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Holocene development of the Marker Wadden area, Lake IJssel (the former Zuider Zee), The Netherlands

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Abstract Detailed analysis of a core taken within the framework of the Marker Wadden project reveals the sedimentary history of the central part of the Netherlands following the Holocene sea level rise. Grain size and thermogravimetric analyses coupled with micropalaeontological and stable oxygen isotope data provide a solid framework for a detailed reconstruction of the landscape during this time interval. The Pleistocene landscape of fluviatile and aeolian deposits was succeeded by periods of marsh growth, brackish semi-enclosed lakes and tidal flats until a permanent connection with the North Sea was established. Palynological data suggest human activities in the immediate surroundings of the research area.

Keywords *• Late Quaternary landscape evolution • sea-level • multiproxy approach*

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INTRODUCTION

The Markermeer is a dramatically silted up area with an extremely low biodiversity, situated at the southern part of Lake IJssel (IJsselmeer), the Netherlands. The Marker Wadden project, a unique nature restoration effort, aims to revert this situation by creating a number of sandy islands with associated marshes and mud flats covering an area of about 100 km^2 **(**Fig. 1). The sands, clays and silts needed for the construction of this ecosystem derive from the subsurface of the Markermeer. Here, Pleistocene sands are covered by a 5–8 m. thick Holocene series of clays, silts and fine sands. The large number of cores taken during the reconnaissance phase of the project provided new insights ino the Holocene development of the area (Laban 2016).

The first stage of the Marker Wadden project involved the construction of five sandy islands surrounded by a vegetated marshland with shallow ponds, creeks and channels. To protect the islands from storms the dredging company Boskalis constructed beaches, sand banks and low dunes, linked by a rock dam. This will provide a gradual transition from land to water, as well as create a varied bottom topography. It is expected that sediments will settle

Fig. 1 Research area and location of the core transect (Source: Natuurmonumenten)

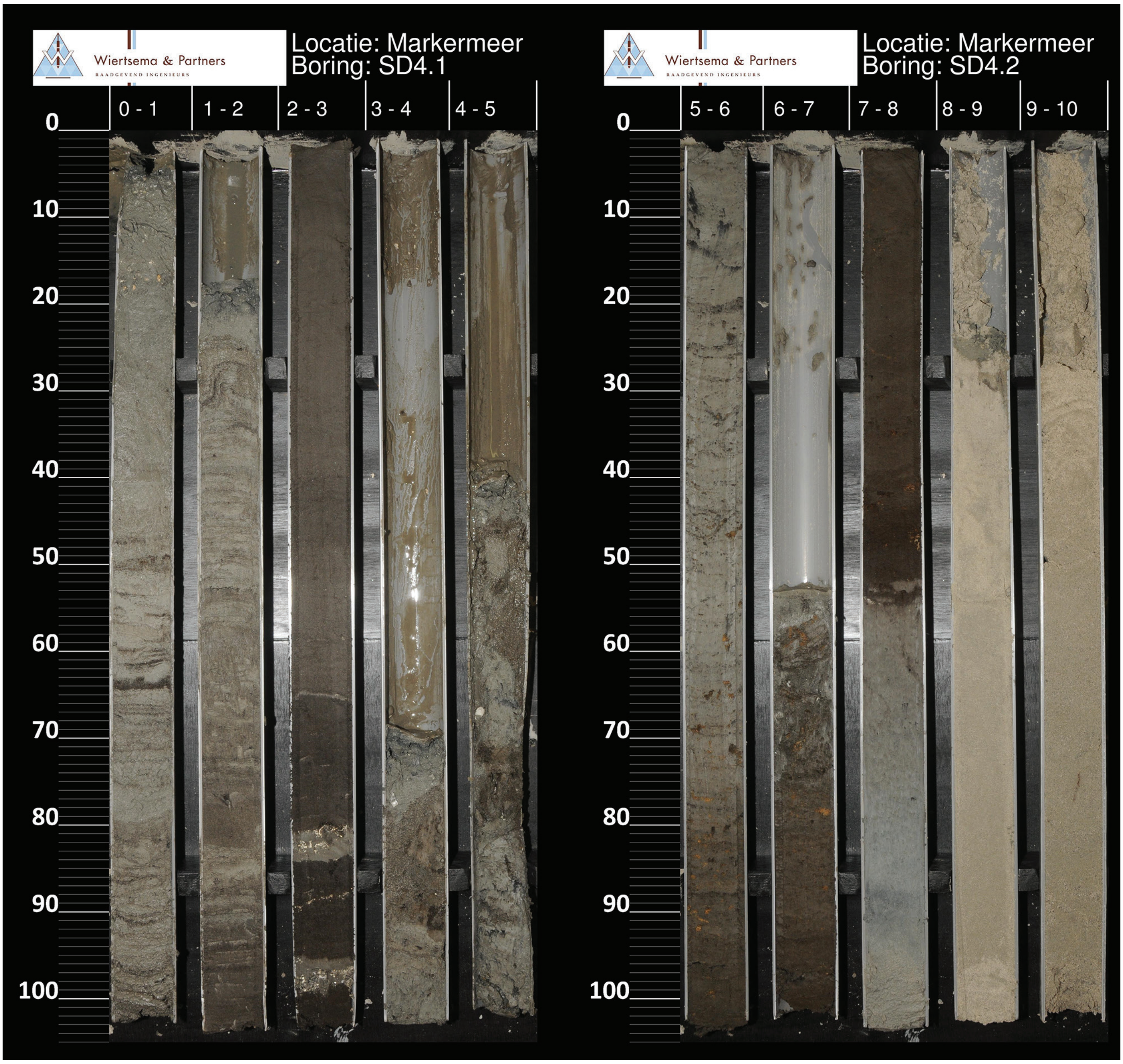

Fig. 2 Core SD–4 from the Markermeer with Pleistocene sands bottom right

in the shallow areas and creeks, thus functioning as a natural water purification system. In addition, a 10 m deep trench will be constructed targeted to collect the fine-grained sediments from the Markermeer. This 'sediment trap' will increase the transparency of the water. The captured sediment will be used for the construction of the next phase.

Following the Valletta Treaty (formally the European Conv1ention on the Protection of the Archaeological Heritage, the Malta Convention) archaeological investigations were carried out on the Pleistocene highs where Late Palaeolithic and Mesolithic artefacts could be expected. Similarly Early Holocene deposits might reveal Late and Middle Neolithic occupation.

