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A staged geogenetic approach to underwater archaeological prospection in the Port of Rotterdam (Yangtzehaven, Maasvlakte, The Netherlands): A geological and palaeoenvironmental case study for local mapping of Mesolithic lowland landscapes

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ABSTRACT

This study presents the geogenetic approach to detect presently drowned archaeological sites in the transgressive palaeoenvironment of the Holocene Rhine-Meuse delta. A staged and practical approach is advocated in which subsurface archaeological predictions are based on geological mapping and palaeoenvironmental reconstruction of the underwater location. The study area is located in the Maasvlakte harbour extension of the Port of Rotterdam, formerly a part of the southern North Sea. Prior to construction works, it was suggested that dredging of the new harbour (Yangtzehaven) would disturb the subsurface stratigraphy to around −21 m below present mean sea level, a zone which is known to contain archaeological remains. The staged approach makes use of geological data starting from a conceptual model that indicates the depths of layers that could be rich in Upper Palaeolithic/early Mesolithic artefacts. This initial model is used to determine the strategy of the subsequent phases of investigation, such as whether to proceed with dredging as part of the engineering work, down to 17 m water depth, to remove the upper (younger) sands and thereby improve the opportunities for underwater survey of fluvio-deltaic layers of Mesolithic age. Following the development of the initial site model, a full-area investigation was carried out using geophysics and coring, the latter providing material for palaeoenvironmental analysis. This allowed the reconstruction of the long-drowned former landscape, which included inland dune areas and local drainage systems and provided the physiographic context for the geoprospection of Mesolithic archeology. This predictive modeling identified two areas in the harbour for detailed investigation, again employing geophysics and coring at higher resolutions, allowing fine tuning of the palaeolandscape models at the localities of presumed highest archeological potential. Cores from one of the selected areas, an inland dune area within the Early Holocene wetland region, yielded in-situ evidence of Mesolithic occupation of this site in what is now the southern North Sea. These finds and the palaeolandscape context created with the data from the prospection phases were critical in the decision to undertake an underwater archaeological excavation using a large, boat-mounted grab sampling system. This paper provides an account of the geological and palaeoenvironmental work undertaken in the prospective phases leading up to the discovery of the site, highlighting the importance of the staged geogenetic approach for informing sampling strategies and securing high-quality information on landscape contexts, which in turn, informed archaeological decision-making and geoprospection strategies. Such an approach has wider generic application for palaeolandscape reconstruction and mapping at regional scales.

1. Introduction

The archaeological potential of the continental shelf has long been recognized (e.g. Fischer et al., 2011). Driven by fluctuations of

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Fig. 1. Location of the Yangtze harbour within the Maasvlakte area (Port of Rotterdam, the Netherlands).

many tens of metres in sea-level change over the Pleistocene and Early Holocene, many prehistoric archaeological sites and palaeolandscapes around the coastal margins are now submerged. Consequently, it is not uncommon to find scattered traces of Palaeolithic and early Mesolithic human activity in shallow coastal waters (e.g. Momber, 2000, 2011; Hijma et al., 2012; Stapert et al., 2013; Bicket et al., 2011). Underwater archaeological investigation has recently experienced renewed interest (Peeters et al., 2009; Peeters, 2011; Peeters and Cohen, 2014). Fitch et al. (2005) and Gaffney et al. (2007) ascribe the increasing activity on the one hand to developments in the archaeological sciences and, on the other hand, to improved technologies for reconstructing palaeolandscapes such as those of the Dogger Bank area in the central North Sea. Compared to archaeological campaigns on land, underwater investigations are particularly challenging in terms of costs, risk of failure and data uncertainties (Bailey, 2004). Consequently, an underwater archaeological study is typically carried out at substantially less sampling resolution than an equivalent terrestrial study. Palaeogeographic reconstruction (i.e. the creation of 'palaeolandscape models' based on a combination of geological mapping, dating and palaeoenvironmental research), is an essential methodology for determining areas of preservation and targeting geological surfaces with high archaeological potential (e.g. Schmölcke et al., 2006; Bailey and Flemming, 2008; Bailey and King, 2011), especially in drowning coastal areas that have experienced tectonically subsidence and/or sea level rise, such as the southern North Sea (Cohen et al., 2014). Furthermore, the development of palaeolandscape models is essential to place archaeological finds in their environmental context when discovered.

Site investigation using multiple techniques is key to the construction of palaeolandscape models. Geophysical methods are commonly applied in offshore environments (e.g. Gaffney et al., 2007; Van Heteren et al., 2014). Comparison and correlation of geophysical data with more rarely available *in-situ* data such as borehole logs, allows for the identification of relevant layers in the geophysical data (ground truthing). Furthermore, by combining information on Holocene sea-level rise with the elevation of the youngest terrestrial palaeosurfaces on the seabed, former environmental conditions, location of human settlement and movement/migration patterns can all be understood (e.g. Veski et al., 2005; Dolukhanov et al., 2010; Stock et al., 2013). With such knowledge charted in archaeological prediction maps, site prospection and heritage management efforts can be focused on the areas with the highest potential for finding archaeological remains, enabling systematic, efficient geoprospection, recovery, and protection of large, archaeologically sensitive areas.

This study presents the application of an innovative, staged methodological approach for predictive underwater landscape mapping, developed as part of an archeological investigation in the Yangtze harbour site (Maasvlakte, Port of Rotterdam). The Yangtze harbour was extended and deepened to connect the Maasvlakte 2 new seaward harbour extension of the Port of Rotterdam (The Netherlands; Fig. 1) to the existing Maasvlakte 1 extension that was built in the 1970s and early 1980s. Maasvlakte 2 is the latest enlargement of the Port of Rotterdam, one of the largest and busiest harbours globally. Construction work started in 2007 and the interconnecting harbour was built in several stages; in total, it is approximately 3 km long and 500 m wide, an area of about 1.5 km^2. In 2009 most of this area was deepened to 17 m −(NAP; this is the Netherlands ordnance datum and equates to present mean sea level). By the end of 2011 the harbour was dredged to the maximum depth of 20 m −NAP, destroying the former Late Pleistocene land surface and the Early Holocene deltaic deposits covering it, including archaeological-bearing strata. In order to mitigate the destruction of the cultural and environmental remains, geological and archaeological surveys were undertaken between 2009 and 2011 with the aiming of identifying potential archaeological heritage remains (Smit, 2011). The final cut-through and creation of the harbour occurred in 2012 (Fig. 2) and the area has since been renamed the Yangtze canal. The works are scheduled to finish in 2014.

From previous regional geological mapping it was known that a complex stack of deposits of Late Pleistocene and Early Holocene age was to be encountered at the broad depth range of 17–25 m −NAP, below the bed of the proposed extended and deepened harbor (Hessing et al., 2005; Moree et al., 2012; Weerts et al., 2012).

Fig. 2. Aerial view of the Yangtze harbour after the cut-through of the harbour between Maasvlakte 1 and 2 in 2013.

Therefore, from the initial planning stages of the harbour extension (2005), it was known that Palaeolithic and Mesolithic heritage might be present in the deposits that would be dredged and removed at depths of between 15 and 22 m below Mean Sea Level (MSL).

Therefore, from an archaeological mitigation perspective, it was important to consider if sites would be encountered during excavation of the harbour floor, since changing the harbour location or depth of construction to conserve any potential remains was not be an option, and neither would dry pit archaeological excavation be practical. Hence, the research question at the start of the project was to develop the best methodology to prospect for archaeology in the Pleistocene and Holocene terrestrial deposits that were to be removed. An underwater survey of the seabed by divers was not regarded as efficient, because the potential archeology surfaces and layers occurred a few metres below the proposed harbour floor and divers could not reach these. Therefore it was decided that mapping and sampling of the shallow geology of the harbour floor was the best way to reconstruct palaeoenvironments and to prospect for submerged archaeological remains. A good insight into the palaeolandscape would help to identify optimal locations where prehistoric humans may have frequented, which in turn, would provide targets for sampling. This approach starts from palaeolandscape reconstruction and is an extension of 'the geogenetic approach' (cf. Groenendijk and Vos, 2002), which is designed to enable near-shore underwater archaeological prospection.

Importantly, in a geogenetic approach, archaeological prospection is addressed at the level of discrete lithological units that make up the subsurface stratigraphy (Vos and Bazelmans, 2002). From initial stages, for each unit that might be encountered, a palaeoenvironmental assessment is made, including the chances of encountering archeology in each unit. The approach in the Yangtze harbour project is comparable with that of Tizzard et al. (2011) and Bicket et al. (2014) as applied to an area of the North Sea floor 11 km off the Great Yarmouth coast (Norfolk, England); comparison of the two areas (and others) is considered further in the discussion section of this paper.

The archaeological investigations were undertaken to comply with Dutch laws based on the EU Valletta Convention on the Protection of Archaeological Heritage (1992). Other initiatives for this region include the North Sea Prehistory Research and Management Framework (NSPRMF; Peeters et al., 2009), which aims to organize the study and preservation of the submerged archaeology of the North Sea. The Port of Rotterdam reserved a budget for the Archaeological Research Program Maasvlakte 2, as part of an agreement with the national heritage agency of the Netherlands (Rijksdienst voor het Cultureel Erfgoed; RCE). A permanent archaeological committee Maasvlakte 2 was established to coordinate heritage protection at the various locations of engineering work for the harbour extension, of which the Yangtze harbour project was one part (see also: Weerts et al., 2012).

The committee included representatives of: the port authorities (Port of Rotterdam); the national heritage agency (RCE); the engineering consortium responsible for the construction of the Maasvlakte 2 (PUMA); the Bureau for Archaeological Studies of the Municipality of Rotterdam (BOOR) and; the Research Institute Deltares (Dept. of Applied Geology and Geophysics). Stages and procedures implemented throughout the investigation in the Yangtze harbour were discussed at depth and formalized by the committee.

The investigations in the Yangtze harbour were executed by BOOR and Deltares in co-operation with TNO Geological Survey of the Netherlands, surveying contractor Marine Sampling Holland, and archaeological investigation contractor ADC ArcheoProjecten. In later phases of the project, after the discovery of archaeology and the decision to excavate had been made, further sub-contractor parties were included. The process was supervised by the Cultural Heritage Agency of the Netherlands (RCE). The results of this palaeolandscape research have been incorporated into the Arch-Manche project, which is part of the European Interreg IVa Program.

2. Geogenetic approach in the Yangtze harbour project

Research over the past few decades, including work related to the construction of Maasvlakte 1, had shown that fluvial deposits of Pleistocene age in the area contained Stone Age archaeology. Palaeolithic and Mesolithic discoveries were found *ex-situ* in sand used to construct the artificial beach of the Maasvlakte 1 area in the 1970s and 1980s (Louwe Kooijmans, 1975, 2005; Verhart, 1988, 2005). The sands used to create the harbour extension and its beaches, were mainly Late Pleistocene and Early Holocene fluvial deposits, excavated from dredged harbours and offshore locations immediately surrounding the Maasvlakte, from depths of about 20–40 m −NAP (e.g. Hijma et al., 2012). The proposed works in the Yangtze harbour would disturb the same geological levels, but on this occasion the opportunity existed to record the sediments of the harbour floor before dredging commenced and hence prospect for *in-situ* submerged archaeology.

The area of investigation of the Yangtze harbour, the study area, is provided in Figs. 3 and 4. As the geological framework provided the foundations of this investigation, a lithological–geological layer model of the study area was developed and maintained through the various phases of the staged approach. Besides new data collected for this archaeological project, the model incorporated the site investigation and geotechnical engineering data collected for the larger Maasvlakte 2 project, as well as archived data from earlier construction projects. The sedimentary environments represented by the various lithological units (lithofacies) were logged, mapped and described. Subsequently, an assessment was made of the time period in which each of the lithofacies was formed, based on regional insights of sea-level rise (e.g. Hijma and Cohen, 2010). With this information, a palaeolandscape model was constructed, in which the most promising archaeological locations could be highlighted, allowing the next steps of surveying strategy to be determined.

