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The role of a proto-Schelde River in the genesis of the southwestern Netherlands, inferred from the Quaternary successions and fossils in Moriaanshoofd Borehole (Zeeland, the Netherlands)

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† To our regret Dr David Mayhew passed away 3 October 2012. We would like to attribute this paper to the memory of this great scientist and colleague.

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Abstract

We investigated the Quaternary lithological succession and faunas in a borehole near Moriaanshoofd (Province of Zeeland, SW Netherlands), in order to improve our understanding of the depositional context of classical Gelasian mammal faunas from the region. The fossils mostly derive from the base of a fossil-rich interval between 31 m and 36.5 m below the surface, that was initially interpreted as a Middle or Late Pleistocene interglacial marine unit, but turned out to be a Late Quaternary fluvial unit with large amounts of reworked fossils and sediments. Eocene mollusc taxa pinpoint Flanders (Belgium) as the source region for this river. Within the base of this paleo-Schelde River fossil material of various stratigraphic provenance became incorporated.

Keywords: Pleistocene, Eocene, stratigraphy, reworking, Schelde, mammals, molluscs

Introduction

While studying stratigraphic successions in a borehole near the Schelphoek (Fig. 1; Slupik et al., 2007), uncertainties remained about the intervals overlying the Early Quaternary (Gelasian) Maassluis Formation. Deposits directly overlying the Maassluis Formation were previously tentatively assigned to the Eem Formation which is of the Eemian age (MIS 5e) (Slupik et al., 2007) with an assumption that these deposits could also originate from some periods within the Middle Pleistocene. Also the provenance of the mammal faunas from the adjacent Oosterschelde estuary (De Vos et al., 1995, 1998; Mayhew et al., 2008; Reumer et al., 1998, 2005) remains uncertain. Since 1955, once a year a fishing-vessel expedition is organised with the aim to search for fossils at the bottom of two 40-45 m deep tidal channels in the Oosterschelde estuary (see for detailed information in Reumer et al., 1998, 2005). The fossils are dredged by mean of fishing-nets. Through the decennia of collecting activities, a large amount (hundreds of fossils) of mostly Early Pleistocene vertebrate fauna has been assembled and the composition of the fauna is thought to be well known. But the fossils are not available for direct observation in the sedimentary record, they are found *ex situ*, at a depth of 40-45 m below the water surface. Therefore their geological position within the

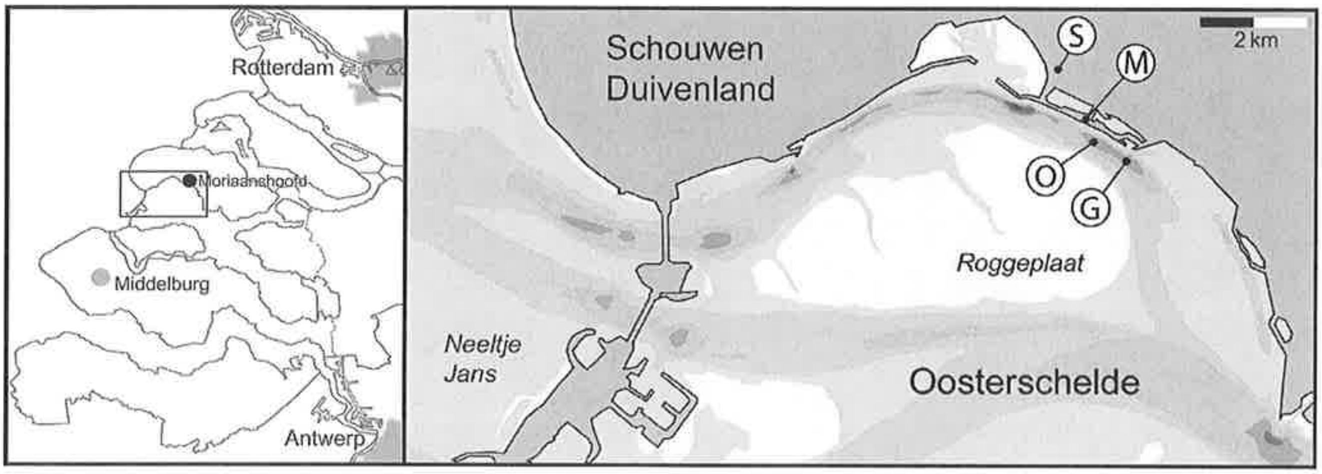

Fig. 1. Location of the borehole (with detailed map). Dredging localities: O – Olifantenputje; G – Gastenputje; S – Schelphoek borehole; M – Moriaanshoofd borehole (this paper) (coordinates: 3°50'09" E, 51°40'50" N; RDX = 047.740; RDY = 411.380).

succession remains unknown. It is not clear from which stratigraphic unit the Oosterschelde vertebrate fauna derives. The stratigraphic provenance of the fauna still has to be clarified.

In order to improve our understanding of the Quaternary successions in general and the depositional context of the mammal faunas of Gelasian age in particular we drilled a second borehole closer to the present-day tidal channels of the dredged fauna (De Vos et al., 1995, 1998; Mayhew et al., 2008; Reumer et al., 1998, 2005) (Fig. 1).

Materials and methods

The borehole is located south of Moriaanshoofd on the island of Schouwen-Duiveland (province of Zeeland; southwest Netherlands). A suction core was performed by the Van Elburg Drilling Company, between 25 and 28 august 2008 (Fig. 1). The borehole was located adjacent to the Oosterschelde dike south of Moriaanshoofd and reached an end depth of 62 m (TNO – Geological Survey of the Netherlands borehole number B42G0769). The surface elevation at the borehole location was 4.19 m +N.A.P. (Dutch Ordnance Level, ~ mean sea level).

Coring was performed in half-metre intervals. From each interval about half a kilogram of raw sediment was taken for lithological description and analyses. Additionally, larger samples of approximately 2-3 kg of sediment were taken at one-metre intervals and washed and sieved (sieve mesh 1 mm) and analysed for fossil content (see procedures in Slupik et al., 2007). Fossils were picked from wash residues and identified. Molluscs were counted. All sediment samples were visually and microscopically examined. Lithological descriptions follow procedures outlined in Bosch (1999). Grain size was partly determined by visual sample description (using microscope Wild M5A equipped with ocular micro-scale measure bar) and partly performed on a laser particle sizer Malvern Instruments Ltd, UK at the Department of Earth Sciences, University of Utrecht.

The sediment samples and mammal remains of the Moriaanshoofd borehole are archived at the Natuurhistorisch Museum Rotterdam (NMR) and the molluscs are archived at the Naturalis Biodiversity Center in Leiden. Comparison of the colour of the sediments between the two boreholes proved difficult, as the analysis of the Moriaanshoofd samples took place within a year after drilling, whereas the Schelphoek samples were analysed after several decades, so that oxidation had affected the colour significantly.

Six radiocarbon datings on peat and wood fragments were performed by the laboratory of the 'Koninklijk Instituut voor het Kunstpatrimonium' (the Royal Institute for Cultural Heritage) in Brussels, Belgium, following procedures outlined in Van Strydonck and Van der Borg (1990-1991), and reported following Stuiver and Pollach (1977). All accelerator mass spectrometry (AMS) measurements follow Nadeau et al. (1998).

The lithostratigraphic terminology follows Weerts et al. (2000), Westerhoff et al. (2003) and TNO (2013) and the chronostratigraphy is according to the ICN/IUGS (2009) definitions. All depths are given below the ground surface (4.19 m +N.A.P.).

Results

The lithology, stratigraphy, grain size, facies (units), shell frequency and age estimates are summarised in Fig. 2. Analytical results are given in Tables 1-4 and Appendix 1. In the borehole five lithological units were recognised (A-E). The units were assigned to the Maassluis Formation, Koewacht Formation, Kreftenheye Formation, Boxtel Formation and Naaldwijk/Nieuwkoop Formations (Fig. 2).

