to Nivelles, and isolated spots in Walloon Brabant: Central Brabant Sst. Tienen-Jodoigne: Gobertange Sst.	absent	absent
Siliceous sandstones	Mostly small capricious bulbs	Mostly numerous capricious bulbs, slabs and layers. Spherical bulbs in facies M	Mostly rather rare capricious bulbs, slabs and layers. Spherical bulbs in facies M
Ironstones (only in weathered facies)	Not common and not bulky.	Often present: thin layers or capricious shapes and plates. Very thick ironstones may occur in facies M.	Not so often: thin layers or capricious shapes and plates. Very thick ironstones may occur in facies M.
Exclusive sedimentary facies (Houthuys, 2011)	Bf	Bm	Bc

Sedimentary facies (Houthuys, 2011) shared between Members	Bx	Bx Xb, X, M	Xb, X, M

12.6 Comparison of previously published subdivisions with present Members

Publication	Previously published unit	Present Member and facies
Houthuys & Gullentops (1985)	Zand van Alconval	Neerijse Member and Bierbeek Member (non glauconiferous facies)
	Zand van Le Foriet	Machelen Member (calcareous facies)
	Zand van Kapittel	Machelen Member (decalcified facies)
	Zand van Sart-Moulin	Bierbeek Member (non glauconiferous facies)
Houthuys & Fobe (1988) = Marechal (1991) = Geets (2000)	Archennes Member	Bierbeek Member (glauconiferous facies)
	Bois de la Houssière Member	Bierbeek Member (non glauconiferous facies)
	Chaumont-Gistoux Member	Neerijse Member and Bierbeek Member (both non glauconiferous and with sedimentary facies M)
	Neerijse Member	Neerijse Member (carbonate facies)
	Diegem Member	Machelen Member (carbonate and decalcified facies)
Vandenberghe & Gullentops (2001)	Diegem Sand	Machelen Member (carbonate facies)
	Kraaiberg Sand	Bierbeek Member (glauconiferous facies)
	Neerijse Sand	Neerijse Member (carbonate and decalcified facies; glauconiferous)
	Gobertange Sand	Machelen Member (carbonate facies with Gobertange Sandstone)

13 Procedure for field observations and attributing them to a Member

First step: Define sample locations and register their coordinates. In several metres high outcrops and in boreholes, take sample locations that are vertically about 1 m apart. In long outcrops (e.g. roadsides), define sample locations at horizontal distances that allow to catch the variation: the locations may be 10 to 50 m apart. Record the Lambert 72 X, Y and elevation in TAW.

Second step: describe the sample locations from the first step in terms of properties that define the Members and lithostratigraphic facies:

1. Grain size. Analyse or estimate a central value (mode or median) using at least a magnifying lens and sand ruler. Additionally, note sorting, presence of fine or coarse grains.

2. Colour. It is no discriminating property but may help in evaluating facies.
3. Estimate or analysis of carbonate content.
4. Estimate or analysis of coarse, dark green or blackish glauconite pellets content. Absence is also important to note. Remark: whenever a sample contains fine sand, very fine grained light green glauconite is always present as a small (often less than 1%) subdominant admixture. This property is not needed.
5. Presence of lithifications: cement type (carbonate, silica, iron oxide), shape (continuous layer, platy, capricious boulders, spherical boulders), dimension (decimetres, hand size, very large and massive).
6. Primary sedimentary structures: homogeneous, homogenized (bioturbated), homogenized (alteration), with burrows, horizontal laminae, cross bedding. If possible, determine the sedimentary facies according to Houthuys (2011): X, Xb, Bx, Bc, Bm, Bf, M (see below).