Core SD–4 (Fig. 2), containing the most complete stratigraphical record, was selected for detailed sedimentological and micropalaeontological analysis.

STRATIGRAPHY

The late Quaternary history of the central part of the Netherlands is well documented (a.o. Lenselink and Menke 1995; Makaske *et al*. 2002; Vos 2015). In recent years Vos (2015) and Vos and De Vries (2016) published a series of detailed palaeogeographical maps. New information became available during the initial phase of the Marker Wadden project when an extensive coring operation was carried out. A first description of the cores was performed by an archaeological reconnaissance team. The stratigraphic summary presented below is based on the succession seen in core SD–4 (Fig. 2); lithological units 1–8). The Pleistocene fluvial sediments in this area were deposited during the Weichselian Early and Middle Pleniglacial by a branch of the river Rhine, and belong to the Kreftenheye Formation, Unit 1 (Peeters *et al*. 2015; Vos 2015). The palaeogeographical situation during this time interval is shown in Fig. 3. In core SD-4 sediments of this formation are present between 1000 and 890 cm (Fig. 2). They consist of poorly sorted clean quartz sands.

During the Late Pleniglacial aeolian dunes were formed on which late Paleolithic and Mesolithic human settlements could be expected. These sediments belong the Wierden Member (Unit 2) of the Kreftenheye Formation (Vos, 2015). In core SD–4 the interval between 890 and 790 cm is assigned to this unit. Sediments of the overlying Singraven Member (790–750 cm; Unit 3) are creek deposits consisting of fine-grained sand containing small amounts of organic plant material.

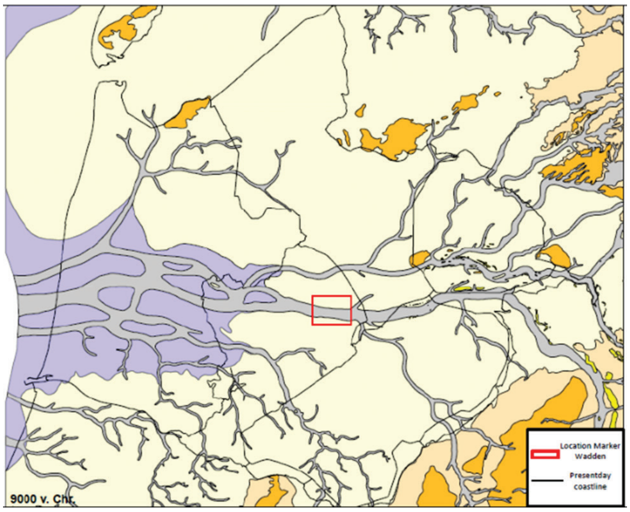

Fig. 3 The Late Weichselian situation c. 9000 years B.C. The red square is the area of investigation. Dark yellow represents ice pushed areas, light yellow the Pleistocene surface between 0 and -16 m Amsterdam Ordnance Datum. In purple the area > -16 m Amsterdam Ordnance Datum, the black line is the present coastline (after Vos and De Vries 2016)

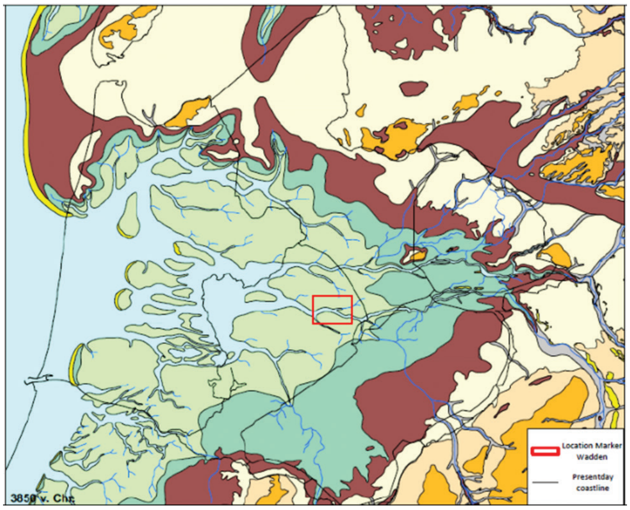

Fig. 4 The area around 3850 years B.C.; part of an intertidal environment, the red square is the area of investigation, the black line the present coastline (after Vos and De Vries 2016)

Between c. 9000 and 5000 year B.P. the groundwater table was rising due to a gradually increasing sea level. Marshes developed and a peat layer, the Basal Peat (*Basisveen*; Unit 4), was formed. In core SD–4 this unit is rather thin. During the ongoing sea level rise the landscape became part of an intertidal area with mudflats belonging to the Wormer Member (Unit 5) of the Naaldwijk Formation (Fig. 4). The clays and silts with minor amounts of fine grained sands of the Wormer are present between 750 and 300 cm.

Between 5000 and 3000 years B.P. a return to marshland took place in which a peat layer was formed, the Hollandveen Member of the Nieuwkoop Formation (Fig. 5).

Fresh water lakes formed in the marshes between 4000 and 2400 years B.P. due to the fluvial input from rivers from eastern direction and the lack of outlets to the North Sea and Waddenzee to the north. The lakes increased in size by eroding the marshland and peat. At the bottom of the lakes fine sand and clay was deposited with peat remnants, the Flevomeer deposits (Unit 6; 300–180 cm) of the Naaldwijk Formation (Fig. 5). From 2400 year B.P. onwards the Waddenzee invaded the area from the north and changed it into a brackish environment, the Almere Lagoon (Van Loon and Wiggers 1975). The sediments deposited belong to the Almere Layer (Unit 7; 180–30 cm), characterized by the alternation of thin clay/sand layers. Around 1600 A.D. a permanent connection with the Waddenzee was established and marine sediments were deposited assigned to the Zuiderzee Layer (Unit 8; 30–0 cm) of the Naaldwijk Formation. In 1932 the Zuiderzee was in the North disconnected from the Waddenzee by a 30 km long dam, and a fresh water lake was formed, the Lake IJssel (Vos 2015).