Unit A (36.5-62 m; Maassluis Formation)

The unit consists of fine to middle-grained grey sands with silt in some intervals (Table 1). Light brown and brown-grey clay

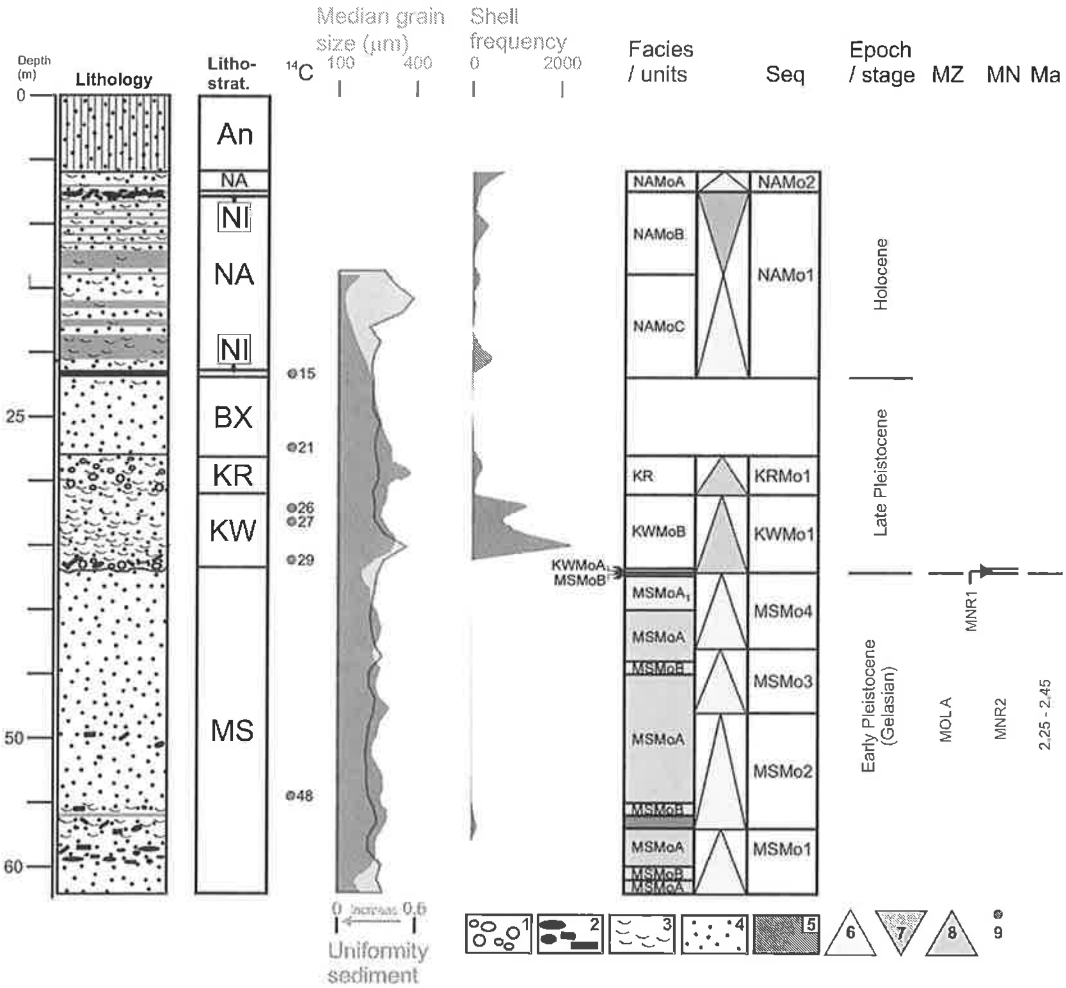

Figure 2 Lithostratigraphic framework of the Moriaanshoofd borehole. 1 – Gravel/pebbles; 2 – Peat and wood pieces; 3 – Shells and shell fragments; 4 – Sand; 5 – Clay; 6 – Deepening trend / transgression; 7 – Shallowing trend / regression / progradation; 8 – Fluvial sequences; 9 – Samples ^{14}C-dated; Uniformity sediment – coefficient judging sorting; Seq – Sequence; Depth (m) – Metres below surface; Lithostrat. – Lithostratigraphy; ^{14}C – Radiocarbon dating, numbers correspond to sample numbers in Table 2; Seq – Depositional sequences; MZ – Mollusc zone cf. Spaink (1975); MN – Mammal zone cf. Tesakov (2004); Ma – Age (million years) as indicated by mammal assemblages; An – Anthropogenic; NA – Naaldwijk Formation; NAMoA, NAMoB, NAMoC – Facies in the Naaldwijk Formation; ; NAMo1, NAMo2 – Sequences in the Naaldwijk Formation; NI – Nieuwkoop Formation; BX – Boxtel Formation; KR – Kreftenheye Formation; KW – Koewacht Formation; KWMoA, KWMoB – Facies in the Koewacht Formation; KWMo1 – Sequence in the Koewacht Formation; MS – Maassluis Formation; MSMoA, MSMoA$_1$, MSMoB, MSMoC – Facies in the Maassluis Formation; MSMo1, MSMo2, MSMo3, MSMo4 – Sequences in the Maassluis Formation

fragments and clay pebbles, some of which indurated, and lithic fragments (sandstone, lydite-like) occur in variable amounts. In a small part of the samples shells and shell fragments, often strongly worn, are very common, while most samples are barren (Table 3). Some microvertebrates remains were found (Table 4). Most of the sediment of the unit is free of carbonate. The lower boundary of Unit A was not reached in the borehole.

Several sub-units are recognised, each with distinct features. Each of these sub-units represents a specific depositional environment and is therefore referred to as a facies unit. The sub-units are closely related in terms of sediment properties and textural features, suggesting that they also are closely related in terms of depositional setting.

Interpretation

The facies properties (Table 1) and their succession are consistent with a shallow marine, tidal-influenced depositional environment (as characterised by Dalrymple, 1994; Reading & Collinson, 1996 and Van den Berg et al., 2007). Unit A is assigned to the Maassluis Formation of De Mulder et al. (2003).

Facies MSMoA

The facies consists of rather poorly sorted sand with small amounts of silt. In two intervals the facies is four and three metres thick and in one interval it is ten metres thick (Table 1 and Appendix 1). In interval 48-53 m, some shell fragments,

Table 1. Facies classification in the record. MSMoA, MSMoA$_1$, MSMoB, MSMoC – facies in the Maassluis Formation; KWMoA, KWMoB – facies in the Koewacht Formation; NAMoA, NAMoB, NAMoC – facies in the Naaldwijk Formation.

Facies/ units	Depth (m b.s.)	Lithology	Median grain size (µm)	Interpreted environment
NAMoA	6-8	Sand, grey, numerous thin clay layers in the upper part; clay, grey with laminated sandy partings in the lower part; some shells		Supratidal
NI	7.75-8	Peat, black, with wood remains		Peat swamp
NAMoB	8-14	Clay, grey, in some parts laminated (intercalated) with sand, slightly silty; shell fragments		High intertidal to supratidal mud flat (or possibly salt marsh)
NAMoC	14-22	Sand, grey, medium fine- to medium coarse-grained that grades into partially laminated sandy clays; some shell fragments and shell debris	125-214	Subtidal to intertidal sand flat
NI	21.7-22	Peat; dark brown		Peat swamp
KWMoB	31-36.5	Sand, grey, medium coarse to coarse-grained; some clay clasts; very abundant shells; some peat fragments and wood pieces	288-321	Fluvial deposition
KWMoA	36.5	Layer of sand, light grey-beige, fine to medium coarse-grained, poorly sorted, strongly silty; rounded, brown claystone clasts with a diameter of up to few centimetres and some very fine gravel consisting of black, lithic fragments; some teeth of small vertebrates	220	Fluvial deposition
MSMoA	40-44 45-55 57-60 61-62	Sand, grey to dark grey, fine to medium coarse, grains subangular to rounded, rather poorly sorted to well sorted in some parts, silty; clay clasts mainly irregular in shape in various amounts; some glauconite; some black lithic clasts in some parts; non calcareous; may contain some: shell fragments, (worn) foraminifers, peat fragments, wood pieces, some scarce remains of sea-urchins and fishes	189-299	Tidal channel fill
MSMoA$_1$	37-40	Sand, rather dark grey, rather fine to medium coarse, poorly sorted to rather well sorted, large amounts of fine mica flakes; some fine sandy clay laminae, some light grey consolidated clay clasts; some peat fragments, some foraminifers and few bone fragments	191-228	Tidal channel fill
MSMoB	36.5-37 44-45 55-56 60-61	Sand, light grey with brownish beige shade, medium fine- to medium coarse-grained, rather poorly sorted, strongly silty; may contain some small shell fragments and some land derived plant material as peat fragments and wood pieces	169-293	Tidal deposits; possibly tidal channel upper flanks (edges) – setting outside tidal channel bedding
MSMoC	56-57	Sand, light beige-grey, medium coarse-grained, grains rounded to subangular, rather poorly sorted, slightly silty; some very fine quartz gravel, some glauconite, some clay clasts; large amounts of shell fragments angular in shape	279	Lag of tidal gully (main tidal channel within the tidal flat channels network)