Third step: attribute the sample locations to a Member and its facies

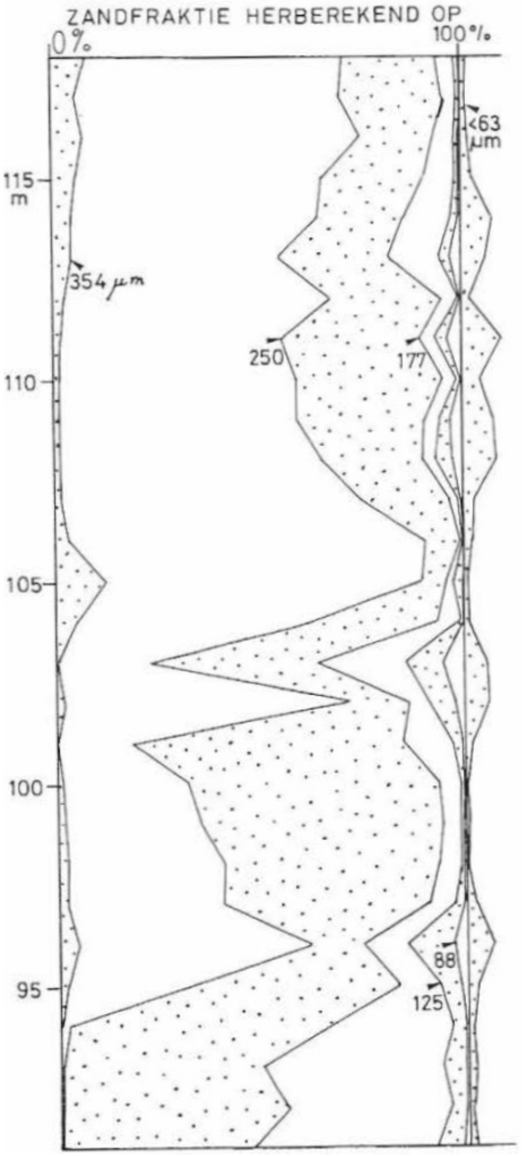
Fourth step: evaluate the Member and facies attributed to the samples in the third step and integrate larger intervals, thereby neglecting intervals of 1 or 2 samples with a different interpretation. Boreholes cutting through the entire Brussels Formation will often meet one or two Members; repeats over the vertical are possible.

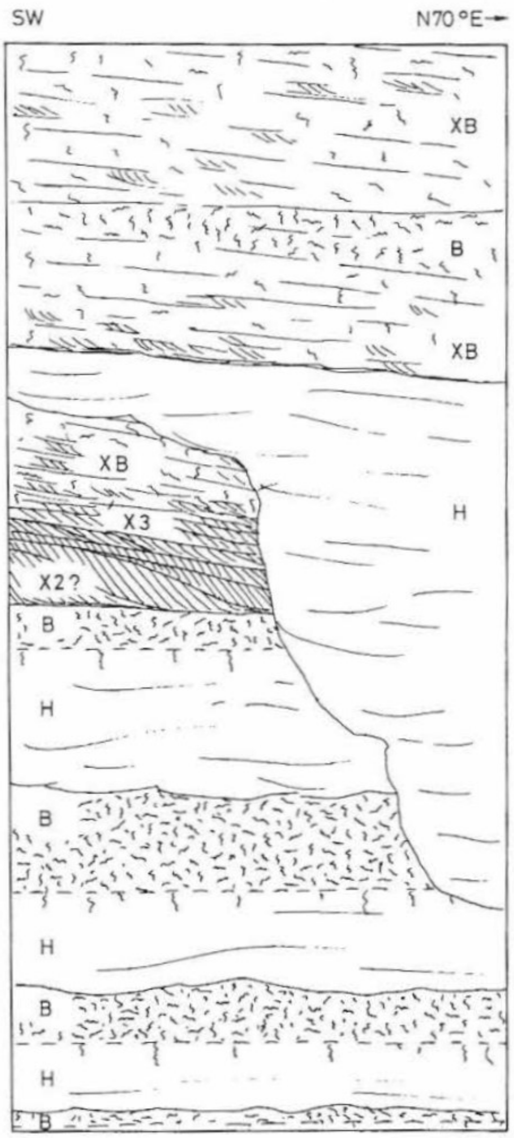
14 Application of the lithostratigraphic subdivision

A joint initiative over the Regions of Belgium, that would store all observations in an integrated database covering the entire extent of the Brussels Formation and containing the properties and interpretations of Members and facies per sample location, will ultimately allow to construct outcrop maps, horizontal and vertical sections and 3D models displaying the variation inside the Formation. This database should also maximally incorporate and translate existing observations. A few examples of how this can be done for outcrop and borehole is shown below.

14.1 Braine-l'Alleud, Alconval sandpit

This large sandpit was exploited in the second half of the 20th century and is now abandoned and landfilled. A photo is given by Houthuys (2011, fig. 10). A vertical profile was sampled in the 1980s (see log below from Houthuys, 1990, fig. 4.24).





This profile would result in the following records (small intercalations are disregarded):

