Geological setting of gravel occurrences on the Belgian part of the North Sea

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INTRODUCTION

According to D'Olier (1981), the Flandrian sea-level rise caused a transgression over an initial surface topography whereby the present sandbank positions and shapes reflect ancient transitory islands, coalesced beaches, confluent channel bars and changing coastline positions. It is known that in this region of the North Sea, most of the underlying Palaeogene units consist of clayey sediments, alternated with only a few sandy layers (for a synthesis see Le Bot et al., 2003). On top of these are, apart from scour hollow infillings with Pleistocene sediments, the sandbanks, which consist of Holocene sediments. A thin gravel lag veneer would form the lower part of the Holocene sediments followed by a sandy succession. Kirby and Oele (1975) found out that in the nearby Sandettié–Fairy Bank area, there is a well-developed graded succession from flint and shell gravel at the base up to shelly quartz sands. This succession indicates a decrease in energy conditions at the bed during the period of deposition and a subsequent slow regional rise in sea-level. Most probably the succession is a drape over an originally irregular seabed. This is clear in Figure 1 that the thickness of the Holocene clearly follows the present sandbank topography and reveals the initial lows and highs. Moreover, the Holocene thickness is less than 2.5m in the swales between the sandbanks, indicating possible source areas where gravel can be found (Figure 1).

Interestingly, the Top Tertiary erosion surfaces show clearly identifiable scarp that traverses the region of the Hinder Banks from east to west (Figure 1). This Offshore Scarp is easily recognized in the present-day bathymetry. From south to north, it induces a depth decrease of 2 to 3m.

The distribution of gravel occurrences on the Belgian part of the North Sea is generally poorly known. The map of Veenstra (1964) did show higher gravel amounts near the southern parts of the Westhinder and Oosthinder, based on 50 Van Veen samples in the region of the Hinder Banks (Figure 2).