For each lithological layer in the model, the archaeological potential was evaluated and the likelihood of finding artefacts assessed, on the basis of the palaeoenvironmental conditions during and after the deposition of the sediment layer. Earlier studies suggested that the top of the Pleistocene substrate was expected at about 20–22 m −NAP, represented by a buried valley floor formed at the end of the Last Glacial (Van Staalduinen, 1979; Busschers et al., 2007; Busschers, 2008), with inland aeolian dunes forming local topographic highs (Kasse, 1995; De Groot and De Gans, 1996; Hessing et al., 2005; Hijma et al., 2009). Previous research has shown that these 'river dunes' are particularly promising localities for Mesolithic and Early Neolithic settlement within past wetland environments (e.g. Louwe Kooijmans, 1980; Louwe Kooijmans, 1985, 2005; De Ridder, 2000). In the absence of direct dating, the age-model for the top of the fluvial sand included information on terrace stratigraphy (subtle height differences; lower is younger) and style of aeolian cover (sheets of coversand are older, isolated dunes are younger). Depth and thickness of floodplain overbank facies also provided indirect age information (thicker/deeper bases are more proximal to younger channels; Hijma et al., 2009). These sandy sediments are covered by deltaic peat and clay layers, associated with submergence of Holocene landscapes. The age-model of these deposits includes information on post-glacial sea-level rise and they are part of a transgressive sequence that culminated in the Rhine-Meuse delta in the Middle and Late Holocene (landward

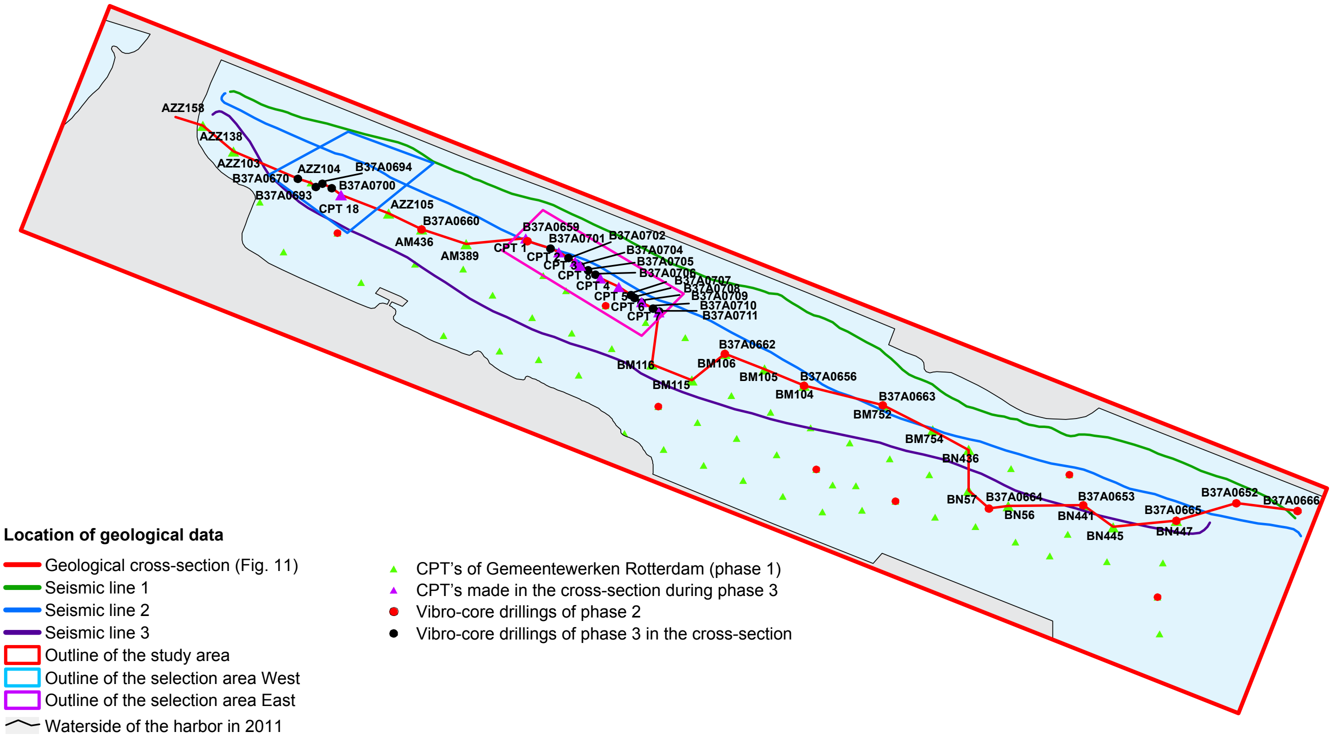


Fig. 3. Location map of the Yangtze harbour study area.

shifting of the landscape zones depicted in Fig. 5). Trangression buried the valley landscape including the dunes that had persisted since the first millennia of the Holocene. Over a large area of the harbour floor, an Early Holocene drowned landscape lies preserved from this time period. At the time of the transition of the Boreal to the Atlantic (about 7000 BC) the study area comprised a fluvial landscape (conceptual model in Fig. 6; analogue modern environment in Fig. 7), with swampy flood basins that received freshwater from the main channels of the Rhine and Meuse river system (Hijma et al., 2009; Hijma and Cohen, 2011); the river mouth was to be found further offshore (Hijma et al., 2012; Sturt et al., 2013). In this landscape, local channel systems in the floodplain were

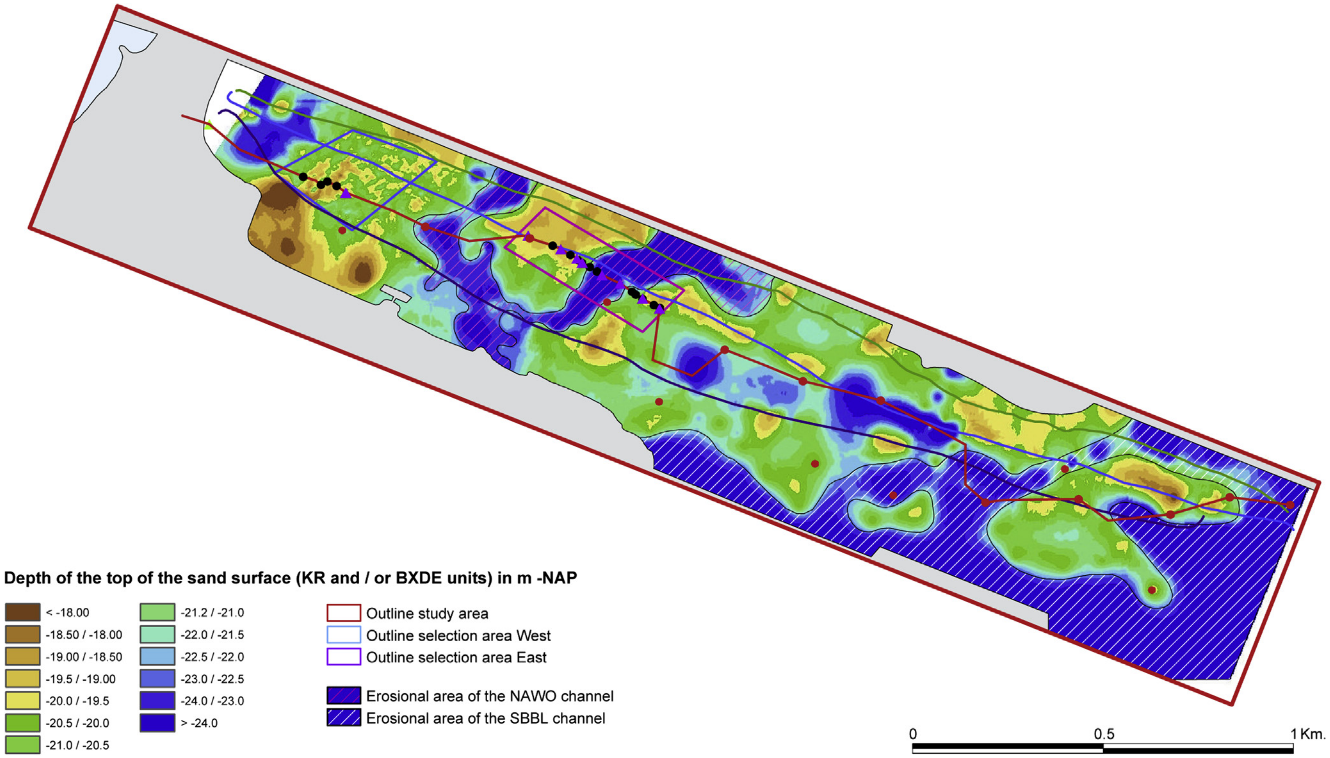


Fig. 4. Map of the top of Late Pleistocene/early Holocene sand surface (top of the KR and BXDE units) of the Yangtze harbour study area.

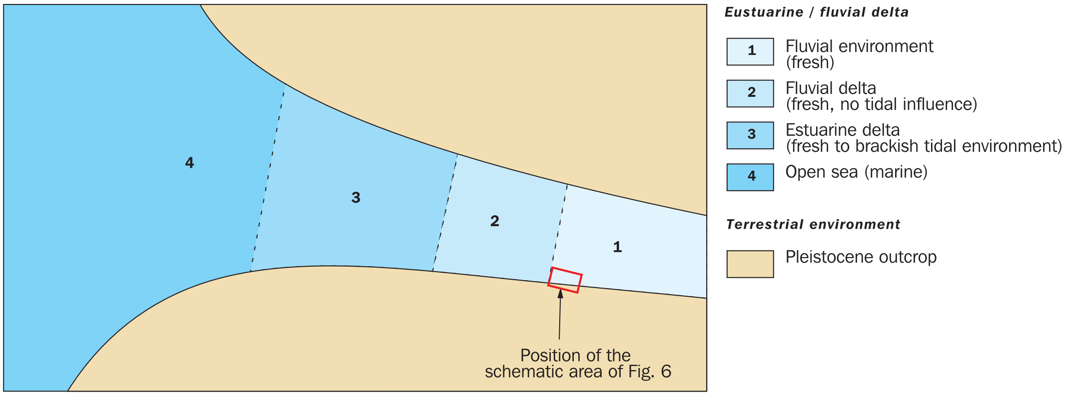


Fig. 5. Schematic classification of the main landscape types within a funnel shaped river mouth. The position of the Yangtze harbour around 7000 BC in this schematic area is shown with a box (see also Fig. 25).

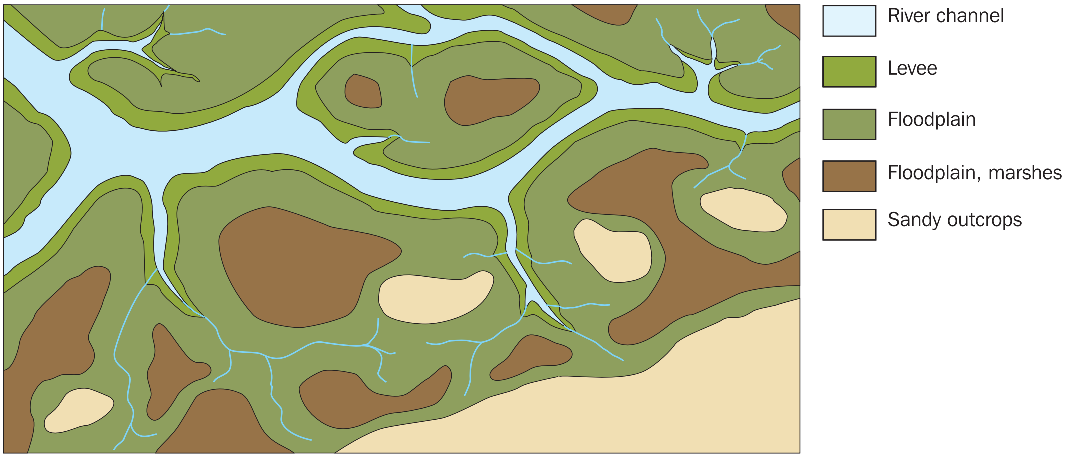


Fig. 6. Schematic representation of the sedimentary environments in the Yangtze harbour area around 7000 BC (box in Fig. 4).

assigned a higher likelihood for the presence of archaeology because it was assumed that humans would move through these waterways and settle along the edges of these channels. Overlying this sequence, at a depth of about 17 m −NAP, marine sands occur. Associated marine tidal channel structures have locally eroded the older sequence, and therefore these zones were regarded as being of low stone-age archaeological potential. The investigation thus aimed to trace the different depositional environments at a depth of between 17 and 22 m −NAP and to select the most promising archaeological locations for excavation (Vos et al., 2012; Fig. 8).

The investigation of the study area was a multi-phase process, with three stages of mapping and sampling for prospection, culminating in the fourth phase of excavation by means of large-grab sampling:

Phase 1: **Desk study**, capture, process and interpret existing geological data. Young anthropogenic overburden dredged away. Survey design Phase 2

Phase 2: **Implementation of the inventory field survey** (survey and coring). Analysis and reporting of the palaeolandscape data

Fig. 7. Contemporary aerial view of the Cumberland Marshes in Canada (Van Asselen, 2010), a representative picture of the landscape of the Yangtze harbour around 7000 BC.

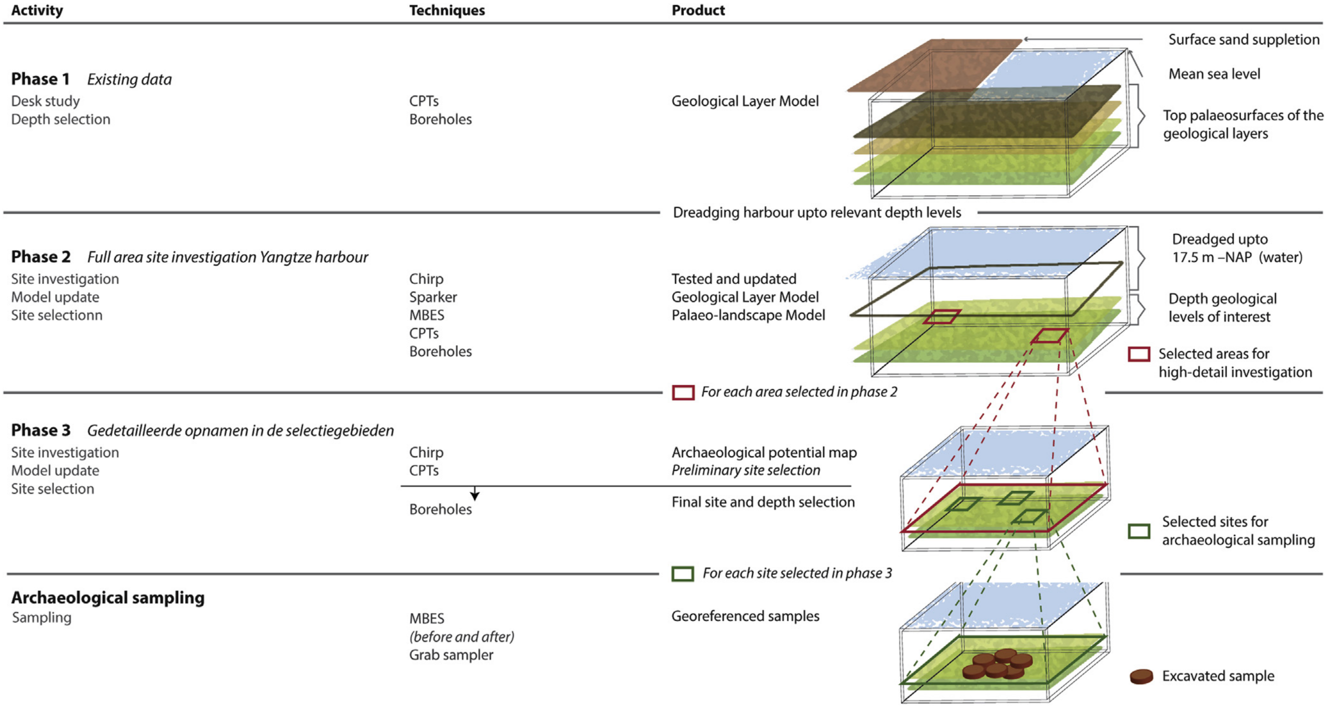


Fig. 8. Geogenetic, staged approach applied in the prospection study of the Yangtze harbour. For each phase, the activities carried out, the techniques used products delivered are mentioned.