foraminifers and echinoderm spines occur. Interval 40-44 m contains some bone fragments and small amounts of shell fragments.

Interpretation

This facies is interpreted as tidal channel fills. The lowermost interval of this facies is 61 to 62 m, at the base of the borehole so that the complete thickness of that interval is uncertain. The poorly sorted sand with some silt could reflect deposition on a sand flat or outer parts of a mixed flat (cf. Fig. 12, p. 201 in Dalrymple, 1994; Reading & Collinson, 2006; Van den Berg et al., 2007).

Facies MSMoA$_1$

The facies occurs in the upper part of the Maassluis succession (37-40 m). The facies is similar to facies MSMoA in terms of composition and origin (Table 1). An important difference is that facies MSMoA$_1$ consists of generally finer grained (Table 1) poorly to rather well sorted sand, and contains large amounts of very fine mica grains.

Interpretation

The facies is interpreted as a tidal channel fill.

Facies MSMoB

The facies is up to one metre thick and consists of poorly sorted silty sand containing clay clasts angular in shape with sharp edges and also rounded clay clasts. Clay clasts have similar dimensions and are mostly coated by sand grains.

Interpretation

The grain-size composition and the occurrence at the top of the presumed channel fills are consistent with a derivation from laminated tidal sediments or flaser bedding (or tidal-fluvial zone as defined in Van den Berg et al., 2007). Medium coarse to coarse sands in the interval 55-56 m could point to tidal channel deposition. Sedimentary structures are not seen in the samples so that more detailed interpretations of the depositional setting are not possible.

Some of the clayey clasts may represent reactivated mud drapes but possibly much of the mud had been transported in the form of faecal pellets. The irregular, sharp edged clasts are presumed to result of fragmentation of thin mud layers during the drilling process.

Facies MSMoC

This facies occurs only at 56-57 m depth and consists of a shell bed. The sediment consists of coarse particles, clay clasts and numerous fragments of shells (angular in shape). The shell fragments are strongly abraded and represent a low-diversity suite of coastal species (such as *Littorina saxatilis, Nucella lapillus, Mytilus trossulus*) (Table 3).

Interpretation

The facies is interpreted as a basal scour lag of a tidal channel.

Depositional sequences

The Maassluis Formation interval in Moriaanshoofd Borehole is composed of four depositional sequences (MSMo1-MSMo4, Fig. 2) made up of facies successions/associations that represent lateral migration of depositional tidal systems. Lateral migration of tidal channels leads to the formation of fining-upward sequences (see in Dalrymple, 1994; Reading & Collinson, 1996 and Johnson & Baldwin, 1996).

Sequence MSMo1 (62-57 m) covers deposits of tidal channel fill / tidal flat. Interval 57-56 m is a lag deposit and therefore, per definition, a major boundary or unconformity. This interval is interpreted to form a basis of a sequence MSMo2 wherein the lag deposit is overlain by the deposits of tidal channel upper part.

Sequence MSMo3 (43-49 m) covers tidal channel basal part to tidal channel fill deposits. Sequence MSMo4 (36.5-43 m) comprises deposits of tidal channel fill to tidal flat. The four sequences reflect transgressive trends within the depositional setting.

Age

The mollusc fauna in the interval 55-62 m (Table 3) is consistent with Mol A (*Hydrobia ulvae-Mya arenaria*) zone of Spaink (1975) indicative of a Gelasian age (Fig. 2).

Arvicolid remains with several *Mimomys* species from the Maassluis Formation (Table 4) represent a Gelasian assemblage. Notably *Mimomys praepliocaenicus* and *M. tigliensis* indicate a Gelasian age (see also discussion) and allow the assemblage to be placed in the biozone MNR2 of the system of Tesakov (2004), indicating an age of ca 2.25-2.45 Ma (Fig. 2, see discussion below). We consider the ^{14}C age of >47,200 BP recorded at 54-55 m to be at or below the detection limit of radiocarbon dating.

Unit B (31-36.5 m; Koewacht Formation)

The deposits in the interval are composed of light grey, coarse-grained sands containing some gravel and abundant indurated clay pebbles in its basal part. Shells, mostly well-preserved, are common to very abundant. The deposits abruptly overlay the finer-grained sands of Unit A that lacks shells in its upper parts. Two lithological units are recognised (Table 1) forming one depositional sequence (KWMo1) (Fig. 2).

At the base, at 36.5-36 m a silty sand layer occurs containing rounded, brown claystone clasts with a diameter of up to few centimetres and some very fine gravel consisting of black, lithic fragments. The sand is fine to medium coarse-grained and poorly sorted (unit KWMoA). The basal interval contains an assemblage of only rooted arvicolids, including *Mimomys tigliensis* and *M. reidi* (biozone MNR1 of Tesakov, 2004: ca 2.1-2.25 Ma). The basal lag is overlain by a very shell-rich interval (31-36.5 m) (unit KWMoB). Shallow marine molluscs, especially shells of *Macoma balthica*, are abundant and mostly well-preserved. However, differential preservation, and taxa with incompatible ecological (Table 3) as well as stratigraphic signatures occur. A small fraction of the shell fauna consists of Middle Pleistocene, Gelasian, Pliocene and Eocene taxa. The latter includes *Homalaxis* cf. *serratus, Haustator solanderi, Limopsis granulata, Claibornicardia aalterensis* and *Arcturellina* sp.

Interpretation

Unit B is assigned to the Koewacht Formation of Kiden (2010). The rounded nature of the claystones and the occurrence of ecologically and stratigraphically incompatible taxa combined with the very well-rounded sand grains that are incorporated from earlier reworked and sorted sediments, all point to reworking and deposition by currents. The Eocene taxa, more abundant than the Pliocene taxa, indicate a fluvial (proto-Schelde) provenance from the Ghent region (Belgium) where Eocene taxa are found at and near the surface (see discussion). The predominance of well-preserved coastal marine mollusc taxa is attributed to reworking in proximal setting of probably Eemian (MIS 5e) marine deposits.

Age

The ^{14}C ages (33,220-49,820 BP) (Table 2) of the Koewacht Formation show no straightforward age-depth relationship and one sample is very close to the lower limit of the ^{14}C dating range (Briant et al., 2005). The formation must postdate the youngest ^{14}C age found, viz. 33 ka (see discussion below).

Between 33-35 m two teeth of the genus *Microtus* were found (Table 4). Their morphology indicates a Late Pleistocene or Holocene age. In the interval from 35 to 36.5 m an assemblage of only rooted arvicolids occurs, including *Mimomys tigliensis* and *M. reidi*. It differs from the underlying Maassluis Formation Gelasian assemblage by the presence of teeth definitely attributable to *M. pliocaenicus* and the absence of teeth definitely attributable to *M. praepliocaenicus*. This basal lag assemblage is referred to biozone MNR1 of Tesakov (2004: ca 2.1-2.25 Ma) (Fig. 2). Some arvicolid specimens have a relatively fresh unrolled (i.e. not-damaged) and little mineralised appearance with preservation of fine surface details. This suggests an origin from Early Pleistocene freshwater sediments, indicating reworking and redeposition. No characteristic Middle or Late Pleistocene vole species were recorded in the basal part of the interval. The vast majority of the mollusc fauna indicates a Late Pleistocene age. Strongly abraded Early-Middle Pleistocene taxa, such as *Corbicula*, also occur.