As already described in the past (Veenstra, 1964; Veenstra, 1969 and Tytgat, 1989), the main gravel types in the Southern Bight of the North Sea consist of flint or silex, limestone, sandstone quartz, quartzite and some igneous rocks. Considerable variation in pebble lithology is seen within this region, but flint is the dominant component (Cameron et al., 1987). Most of the gravel originates from reworking by the marine transgression of deposits resting on the early Holocene land surface. These may have included fluvial-terrace deposits (D’Olier, 1975) or beach gravels formed from material of fluvial origin (Veenstra, 1971). Some of the flint pebbles show percussion marks on their surfaces, indicating beach processes, according to the early views of Veenstra (1969). A re-analysis of four samples taken by Veenstra (1969) in the Noordhinder region reveals that flint and to a lesser extent quartzite occurs more as large fragments (>8mm), whilst quartz occurs more as small fragments (1 – 4 mm). Limestone is most abundant in the grain size range between 16 and 2 mm; sandstone and igneous fragments are equally distributed over the grain size range. When averaging the four samples, 31% of the gravel is flint, 27% is limestone, 18% is quartz, 10% is sandstone, 9% are igneous rocks, 4.7% is quartzite and only 0.3% is chalk.
Most probably the large amount of flint pebbles finds its origin in the Cretaceous deposits outcropping near the mouth of the Thames whereas the more weathered light-coloured pebbles, with a nucleus, frequently occur in the Diestian formation and at the base of the Palaeogene (Tytgat, 1989). The sandstone pebbles are well rounded mostly and are either similar to those of the Diestian Formation or similar to those of the Mont-Pansisel Formation (Tytgat, 1989). The smaller, well-rounded, quartz grains probably have a Rhine/Meuse/Scheldt and Thames origin. The igneous rocks might be brought in by the Rhine or Meuse and might be originally from the volcanic Eiffel area.
Most of the gravel, present in the swales between the sandbanks, belongs to the Kreftenhaye Formation, part of it might belong also to the older Urk and Sterksel Formations. The Kreftenhaye Formation has a general onland thickness of 10 to 25m and the general lithology consists of medium to very coarse sand and medium to very coarse gravel (Busschers et al., 2005). The dominance of coarse-grained sands, high concentrations of gravel, numerous internal scour surfaces, small-scale fining upward sequences and a clear lag deposit at the base of the unit, point towards deposition in a fluvial channel system (Busschers et al., 2005). Moreover, the upper part of the Kreftenhaye Formation consists of a sheet of gravelly sand capped by a bed of strongly consolidated sandy clay. Morphologically, the top of the Kreftenhaye Formation can be described as buried fluvial terraces of the Rhine (Makaske et al., 2005). The geochronology of the Kreftenhaye Formation is however still poorly understood (Törmqvist et al., 2000), primarily due to the lack of organic matter suitable for dating. To the north, thin layers of volcanic tuff occur in the sand, being deposited from late Weichselian volcanoes active in the Eifel area (Balson et al., 1991).
Fig. 3: Re-analysis of the gravel composition of four samples, taken in the Noordhinder region, based on Veenstra (1969).
<table>
<thead>
<tr>
<th>Formation Name</th>
<th>Onland thickness</th>
<th>General lithology</th>
<th>Genesis</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kreftenhaye</strong>&lt;br&gt;UK: Eem/Brown Bank&lt;br&gt;B: ?</td>
<td>10-25m</td>
<td>-Medium to coarse sand&lt;br&gt;-Medium to coarse gravel</td>
<td>-The bottom part is deposited by a braided ice marginal river flowing to the west containing fresh water and melt water of the ice cap. &lt;br&gt;-The middle part consists partly of meandering Rhine deposits of the Eemian and partly of fluviolacustrine infill of the glacial IJssel Daal basin during the Late Saalian and Eemian. &lt;br&gt;-The upper part consists partly of material transported by the Rhine, partly of fluvial reworked marine sediments of the Eem Formation and partly by meandering rivers.</td>
<td>Late Saalian to Early Holocene</td>
</tr>
<tr>
<td><strong>Urk</strong>&lt;br&gt;UK: Egmond Ground and upper part of Yarmouth Roads&lt;br&gt;B: ?</td>
<td>20-40m</td>
<td>-Medium fine to very coarse sand&lt;br&gt;-Fine to very coarse gravel</td>
<td>- Fluvial Rhine deposits, downstream also freshwater deposits.</td>
<td>Late Cromerian to Middle Saalian</td>
</tr>
<tr>
<td><strong>Sterksel</strong>&lt;br&gt;UK: Yarmouth Roads&lt;br&gt;B: Lommel and Bocholt Sands, Winterslag Sands and Zutendaal Gravels</td>
<td>15m</td>
<td>-Medium coarse to very coarse sand&lt;br&gt;-Gravel&lt;br&gt;-Clay layers</td>
<td>- The coarse sand and gravel are fluvial channel deposits of the Rhine and Meuse. &lt;br&gt;- The strongly layered clays are rest channel deposits in abandoned meander turns and/or bank deposits</td>
<td>Latest part Early Pleistocene and Middle Pleistocene</td>
</tr>
</tbody>
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**Fig. 4:** Late Quaternary chronostratigraphy for Northwest Europe (after Zagwijn, 1975, 1992) and lithostratigraphic units in the study area (after Doppert *et al.*, 1975). EW = Early Weichselian, MW = Middle Weichselian, LW = Late Weichselian, EP = Early Pleniglacial, MP = Middle Pleniglacial, LP = Late Pleniglacial (table after Törnqvist *et al.*, 2000).
Fig. 5: Northwest European climate conditions and global sea level during the Late Saalian and Weichselian periods. Chrono-stratigraphical framework for northwestern Europe after Zagwijn (1974), Vandenberghe (1985) and De Mulder et al. (2003). Marine isotope record after Bassinot et al. (1994). Sea-level record derived from North Atlantic and Equatorial Pacific benthic oxygen-isotope data (Waelbroeck et al., 2002). Error envelopes in all records were taken from the original sources. The chrono-stratigraphical position of the sedimentary units and unconformities in the study area are shown on the right. Although this figure suggests that deposition was essentially continuous, the exact time duration of the depositional units (as proportion of total covered time), especially for the older units, remains unknown with current dating accuracies (Figure from Busschers et al., 2005).