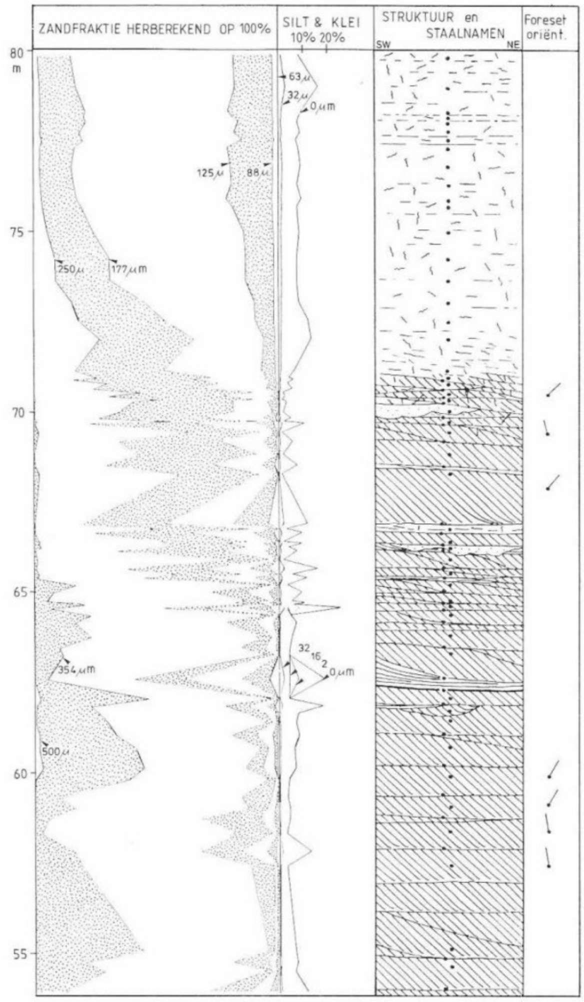
Lambert 72 X 148250, Y 154550, 104-117 m TAW: Bierbeek Member, decalcified, non-glauconiferous, sedimentary facies M (*previously H*) and Bc (*B*)

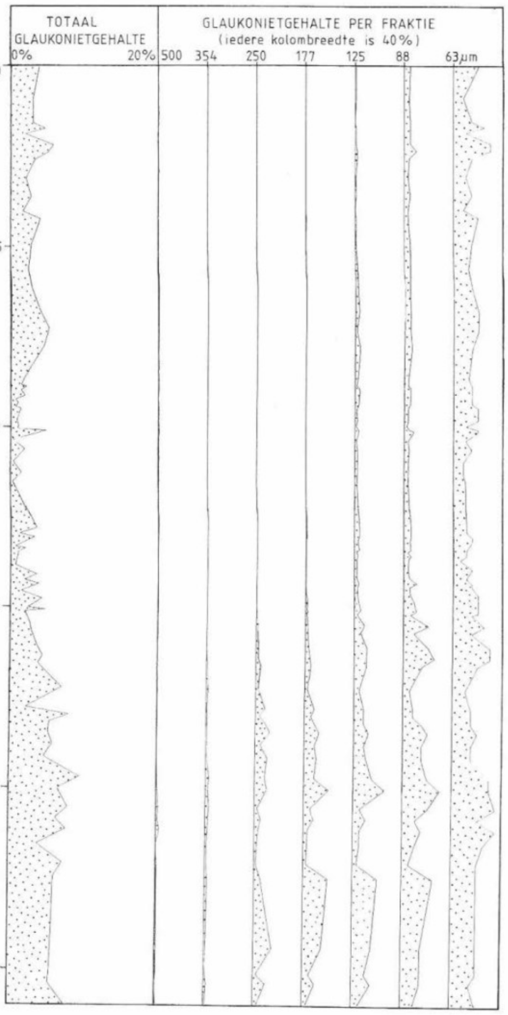
Lambert 72 X 148250, Y 154550, 92-103 m TAW: Neerijse Member, decalcified, non-glauconiferous, sedimentary facies X (*X2, X3*), Xb (*XB*), M (*H*) and Bm (*B*)

(from the regional context, we know that the Machelen Member is present below the profile. The lowest sample could equally well be attributed to that Member, certainly if several metres below would display the properties of it).

14.2 Huldenberg Wolfshagen sandpit

This large sandpit was exploited in the second half of the 20th century and is now abandoned and landfilled. A vertical profile was sampled in the 1980s (see log below from Houthuys, 1990, fig. 4.24).





This profile would result in the following records (small intercalations are disregarded):

Lambert 72 X 167000, Y 163400, 73-80 m TAW: Machelen Member, decalcified, non-glauconiferous, sedimentary facies Bx and Bf

Lambert 72 X 167000, Y 163400, 66-73 m TAW: Neerijse Member, decalcified, non-glauconiferous, sedimentary facies X, Xb and Bm

Lambert 72 X 167000, Y 163400, 54-66 m TAW: Bierbeek Member, decalcified, glauconiferous, sedimentary facies X

14.3 Expression in geophysical well logs

The Brussels sand Formation is generally characterised by a low Gamma Ray response and a high Resistivity signal. Often the GR values decrease upwards while the RES values increase upwards, a trend thought to reflect the overall coarsening upwards grain size observed within the Brussels Formation.

A few examples of geophysical-log-based interpretations delineating the members within the Brussels Formation are shown in annex 4: the Halle 115E B/2 435a, Overijse 102E0355 and Bierbeek 103E0250 boreholes. The interpretation is based on nearby outcrop data and on well-described nearby drillings; unfortunately no analyses in the 3 boreholes themselves are available to support the interpretation shown in annex 4. Also the boundary between the members might in reality be gradual rather than the sharp lines used in annex 4.