Decision on selection of areas for high-density survey Phase 3 (two areas)

Phase 3: **Detailed investigation in two selected areas** (survey and coring). Analysis and reporting of the palaeolandscape data Decision-making for archaeological excavation Selection of locations for excavation by large-grab sampling (pits 1–3)

Phase 4: **Execution of archaeological excavation** (using a crane from a pontoon). Archaeological assessment of the sampled materials Archaeobotanical and archaeozoological assessment of the sampled materials. Completion of reporting palaeolandscape results. Integration of palaeolandscape results with archaeological results.

From each project phase, detailed technical reports listing and discussing the results have been produced in Dutch (listed in a subsection of the reference list). The results of each phase were used to define the approach of the next phase. The first tentative results of this approach were preliminary reported by Weerts et al. (2012). The results of the project include a 360-page report (in Dutch) outlining the main results of the prospective phases, the results of the archaeological excavation phase, and a synthesis placing the findings in a regional context as well as digital appendices (Moree and Sier, 2014). An English translation of the report is in production and is expected late 2014. From this body of primary data, this paper extracts the geological and palaeoenvironmental strategies and results and outlines how this information was fed into the archaeological decision process.

2.1. Phase 1: desk study, capture of existing local data

In the first phase an estimate was made of the most likely depth of possible archaeological remains. Using existing data from Cone Penetration Tests (CPTs) and geotechnical boreholes drilled for the construction of the harbour, a preliminary geological model of the study area was built. At this stage (2007), the surface area of the plan was still about 5 m + NAP. For the study area 133 CPTs were available (Figs. 3 and 4), of which eight were coupled to boreholes. Most of the CPTs penetrated down to the Pleistocene substrate, thus including the relevant layers. The cone resistance and friction parameters obtained with the CPTs were calibrated with the lithological units through correlation with the borehole log and subsequently grouped into a geological model. In the model, the palaeosurfaces representing the top of the Pleistocene sand and the top of the deltaic deposits were interpolated between data points (using Kriging techniques) and manually adjusted for inconsistencies.

The surfaces in the palaeolandscape model of phase-1 represent the interfaces between different geological formations. As such, the model serves to draw the first hypotheses to delineate the higher sand outcrops, the fluvio-deltaic environment and the complex of (Sub-atlantic) tidal channel incisions. This palaeolandscape model was used to provide the first estimate of the depth levels associated with the areas of highest archaeological potential and to make a plan for the next step in the research, the fieldwork associated with the full site investigation of the study area.

2.2. Phase 2: full study area site investigations

At the start of this phase, it was particularly beneficial that the younger marine sands and modern anthropogenic debris, derived from the construction of Maasvlakte 1, had been removed by dredging down to 17 m −NAP, prior to the archaeological surveys. This brought the great advantage of allowing seismic surveys and relative low-cost sampling of the interval between 17 and 22 m −NAP by means of vibrocore drillings (reaching 5-m below the dredged harbour floor). Geophysical site investigations were carried out using an Edgetech X-Star Chirp Sub Bottom Profiler and a Geo-resources Sparker system (Vos, 2013). The Chirp was configured at a wavelength of 30 ms, with frequencies of 0.5–7.2 kHz. The Sparker was configured with a signal energy of 400 J with a recording length of 100 ms and survey was carried out in single-channel as well as multi-channel modes. Position information

Fig. 9. Image of the Yangtze harbour cores in sediment description laboratory of Deltares/TNO in Utrecht.

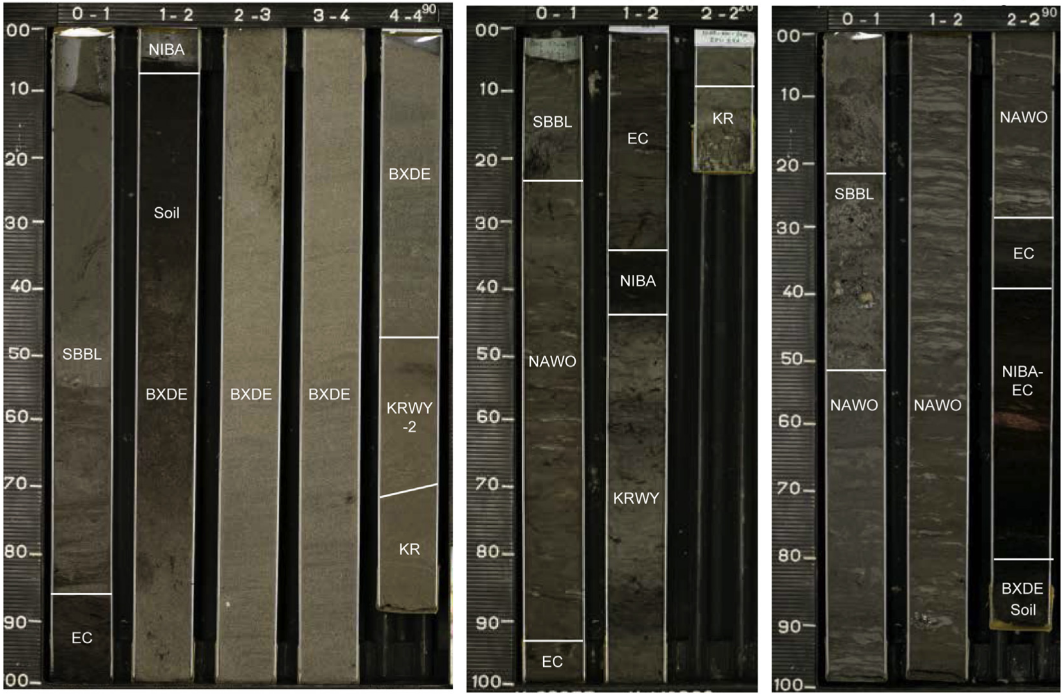
was provided by a DGPS system. Both surveys were carried out at a speed of 2–3 knots. Shortly after the site investigation, a multibeam survey (MBES) was performed to accurately determine the bathymetry of the full Yangtze harbour. Seventeen boreholes were drilled from the seabed using a Vibrocore system, with a sample core length of 5 m. As the Early Holocene clay deposits were very stiff, the core experienced high friction, yielding 2.2–4.5 m recovered sample length. All the cores were photographed in the laboratory (Figs. 9 and 10).

In the part of the harbour which had been dredged down to a depth of 17 m, three large west–east running lines (transects) were surveyed (seismic lines 1–3, Figs. 3 and 4) with the Chirp and Sparker systems. The records showed good results. The palaeosurfaces of the top of the Pleistocene fluvial sand (including the river dune sands) and the top of the organic and clayey deltaic deposits were clearly visible on the seismic reflection images. Also the tidal channel incisions were easily recognizable on these images, allowing the spatial distribution of these features to be reconstructed. In the western part of the study area, palaeodune topography was visible on the seismic profiles, though these features had not been recognized as such in the CPT data analysed in phase 1 because the cones resistance was relatively low and variable; hence these sands had been erroneously interpreted initially as a gully facies.

Seventeen vibrocores were taken to yield high-quality information on the sedimentary characteristics of the lithological layers of interest between 17 and 22 m −NAP (Fig. 10). The layers are classified according to the lithostratigraphical classification of the Netherlands (Törnqvist et al., 1994; Westerhoff et al., 2003) and are described in Table 1.

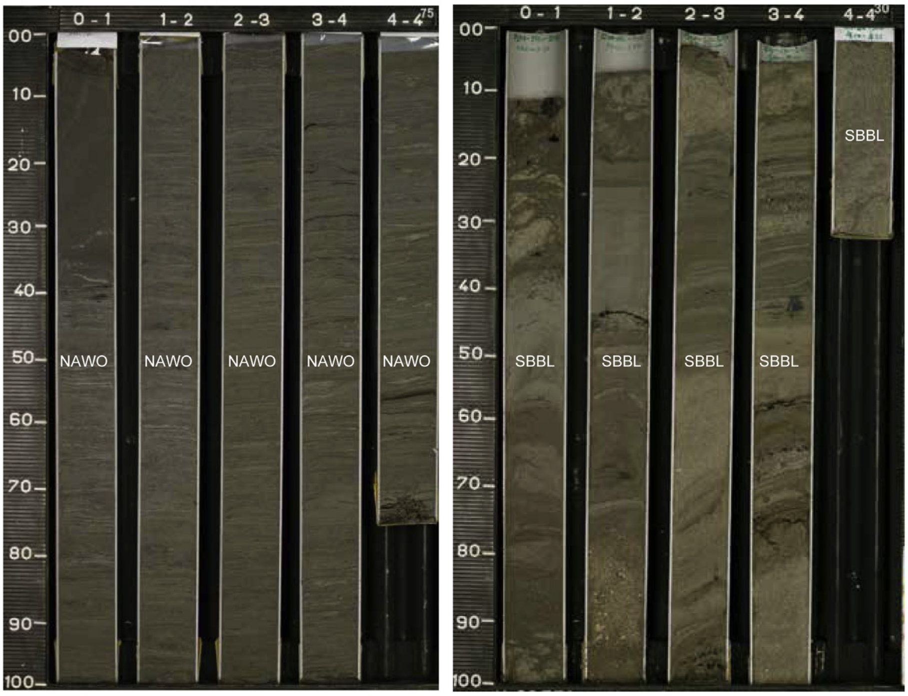
Table 1
Description of the lithostratigraphic units encountered between 17 and 22 m −NAP.

Unit	Code	Lithology, lithofacies	Depositional environment	Age
Kreftenheye Formation, undifferentiated	KR	Medium fine to coarse sand (150–300 μm), poor in humus, top laminated with clay or loamy layers	Floodbasin of meandering river, “upper bar” facies shifting to a “lower overbank” facies to the top (Hijma and Cohen, 2011)	Late Glacial/Pre-boreal
Kreftenheye Formation, lower layer of the Wijchen Member	KRWY-2	Laminated, grey loam, sandy clay and clayey sand. Layer is generally a few cm to tens of cm thick and found under the river dune sands (BXDE)	Lower overbank deposits in the fluvial floodplain	Pre-boreal
Boxtel Formation, Delwijnen Member	BXDE	Well sorted fine sands, median grain size 150–210 μm. Where not eroded, a dark humus soil is present in the top.	Aeolian sands, river dune	Pre-boreal
Kreftenheye Formation, Wijchen Member Where the KRWY layer is separated by dune sands, this layer is called the “upper” Wijchen layer.	KRWY	Stiff grey clay, medium to high silt content. At the base, very loamy and laminated with fine sand layers. Dark zones are present in the layer which consist of charred plant material and fine charcoal particles (Kappel and Exaltus, 2013). To the top the layer gets increasingly rich in organic matter.	Lower overbank deposits in the fluvial floodplain	Pre-boreal/Boreal, up to about 7000 BC
Formation of Nieuwkoop – Basal Peat Member	NIBA and NIBA-EC	Amorphous, compact, brown to dark brown peat. Macroscopic plant remains fragments of reed, roots and small pieces of wood. The layer is generally clayey, clayey peat (NIBA) and peat clays (EC) alternate	Peat bog, frequently flooded and parts permanently underwater. Peat formation is the result of rising groundwater table; freshwater, no direct marine influence.	Boreal/Atlantic, about 7250–6500 BC
Echteld Formation	EC	Silty clay, grey brown, humus to strongly humos and often laminated on humusness On top of the NIBA-EC layer. Wood remains and reed roots are present. In the top, also thin layers of silt occur.	Tidal floodbasins and Interdistributary bays. Subaquatic deposits, freshwater to slightly brackish, marine contact, fresh-water tidal environment.	Atlantic, about 6500 –6250 BC
Naaldwijk Formation, Wormer Member	NAWO	Clay, grey, poor in humus, strongly silty and layered with few to many sand layers. Marine shells remains are not present.	Predominantly sub-aquatic deposits formed in a tidal estuary. Slightly brackish to brackish.	Atlantic, younger than about 6250 BC
Southern Bight Formation, Bligh Bank Member	SBBL	Marine deposits, very fine to moderately coarse sand	Off-shore environment (“sea sands”) and channels of the tidal inlet of the estuary.	Sub-Atlantic/sub-recent age.


B37A0676: River dune sequence

B37A0653: Delta/floodplain sequence

B37A0680: Delta/dune sequence


B37A0706: NAWO-channel sequence

B37A0652: SBBL-channel sequence

Fig. 10. Four sediment cores from the base of the Holocene in the Yangtze harbour area. For the location and stratigraphy, see Figs. 3 and 11 (B37A0652, B37A0653, B37A0706) and Figs. 17 and 21 (B37A0676).