HISTORY

Geological characteristics of marine gravel deposits

Most modern shelf systems have an initial lithofacies, which is a coarse, discontinuous lag, which may occur as a ridged sheet (Swift et al., 1991). The leading edge of this sheet lies at the foot of the shoreline, and it forms the debris of the erosional retreat process (Swift et al., 1972). Quaternary low stands rejuvenated rivers as they crossed the exposed shelf, and in many cases, the low stand shelf valleys contain gravel. The retreating shoreline has breached these gravelly valley fills and has redistributed them as a marine basal transgressive gravel (Belderson and Stride, 1966; Figueiredo et al., 1981). Where they occur, such gravels typically form in thin, discontinuous, shore-parallel bands, marking successive phases of shoreline retreat. The gravel is overlain by several meters of sand. The sand is discontinuous and in areas of strong storm or tidal currents may be lacking altogether, so that the gravel is exposed at the seafloor. The basal gravel here continues to be reworked by shelf currents (Swift et al., 1991).

Fluvial deposits, associated with relative sea-level fall (80-40ka), can constitute a considerable part of preserved strata (‘falling-stage systems tract’). Interglacial transgressive and highstand systems tract tend to have a relatively low preservation potential (Törnqvist et al., 2000). The
coarse deposits transported and deposited during the cold stages have a better preservation potential than the finer interglacial deposits.

**Geological history of the Ice Ages in the Southern North Sea**

The Quaternary history of the Rhine-Meuse system in the Netherlands is complex, because advancing Pleistocene ice sheets and the periglacial processes at their neighbouring areas strongly modified the geomorphology, and, hence, fluvial drainage directions (Törnqvist et al., 2000). Prior to the Elsterian glaciation, the Rhine and Meuse Rivers drained to the northwest and extended their courses onto the continental shelf of the North Sea during relative sea-level lowstands. During the Elsterian glaciation, the area overridden by the ice was subjected to total landscape remodelling, with old river courses destroyed or buried (Gibbard, 1988). An entirely new landscape was formed beneath the ice by glacial and glaciofluvial erosion and deposition; the sculpturing of deep glacial valleys was to have a striking palaeogeographic impact after the ice retreat. At the ice margin, major river valleys were dammed all across the region. The Thames and its tributaries were diverted southwards, the Elbe was dammed and the North German Rivers were deflected westwards. However, the most striking feature was the development of a massive ice-dammed lake in the southern North Sea, into which the Thames, Rhine, Meuse, Scheldt and possibly the Ems all discharged. Overspill of this lake almost certainly initiated the Dover Straits and greatly enlarged the Channel River system (Gibbard, 1988). This is confirmed by the deep scars, which have been found on the Channel seabed. Remnants of this lake are the lacustrine deposits found north of our study area (Figure 5).

Throughout the cold stages of the Pleistocene, the rivers overwhelmingly deposited gravels and sands derived either from periglacial weathering or glacial sources (Gibbard, 1988; reconstructions from Figure 6 to 8: [http://www-opg.geog.cam.ac.uk/research/nweurorivers/](http://www-opg.geog.cam.ac.uk/research/nweurorivers/)). The result is that valley systems contain vast thickness of cold-climate sediments deposited by rivers that flowed in a braided or wandering, often multi-channelled form. These sediment accumulations are generally separated by periods of non-deposition or incision outside subsiding areas. Throughout this cold stage and the following alternation of cold and warm stages and enhanced by isostatic movements there have been several incisions of rivers in older deposits creating river terraces. These have been recorded in the Thames region (Bridgland, 2000), in the Rhine area (Boenigk and Frechen, 2006) and in the Meuse area. These river terraces consist mostly of gravel deposits.