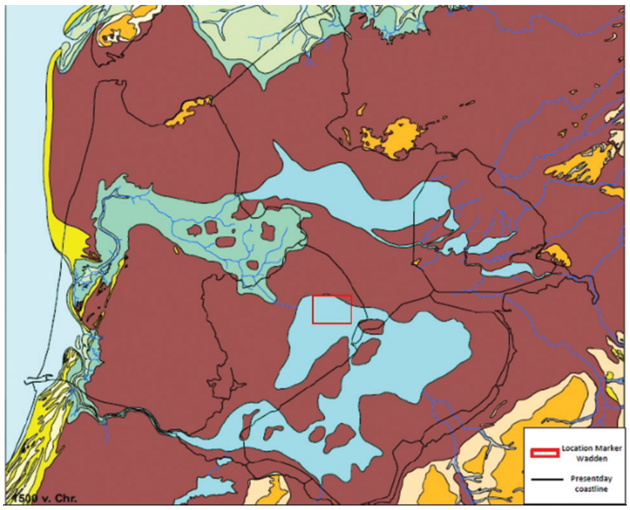

Fig. 5 The area around 1500 years B.C., covered with marshes and fresh water lakes (after Vos and De Vries 2016)

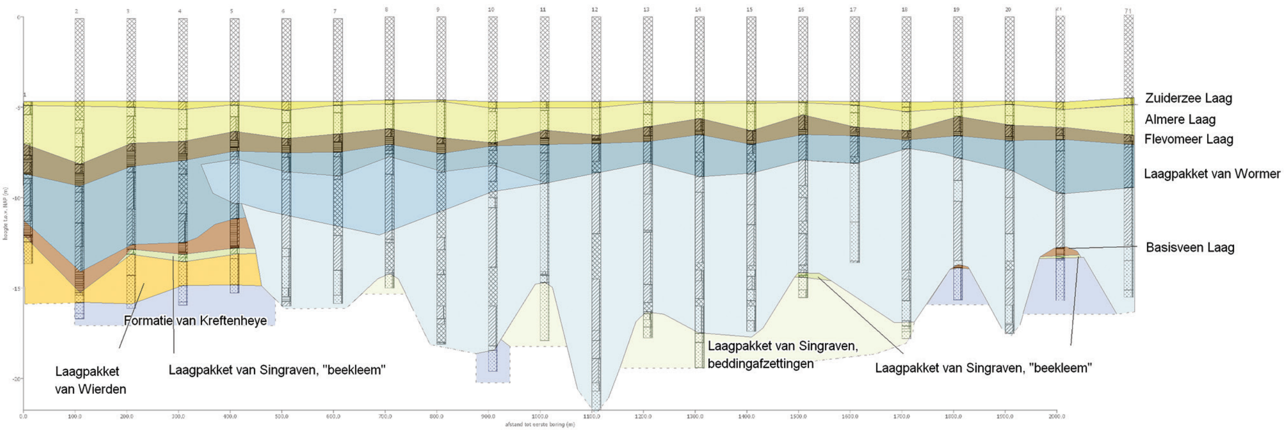

Fig. 6 The core transect and position of core SD–4 (No. 4 from the left; Laag = Layer; Laagpakket = Member) (After Huizer 2016)

MATERIAL AND METHODS

Core SD–4 containing the most complete sequence of the NE–SW transect (Figs. 1, 6), was selected, described and sampled for further analysis. A total of 64 samples was taken for grain size- and thermogravimetric analysis (TGA) and micropalaeontological studies. For grain size the Sympatec HELOS/KR Laser Diffraction Particle Size Analyser was used, following standard sample preparation methodologies (Konert and Vandenberghe 1997), for thermo gravimetric analysis the LECO TGA–701, both at the Laboratory of Sediment Analysis at the VU Amsterdam. For micropalaeontological analysis ca. 20 cm^3 of sediment were washed over a >63 µm sieve to remove the clay/silt fraction, dried on a hotplate and studied under a binocular microscope. Results are given in a semi-quantitative mode where 0 = absent, 1 = present, 2 = rare, 3 = common, 4 = rich, and 5 = abundant. Stable oxygen isotopes on the ostracod species *Cyprideis torosa* and the foraminifer *Ammonia beccarii* were carried out on the GasBench-ll at the Stable Isotope Laboratory at the VU Amsterdam.

The grain-size distribution data set has been decomposed in a series of end-members with the currently most accurate end-member modelling algorithm AnalySize (Paterson and Heslop 2015; Van Hateren *et al.* (in press). Following the procedure described in Van Hateren *et al*. (in press), a mixing model expressing all the grain-size samples (n = 64) as mixtures of six end members has been produced. Details of the technical aspects of and rationale behind end-member modelling in general are given in e.g. Weltje (1997), Prins and Weltje (1999) and Weltje and Prins (2003, 2007).

Samples for palynological analysis were gently boiled in KOH, after which samples were sieved over a 200 µm mesh. The residue was then treated in an acid solution removing all organic material. Recovery of the pollen grains is by means of heavy liquid separation with a density of 2.0. The pollen is transferred to an Eppendorf tube containing glycerine, after which pollen slides can be prepared.

RESULTS

Thermogravimetric analysis (TGA)

The thermogravimetric results depicted in Fig. 7 have been subdivided into three domains, LOI330, which represents easily combustible or relatively fresh organic matter, LOI550, representing all organic matter including the LOI330 fraction plus the more degraded organic matter, and finally, the carbonate fraction that dissociates between 615 and 1000 ºC. This subdivision allows a quick overview and comparison with the recognized lithostratigraphic units: the lowermost units, from ~10 m to 7.6 m below the top of the studied core are almost devoid of organic and carbonate matter. A sharp increase in LOI330 and LOI550 content, from a few percent to over 30%, occurs together with an increase in carbonate content, from 1 to 10%, between 756 at 740 cm, and marks the transition into the remains of the Basal Peat (*Basisveen*). Whereas LOI330 and LOI550 content show quite substantial variation upwards in the core, with maxima from 740 to 590 cm, and 296 to 197 cm, and minima between 510 and 396 cm, and from 167 cm to the top of the core, the carbonate content fluctuates only modestly. Between 740 and 279 cm carbonate percentage varies between 5 and 11%, from 260 to 197 cm with the lowest values between 4 and 5%, and towards the top slightly more fluctuation with concentrations between 5 and 11%. Remarkably, in the case of the first maximum in organic matter between 756 and 740 cm, the carbonate content is also high, whereas at the second maximum between 260 and 197cm the carbonate content is substantially decreased. Not shown is the relative LOI330 contribution to the LOI550, which, interestingly, follows the