The Middle and Late Pleistocene fluvial sediments in the southwest Netherlands that are deposited by the Schelde River system are assigned to the Koewacht Formation (Kiden, 2010) (see further in discussion).

In works predating Kiden (2010) deposits of the Schelde River have been assigned to a variety of lithostratigraphic units and ages. The Koewacht Formation partly replaces the following lithostratigraphic units (in parentheses literature references in which previously defined units were referred to): Vlissingen deposits (Van Voorthuysen, 1957), Schouwen Formation (Van Rummelen, 1965), Schouwen deposits within Eem Formation and Eem Formation (Van Rummelen, 1970, 1978), Twente Formation and Kreftenheye Formation (Doppert et al., 1975) and Boxtel Formation (Schokker, 2003).

The Koewacht Formation, as defined by Kiden (2010), was deposited from Saalian (Middle Pleistocene) to Weichselian (Late Pleistocene) times.

Table 2. Radiocarbon ^{14}C ages.

Sample number in the borehole	Depth (m below surface)	^{14}C age (BP)	Calibrated age (BP) (95%)	Sample number at the laboratory
15	21-22	7680±40	8550-8400	KIA-40438
21	27-28	37,950+970-870		KIA-40439
26	32-33	33,220+540-510		KIA-40440
27	33-34	49,820+5390-3200		KIA-40441
29	35-36	35,240+690-640		KIA-40443
48	54-55	>47,200		KIA-40445

Unit C (28-31 m; Kreftenheye Formation)

The deposits in this unit consist of grey sands. In the lower part sand is coarse-grained and contains common shells. At the bottom some fine gravel and clay clasts occur. In the upper part sand is medium to coarse-grained. Few fine shell fragments occur. Grains of pink quartz within the deposits are very common and the sand grains as well as the claystones are well-rounded.

Interpretation

The features of sediments point to the Kreftenheye Formation (Busschers & Weerts, 2003; Busschers et al., 2007; Hijma et al., 2012). The Kreftenheye Formation as defined in Busschers and Weerts (2003) is considered to be deposited by (precursors) of the Rhine between Late Saalian and Early Holocene, but mostly during the Weichselian. Here, the deposits are assigned to one depositional sequence KRMo1 (Fig. 2).

The Unit C (Kreftenheye Formation) in the record at Moriaanshoofd overlays Unit B (Koewacht Formation) and is therefore of younger age (<33 ka).

Unit D (22-28 m; Boxtel Formation)

The Boxtel Formation in the Moriaanshoofd Borehole is composed of fine-grained to coarse-grained well-rounded sands. Shells are lacking apart from an odd fragment that probably represents contamination from overlying intervals. Fragments of wood and peat occur.

The Boxtel Formation abruptly overlies the coarser shelly sands of the Kreftenheye Formation. A fining-up trend is found in the sediments.

Interpretation

The Boxtel Formation represents local small-scale fluvial and/or fluvio-aeolian deposition in a cold climate setting (Schokker, 2003; Schokker et al., 2005, 2007).

Age of the Boxtel Formation

Sample 27-28 m b.s. yielded a ^{14}C age of 37,950 BP (Table 2). Its stratigraphic position in the borehole indicates a much younger age (see discussion).

Table 3. Mollusc occurrences.

Species / Depth (m)	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	19-20	20-21	21-22	22-23	23-24	24-25	25-26	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	37-38	46-47	55-56	56-57	57-58	58-59	59-60	60-61	61-62
Polyplacophora indet.																										1	2									
Gibbula indet.																					1	1		1	1											
Theodoxus fluviatilis														1																						
Viviparus indet.																										1										
Valvata piscinalis														1										1		1	4									
Bythina tentaculata opercula														13								1		1	9	13	48									
Bythina tentaculata														4																						
Turritella communis																					1				1											
Haustator solanderi																						1			5	1	5									
Littorina saxatilis tenebrosa	131	3												3	1																					
Littorina saxatilis/littorea													1							1	6			4	4	8	7			6	26	3				
Lacuna vincta																								9	1		11									
Peringia ulvae	5	23	61	47	222	86	18	6	2	16	4	2	86	248	4		1	1		4	28	27	2	200	81	150	300									
Ecrobia ventrosa	500	200											4	35	1							1		51	13	44	88									
Rissoa parva interrupta																								20	15	5	5									
Tornus subcarinatus																								1			3									
Homalaxis cf. *serratus*																											1									
Caecum indet.														1																						
Epitonium clathrus																					1				1		1									
Euspira hemiclausa																									1		4									
Nucella lapillus																															6					
Buccinum undatum																							1	1		1	1									
Hinia reticulatus/nitidum																								1		1	3									
Hinia pygmaea																									1		2									
Amyclina labiosa																											1									
Oenopota turricula																					1			1	1		2									
Turbonilla crenata																					1															
Turbonilla sp.1																								2		2										
Turbonilla sp.2																								1												
Retusa obtusa					2		1						3	9								1		2	1		14									
Haminoea navicula																						1														
Anisus leucostoma																											1									
Planorbis planorbis																								1												
Gyraulus crista																								1												

Table 3 continued.

Species / Depth (m)	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	19-20	20-21	21-22	22-23	23-24	24-25	25-26	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	37-38	46-47	55-56	56-57	57-58	58-59	59-60	60-61	61-62
Gyraulus acronicus																								1												
Gyraulus rossmaesleri																								1												
Galba truncatula																										2										
Stagnicola palustris sl																								1			1									
Radix peregra/ovata																								1												
Succinea cf. *schumacheri*																								4		1	8									
Succinea oblonga																						1		6												
Succinea elegans/putris																									1											
Columella columella																								2			1									
Vertigo genesii																								2												
Pupilla muscorum	2																							5	1	1	2									
Vallonia pulchella	8																							1												
Trochulus hispidus																								1			1					1				
Candidula indet.	1																																			
Helicellinae indet.	6																																			
Nucula nucleus																											1									
Nuculoma tenuis																											1									
Acila cobboldiae																										1										
Yoldia indet.																					1			1	3	3	4			1	3					
Limopsis granulata																								1												
Mytilus edulis	12	1		1	84	28	4	2	4	1	3	1	4	8	1	1	1		1		7	2	2	28	10	17	30	1								
Mytilus trossulus																														17	70	4	1	1	1	1
Ostrea edulis		1											1	2							2	1	1	11	8	11	24									
Cubitostrea indet.																									1											
Heteranomia squamula									5																											
Aequipecten opercularis								1	4	1	1																									
Mimachlamys varia																								2		2	1									
Lucinella divaricata																										1	1									
Diplodonta astartea																											1									
Hemilepton nitidum																								1												
Kurtiella bidentata	2			3	7	5		4	14	2	8		4	12	1									50	5	11	48									
Tellimya ferruginosa											2		1													1										
Arcturellina sp.																								1	2		3									
Claibornicardia aalterensis																								1	1	1	3									
Cyclocardia scalaris																								1	1	2	5									

Table 3 continued.