With the phase-2 results collected the geogenetic paleolandscape model was revisited and improved. At this stage, three palaeosurfaces were identified and modelled: the top of the sand surface (top of KR and BXDE unit); the top of the peat and clay layers (top of the combined unit of KRWY, NIBA, EC and NAWO); and the seafloor elevation in the harbour at the time of survey (spring 2011). The palaeosurface of the top of the sand within the study area was the main layer of archaeological potential and interest. This surface, generated from the 3D model, is depicted in Fig. 4. In the western part of the study area a higher river dune area (elevation higher than 20 m −NAP; yellow-brownish colour) was recognized and in the middle and south-eastern parts of the area, tidal channel incisions were recorded. The vibrocore data pointed out that the central palaeochannel fill consisted of Middle Holocene NAWO deposits and the south-eastern channel fills comprised Late Holocene SBBL deposits.

The sedimentary sequence of the harbour floor as mapped in 2011 is shown in a geological west–east cross-section. For the

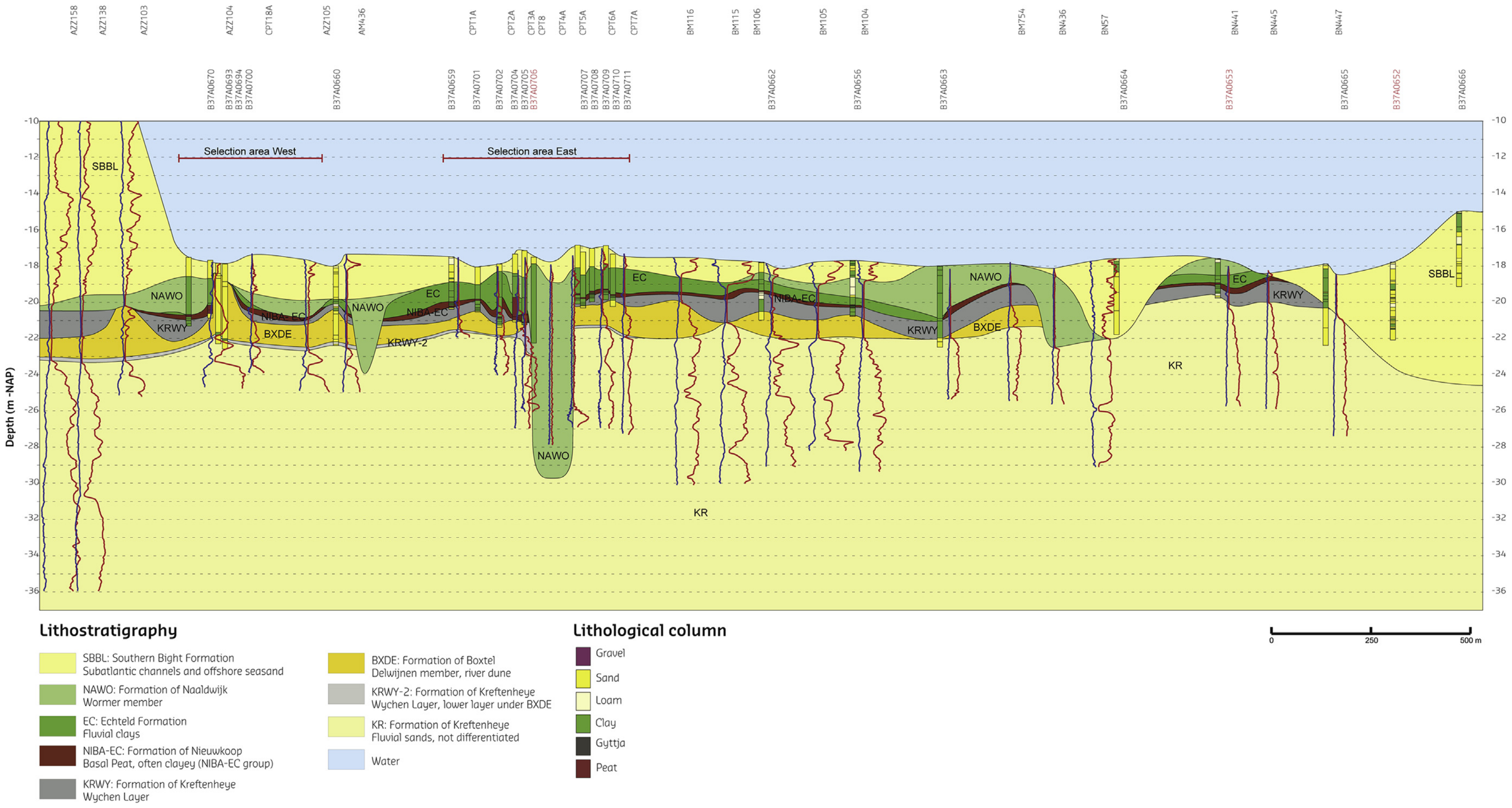


Fig. 11. Geological west – east cross-section through the Late Pleistocene/early Holocene deposits of the study area. Location profile, see Figs. 3 and 4.

location of the drilling- and probe data used to construct the geological profile, see Fig. 11. The top of the sand surface (KR and BXDE sand) ranges from *circa.* 27.5 m −NAP within the eroded parts to 18.5 m −NAP in the highest parts of the river dune. The west–east channel incision in the central part of the profile dates from the Atlantic (NAWO layer: greenish colour), whilst the channels in the eastern part from the Sub-Atlantic (SBBL layer: yellowish colour). The latter category is much sandier and has a larger grain size than the NAWO channel deposits which are laminated with fine sands and thin clay layers. Where the marine have not been incised deeply, the SBBL unit blankets the material at a level of around 19 m −NAP. The contact between the marine sands and the deltaic deposits is always erosive, as is the interface with the top of the river dune (borehole B37A0700; Fig. 11); thus, originally the river dune body was higher. It is estimated that the original top of the dune may have lain at about 15–16 m −NAP, which means that after its formation at the beginning of the Holocene, the top of the dune probably stood 4–6 m above its surroundings.

The top of the KR sand surface to the west of the BXDE sand dune body is around 23.5 m −NAP (CPT AZZ138) and is not eroded. Towards the east, the KR river sand rises to ~19.5 m −NAP (borehole B370653). Overlying the fluvial KR sand, the KRWY layer has been deposited (gray colour). This layer had a thickness of 0.1–1.0 m; the height difference between them may amount to more than 2.5 m. Despite the height differences this layer exhibits the same lithological characteristics throughout the study area. At the base, the KRWY clay layer is grey, loamy and laminated with thin sand layers. Towards the top, the clay layer gets increasingly darker and contains more and more organic material. Furthermore, the layer contains one or more dark intercalated zones, consisting of clay with carbonized plant remains and fine charcoal (Kappel and Exaltus, 2013).

The KRWY layer is wedged against the BXDE sand body between 20 m and 19 m −NAP. Directly beneath the dune sand body a loamy clay layer occurs at a depth of 22 m–23 m −NAP. These are counted as belonging to the KRWY-2 layer. Lateral to the dune sand body, clay layers of the KRWY and KRWY-2 units merge together and form one unit. The NIBA layer (brown colour), which is situated on top of the KRWY layer and/or BXDE sand, also exhibits a wavy surface. The lowest level of the base of the NIBA layer lies around 21 m −NAP in the study area and the highest level of NIBA base is around 19.5 m −NAP. In terms of clay incorporation and thickness (a few cm to 0.5 m) the peat varies from place to place. The NIBA layer is covered by EC clays and laminated clays of the NAWO layer unit. The EC – NAWO clays may gradually merge into each other but can also have an erosive contact in places where NAWO channel deposits have incised into the underlying sediments.

To obtain direct age-estimates for each geological unit in the study area, a suite of radiocarbon (^{14}C) and optically stimulated luminescence (OSL) samples were taken from the cores (Tables 2–6). Samples were also taken from core material derived from the two areas selected for more detailed study during phase 3 (W and O sample codes). The ^{14}C-dating (Tables 2–5) was carried out by laboratories in Põznan (Poland; Poz nrs.) and Groningen (Netherlands; GrN nrs.) on organics in the KRWY, NIBA, and EC layers. The OSL dating was carried out by the Netherlands Centre for Luminescence Dating (NCL) in Delft (nowadays relocated to Wageningen; Table 6). Protocols and technical details can be found in a separate report (Project NCL-7612; Wallinga and Versendaal, 2014). Calibration of radiocarbon dates was undertaken using OxCal 4.2 (Bronk Ramsey, 2009) and IntCal13 (Reimer et al., 2013).

By the end of Phase 2, a first round of ^{14}C dates had been produced by the lab and these were used to plan Phase 3 and Phase 4 activities.

Table 2
^{14}C dates on charcoal within the Wijchen bed (Unit KRWY).

Borehole number	Sample code	Litho-stratigraphy	Material	Depth m −NAP	Lab. nr.	^{14}C date BP	2-S range cal BP	Median BC
B37A0653	657-M7/197	KRWY	Charcoal	19.03	Poz 36916	8390 ± 50	7570–7472	7472
B37A0653	653-M2b/160-166	KRWY–black soil	Charcoal	18.98	Poz 36910	8040 ± 50	7137–6770	6956
B37A0653	653-M1b/188-194	KRWY-black soil	Charcoal	19.21/19.27	Poz 36909	8630 ± 80	7939–7535	7670

Table 3
^{14}C dates on materials from the base of the Basal Peat (Unit NIBA).

Borehole number	Sample code	Litho-stratigraphy	Material	Depth m −NAP	Lab. nr.	^{14}C date BP	2-S range cal BP	Median BC
B37A0653	653-M3/143	NIBA on top of KRWY	Fine matrix	18.76	Poz 36913	7660 ± 50	6599–6433	6506
B37A0707	East-7/272,5-275	NIBA – clayey, on KRWY	Macro remains	19.59/19.62	GrA 55010	7755 ± 40	6649–6483	6581
B37A0711	East-11/235-238	NIBA – clayey, on KRWY	Macro remains	19.70/19.73	GrA 55012	7875 ± 40	7023–6610	6726
B37A0673	West-4/213-216	NIBA on BXDE	Macro remains	19.85/19.88	GrA 54926	7880 ± 55	7029–6606	6753
B37A0675	West-6/226-228	NIBA on BXDE	Macro remains	19.90/19.92	GrA 54928	8030 ± 60	7135–6699	6939
B37A0675	West-6/226-228	NIBA on BXDE	Macro remains	19.90/19.92	GrA 54928	8030 ± 60	7135–6699	6939
B37A0675	West-6/226-228	NIBA on BXDE	Macro remains	19.90/19.92	GrA 54928	8030 ± 60	7135–6699	6939
B37A0697	West-28/222-223	NIBA on KRWY/BXDE	Macro remains	20.31/20.32	GrA 54924	8100 ± 50	7305–6832	7093
B37A0674	West-5/270-272	NIBA – on KRWY/BXDE	Macro remains	20.35/20.37	GrA 55016	8220 ± 40	7355–7078	7237
B37A0692	West-23/305-310	NIBA – clayey On BXDE	Macro remains	20.76/20.81	GrA 55038	8230 ± 40	7448–7082	7248
B37A0688	West-19/319-321	NIBA – clayey, on KRWY	Macro remains	20.87	GrA 55018	8160 ± 40	7306–7061	7147
B37A0705	East-5/393-395	NIBA – clayey, on KRWY	Macro remains	21.09/21.11	GrA 55001	8135 ± 40	7298–7049	7124

Table 4
^{14}C dates on materials from the upper part of the Basal Peat (Units NIBA and NIBA-EC).

Borehole number	Sample code	Litho-stratigraphy	Material	Depth m −NAP	Lab. nr.	^{14}C date BP	2-S range cal BP	Median BC
B37A0653	653-M4/135	NIBA-clayey	Fine matrix	18.95	Poz 36943	7560 ± 60	6559–6251	6423
B37A0705	O-5/351-355	NIBA-clayey	Macro remains	20.68/20.71	GrA 55002	7635 ± 40	6589–6429	6476
B37A0707	O-7/275	NIBA-clayey	Fine matrix	19.61	GrA 55034	7715 ± 40	6633–6470	6545
B37A0711	O-11/224-226	NIBA-clayey	Macro remains	19.59/19.62	GrA 55011	7565 ± 40	6481–6368	6433
B37A0674	W-5/244-246,5	NIBA-clayey	Macro remains	20.09/20.12	GrA 55015	7720 ± 40	6635–6473	6548
B37A0692	W-23/260-262	NIBA-clayey	Macro remains	20.31/20.33	GrA 55031	7760 ± 40	6651–6484	6589

Table 5
^{14}C dates on plant material from the freshwater-tidal clays of the Echteld Formation (Unit EC).

Borehole number	Sample code	Litho-stratigraphy	Material	Depth m −NAP	Lab. nr.	^{14}C date BP	2-S range cal BP	Median BC
B37A0655	655-M6/40	EC	Root of reed	16.08	Poz 36915	7360 ± 50	6350–6088	6230
B37A0653	653-M5/112	EC	Wood	18.45	Poz 36914	7300 ± 50	6326–6051	6155
B37A0659	659-M8/157	EC	Root of reed	18.81	Poz 36942	7400 ± 50	6409–6102	6294
B37A0656	656-M10/206	EC	Wood	19.83	Poz 36908	7300 ± 40	6231–6071	6154
B37A0656	656-M9/221	EC	Wood	19.98	Poz 36917	7140 ± 50	6094–5899	6016

Table 6
OSL dates on the river dune sands (Unit BXDE) and the fluvial surface below it (Unit KR).