Glacio-eustatically and isostatically controlled sea level changes are characteristic of the Pleistocene. In Northwest Europe low sea levels during the cold periods caused great expansion of the drainage system onto the surrounding continental shelves. For much of the Lower and Middle Pleistocene, the southern North Sea was occupied by the huge delta complex of the North German rivers, the Rhine, Thames, Meuse and Scheldt (Gibbard, 1988). The ice sheet during the Saalian, covering the northern part of the Netherlands forced the Rhine–Meuse system to follow a route farther south, roughly similar to the present course of these rivers. However, during the latest Saalian, the Eemian and Early Weichselian, the Rhine followed a more northerly route through the country due to the creation of glacially eroded depressions. The present course was reoccupied from the Middle Weichselian onwards. It is important to note that the Meuse always approximately followed its present course since the Saalian. Pleistocene Rhine and Meuse sediments deposited after the peak of the Saalian glaciation belong to the Kreftenhaye Formation. The smaller Scheldt river and some other small rivers flowed northward until they were blocked by the cuesta of the Boomshe Clay which was only broken through in the late Weichselian, causing these rivers to flow westwards into the Ostend Valley. This Valley is described by Liu (1992) and is especially outspoken in the area close to the coast. The Scheldt river most probably did not bring in a lot of gravel material as it was a smaller river and no river terraces have been formed.
The interglacial following the Saalian is the Eemian. The deposits of this formation have not been completely eroded on the Belgian part of the North Sea. They formed a more or less continuous layer of sandy deposits. These deposits have been preserved in the area north of the Offshore Scarp and form the basal layer of the parts of the Hinder Banks north of this scarp. This means that the initial stages of the northern parts of the Hinder Banks have been formed in the Eemian, and were then partly eroded during the following Weichselian period. The ice sheet during the Weichselian however did not extend as far south as during previous ice ages, which might explain why not all Eemian deposits in the study area have been eroded. During the following Holocene sea-level rise, the present morphology of sandbank systems has been finalised.
During the late Saalian glacialiation, the Fennoscandian ice sheet covered the northern part of the Netherlands. In front of the ice mass, an ice marginal system developed that transported coarse-
grained sand and gravel (Busschers et al., 2005). Transport of the coarse grained material most probably occurred during peak discharge related to spring release of glacial melt water and snow melt.

The gravel in the study area is partly glacial material, partly fluvial material. The Rhine and Meuse did not enter this area of the southern North Sea before the Saalian when the Rhine was diverted south by ice that reached the central Netherlands. Large blocks could be transported by river ice in winter periods and is then carried downstream in spring during the melting season. Spring is the period when these rivers do most of their work because of melting snow and ice. The rivers Rhine, Meuse, Scheldt and several rivers from Britain too entered the Southern Bight of the North Sea during the Saalian and Weichselian and these rivers were carrying gravel derived from land areas. They were also fed by melt water from glaciers. The largest blocks are either of Elsterian age, brought in by ice fragments transported in the proglacial lake or either from Saalian age when large ice flows brought in large blocks transported by the Thames or Rhine.

The Offshore Scarp is probably a remnant of the bedrock slope between river terraces. Both levels (above and below the scarp) are essentially fluvial landforms, altered by shallow marine action and with former surfaces some 4-8 m above the platforms now, whereby all the terrace-building-materials, except the coarsest material, are washed away by later wave action (pers. comm. K. Cohen). The area is probably the SE side of a wide valley of a joining Rhine-Meuse and Thames system. Ancient river courses seldom have paired-terraces. It is far more common for them to have remnants preserved only on one side of the valley. This results from multiple periods of incision that causes the river to off-step in a particular direction. This is also found in the Thames (Bridgland, 2000) and Rhine areas (Boenigk and Frechen, 2006). The Dover Strait itself probably has a funnelling effect, and this could preserve ancient river terraces, especially those from Saalian and Early Weichselian glacial stages, because in the last glacial, the trunk channel (Rhine, Meuse and Thames) probably carried less water (no Scandinavian melt water) than in the periods before.

As the melt water flow had to be towards the south, the flint is not brought in from the Dover Strait. The flint in the gravel can be derived from Britain or from Belgian rivers all of which drain chalk bedrock areas (e.g. almost all of the streams from East Anglia transport flint as their main pebble-forming lithology). There was no fluvial flow towards the north in the study area once the Straits were breached, except presumably tidal flow at marine highstands, although recycling of gravel probably repeatedly occurred during sea-level rise or fall events.
Fig. 9: A. Idealized transverse section through the Lower Thames terraces (Bridgland; 2000). B. Idealized sketch of the terrace staircase in the Middle Rhine area, including Tertiary terraces and gravel beds, the Lower Pleistocene terraces (LPT), the Upper Terraces (UT1-4), the Middle Terraces (UMT-LMT2) and the Lower Terraces (Older LT and Younger LT) (Boenigk and Frechen, 2006).
Fig. 10: Distribution of Quaternary channel deposits, reflecting the input of river sediments, forming the Kreftenheye Formation, brought in by the Thames, Rhine, Meuse and Scheldt. Base map of Balson et al. (1991) added with the new information on the Belgian part of the North Sea.
Fig. 11: Cartoon of the presumed geological evolution of gravel deposits during the middle and late Quaternary.
LITERATURE CITED


VAN LANCKER ET AL., this report.