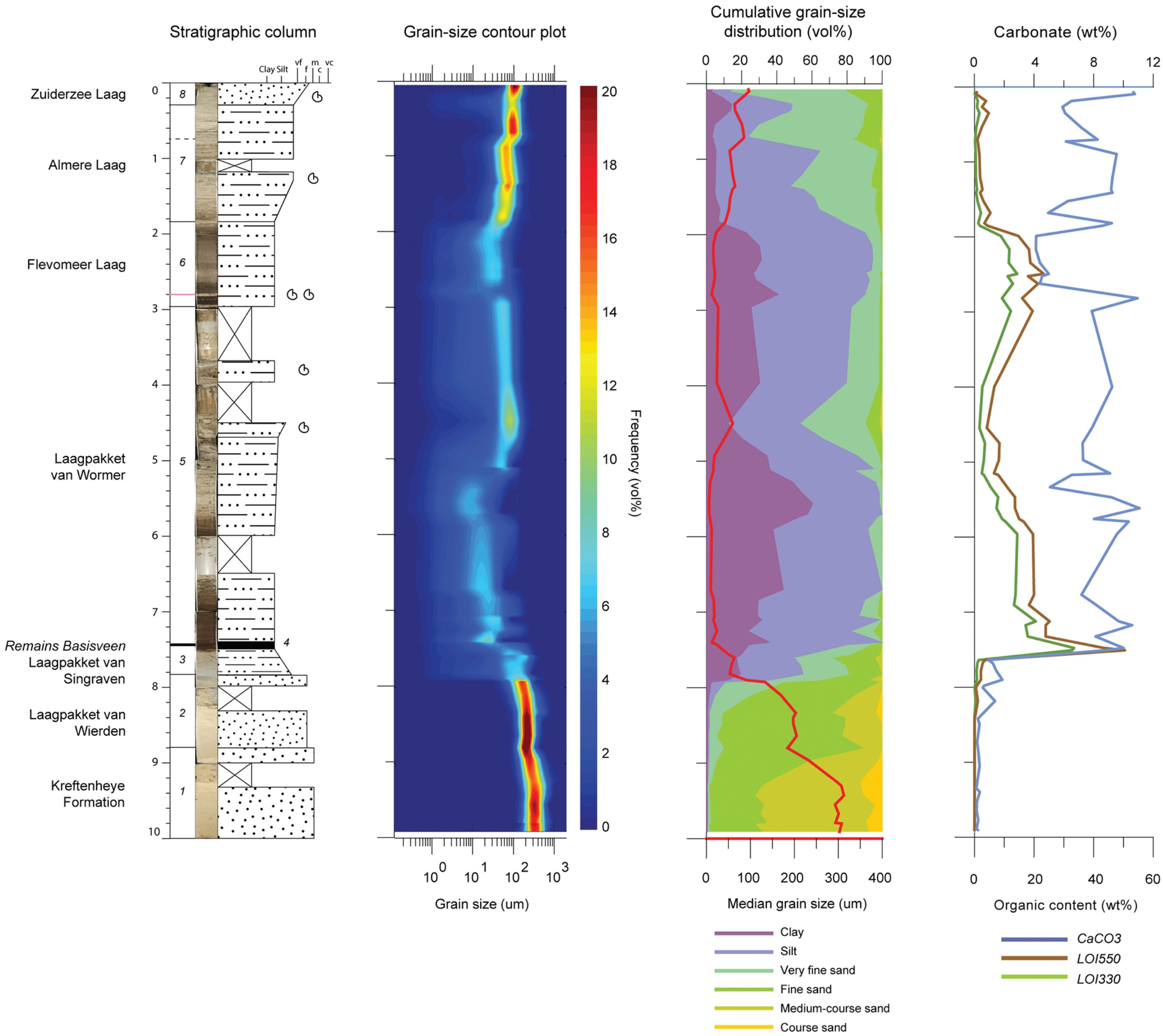

Fig. 7 Composite plot of the grain size- and TGA analyses. From left to right the stratigraphical column, the contour plot of the grain size distribution, the cumulative grain size distribution including median grain size (µm; red line) and the total organic and carbonate content are given

maxima in organic matter content as shown in the Fig. 4 (left), suggesting that reworking of deposited organic material is modest.

Grain size analysis

The grain size results of core SD-4 are plotted as a grain size contour plot and a cumulative size distribution graph next to the lithostratigraphic column and core photograph in Fig. 7. The grain size contour plot shows that the basal units (7.9–10 m) are composed of well-sorted sands, dominated by coarse- to medium-coarse sand from 9–10 m (Unit 1) and fining-upwards to mainly fine-sands from 7.9–9 m (Unit 2). At 7.9 m an abrupt change to less sorted, silty fine-grained sands can be observed, continuing to 7.5 m (Unit 3), up to the base of the Basal Peat layer (Unit 4). From 7.4 to 2.0 m (Units 5 and 6) the sediments are clearly less-well sorted and dominated by clay and silt. Two fining-upward sub-units can be distinguished: the lower sub-unit (from 5.5–7.4 m) is almost exclusively composed of silt and clay, the upper sub-unit (4.5–2.0 m) contains very-fine sands at the base and grades upward into clayey silts. From 1.8 m upwards an overall coarsening-upward trend can be seen, ranging from poorly-sorted clayey silts at the base of Unit 7 to very-well sorted very fine sands at the top (Unit 8).