Borehole	Sample code	Stratigraphy of sample	Depth m −NAP	Lab. nr.	Age B2K	Age BC	Bayesian cal. age BC
B37A0676	West 7/1.38/1.50	Top BXDE, humus soil	19.09/19.21	NCL-7612215	8500 ± 500	6500 ± 500	6900 ± 300
B37A0676	West 7/1.85-1.95	BXDE humus soil	19.56/19.66	NCL-7612216	10,400 ± 800	8400 ± 800	7800 ± 450
B37A0676	West 7/4.72/4.82	KR below KRWY-2	22.43/22.53	NCL-7612217	10,900 ± 700	8900 ± 700	9850 ± 350
B37A0686	West 17/1.65/1.75	Top BXDE humus soil	18.77/18.87	NCL-7612218	9900 ± 500	7900 ± 500	7750 ± 400
B37A0686	West 17/4.35/4.45	BXDE lower part	21.47/21.57	NCL-7612219	11,000 ± 600	9000 ± 600	9000 ± 350
B37A0687	West 18/2.31/2.40	Top BXDE humus soil	19.51/19.60	NCL-7612220	8400 ± 500	6400 ± 500	6850 ± 300
B37A0687	West 18/3.43/3.55	BXDE humus soil	20.63/20.75	NCL-7612221	10,700 ± 600	8700 ± 600	8900 ± 300
B37A0687	West 18/4.30/4.40	KR below KRWY-2	21.50/21.60	NCL-7612222	11,500 ± 700	9500 ± 700	9900 ± 350
B37A0694	West 25/4.20/4.30	KR below KRWY-2	22.06/22.16	NCL-7612224	12,600 ± 800	10,600 ± 800	10,050 ± 450
B37A0699	West 30/3.40/3.50	BXDE on top KRWY-2	21.38/21.48	NCL-7612225	11,100 ± 700	9100 ± 700	9100 ± 350
B37A0699	West 30/4.20/4.30	KR below KRWY-2	22.18/22.28	NCL-7612226	11,800 ± 700	9800 ± 700	9950 ± 400

Table 7
Order of dates for the Bayesian calibration of selected ^{14}C and OSL dates from area West.

```
Sequence("Area West")
   Boundary("a few dm below the top of Unit KR");
   Phase("Abandonment river system underneath dune")
   {   C_Date("7612224", -10600, 800);  C_Date ("7612226", -9800, 700);
       C_Date("7612222", -9500, 700);   C_Date ("7612217", -8900, 700);   };
   Boundary("KRWY-2");
   Phase("Aeolian activity creating the dune (Unit BXDE) ")
   {   C_Date ("7612225", -9100, 700);  C_Date ("7612219", -9000, 600);
       C_Date ("7612221", -8700, 600);                                    };
   Phase("Pit 2 burned bone 14C (Zeiler and Brinkhuizen, 2014:218)")
   {   R_Date ("GrA-56453", 9215, 45);  R_Date ("GrA-56454", 9205,        };
       45);
   Phase("Colluvial disturbance of humified top-soil on dune flanks")
   {   C_Date ("7612216", -8400, 800);  C_Date ("7612218", -7900, 500);
       C_Date ("7612215", -6500, 500);  C_Date ("7612220", -6400, 500);   };
   C_Date ("abrupt drowning event", -6500,44)                             };
   Boundary("dune top");                                                  };
```

Remark: the order of the dates is specified in CQL (chronological query language) for use in the OxCal 4.2 age-calibration software (Bronk Ramsey, 2009).

The various OSL dates from within the BXDE unit (Table 6) show a 2000-y spread in mean age, that is larger than the error (±500–800 years). Dates from near the top of darkened humic soils on the dune sides (boreholes B37A0676 and B37A0687) are relatively young (6500 ± 500 BC; Early Atlantic, Fig. 12) and these presumably date colluvial processes reworking sediment around the affected dune flanks, and do not date aeolian activity forming the dune. Micromorphological studies on the cored material provides independent indications for such mass-movement processes (Kappel and Exaltus, 2013), following soil formation on the dune (Vos and Cohen, 2014). With the exception of these dates that constrain colluvial processes, the remaining OSL-ages from the dune sand date the aeolian activity that created the landform.

Inland dune formation in and along the Rhine-Meuse palaeovalley and further upstream, is known to have peaked in the Younger Dryas and Pre-boreal (Verbraeck, 1974; Kasse, 1995; Berendsen and Stouthamer, 2001; Hijma et al., 2009). The results collected in this study confirm that picture of activity (notably in selection area West), indicating that dune formation peaked in the Pre-boreal, around 9000 BC. In isolation, the OSL age-ranges would suggest dune formation up to 8000 BC and ^{14}C dating of burnt bone collected alongside Mesolithic archaeology recovered in Phase 4 (Zeiler and Brinkhuizen, 2014:218) suggests it ceased by 8500 BC (Vos and Cohen, 2014). When all OSL and ^{14}C dates from area West are combined and calibrated in sequence (Table 7), main dune formation is bracketed between 9100 and 8900 BC and colluvial processes reworking humified dune top-soil are dated to between 7800 and 6800 BC (Table 6).

The episode of dune formation separates two periods of *floodplain* sedimentation in the study area: the dune-covered lower KRWY-2 unit (ca. 9500 to 9000 BC; Table 6) and the dune-foot overlying Unit KRWY (ca. 8500 to 7500 BC; Table 1). On relatively higher parts of the dune flanks, the KRWY floodplain facies (stiff clays of typical bluish colour, somewhat pedogenically modified; Törnqvist et al., 1994; Hijma et al., 2009) appear to have continued forming until 7000 BC (in the late Boreal, Table 2). At that time, however, lower areas in the landscape had begun collecting wetter *floodbasin* deposits comprising humic clays and clayey peats (Basal Peat and EC intercalations; Table 3), of varying botanic composition and facies (Bos et al., 2012).

2.3. Regional context: rise of water levels and palaeoenvironnmental change

2.3.1. Groundwater and sea-level rise

The main driver for the accumulation of the Early Holocene deposits burying the valley floor and the inland dunes was the rise of the groundwater table, for which sea-level rise in areas downstream of the study area was the main driving factor. This is the same mechanism as described in more inland parts of the Rhine-Meuse delta (e.g. Jelgersma, 1961; Van de Plassche, 1982; Kiden et al., 2002; Cohen, 2005; Hijma and Cohen, 2010), though given the downstream position of the study area, the onset is relatively early on.

At the very beginning of the Holocene (ca. 9500 BC), sea-level in the southern part of the North Sea was still low, about 35–40 m below present (Kiden et al., 2002; Sturt et al., 2013). Therefore, at this time, the central part of the North Sea, were still dry land and mainland Britian was connected with the European continent. As post-glacial eustatic sea-level rise proceeded (e.g. Milne and Mitrovica, 2008; Smith et al., 2011), the dryland of the southern North Sea was drowned and the palaeocoastline came closer to the study area (e.g. Beets and Van der Spek, 2000).

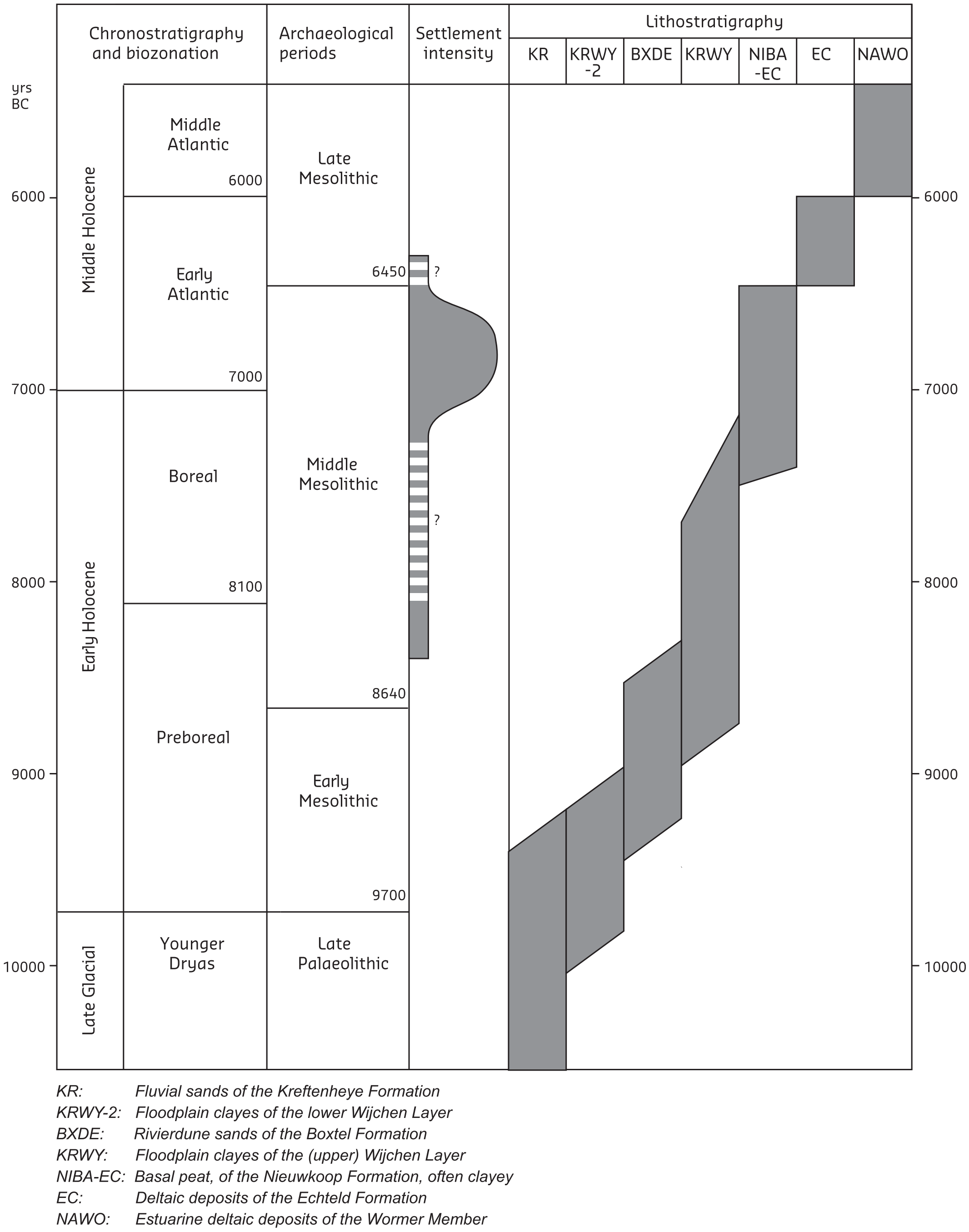


Fig. 12. Stratigraphic table of the Early Holocene, with the time stratification of the lithological units of the study area.

The results from Phase 2 (further confirmed and scrutinized using data from Phase 3; Tables 3–5) show that the study area became part of the deltaic wetlands that are the landward boundary of base level rise at the river mouth from about 7500 BC onwards. At 20.8 m –NAP Basal Peat began accumulating *ca.* 7250 BC, at 19.0 m –NAP about 6650 BC. The contact of the Basal Peat with freshwater tidal muds (EC) dates to 6500 BC, based on samples from the top of the Basal Peat (Table 4). This environment persisted until *ca.* 6000 BC (Table 5), after which the area became a sub-aqueous estuarine/shallow marine system. The results confirm and add detail to earlier palaeogeographical mapping of the wider Rhine-Meuse valley below Rotterdam (Hijma et al., 2009; Hijma and Cohen, 2012). Being positioned in the southern rim of the Rhine-Meuse river plain, the groundwater table not only rose in response to sea level rise and associated riverine flooding, but also because it affected the local groundwater tables in the coversand landscape to the south and in the dune complexes of the study area itself. The fringes of peat formation against the dune flank was affected by groundwater seepage, besides occasional river flooding (similar to areas upstream; Van de Plassche, 1982; Cohen, 2005). This meant that peat began forming decimetres higher/centuries earlier along the dune flank than it may have done at positions more central in the river plain itself at this time. The time frame 7500 to 7000 BC appears to have seen steady, though a relatively slow rise of the groundwater table, which by 7250 BC was positioned at a depth of 21.0 to 20.5 m – NAP (Table 3). Thereafter the groundwater rise seems to have accelerated a little, due to continued sea-level rise and palaeogeographic changes which saw the coast line/river mouth approach the study area as part of this transgressive phase. Around 6500 BC, peats encroached on the river dune flank to a height of approximately 18.75 m −NAP. In the period between 7250 and 6500 the rise of the groundwater table was about 30 cm per century (Fig. 13). With the rise of the groundwater table and the approaching sea, there was a general decline of floodplain gradient in the area (Van Dijk et al., 1991; Cohen, 2005; Hijma and Cohen, 2010; Van de Plassche et al., 2010), which in turn, altered conditions of river flooding and sediment delivery. In the most distal places, waterlogged by elevated groundwaters, organic deposits accumulated, while in equally wet areas that received more fine sediment delivery during floods, humic clays dominated. This explains why the Basal Peat stratigraphic level in the area (our NIBA-EC complex unit) is an intercalation of true peats (NIBA) and humic fluvial clays (EC). Therefore, sea-level rise stimulated (indirectly) the accumulation of organic and clastic deposits between 7250 and 6500 BC in the study area. If areas closer to the main Rhine channel of the time, to the north of the study area are also included (Hijma and Cohen, 2010, 2011; Vos and Cohen, 2014), peat formation can be considered to have started around 7500 BC.