In the examples of annex 4 it may be noticed that in particular the Machelen Member is characterised by a much lower RES signal than the Bierbeek and Neerijse Members. The boundary of the Brussels Formation with the underlying Kortrijk Formation of the Ieper Group seems best expressed by a sharp reduction of the GR signal in the former.

In many boreholes, the boundary of the Brussels Formation with the overlying Lede Formation is often difficult to identify on geophysical logs alone. A complicating factor is the common presence of sandstones in both formations that may strongly influence the geophysical log pattern. There is a lack of well sampled and analysed boreholes to calibrate the geophysical pattern in such cases. This remark actually applies also to the Brussels Formation in general.

15 Occurrence of Members and facies

At this stage it is too early to present a map showing the new Members. Proxies for the occurrence of Members and facies are shown in the maps in annexes 1-3 and 5-6, for the main occurrence of the Brussels Formation in central Belgium. All maps also show contour lines of the basal surface of the Brussels Formation. Note that in areas with scarce observation points and in areas near the actual outcrop, the lines are interpreted.

Ann. 1 shows the occurrence of coarse glauconite pellets. They can occur at the base, in the lower part, over the entire vertical or inserted as an intercalation in the Brussels Formation.

Ann. 2 shows observed old buildings in the rural areas that used construction stone from the Brussels Formation. During field observations, only buildings interpreted to be older than the beginning of the 19th century were recorded. Observations from city centres were mostly left out as it is assumed that more use of imported stones could have been made there. Typical rural historical buildings are churches, castles, farms, barns, supporting walls. From the 19th century widespread use was made of industrially mined and transported Gobertange sandstone. Such use has not been recorded. The resulting map is thought to give a good indication of local sandstone in the Brussels Formation. The rural buildings with carbonate sandstone testify to the presence of the calcareous facies of the Machelen Member. Those with iron sandstone testify often to the presence of sedimentary facies M, the only facies where massive ironstone occurs.

Ann. 3 shows observations of sedimentary facies M, either by direct observation (confirmed) or by indirect indications (potential). An example of an indirect indication is the use of cylindrical silicified concretions in an old building.

Ann. 5 shows observations of grain size classes. They are the most direct proxy of the new Members. Due to map limitations, the coarsest class per observation location is displayed. The geographical mixing of grain size classes is an almost equally good indicator of the mixing of Members in an area, which then also takes place in the vertical dimension.

Ann. 6 is a separate map of observations of sedimentary facies Bf (the calcareous and decalcified facies). These are uniquely part of the Machelen Member.

The maps allow the following preliminary conclusions about the extent of the Members:

- the Machelen Member occurs everywhere with the exception of the SE of the extent. It is rare in a S-N strip south of Leuven;
- the Bierbeek and Neerijse Members occur everywhere with the exception of the SW of the extent;
- the central part of the extent shows a rapid lateral change of Members. The maps only show one property per location and thus is a simplification. It is known that in the same area, also in the vertical sense multiple Members occur. The area shows deep incisions in the basal surface and a large number of observations of sedimentary facies M;
- the glauconitic facies don't occur in the western half of the main extent. But also in the eastern half, it is not the exclusive facies;
- facies M is not found where the glauconitic facies takes up the entire vertical section.

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17 Annexes

Ann. 1. Outcrop and subcrop map of the Brussels sand Formation in its main extent in central Belgium and indication of content of coarse glauconite. Note: Ann. 1-3 and 5-6 are views extracted at the date of this document from a geographical database containing field observations and borehole interpretations by the first author. This database is not complete. It is continuously being expanded when new observations become available.

Ann. 2. Central extent map of the Brussels sand Formation and (non-exhaustive) indication of historic rural buildings using either carbonate sandstone or iron sandstone extracted from the Brussels Sands and locally, NE of Brussels, also from the Lede Formation.

Ann. 3. Central extent map of the Brussels Formation, with indication of the occurrence of sedimentary facies M (massive beds, breaching turbidites).

Ann. 4. Gamma Ray and resistivity logs of boreholes Bierbeek (GSB 103E0250), Overijse (GSB 102E0355) and Halle (DOV B/2-0435a), with interpreted Formations and Members inside Brussels Formation.

Ann. 5. Central extent map of the Brussels Formation, with indication of grain-size class. Note that per observation location, here only the coarsest observed grain-size class is shown. The grain-size class is the most important proxy for the new Members.

Ann. 6. Central extent map of the Brussels Formation, with indication of observation points of sedimentary facies Bf (including decalcified occurrences). Facies Bf is an important proxy for the Machelen Member.