End member modelling

The ‘goodness-of-fit’ (r2) statistics were computed with AnalySize for mixing models with 2–10 end-members (Fig. 8A). Both the sample-wise R2 (Fig. 8A) and class-wise R2 (Fig. 8A and 8B) statistics show that the sediments can be adequately

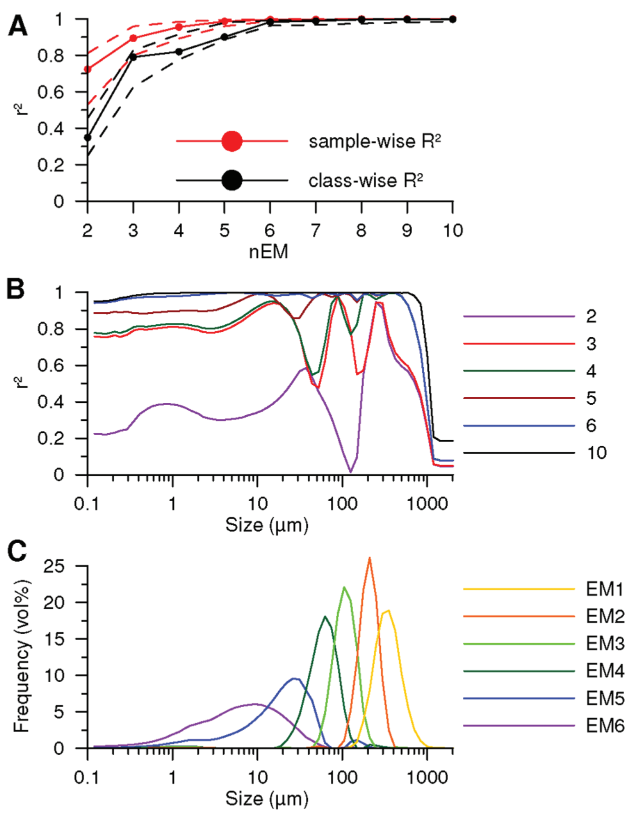

Fig. 8 End-member modelling results of core SD-4. A). The median sample-wise and class-wise R2 values as well as the 25th and 75th percentiles (dotted lines) plotted versus the number of end-members (nEM, with n varying between 2 and 10). B) Class-wise R2 values plotted versus grain size for a number of end-member models with nEM varying between 2 and 10. C) Modelled end-member grain size distributions for the 6-end-member model. The EMs have clearly defined modes (from EM1 to EM6) at 354, 210, 105, 63, 26 and 9 µm, respectively

described as mixtures of six end-members. The six-end-member model explains on average 98% of the observed variance in the grain size dataset. The computed end-members are characterised by unimodal (in case of EM5 also fine skewed) grain size distributions (Fig. 8C) with clearly defined modes at 354 (EM1), 210 (EM2), 105 (EM3), 63 (EM4), 26 (EM5) and 9 µm (EM6), respectively.

The range in end-member compositions exemplifies the wide range of grain sizes occurring in core SD–4. EM1 and EM2 are composed of sand grains that can only have been transported as bed load, either by running water or by wind. In contrast, end members EM4, EM5 and EM6 must have been transported as suspended load. EM3 probably resembles a sediment fraction which might be best interpreted as 'modified saltation', so transitional between bedload and suspended load.

The distribution of the end members in core SD–4 shows some important stratigraphic zonations and trends. EM1 is found in high percentages exclusively in Unit 1; this coarse sandy end-member is therefore interpreted as a fluvial bedload component. EM2 clearly dominates Unit 2 and is interpreted as a cover sand component (aeolian bedload). EM3 is present in relatively high percentages (>20%) in Unit 3, upper part of Unit 5 and in Units 7–8. In Unit 3, EM3 is found mixed with EM2, and reflects overbank deposits in which some reworking of the cover sands occurred. In Units 5–8, the sediments are exclusively composed of EM3-EM6; the varying contributions of the end-members reflecting changes in the energy conditions in the (freshwater to tidal; see below) basin, with high abundances of the sandy and silty suspended load EMs (EM3, EM4) reflecting high-energy conditions, and high abundances of the silty and especially the clayey EMs (EM4, EM5, EM6) reflecting low-energy conditions.

Micropalaeontology

In total 64 samples from core SD–4 were analyzed for their (micro)palaeontological content (Fig. 10). Lithological units and sample positions are indicated to the left of the figure.

Samples from the Kreftenheye Formation and the Wierden Member contain no microfauna/flora. The Singraven Member, however, yields small amounts of organic plant material. Two samples from the Basal Peat were analyzed for their pollen content. *Alnus* and *Cyperaceae* pollen are dominant, while wetland species such as *Mentha aquatica*, *Typha latifolia, T. angustifolia* and *Sparganium* sp. are common. In addition fern spores are observed.

In the lower part of the Wormer Member some plant debris is found. Detailed analysis within this unit is hampered by two intervals with no recovery. From ca. 500 cm upcore benthic foraminifera make their first appearance with species such as *Jadammina macrescens, Trochammina inflata, Ammonia* sp. and *Elphidium craticulatum*. The former two species are associated with marsh deposits; they possess an agglutinating test characteristic for environments with a low pH. The other two species have a calcareous test and characterize tidal flats. Ostracods, e.g *Cyprideis torosa* are well represented, both by single valves of all growth stages (instars) and by doublets, pointing to in situ preservation. Current action would otherwise have sorted the various size classes. The first occurrence of molluscs is at the same level; species include *Cerastoderma edule*, *Mya arenaria*, *Mytilus edulis* and *Ostrea edulis* together with specimens of *Balanus sp*. and *Peringia ulvae*.

Foraminifera are absent from the Flevomeer, except for the sample at the top of this unit, which contains *Ammonia beccarii, Haynesina germanica*, *Elphidium craticulatum* and high numbers of the ostracode species *Cyprideis torosa.* Only smooth valves