At *ca.* 6500 BC, a marked change in deposition occurred in the study area. This had been postulated from dates and sea-level index points obtained 30 km upstream (Hijma and Cohen, 2010) and attributed to an event of accelerated sea-level rise (Fig. 13). The collected data for the top of the Basal Peat in the study area (Table 3) corroborates the date of 6500 BC on multiple occasions and confirms the event-like timing of submergence. The wetland terrestrial landscape (NIBA-EC) with dune topography became a sub-aqueous depositional environment, best characterized as the upper reaches of an estuary (Hijma et al., 2009; Hijma and Cohen, 2011), changing from a micro-tidal to meso-tidal regime (Van der Molen and De Swart, 2001). The cause of the sudden drowning of the study area and the creation of the transgressive contact is the result of a sea level ‘jump’ and associated change in the tidal range. The timing of this event conspicuously coincides with dating of the abrupt drainage of the Laurentide proglacial Lakes Agassiz and Objibway in Canada; furthermore, the 8.2-ka North Atlantic cold climate event that followed drainage (Leverington et al., 2002; Wiersma, 2008), provides an extra reason to explain the repeated

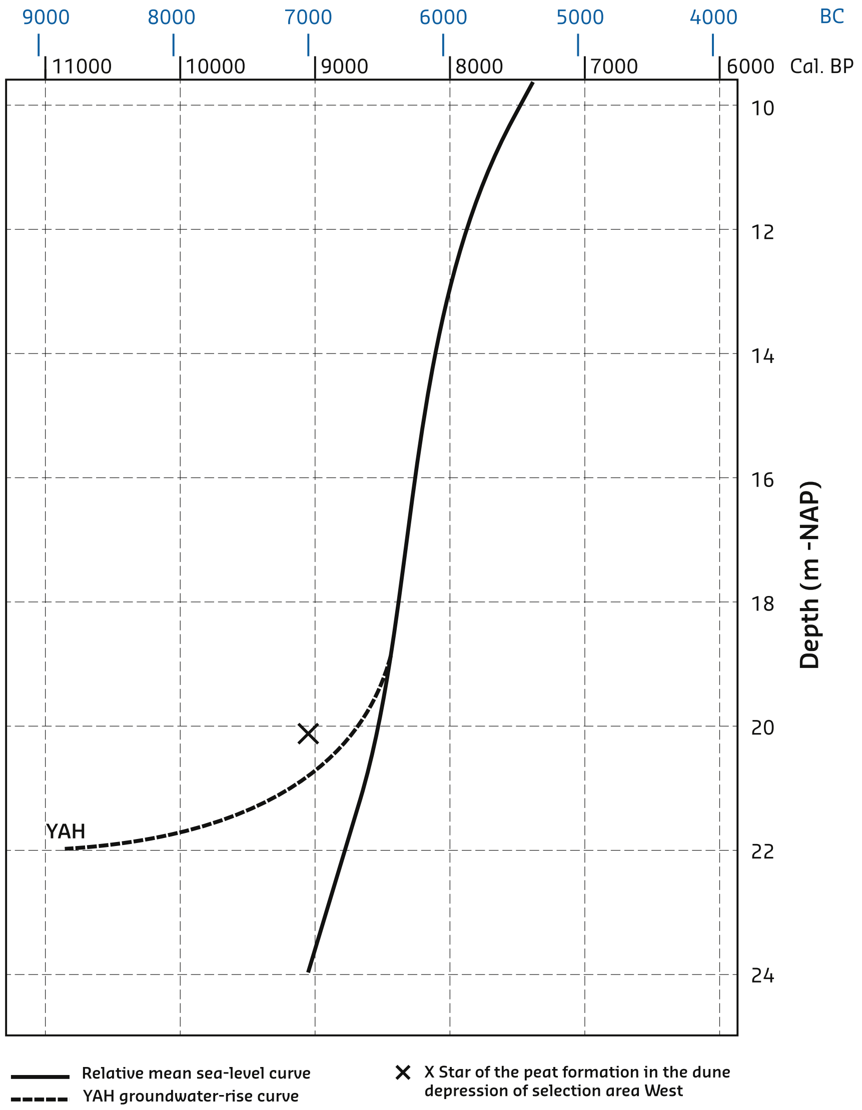


Fig. 13. Time–depth curves of the Early Holocene sea-lever and groundwater table rise. After Hijma and Cohen, 2010 and data of the Yangtze harbour area (groundwater curve).

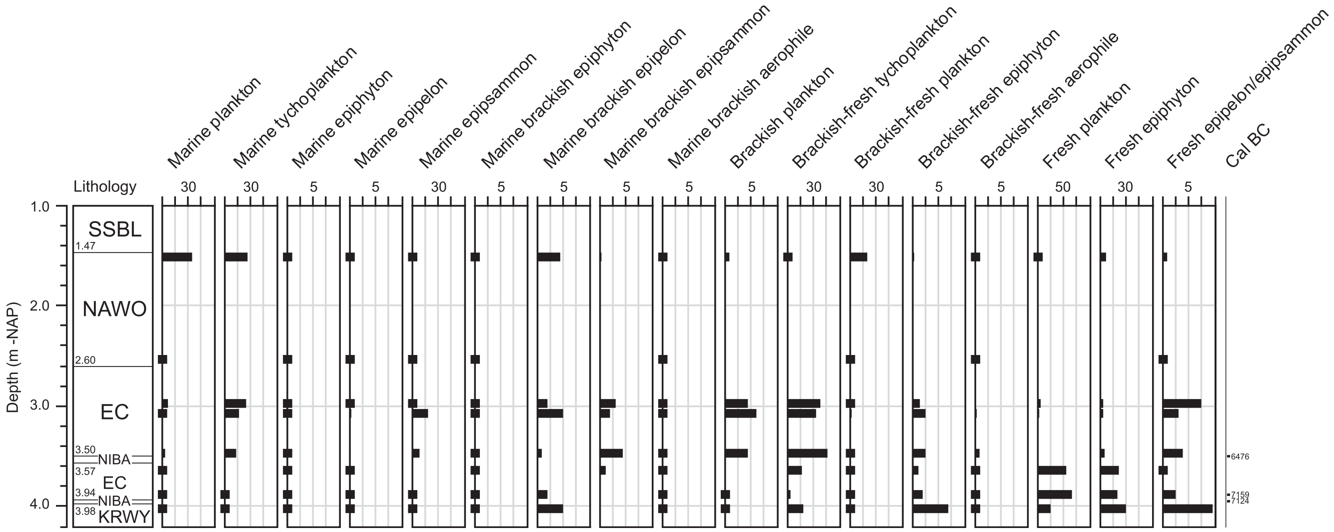


Fig. 14. Diagram of percentages of the relative abundance of the ecological diatom assemblages (groups) analyzed in samples of different lithological units present in the cores of borehole B37A0705 (selection area East).

reproduction of top-of-basal peat ages of 6500 BC in the wider Rotterdam region (Hijma and Cohen, 2010; Törnqvist and Hijma, 2012). Just as sea level had been rising before the 6500 BC ‘jump’, it also continued to rise afterwards at a rate decelerating from 1 m per century to decimetres per century, which made that waters continue to deepen for millennia afterwards. The region transformed into an estuarine delta and eventually became an offshore area (Van Heteren et al., 2002; Rieu et al., 2005; Hijma et al., 2010). These transgressive developments based on sedimentary-geological mapping and dating of organics, can be further detailed using palaeoenvironmental information derived from pollen and diatoms.

2.3.2. *Palaeoenvironmental reconstruction*

During phase 2, a total of 77 samples of the KRWY, NIBA-EC, EC and NAWO units, derived from several borehole cores in the study area, were taken for pollen and diatom analysis. The scanning of slides provided a global palaeoenvironmental interpretation for the investigated layers (Bunnik et al., 2009; Cremer and Bunnik, 2010). This preliminary interpretation was used to enhance the palaeolandscape reconstruction, which in turn informed the archaeological expectation model of phase 3. In the last stage of the investigation, 41 pollen and 24 diatom samples were analysed (Cremer et al., 2013). In addition, eight new boreholes from selection areas East and West (phase 3) provided 80 pollen and diatom samples, which were scanned for their palaeoenvironmental significance. Twenty samples for each discipline were selected and analysed further.

A representative borehole (B37A0705) in which the whole sequence of KRWY, NIBA-EC, EC and NAWO layers were present, was investigated using pollen and diatoms. The borehole was located in selection area East and a description of the research on this borehole is presented below together with the pollen and diatom diagrams (Figs. 14 and 15).

2.3.2.1. *KRWY unit: 4.10–3.98 m below HB (Harbour Bottom; 21.26–21.14 m –NAP)*

2.3.2.1.1. Diatoms. The diatoms in this layer were dominated by four ecological groups (Vos and De Wolf, 1993): freshwater epiphytes, freshwater plankton, brackish- and freshwater tychoplankton and freshwater epipelon/epipsammon. At the species level, the following freshwater species were found most commonly: *Epithemia adnata* (epiphyton), *Aulacoseira crenulata*, *Aulacoseira subarctica* (both plankton), *Staurosira venter*, *Pseudostaurosira brevistriata* (both tychoplankton), *Cocconeis placentula* (epiphyton) and *Amphora pediculus* (epipelon). The only marine-brackish diatom species which occured was a small number of *Gyrosigma attenuatum*, which however, also tolerates freshwater conditions. Marine diatoms were not present.

2.3.2.1.2. Pollen. The pollen sample from this layer belongs to pollen Zone A. This zone was characterized by high values of *Pinus* pollen. Apart from *Pinus* small percentages of pollen of thermophilic species such as *Corylus*, *Quercus*, *Ulmus* and *Tilia* were present. In addition, pollen of marsh vegetation (reed-sedge vegetation) and pollen from a number of freshwater plants occurred. A common type of spores in this zone was *Ophioglossum vulgatum*, a small species of fern which during the Early Holocene often occurred in relatively high percentages in near coastal sediments. Currently, this species is found mainly in wet dune valleys. Marine indicators such as pollen of salt-tolerant plants, dinoflagellates and foraminifera were absent. The high values of *Pinus* and the still relatively low values of the thermophilic species indicate a Boreal age for the KRWY layer.

2.3.2.1.3. Palaeoenvironment. The KRWY layer in borehole B37A0705 lies relatively low and along the edge of a trench-like depression (palaeostream system). The humid conditions account for the fact that the diatoms have been preserved relatively well there. In higher-level samples of the same KRWY layer of other cores the diatoms have often been corroded and dissolved by soil formation processes. The KRWY deposits were formed in a freshwater environment, which was probably permanently submerged for long periods of time. The co-occurrence of the planktonic, tychoplanktonic, epipsammic and epiphytic habitats corroborate this interpretation. The site was beyond the sphere of influence of the sea.

2.3.2.2. *NIBA-EC complex: 3.98–3.50 below HB (21.14–20.66 m –NAP)*

2.3.2.2.1. Diatoms. This layer comprised mainly species of freshwater planktonic and freshwater epiphyton habitats. Brackish–freshwater tychoplankton occured only in relatively small quantities. In the groups mentioned *Aulacoseira crenulata*,

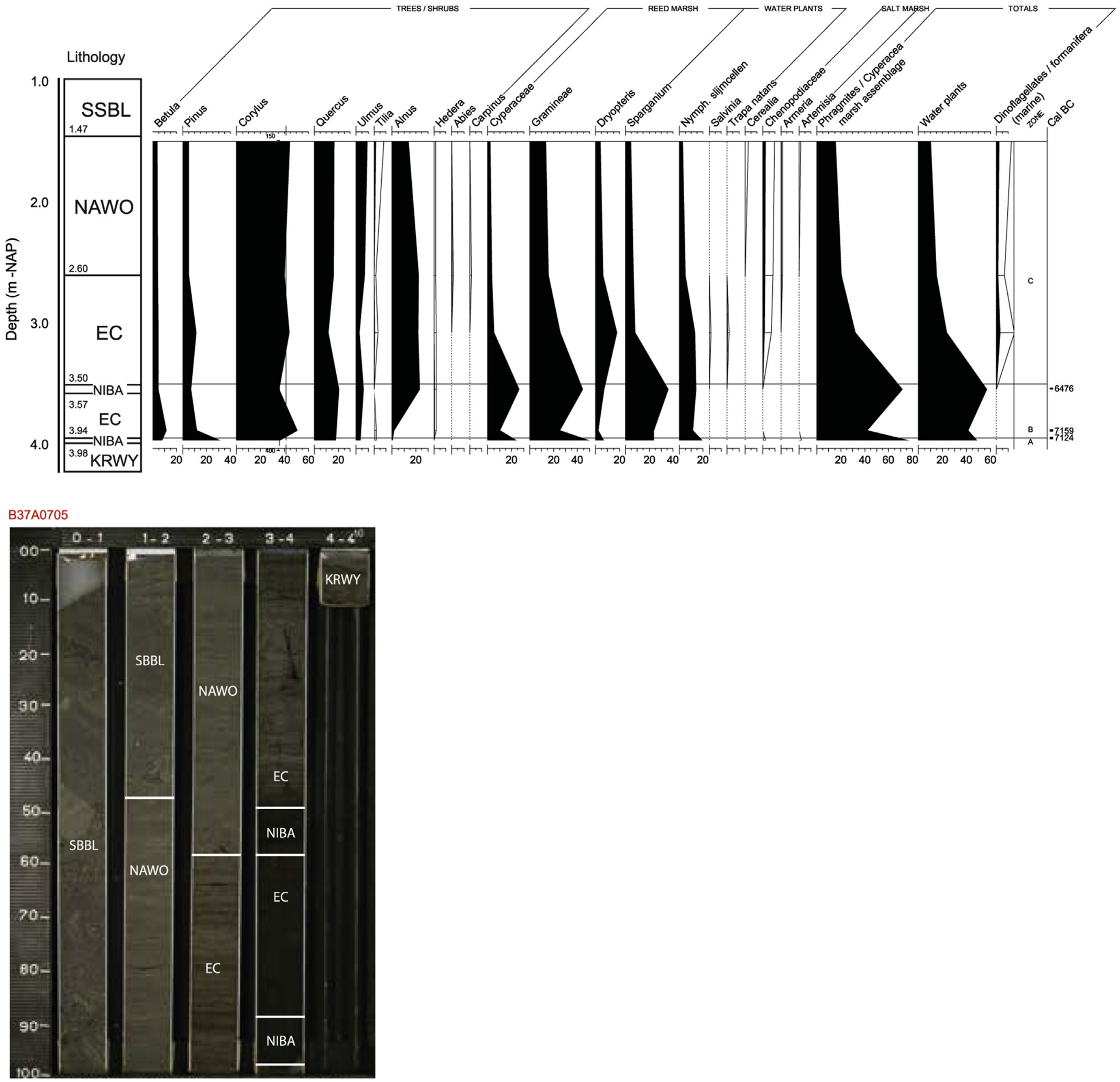


Fig. 15. Diagram of the pollen assemblages analyzed in samples of different lithological units present in the cores of borehole B37A0705 (selection area East).