Species / Depth (m)	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	19-20	20-21	21-22	22-23	23-24	24-25	25-26	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	37-38	46-47	55-56	56-57	57-58	58-59	59-60	60-61	61-62
Cyclocardia chamaeformis																											1									
Goodallia triangularis																					1			2			4									
Pteromeris corbis																											1									
Astarte incerta																								1		1	3									
Astarte obliquata																											1									
Tridonta montagui																															1					
Digitaria digitaria																										1	2									
Cerastoderma edule	8	5	13	8	6	7	3	2	4	3	1	1	21	55	4					4	15	7	4	13	33	25	96									
Cerastoderma glaucum	15												1	30							6			44	2	7	10									
Serripes groenlandicus																									1		1									
Mactra stultorum																					1			1	2		1									
Spisula subtruncata							7	4	32	2	13		1	2				2		8	62	13	5	300	130	200	300									
Spisula elliptica																					3	2	1	15	49	17	59									
Solen marginatus																											1									
Phaxas pellucidus									2																											
Ensis arcuatus																											2									
Ensis minor																											1									
Ensis indet.																							1	1	1	1	1									
Angulus tenuis									2		4			1						1	1			9	1	12	36									
Angulus donacina									4											1			1													
Angulus fabula																				3	8			25	18	8	16			1						
Angulus pygmaea									1																											
Macoma balthica	5		14	14	11	12	1	8	70	5	36		21	22					1	5	19	6	11	90	105	200	300			1						
Macoma praetenuis																					2			4	10	5	7									
Macoma obliqua																								2	1	6	4			1						
Gastrana fragilis																										1	2									
Donax vittatus											1										4	1	2	45	30	64	117									
Abra alba									16		3		1							6	22	3	3	148	79	90	200									
Abra prismatica																								2	3	6										
Scrobicularia plana	1	3	6	4	11	1							6	10		1	1			3	15	2	4	22	24	21	41									
Arctica islandica																									1		1			1	8	1	1			
Dosinia indet.																										1	1									
Chamelea striatula																											1									
Venerupis senescens																			1		2	1		3	3	8	5									
Venerupis decussatus																											1									

Table 3 continued.

Species / Depth (m)	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	19-20	20-21	21-22	22-23	23-24	24-25	25-26	27-28	28-29	29-30	30-31	31-32	32-33	33-34	34-35	35-36	37-38	46-47	55-56	56-57	57-58	58-59	59-60	60-61	61-62
Corbicula fluminalis auct.																					2			3	2	4	23									
Pisidium amnicum																										1	2									
Pisidium casertanum																						1					2									
Pisidium henslowanum																								10			1									
Pisidium milium																								1												
Pisidium nitidum																								1												
Pisidium subtruncatum																					1			8												
Pisidium supinum																				1							4									
Sphaerium corneum																										1										
Sphaerium cf. *subsolidum*																										1	2									
Mya arenaria																				1				1	2		5									
Varicorbula gibba																				3	6	2		13	4	15	37				4	1				
Saxicavella jeffreysi								2	4	2	1													1												
Pholas dactylus																								1			2									
Barnea candida									1	1			4	1	1					4	1		24	23	28	49										
Zirfaea crispata									1													1			1		1									
Turitella indet.																											6									
Natica indet.																					1			7	1		1									
Nassarius indet.																					1															
Gastropoda indet.																							2	1		1	8			1						
Nuculidae indet.																								1	1	1										
Pulmonata sp.	19													4										6	1		13					1				
Cyclocardia indet.																								1												
Carditidae indet.																											2									
Astarte indet.																									1											
Spisula indet.																				2						95	100									
Macoma indet.																					2															
Venerupis indet.																														1						
Sphaeriidae indet.																				1	1	1		23		3	11									
Mya indet.																					1		1		1	4										
Bivalvia indet.														1												1	25			3						
Succinea indet.																						1				3										
Columella indet																								1												
Cerastoderma indet.																										37	100		1							
Pisidium indet.																											1									

Table 4. Mammal occurrences.

Taxa	Depth (m b.s.)					
	33-36	36-37	37-62	54-55	55-56	56-58
Mimomys pliocaenicus		•				
Mimomys praepliocaenicus/ pliocaenicus		•		•	•	•
Mimomys praepliocaenicus			•	•	•	
Mimomys tigliensis		•		•		
Mimomys reidi		•		•	•	•
Pitymimomys sp.		•				
Microtus sp.	•					
Microtus agrestis	•					
Desmana sp.		•				
Soricidae	•					

Unit E (<22 m; Naaldwijk/Nieuwkoop Formation)

The Naaldwijk Formation in the Moriaanshoofd Borehole is composed of grey, fine to coarse-grained sands with an interval of grey clay and finely layered to laminated sand-clay alternations. Shell debris and shells occur in variable amounts. The upper six metres consists of anthropogenic sediments used for dike construction. At the bottom (21.7-22 m) and in the interval 7.75-8 m thin peat layers occur that are attributed to the Nieuwkoop Formation. Three lithological units are recognised (bottom up): NAMoC, NAMoB and NAMoA (Table 1).

Interpretation and age

The record of the Naaldwijk Formation and the Nieuwkoop Formation combined represent two depositional sequences.

The succession of peat and the overlying facies within the Naaldwijk Formation (NAMoC, NAMoB) form a single depositional sequence (NAMo1) (Fig. 2).

Overlying the basal peat (21.7-22 m) is an interval of fine to coarse-grained sands that grade into (partially laminated) sandy clays. The mollusc fauna consists of a mixture of intertidal to shallow subtidal mesohaline taxa (Table 3). Above 20 m b.s. the mollusc fauna (species) becomes fully marine. The interval from 14 to 18 m is interpreted to cover the high-stand deposits within the Naaldwijk Formation since it contains fully marine mollusc taxa (Table 3) and sandy and sandy/clayey layered sediments that are interpreted to originate in the lower part of the tidal setting. In this view the maximum flooding surface within the formation in the record at Moriaanshoofd occurs at 14 m depth.

Above 14 m a shallowing trend is interpreted. The deposits are characterised by silty clay grading into laminated or finely layered fine sand-silt alterations that indicate deposition within the upper tidal flat. Faunas become progressively dominated by shallow water species, and increasingly mesohaline and even oligohaline taxa occur. At the top of the sequence (7.75-8 m) a thin peat layer occurs (Nieuwkoop Formation).

The top part of the succession (6-7.75 m; unit NAMoA) contains sandy clays and sands, and is dominated by mesohaline mollusc taxa as well as common remains of terrestrial snails. The unit NAMoA is interpreted to represent a transgressive part of sequence NAMo2. The Naaldwijk Formation forms the Holocene clastic coastal infill in the western Netherlands (Weerts, 2003) and intertongues with peat layers of the Nieuwkoop Formation that formed mainly on the landward side of the coastal plain (Weerts & Busschers, 2003)

Deposits in the lower part of the Naaldwijk Formation in the Moriaanshoofd record (8-21.7 m) are consistent with the Wormer Member and deposits in the upper part of the Naaldwijk Formation (6-7.75 m) are consistent with the Walcheren Member of the Naaldwijk Formation as defined by Weerts (2003) (see also Hijma et al., 2009 and Westerhoff et al., 2003)

The origin of the Naaldwijk Formation is related to the Holocene transgression that postdated the last glacial period of the Late Pleistocene (see for detailed approach Hijma et al., 2009, 2010; Hijma & Cohen, 2010 and for the paleogeographic reconstructions Vos et al., 2011).

The Rhine-Meuse paleovalley (Busschers et al., 2007; Hijma et al., 2009 and Hijma & Cohen, 2011) had been transgressed gradually in the course of Holocene and underwent successive transformation from a river valley to an estuary under the influence of rapidly rising sea-level between 9 ka and 6 ka (Hijma & Cohen, 2011; Hijma et al., 2009).

According to paleogeographic reconstructions in Hijma & Cohen (2011) and Hijma et al. (2009) in the area to the south-west of the paleovalley, where Moriaanshoofd is located, tidal basin existed already at 8.5-8.0 ka pointing to transgression in that time period. A single ^{14}C age from the basal peat layer in the Moriaanshoofd record (Table 2) shows that the Holocene transgression reached the Moriaanshoofd area around 7680 BP.