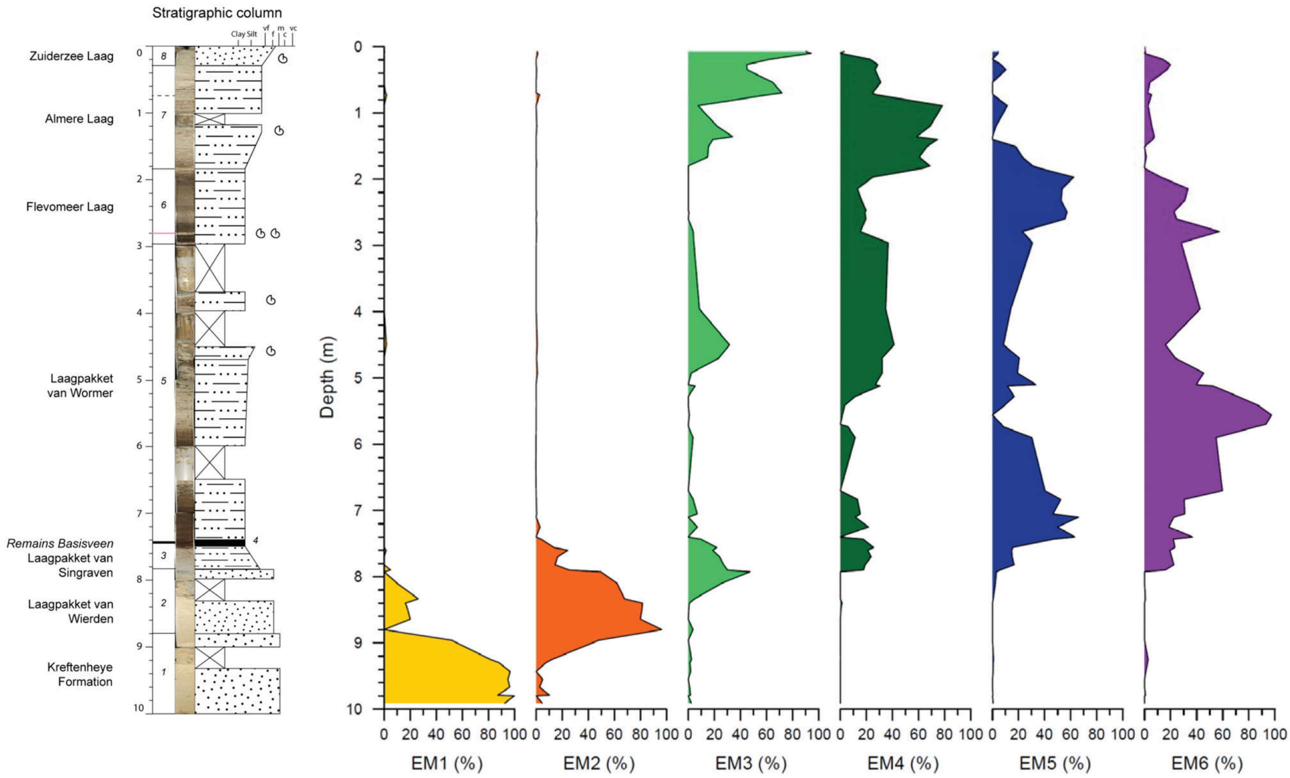

Fig. 9 Stratigraphic EM abundances (in %) for the 6-end-member model in core SD4. Unit 1 is clearly dominated by the coarse-sandy EM1, Unit 2 by the intermediate-sandy EM2, Units 3 by a mixture of EM2 and the fine-sandy EM3 and Units 4 to 8 by a mixture of EM3 and the muddy (silty to clayey) end members EM4–EM6

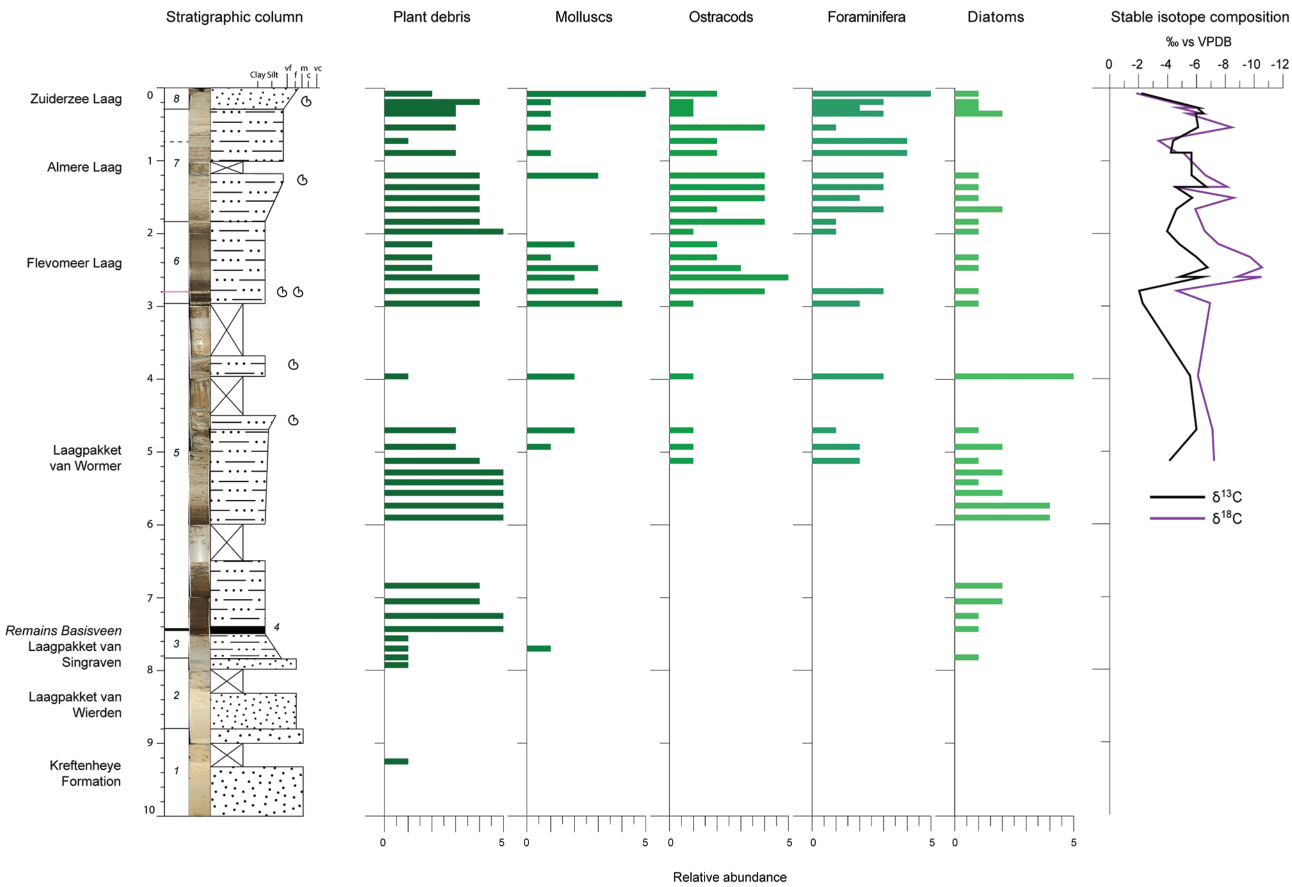

Fig. 10 Composite plot of the distribution of plant material and selected biota through core SD–4. Numbers refer to the relative frequency of each group: 0 = absent, 1 = present, 2 = rare, 3 = common, 4 = rich, 5 = abundant