Aulacoseira islandica, *Aulacoseira subarctica* (all plankton) and *Epithemia adnata* (epiphyton) were most commonly found; marine diatoms were not present.

2.3.2.2.2. Pollen. The pollen samples from the NIBA-EC group belong to pollen Zone B. In this zone, the percentage of pollen of *Pinus* clearly decreased and the percentages of thermophilic tree species such as *Corylus*, *Quercus* and *Ulmus* increased. *Hedera helix* was also found in this zone and there was a strong expansion of pollen types of marsh and open water vegetation. Apart from Cyperaceae and *Dryopteris* types, species indicating marsh fern-reed-sedge vegetation included were, *Typha latifolia*, *Sparganium* and *Alisma plantago-aquatica*. In addition, taller plants of wetland habitats were present, including *Filipendula*, *Lythrum salicaria*, *Valeriana oficinalis*, *Iris pseudocorus*, *Euphorbia palustris*, *Calystegia sepium* and Tubuliflorae. Pollen of *Brassicae* species was present and in this context, it probably originated from the marsh plants *Nasturtium* and/or *Rorippa*. Other species from wetland- and riparian vegetation include the type *Polygonum persicaria* type — here probably originating from *P. hydropiper*, *P. minus* or *P. mite*.

In this zone a diverse flora of open water habitats were present in relatively high percentages. Nymphaeoide vegetation was represented by the pollen of *Nymphaea alba* and *Nuphar luteum*, often with large numbers of intact basal hair cells and trichosclereids, indicating minimal transport and a very local origin. *Oenanthe aquatica* type, *Butomus umbellatus*, *Cicuta virosa*, *Berula erecta*, *Apium inundatum* type, *Myriophyllum verticilatum* and *M. spicatum*, *Potamogeton* and *Ceratophyllum demersum* play a role alongside algae such as *Pediastrum*, *Botryococcus*, Zygnemataceae and

Spirogyra. Noteworthy was the regular occurrence of *Salvinia natans* (a free floating water fern) and a single find of *Trapa natans* (water chestnut), a potential food plant for Mesolithic communities. Both species are known from the mid-Holocene of the Netherlands (Zandstra, 1966; Van Haaster and Brinkkemper, 1995; Out, 2010).

2.3.2.2.3. Palaeoenvironment. The diatoms in the NIBA-EC group include species that thrive in freshwater depositional environments. The species composition, with much plankton, but also epiphyton and epipelon/epipsammon, is indicative of a predominantly permanently submerged environment with aquatic plants forming masses of littoral vegetation. The pollen assemblage confirms this and suggests the presence of eutrophic, relatively deep, stagnant open ponds with littoral vegetation and wet brushwood at the edges. The clayey nature of this unit fits within this type of aquatic environment.

2.3.2.3. EC unit: 3.50–2.80 below HB (20.66–19.96 m –NAP)

2.3.2.3.1. Diatoms. In this layer, for the first time diatoms are found, originating from the marine environment. The environmental groups that occurred in the layer are, in addition to the marine habitats of marine tychoplankton, marine epipsammon and plankton, the groups of brackish-freshwater tychoplankton, freshwater epiphyton and freshwater epipelon/epipsammon. At the species level these were: *Staurosira venter*, *P. brevistriata*, *Staurosira construens* (all brackish-fresh tychoplankton), *Fragilaria sopotensis* (marine epipsammon) and *Cymatosira belgica* (marine tychoplankton). In the upper sample of this layer, the number of marine species increased slightly and included *Thalassiosira decipiens* (marine plankton).

2.3.2.3.2. Pollen. The samples from the EC layer belong to pollen Zone C. In this zone, as was the case with the diatoms, the first marine elements were found, including pollen of salt-marsh vegetation (Chenopodiacea, *Armeria*) and further foraminifera and dinoflagellates. The zone was characterised by a marked increase in pollen of *Alnus* and the occurrence of *Tilia*, in relatively low percentages. Furthermore, *Fraxinus*, *Viburnum opulus*, *Humulus lupulus*, *Frangula alnus* and *Myrica* occurred, and in addition *Hedera helix* and pollen grains of *Ilex* also occurred in very low percentages. Also in this zone marsh vegetation and other flora indicative of open freshwater plays a major role. But, the percentages of freshwater plants decreased sharply when the first marine elements of deposition occurred. The decrease in spores of ferns was clearly connected with this. The fact is that marsh ferns (*Thelypteris palustris*) – probably represented the majority of spores of *Dryopteris* type present, which a very halophobic species. Therefore the reed beds rich in marsh ferns decreased in size during the deposition of the EC layer. Also the continuing submergence of the landscape during this deposition period may have brought about the further decrease in this type of vegetation. The environmental picture provided by the pollen assemblage of this zone is characteristic of the Atlantic, which is consistent with the ^{14}C dates from the top of the NIBA-EC unit.

2.3.2.3.3. Palaeoenvironment. The diatoms and pollen spectrum show that the EC layer was formed within the sphere of influence of the sea. Relatively many diatoms of the allochthonous coast group (marine plankton and tychoplankton), foraminifera and dinoflagellates were found in the samples from this layer. These microfossil elements were supplied from the sea by tidal movements, which also caused the depositional environment to become slightly saline. The clays of the layer were deposited largely in a submerged environment of an interdistributary bay. The water in these deltaic lakes was still predominantly fresh to brackish, given the large amount of fresh and brackish-fresh pollen types and diatom species recorded. In light of the lacustrine nature of the deposits, many of the pollen species may have been supplied from elsewhere via circulating water currents. This taphonomic consideration also applies to the marine diatoms (allochthonous coastal group). The increase in these coastal allochthonous diatoms in the upper sample from layer EC indicates a continuous increase in tidal influence and salinity within the study area.

2.3.2.4. NAWO unit: 2.80–1.47 below HB (19.96–18.63 m –NAP)

2.3.2.4.1. Diatoms. In this layer diatoms of mainly marine plankton and tychoplankton groups occurred. In addition, brackish–freshwater plankton was frequently found. Ecological groups that were observed less frequently comprised freshwater epiphyton and marine–brackishwater epipelon. At the species level the most commonly recorded diatoms were: *Thalassiosira proschkinae* (marine plankton), *Cymatosira belgica* and *Delphineis minutissima* (both marine tychoplankton), *Thalassiosira pseudonana* (brackish–freshwater plankton) and *Nitzschia frustulum* var. *inconspicua* (freshwater epiphyton).

2.3.2.4.2. Pollen. The pollen samples from the NAWO layer like those of the EC layer fall in pollen Zone C. Many pollen will have been supplied from the fluvial hinterland, which explains why the pollen zones of the EC and NAWO layers are very similar.

2.3.2.4.3. Palaeoenvironment. The increasing dominance of marine plankton and tychoplankton in this layer indicates that the site was under increasing influence from the sea. The eastern tidal channel deposits of the NAWO layer also point to this assertion (Fig. 16). Freshwater diatoms were still present although in minor amounts. The occurrence of brackish-freshwater, salt tolerant plankton (mainly *Thalassiosira pseudonana*) is indicative of the brackish nature of the depositional environment of the NAWO layer. However, the relatively large freshwater supply from the hinterland is evidenced by the freshwater pollen assemblage, which is still strongly present at this level.

2.3.2.5. SBBL unit: 1.47–0 below HB (18.63–17.16 m –NAP). This unit was not investigated for pollen and diatoms. Deposits were formed in an open marine environment and for the major part are of Sub-atlantic date. The specific molluscan fauna in the younger sea sands allows for macroscopic identification of the top stratum.

2.4. Phase 3 and 4: detailed site investigation of selected areas

2.4.1. Selecting features for detailed archaeological prospection

Once the first results of Phase-2-radiocarbon samples returned from the lab, and with the first cores scanned for palynological content and palaeoenvironmental context, two selection areas (named ‘East’ and ‘West’; Figs. 3 and 4) were selected for detailed geoarcheological investigation as part of Phase 3. The scientific rationale for focusing upon these areas combined general archaeological considerations from the Mesolithic research history of the region, with the detailed palaeolandscape model generated through the geological work undertaken in Phases 1 and 2. In addition, practical matters had to be weighed into the decision (areas at the eastern entrance of the harbour would be less suitable than areas in the centre and the west). In the paper, we focus on the palaeolandscape features that made the managing committee decide to concentrate Phase 3 on Areas ‘East’ and ‘West’.

The features of most interest in Area East were the banks of a suspected palaeochannel, as mesolithic groups may have settled here, using the channel for transport through backswamp areas between the dry hinterland and the active river channel during hunting and gathering trips. It was suspected that the tidal channel (NAWO unit) followed a precursor of this fluvial channel feature: a stream system traversing the wetland from the coversand areas in the south to the main rivers in the north, and/or a residual channel

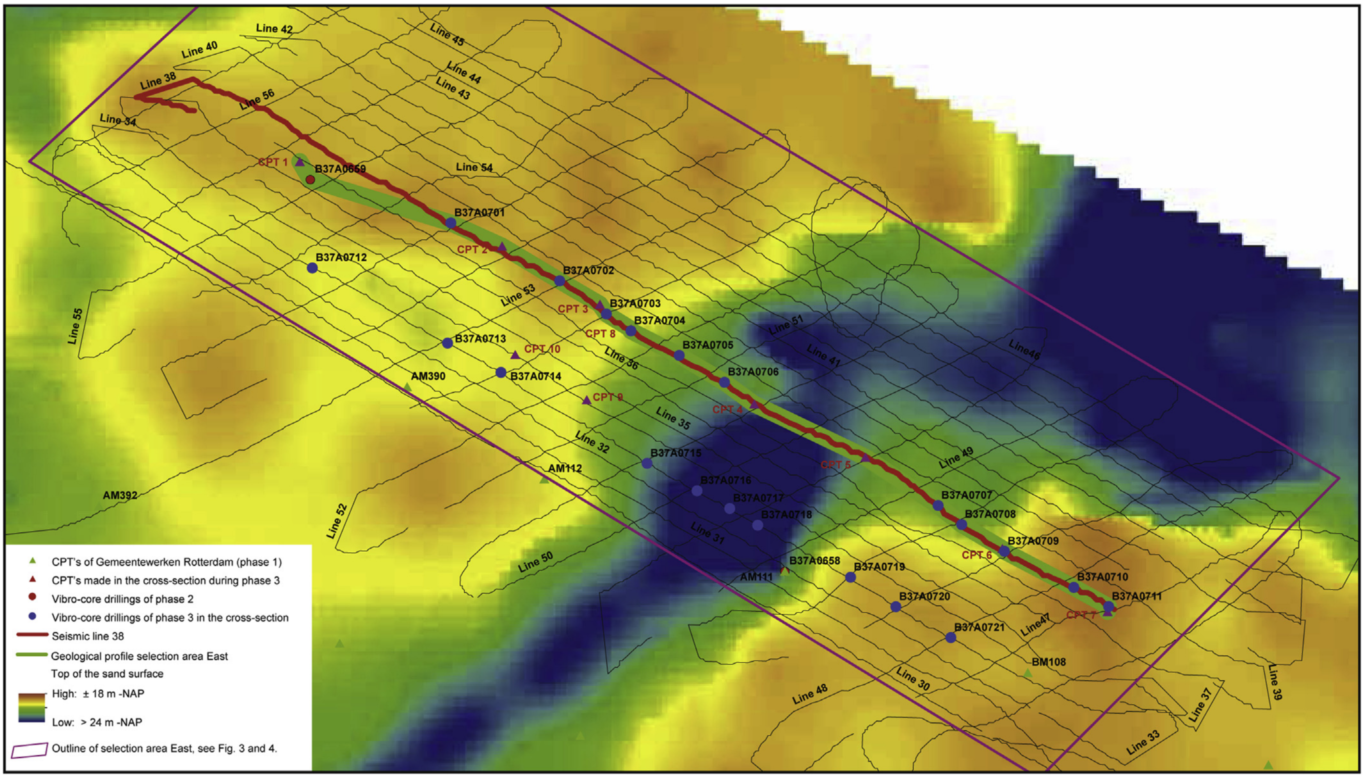


Fig. 16. Map of the top sand surface of the Late Pleistocene/early Holocene deposits of selection area East (top of the KR and BXDE units) with the location of the boreholes and seismic lines.

feature inherited from the end of the late-glacial and the time of inland dune formation (systems that could have functioned between 9500 and 7000 BC).