Discussion

Small mammals refine age estimates for the Maassluis Formation

The biozonation of the Late Pliocene and Early Pleistocene arvicolid faunas of South Eastern Europe (Russian Federation, Ukraine) defined by Tesakov (2004) is considered applicable to Western Europe. This allows to suggest more precise limits than before for the age of this part of the Maassluis Formation, with the assumption that reworking did not substantially affect the age estimates. A detailed discussion of the taphonomy of these small mammal remains is outside the scope of this paper. The presence of *Mimomys praepliocaenicus* in Moriaanshoofd indicates biozones MNR2 or MNR3, and the additional occurrence of *M. tigliensis* (at 55-56 m at Moriaanshoofd, sequence MSMo2) indicates a date not older than the most recent part of biozone

MNR2 (age brackets 2.25-2.35 Ma). These age brackets are based on calibration using magnetostratigraphy (Pevzner et al., 1998), which places the arrival of late *Allophaiomys* faunas between 2-2.1 Ma (biozone MQR11) (see Pevzner et al., 1998).

The small mammals from the Maassluis Formation in the Moriaanshoofd Borehole are similar to those of Zuurland level 11 (Tesakov, 1998; Van Kolfschoten, 1988), assigned to biozone MNR2 (Tesakov, 2004). The Oosterschelde dredged material described by Reumer et al. (1998, 2005) contains arvicolids similar to those found here in the lag deposit at 36-36.5 m (biozone MNR1). The arvicolid material from Schelphoek Borehole 40-45 m, Maassluis Formation cycle 6, described by Slupik et al. (2007) consists of only a few teeth, two of which were referred to *M. pliocaenicus*. However these teeth have insufficient features to assign them to that species or to the older *M. praepliocaenicus*. The Moriaanshoofd material from the Maassluis Formation appears to be somewhat older than the Tegelen arvicolid material with *Mimomys pliocaenicus* placed in biozone MNR1 (Tesakov, 1998, 2004) (see also Mayhew & Gibbard, 1998 and Mayhew and Stuart, 1986).

The sequences in the Maassluis Formation interval in the Moriaanshoofd Borehole are not as clearly expressed as in the Schelphoek Borehole. However, the four sequences documented in the present borehole (MSMo1-MSMo4) match quite well the thickness and depth below surface of the upper Maassluis sequences in Schelphoek Borehole (located at about 900 m distance; Slupik et al., 2007; Fig. 3). The Late Quaternary regional unconformity at the top of the Gelasian deposits is also found at similar depths in both boreholes.

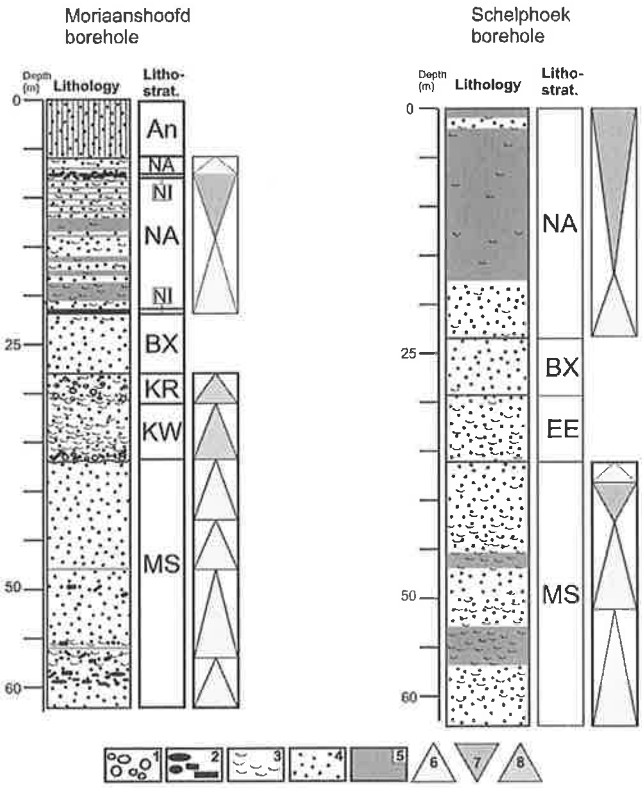

Fig. 3. Correlation of the Quaternary successions in Moriaanshoofd and Schelphoek boreholes. 1 – Gravel/pebbles; 2 – Peat and wood pieces; 3 – Shells and shell fragments; 4 – Sand; 5 – Clay; 6 – Deepening trend / transgression; 7 – Shallowing trend / regression / progradation; 8 – Fluvial sequences; Depth (m) – Metres below surface; Lithostrat. – Lithostratigraphy; An – Anthropogenic; NA – Naaldwijk Formation; NI – Nieuwkoop Formation; EE – Eem Formation; BX – Boxtel Formation; KR – Kreftenheye Formation; KW – Koewacht Formation; MS – Maassluis Formation.

Age of Late Pleistocene successions

The age estimates of the three Late Pleistocene units (Unit B-D: Koewacht Formation, Kreftenheye Formation and Boxtel Formation) in the borehole are not straightforward. The units must have been deposited after the Eemian interglacial (MIS 5e, <115 ka) as typical Eemian mollusc indicator taxa are found in these intervals and prior to the Holocene (MIS 1). The apparent contradictory ^{14}C ages we obtained can be understood as a result of mixing and reworking in these mostly fluvial units and they should provide maximum ages for each of the units. Further correlation with dated units close to the study area constrains the age estimates of each of the units further.

The youngest ^{14}C age obtained for a peat sample from the Koewacht Formation in Moriaanshoofd indicates that this unit must have been deposited after 33 ka (late Middle Pleniglacial or younger). De Koewacht Formation in borehole Moriaanshoofd can be correlated to Unit B4 in the offshore region to the northwest of study site (Hijma et al., 2012 following Busschers et al., 2007) whose age is estimated between 48-30 ka (late Middle Pleniglacial). The B4 Unit of Hijma et al. (2012) represents fluvial deposits of the Rhine-Meuse River system and is assigned to the Kreftenheye Formation, the Koewacht Formation represents coeval paleo-Schelde deposition. The three inconsistent ^{14}C ages obtained from the Koewacht Formation confirm the mixed (reworked) origin for this unit already shown by the fossil content.

The age of the Kreftenheye Formation interval in Moriaanshoofd is older than the maximum age (33 ka) of the underlying Koewacht Formation. Correlation of the Kreftenheye Formation interval from Moriaanshoofd with deposits offshore (Hijma et al., 2012) or in the Rhine-Meuse paleovalley onshore (Busschers et al., 2007) is difficult. The Kreftenheye interval in Moriaanshoofd might correspond to onshore units B5 and B6 of Busschers et al. (2007) that are lumped into a single offshore unit (Hijma et al., 2012). But correlation with the uppermost part of Unit B4 of Hijma et al. (2012) can not be excluded. The depth of the Moriaanshoofd Kreftenheye interval (28-31 m = 23.81-26.81 m NAP) fits best a correlation with the uppermost part of unit B4 or lower part of unit B5 of Hijma et al. (2012). These units correspond to a major southward shift of the Rhine-Meuse system that occurred during the later phase of Middle Pleniglacial to early Late Pleniglacial (around the MIS 3/2 boundary: 30-25 ka, Busschers et al., 2007).

The Boxtel Formation (Unit D; 22-28 m) in Moriaanshoofd is very similar as the interval in nearby borehole Schelphoek (Slupik et al., 2007). In the Rhine-Meuse paleovalley to the northeast of Moriaanshoofd, the formation is represented by river-dunes (Busschers et al., 2007 and Hijma et al., 2009; their unit B6c).

These aeolian deposits yielded age estimates between ca 11 and 15 ka, placing them after the Last Glacial Maximum (LGM) in MIS 2 (Busschers, 2008). However, we cannot exclude that the fluvial reworked aeolian deposits of the Boxtel Formation at Moriaanshoofd are older than the deposits in the Rhine-Meuse paleovalley.