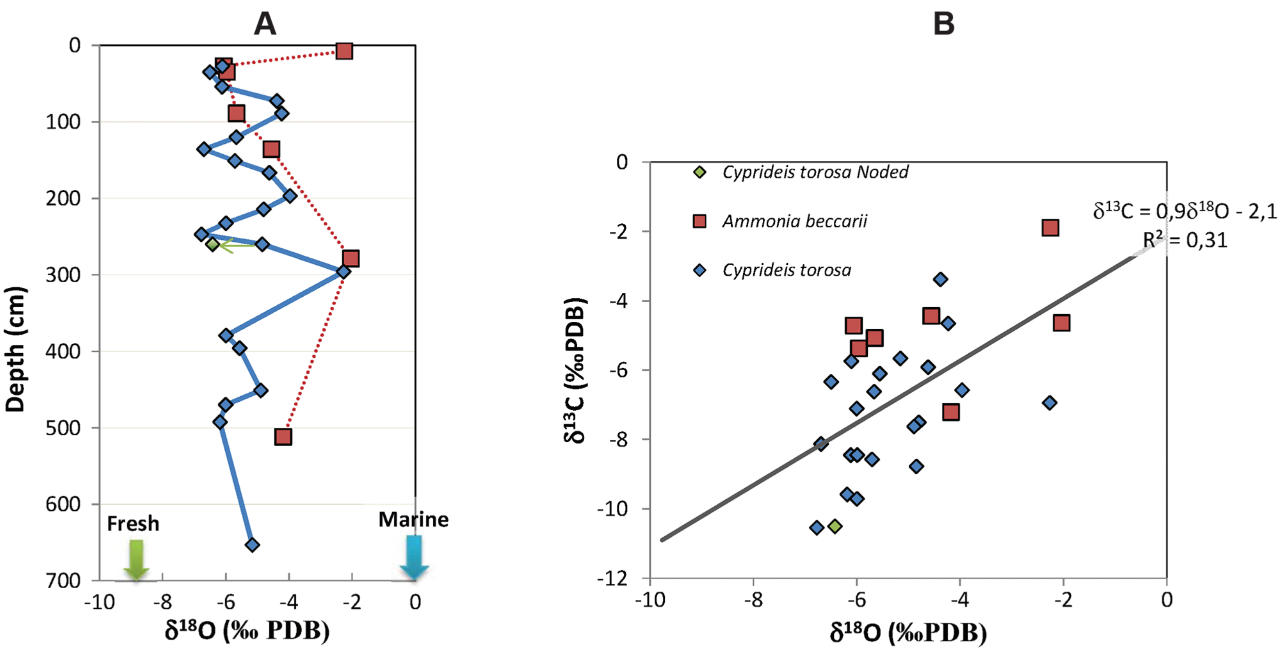

Fig. 11 [A] The oxygen isotopic composition in the ostracod *C. torosa* shows variations of a few permille throughout the core (that are caused by variable mixing of fresh water, river and precipitation, with marine influx). The $\delta^{18}O$ variation in the benthic foraminifer *Ammonia beccarii* shows similar fluctuations. [B] Oxygen- and carbon isotope composition of the analyzed ostracod and foraminifer shells co-vary because of fresh water- sea water mixing

are present. Noded specimens of this species also exist; these are considered represent lower salinities (Van Harten 2000; Frenzel *et al*. 2012). The smooth specimens present in this sample point to higher salinities and indicate a transition to the overlying Almere Layer.

Samples from the two intervals rich in mollusc fragments (300–280 cm) contain *Cerastoderma, Mytilus* and *Peringia* and abundant specimens of the benthic foraminiferal form *Ammonia beccarii*.

Four samples from the Flevomeer were analyzed for their pollen content. Of the tree pollen *Alnus*, *Corylus* and *Quercus* dominate. The freshwater algae *Pediastrum* is dominantly present; of particular interest are the pollen of cereals and *Plantago lanceolata*, indicating anthropogenic activity in the direct surroundings of Lake Flevo. The presence of *Abies alba* and *Picea abies*, two species originating from the Black Forest, Germany indicates that a connection between the river Rhine and its tributaries and Lake Flevo existed.

The transition of the Flevomeer deposits (plant remains, abundant ostracods) to the Almere Layer is shown by the presence of a distinct marine microfauna with the benthic foraminiferal species *Ammonia beccarii, Haynesina germanica*, *Bolivina* sp. and *Neoconorbina* sp. Spines of the echinoid *Echinocardium cordatum* occur regularly. Doublets of ostracods are very well preserved, indicating in situ preservation. Molluscs are represented by the species *Cerastoderma edule, Mya arenaria*, *Peringia ulvae* and the barnacle *Balanus* sp.

Samples from the Zuiderzee Layer contain large amounts of the foraminiferal genera *Ammonia, Elphidium* and *Haynesina*. Ostracods and spines of *Echinocardium cordatum* together with the molluscs *Cerastoderma* and *Peringia* are common.

Stable isotopes

The oxygen isotope and carbon isotope composition of the selected calcitic valves of ostracods can provide information on the water composition and temperature and possibly the biological productivity of the environment in which the ostracods lived. As shown in Fig. 11 a broad similarity in the $\delta^{18}O$ and $\delta^{13}C$ variation throughout the core is apparent. Absolute values vary widely between -6.8 and -2.3‰ (PDB) for the $\delta^{18}O$ and between -10.5 and -3.4‰ (PDB) for the $\delta^{13}C$. The observed covariation and the wide range in isotopic composition likely signifies that both are driven by changing water composition. Since variable mixing of sea and river water over time will result in salinity changes to which the ostracods can adapt, the isotopic variation can be read as an environmental salinity indicator. Corroboration for this comes from the presence of nodes on the ostracod valves at several stratigraphic levels in the core. These nodes are formed under low-salinity conditions (Keyser & Aladin 2004). As it turns out, the analyzed noded specimen at 260 cm in the core is almost 2‰ lighter in $\delta^{18}O$ and $\delta^{13}C$ than the smooth specimen from the same sample. Therefore, it seems that the environmental salinity changed both on short and longer time-scales. Finally, not depicted in Fig. 11, the isotopic composition of the brackish-water benthic foraminifer *Ammonia beccarii* picked from seven levels throughout the core agrees well with the depicted trend in the ostracod's composition.

DISCUSSION

The cores from the Marker Wadden project are of particular interest for the late Quaternary history of the Netherlands as during this time interval the definite configuration of this part of the country took place. At the beginning of the Holocene, the sea level was still low and the Dutch coast was largely open. After the last glaciation large east-west flowing rivers cut into the Pleistocene deposits. Gradually temperatures ameliorated, sea level rose, the coast closed and the present day Lake IJssel was created. The core clearly shows the main sedimentary elements of this history e.g. clear quartz sands in the lower part, followed by peat formation and clays/silts containing marine shells.

The oldest sediment found in the core are quartz sands deposited during the Weichselian Early and Middle Pleniglacial by a branch of the river Rhine, and belong to the Kreftenheye Formation (Peeters *et al.* 2015; Vos 2015). They are described by EM1 (Fig. 9) with a mode of 354 µm and are characteristic for transport as bedload in running water. Indeed, these sediments were deposited in the valley of the proto-Vecht, a system which originated from melting ice after the Saalian glaciation. The system originally had an east-west orientation, flowing to the sea (Lenselink 2001; Vos 2015). The age of these sediments is uncertain, but is at least older than 15 ka (Vos 2015). During the late Weichselian, these deposits were covered by aeolian sands, assigned to the Wierden Member. The grains have a mode of 210 µm (EM2) which is in the higher range of typical aeolian coversands, e.g. 105 to 210 µm (Berendsen 2008).

Fine grained sands admixed with clays and silts overlie the Wierden Member. Minor amounts of plant material and rare diatoms are present, pointing to a pioneer vegetation being established. The organic content of the samples is 2–3%. This interval is assigned to the Singraven Member, interpreted as deposited by creeks flowing to the proto-Vecht.

The Basal Peat is very thin in SD–4, probably due to severe erosion. Fully developed, it has an age of 7–6 ka B.C. The pollen samples contain dominant *Alnus* and *Cyperaceae* indicative of elevated groundwater levels associated with a rising sea level. Wetland species are common. During the ongoing sea level rise the landscape became part of an intertidal area with mudflats, belonging to the Wormer Member of the Naaldwijk Formation. This transition is clearly shown in Fig. 9 where from 800 to 560 cm coarse endmembers EM1–EM3 are gradually replaced by EM4–EM6. This fining up sequence is followed by a return to coarser sediments from 560–300 cm. In the lower part of the Wormer Member sample residues contain mainly plant debris and diatoms, indicating that marine influence was still minimal. The fining upward trend as seen in the distribution of the endmembers and the decrease in organic matter content from 50–10% is interpreted as the gradual takeover of the tidal deposits at the expense of the marsh series. From 520 cm upwards foraminifera, a mix of agglutinating and calcareous species, is present, indicating deposition at the interface between the marsh- and tidal flats. From this level upcore molluscs and ostracods are present as well. The presence of complete growth stages and doublets of the ostracods points to in situ deposition.

From 300–200 cm sediments are very finely grained with a mode of 26 and 9 µm respectively (EM5, EM6) indicating low-energy conditions. They are assigned to the Flevomeer, generally considered to be fresh water sediments. In the lower part two intervals are present containing common shell fragments and abundant specimens of the benthic foraminiferal species *Ammonia beccarii*. As the directly under- and overlying sediments are devoid of both molluscs and foraminifera, these layers are interpreted as storm layers (Troelstra *et al.* 2016). Characteristically, marine indicators such as foraminifera are mainly absent from this interval. Instead the ostracod *Cyprideis torosa* is common. Of interest is that both smooth and noded specimens of this species are found. Noded specimens are suggested to be indicative of lowered salinities (Van Harten 2000; Frenzel *et al.* 2012). Fig. 11 shows that indeed the noded form has lighter stable oxygen isotope values compared to the smooth specimens.

The freshwater character of the Flevomeer is not confirmed by the stable oxygen isotope record of the ostracod *Cyprideis torosa* through the core. Fig. 11 shows that neither a full marine nor a freshwater phase can be claimed. Heaviest values of 2.0‰ were recorded at 279 cm, but this concerns a specimen of *Ammonia beccarii* from a postulated storm layer. Near the top another specimen yielded a value of 2.2‰. Lightest values of -6.8‰ were recorded in a specimen of *Cyprideis torosa* from the Flevomeer. The isotope record of *Cyprideis* through the core shows a pattern of 3.5 cycles in the brackish realm between 'more fresh' and 'more marine'. This feature requires more investigation in adjacent cores to establish if this is a consistent pattern.

Of particular interest is the presence of *Abies alba* and *Picea abies*, two species originating from the Black Forest, Germany. It shows that connection between the river Rhine or one of its tributaries, probably the proto-Vecht, and Lake Flevo existed. The presence of pollen of cereals and *Plantago lanceolata*, indicate anthropogenic activity in the direct surroundings of Lake Flevo.

The overlying Almere Layer shows an increase of sandy and silty suspended load (EM3, EM4). In association with ostracods and molluscs, foraminiferal species make their re-appearance indicating the connection with the marine realm. The lower boundary of the Almere Layer is given at 400 B.C. (Vos and De Vries 2016). Around this time the peat rivers were connected with the Waddenzee though the Flevo lakes (Vos 2015). Through peat erosion the Zuiderzee gradually took shape (Van den Biggelaar *et al*. 2014).

Sediments attributed to the Zuiderzee Layer constitute the top of core SD-4. The sand content increases and the samples contain common marine molluscs, foraminifera and ostracods. The marine connection ended with the construction in 1932 of a 32.5 km long dam, after which a new lake was born, the fresh water Lake IJssel.

CONCLUSIONS

The multiproxy approach taken in the analysis of a pulse core from the Marker Wadden area, Lake IJssel, has resulted in a refined reconstruction of the Holocene palaeoenvironment compared to previous studies. The fresh water character of the Flevo Layer is not confirmed, on the contrary, brackish water conditions prevailed during much of the late Holocene, as shown by the stable isotope analysis on ostracod valves. Where previous archaeological analysis of the Markermeer cores did not find evidence for human occupation, the pollen study in this paper indicates that anthropogenic activities in the immediate surroundings did take place. Furthermore the presence of pollen from Black Forest (Germany) provenance prove that a connection between the general Rhine system and the research area did already exist during deposition of the Flevo Layer sediments.

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