A proto-Schelde River deposit disguised as a marine interval

The shelly interval overlying the truncation of the Gelasian in the Moriaanshoofd Borehole (28-36.5 m) (base of the Koewacht Formation) consists mostly of reworked marine sediments, predominantly derived from local Eemian deposits, is interpreted as a fluvial deposit. The rare Eocene mollusc species derive from the Late Ypresian-Early Lutetian Aalter Formation that crops out in a zone located from Ghent to Brugge to the North Sea off Zeebrugge, Belgium (Steurbaut & Nolf, 1989; Du Four et al., 2006) (Fig. 4). These Eocene taxa therefore indicate an ancient Schelde River that drained northwards from the area around Ghent in Belgium. The modern Schelde River via Antwerp, that became established during the latest Weichselian (Tavernier & De Moor, 1974; Kiden, 1991), eroded and reworked substantial amounts of Miocene and Pliocene sediments and fossils in the vicinity of Antwerp (Kiden, 2006). These modern

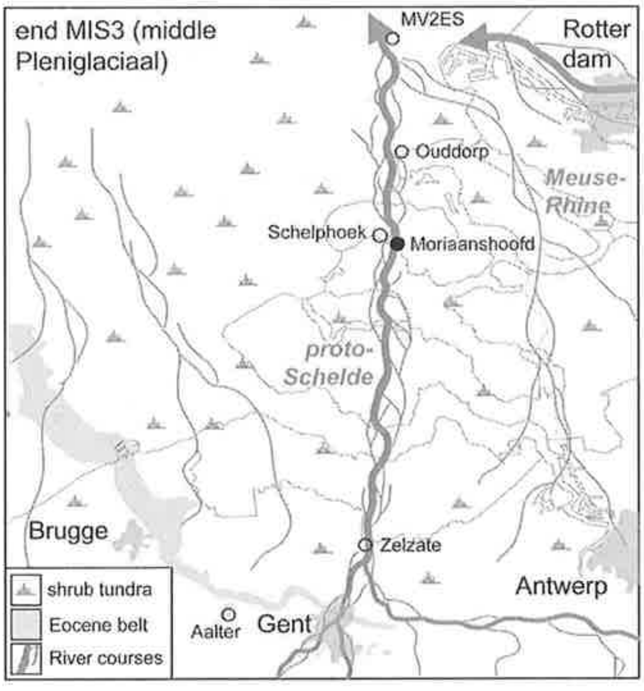

Fig. 4. Paleogeography of the Flemish Schelde River.

'Schelde Sands' are characterised by an abundance of reworked Neogene fossils that are very rare in the area studied here. Low numbers of Pliocene taxa found in the Moriaanshoofd Borehole (e.g. *Astarte incerta, A. obliquata, Cyclocardia scalaris, Amyclina labiosa*) probably derive from the current Westerschelde area. There, Pliocene deposits located at shallow depth have been eroded by Pleistocene rivers. Fluvial deposits containing reworked Eocene taxa probably derived from the Aalter Formation are known from the 'Vlaamse Vallei' near Zelzate (Janssen, 1965). Low numbers of Eocene taxa in the absence of many Neogene taxa are also known from dredging activities in the Hammen and the North Sea off Rotterdam, as well as from the beaches near Ouddorp (De Bruyne et al., 1987). The most northerly reference point for fluvial deposits containing Eocene taxa, probably derived from the Aalter Formation, is a borehole near The Hague (Meijer and Cleveringa, 2009).

A shelly interval similar to that found in the Kreftenheye Formation in the Moriaanshoofd Borehole was found in the Schelphoek Borehole (29-34 m). The latter was attributed to either an Eemian or Middle Pleistocene marine setting (Slupik et al., 2007). There, very low amounts of freshwater taxa as well as oligohaline (0.5-5 per mil) taxa occur in an otherwise polyhaline (18-30 per mil) fauna, also suggest reworking. No stratigraphically older species were found in the Schelphoek Borehole, but nevertheless the shelly interval there presumably should be attributable to the Kreftenheye Formation.

Reworking of deposits and faunas is extensive in Quaternary intervals in SW Netherlands. North of the study area, in the vicinity of Rotterdam, Busschers et al., (2007) found evidence of increased erosive fluvial activity of the Maas-Rhine River system during the late middle to early Late Pleniglacial (MIS 3: ca 24-30 ka). Increased erosive fluvial activity occurred repeatedly during the Weichselian. At the transition MIS 5a-4 (ca 75 ka) sea level dropped considerably from ~25 to ~90 m below present levels, triggering fluvial reworking (Hijma et al., 2012). MIS 4 (75-60 ka) was a period of extensive fluvial incisions across NW Europe including the Rhine and Meuse and also the Flemish Valley. The MIS 3-2 transition (ca 29 ka) coincides with a last phase of a major fluvial incision (Busschers et al., 2007; Hijma et al., 2012).

The incision, erosion and redeposition of older units therein appear related to increasingly colder climate settings during the time leading to the LGM at ca 18 ka.

Busschers et al. (2007) invoke glacio-isostasy to explain and interpret the fluvial evolution of the Meuse-Rhine system. During the Weichselian, multiple large-scale ice-sheet extensions occurred in Britain and Scandinavia. The build-up of the ice-sheets in the Late Middle and Late Pleniglacial caused uplift of the foreland area around the ice margin (forebulge). An area of maximal uplift during the Late Pleniglacial glaciation was situated in the northern Netherlands (for further references see Busschers et al., 2007). The increased incisions and marked shift of channel belt activity is interpreted as reflecting a response to glacio-isostatic upwarping of the area. This induced a lateral shift of the river valley to the south because the north of the valley was updoming slightly more than south. Busschers (2008) also noted the fresh appearance of deposits reworked under these very cold conditions, as did Janssen (1965) earlier for Schelde deposits near Zelzate.

It is well possible that the interval in borehole Schelphoek previously interpreted as Eem Formation (Slupik et al., 2007) corresponds with one of the incisive episodes of the Rhine-Meuse (from MIS 5a/4 - 3/2).

Oosterschelde Gelasian mammals are mostly derived from a Late Pleistocene river lag

The basal lag of the Koewacht Formation in the Moriaanshoofd Borehole contains a considerable concentration of bone material. It is most likely that the vertebrate remains dredged from the adjacent Oosterschelde channels at similar depth are derived from this basal lag. The basal lag material which we presume to be the source of the vertebrate remains has been reworked and concentrated partly from eroded upper parts of the Maassluis Formation (Slupik et al., 2007), and partly from reworked freshwater deposits of similar or later age. Some of the arvicolids in the Moriaanshoofd lag deposits can be assigned to biozone MNR1 of Tesakov (2004), age ca 2.1-2.25 Ma. In previous work, the larger vertebrates found in the Oosterschelde assemblage have been estimated at approximately 1.9 Ma (De Vos et al., 1995, 1998) on the basis of correlations with other (absolutely dated) European localities. This difference of 0.2 to 0.35 Ma might indicate that the age estimates for the larger vertebrate faunas might require revision, but at the same time there is no reason why material dating from different ages should not have been incorporated in the lag deposits. It might also be that the eroded top part of the Maassluis Formation in the Oosterschelde area contained sediments as young as ca 1.9 Ma. Local reworking of Middle Pleistocene material into the coarse lag deposits could explain the recovery of a large *Trogontherium* tibial fragment, suggesting a Middle Pleistocene age, from the deep channel of the Oosterschelde, close to the Moriaanshoofd Borehole (Mayhew et al., 2008).

Extensive reworking challenges a straightforward lithostratigraphic subdivision

The record of the Koewacht Formation indicates a southern origin of the material and fauna, and also locally reworked, possibly also fluvial, deposits. The Kreftenheye Formation shows another, Rhine, source. The record of the borehole shows Schelde-derived deposits as far north as Schouwen-Duiveland. Schelde-derived deposits in the southwest Netherlands have very recently been assigned to the Koewacht Formation – a lithostratigraphic unit defined by Kiden (2010). The Koewacht Formation consists of predominantly sandy deposits of rivers draining the Schelde basin in Belgium and northern France during the Saalian, Eemian and Weichselian through a wide paleovalley north of Ghent (Fig. 4), the so-called 'Flemish Valley' (Tavernier, 1946; Tavernier & De Moor, 1974). The Kreftenheye Formation as defined by Buschers & Weerts (2003) is a lithostratigraphic unit that consist of Rhine River deposits, with additional minor amounts of material from tributary rivers. Here we have not studied in depth the lithological composition of the fluvial units (and especially the gravel) in the Moriaanshoofd Borehole, so we cannot subdivide the deposits in more detail, but we have sufficient evidence of lithological differences (see above) to assign the deposits to the Koewacht Formation that consists of the fluvial units of a southerly origin and also abundant locally reworked (possibly also fluvial) deposits.

The very large role of reworking in the genesis of the stratigraphic successions in the southwestern Netherlands shows that a simple lithological-based (cf. IUGS approach) or a more complex facies-based approach (as advocated by the Dutch Geological Survey) is insufficient for a complete understanding of the geological units. The debate over lithology-based versus genetic-based stratigraphic concepts is very long-standing (Cox and Sumbler, 1999).

According to the code of stratigraphic nomenclature (Salvador, 1994), lithostratigraphic units should be defined and characterised on the basis of lithological properties of rocks bodies and their stratigraphic relations. We show that in the settings studied here some interpretation of the genesis of deposits is required in order to understand the lithological units.

In the Antwerp area massive reworking of mostly Pliocene strata into the Late Weichselian 'Schelde Sands' produced a lithological unit rich in fossils that barely differs from some of the locally underlying Pliocene units. Similarly, the base of the Maassluis Formation has only been understood in the nearby Schelphoek borehole (Slupik et al., 2007) through biostratigraphic and taphonomical evidence. The basal part there also is completely dominated by reworked Pliocene sediments and fossils giving it the appearance of the underlying Oosterhout Formation. So we argue for the involvement of facies successions (or even sequences) as a necessary step in defining geological formations in this region.

Conclusions

The Moriaanshoofd Borehole contains a stratigraphic record of Gelasian (Early Pleistocene) to Holocene deposits represented by six formations.

The Gelasian Maassluis Formation comprises recurring depositional facies reflecting cyclical deposition within a tidal setting. Between the top of the Maassluis Formation and the overlying deposits of Late Quaternary age a major hiatus exists comprising approximately >2.2 Ma.

During Weichselian times (33-24 ka), a proto-Schelde River shaped the northern Oosterschelde area. The river reworked substantial amounts of Early and Middle Pleistocene deposits. At the base of the Schelde derived fluvial sequence that we here attribute to the Koewacht Formation, Gelasian vertebrate faunas were concentrated. This channel lag is almost certainly the main source for the rich vertebrate faunas dredged from the adjacent Oosterschelde deep channel.

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Appendix 1 — Lithological description of the Moriaanshoofd borehole

Depth is given in metres below surface (= 4.19 m above mean sea level - N.A.P.). MSMoA, MSMoA$_1$, MSMoB, MSMoC – facies in the Maassluis Formation; KWMoA, KWMoB – facies in the Koewacht Formation; KR – Kreftenheye Formation; BX – Boxtel Formation; NAMoA, NAMoB, NAMoC – facies in the Naaldwijk Formation; NI – Nieuwkoop Formation.

Depth (m b.s.)	Sediment features	Facies/ units
0-0.5	Black soil; slightly silty and fine sandy; highly calcareous	
0.5-6	Grey sand; anthropogenic	
6-7	Grey sand; fine to medium fine with numerous very thin clay layers; numerous shell fragments; strongly calcareous; bottom part consists of finely layered sandy-clayey complex with some shell fragments;	NAMoA
7-7.75	Dark grey clay; silty; with fine to medium fine sand partings; some shell fragments; highly calcareous	
7.75-8	Black peat with wood remains	NI
8-8.5	Grey clay; weakly silty; rather firm; peaty towards the top; strongly calcareous	NAMoB
8.5-12	Grey clay-sandy finely layered complex; clay is slightly silty; sand is fine; few shell fragments; some wood pieces in the uppermost part; strongly calcareous	
12-14	Grey clay; rather silty; rather firm with layers of fine sand; some shell fragments; strongly calcareous; lowermost part contains finely layered clayey-sandy complex with some shell fragments	
14-16	Grey sand; fine to medium fine; with thin clay layers; some fine shell fragments in the bottom part; strongly calcareous	NAMoC
16-18	Grey to dark grey clay-sandy layered complex; clay is silty; sand is medium fine; strongly calcareous	
18-20.5	Grey to dark grey clay; silty to fine sandy; few shell fragments in the bottom part; strongly calcareous	
20.5-21.7	Grey sand; medium fine to medium coarse; with a few clay layers; some fine shell fragments; strongly calcareous	
21.70-22	Dark brown peat; firm	NI
22-23.5	Light grey sand; medium coarse; not calcareous	BX
23.5-28	Light grey sand; medium fine to coarse; not calcareous	
28-29	Light grey sand; medium coarse; trace of shell fragments; slightly calcareous	KR
29-31	Grey sand; coarse; some clay clasts in the bottom part; some fine gravel; rather abundant shells and shell fragments in the upper part and some fine shell fragments in the lower part; some wood fragments; slightly calcareous	
31-32.5	Grey sand; medium coarse; rather calcareous	KWMoB
32.5-34.5	Grey sand; medium coarse to coarse; some shell fragments in the upper part and rather abundant shells; shell fragments and pieces of reworked peat in the lower part; weakly calcareous	
34.5-36	Grey sand; medium coarse to coarse; some clay clasts in the lowermost part; abundant shells and shell fragments; few wood fragments and reworked peat; not calcareous	
36-36.5	Darkish grey sand; fine to medium fine; with a few light grey hard clay clasts; some black clasts; not calcareous	
36.5	Brown claystone clasts; rolled; up to a few centimetres in size	KWMoA
36.5-37	Dark grey sand; fine to medium fine; strongly silty; some mica; some light grey consolidated clay clasts; some black lithic fragments; not calcareous	MSMoB
37-40	Dark grey sand; fine to medium fine; thin; containing silt to rather strongly silty; fine sandy clay layers; some mica; some light grey consolidated clay clasts	MSMoA$_1$
40-41	Dark grey sand; fine to medium fine; silty; thin; fine sandy clay layers; some light grey consolidated clay clasts; some black lithic clasts; some mica; not calcareous	MSMoA
41-43	Dark grey sand; medium fine; a few fine clay clasts; not calcareous;	
43-44	Dark grey sand; fine to medium fine; some very thin clayey layers; some fine clay clasts; abundant mica; not calcareous	
44-45	Dark grey sand; fine to medium fine; rather strongly silty; numerous thin clay layers; some clay pebbles; not calcareous	MSMoB
45-47	Dark grey sand; fine to medium fine; in the lower part fine to medium coarse; scarce clay fragments; some mica; not calcareous	MSMoA
47-48	Dark grey sand; a few thin; silty clay layers; single clay piece; some mica; not calcareous	
48-49	Grey sand; medium fine to medium coarse; scarce clay clasts in the lower part; a few wood fragments in the uppermost part; not calc.	
49-53	Grey sand; medium fine; some mica; not calcareous	
53-54	Grey sand; madium fine to medium coarse; not calcareous	
54-55	Grey sand; medium fine to medium coarse; some clay pieces; some shell fragments; a few fragments of wood; slightly calcareous	
55-56	Grey sand; medium coarse to coarse; silty; some clay pieces; some wood fragments; slightly calcareous	MSMoB
56-57	Dark grey sand; medium coarse to coarse; very abundant shell fragmentsand shell gravel; a few flat clay pebbles; slightly calcareous	MSMoC
57-60	Grey sand; medium fine; grey; some very thin clay layers; many small hard clay clasts; some shell fragments; slightly calcareous	MSMoA
60-61	Grey; fine to medium fine sand; silty; abundant fine clay layers; clay fragments; calcareous	MSMoB
61-62	Grey sand; fine to medium fine; some thin clay layers; single hard clay clasts; some mica; calcareous	MSMoA