The feature of most interest in Area West was an inland dune complex. Previous research has shown that inland dunes are known to be rich in Mesolithic sites, and seem to have offered optimal places for settlement because of their relatively high elevation above the surrounding riverine wetlands. Based on the elevation of the dune surface (where not truncated by the marine erosion surface) and the collected basal peat dates and knowledge of sea level rise (see above), it was clear that the dune in the Yangtze Harbour would be a potential Mesolithic settlement location from an estimated 9000 BC to about 6500 BC. The initially slow groundwater rise and the resulting burial of the dune foot beneath peat and clay between 7250 and 6500 BC would on the one hand have been beneficial for preservation of archaeology, but on the other hand, reduced the available dry land area on the dune, promoting concentration of archaeological sites. The potential reduction in settlement area is similar to the concept outlined by Amkreutz (2013) for such wetland-surrounded dunes with late Mesolithic and Neolithic site concentrations further upstream in the delta.

2.4.2. Phase 3: high-resolution geophysics and dense coring

In Areas East and West, high-resolution seismic surveys with a Chirp system were carried out, and CPT measurements were made. The seismic lines in the selection areas were laid out with an in-between distance of approximately 50 m, both in longitudinal and transverse directions (Figs. 16 and 19). Based on the initial results from this geophysical investigation supplementary borehole locations were chosen. Boreholes were again drilled with a vibrocore system, yielding recovered samples of 2.3–5.0 m in length. For

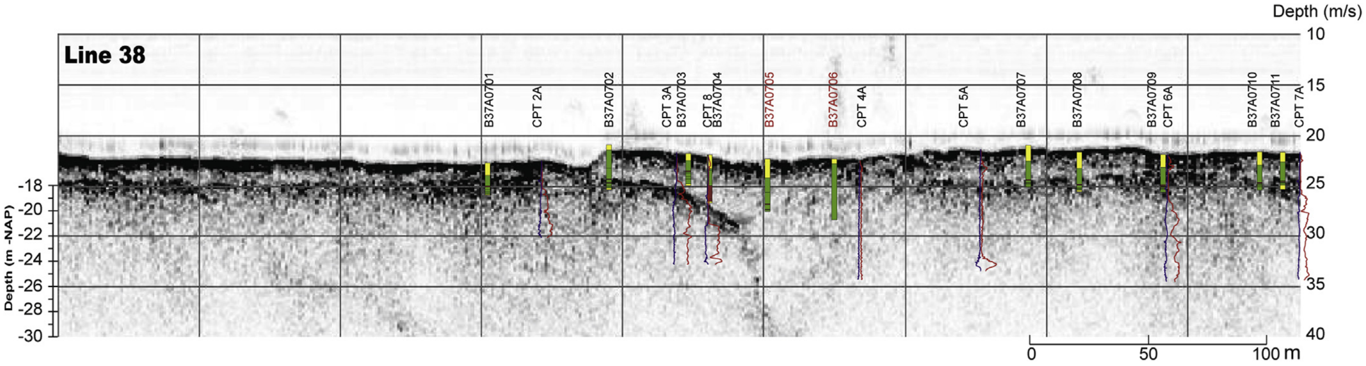


Fig. 17. Results of the seismic survey of line 38 of selection area East, including CPT and bore hole data.

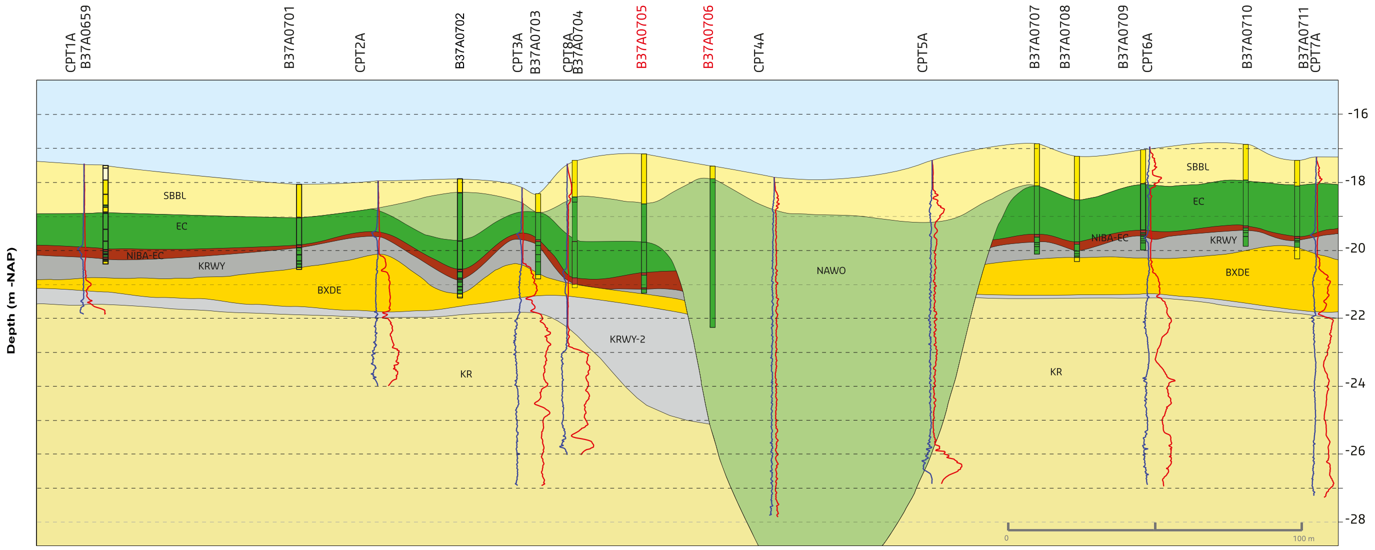


Fig. 18. East-west cross-section of selection area East, geological interpretation based on the data presented in Fig. 17. Legend, see Fig. 11.

Area East 21 holes were drilled whilst investigations of Area West comprised 31 holes.

In Fig. 17, the Chirp dataset for Area East is shown together with the CPT and borehole data on seismic line 38. This information underpins the geological interpretation in Fig. 18. The incision of the investigated palaeochannel structure is clearly visible, as is the structure of the surrounding deposits. De CPTs 3A and 8A and the boreholes B37A0703 and B37A0704 show that the western side of the channel consists of older Holocene deposits (KRWY-2, BXDE, NIBA and EC units). The main channel itself is filled in with fine layered NAWO deposits (boreholes B37A0705 and B37A0706). These deposits can reach a depth of more than 28 m −NAP, as demonstrated by the CPT 4A. The KRWY and NIBA sequence at the western side of the channel indicates that when the area was submerged and the NAWO tidal channel began functioning, it inherited the route of an older secondary channel, predating landscape submergence.

In Fig. 20, Chirp data for Area West is shown together with the CPT and borehole data on seismic line 07. The seismic reflections show a “camel's back” dune structure. The depression in between the two dune ridges (borehole B37A0680) is infilled with peat (NIBA) and clayey deposits (EC and NAWO). The western dune ridge is larger and the top is eroded (borehole B37A0682). The SBBL sea sand has an erosional contact with the dune sands (BXDE), with the original dark palaeosol missing. In oblique section, the double dune ridge structure shows up most clearly (Fig. 21). The sides of the dunes are covered by clay and peat layers of the KRWY and NIBA units to a maximum depth of 19 m −NAP.

The sediments of 21 cores drilled in Area East and 31 cores drilled in Area West were examined for the presence of archaeological artefacts. A vibrocore with a diameter of 10 cm was used for the archaeological sampling. The sandy sediments were wet-sieved over f 10 mm and 2 mm meshes. In Area West, 7 out of 31 cores contained archaeological material in the form of small flint artefacts and fine burnt bone material in the top of the dune sands (Schiltmans, 2012). The presence of this archaeology provided the critical evidence to make the decision to proceed to Phase 4 (Moree and Sier, 2014). In cores B37A0673, B37A0675, B37A0676, B37A0696 and B37A0698, fine fragments of burnt bone and flint artefacts were found. On the basis of these finds, the archaeological committee decided that these borehole locations should undergo archaeological excavation using the crane-mounted grab sampler. In the cores of Area East no archaeological remains were found and hence no further excavation was undertaken.

2.4.3. Phase 4: underwater archaeological excavation through large grab sampling

The archaeological underwater sampling was carried out with a pontoon crane (Fig. 22a) at three find locations on the river dune of selection area West. Sample Pit 1 was excavated around the borehole locations of B37A0675 and B37A0676. Pit 2 was excavated around borehole B37A0673 and Pit 3 around borehole B37A0678. Pit 1 was 6 × 16 m in size and oriented parallel to the flank of a river dune, while sample Pit 2 (9 × 12 m) was perpendicular to the river dune. The third sample location (four pits of 2 × 3 m) was excavated through the top of an eroded river dune (Schiltmans, 2012; Moree and Sier, 2014).

Multi-beam surveys were conducted at all three locations both before and after excavations, allowing for accurate positioning of the acquired samples. For locations 1 and 2, the overburden of sediment (younger sea sand) was removed to reach the depth level of archaeological potential as defined in the geological model. A buffer zone of 0.75 m was maintained to allow for modelling uncertainty in the interpolated top surface of the river dune. Underwater archaeological sampling was carried out by the grab sampler taking a predetermined volume of sediment (2 by 3 m and 0.2 m thick), with the exact location registered using an ultra-short baseline (USBL) system (Vos, 2013). Precise positioning was required to relate archaeological finds to specific geological layers and local stratigraphy. Knowing the precise position of *in-situ* finds significantly increases the scientific value of the objects and enhances future investigative campaigns.

At the surface, on the pontoon, the samples were transferred into a container with each recovered sample assessed by an archaeologist (Fig. 22b). If a sample contained river dune sediments, it was preserved. For each sample, a small portion was taken for further specialized research, while the remainder of the sediment was collected in big bags and subsequently sieved at a nearby site on the waterfront (Fig. 22c). Sieving was carried out using high-capacity sieves with mesh widths of 10 mm and 2 mm.

In total, 46067 finds were reported (Fig. 22d), comprising mainly of charcoal, flint and fragments of animal bone (Moree and Sier, 2014). Both burnt and unburnt bone fragments were found. The bones and sampled plant remains such as fruits and tubers provide

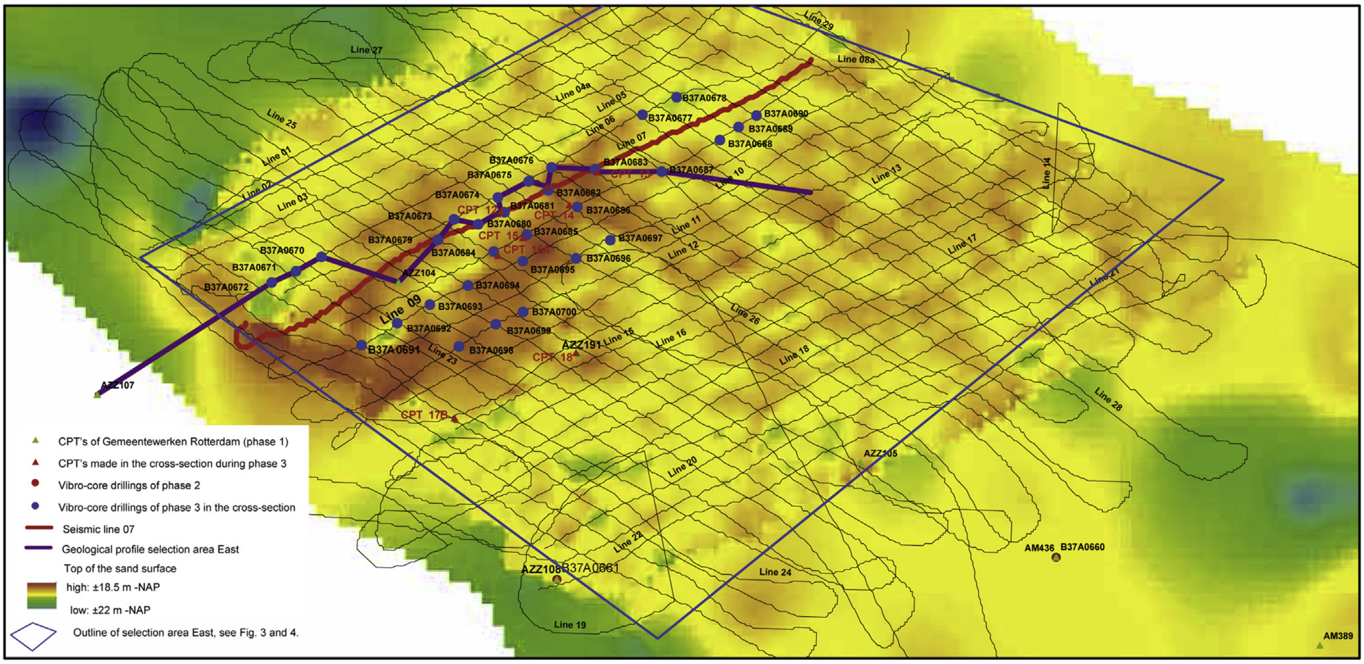


Fig. 19. Map of the top sand surface of the Late Pleistocene/early Holocene deposits of selection area West (top of the KR and BXDE units) with the location of the boreholes and seismic lines.

a good insight into the food regime of the Mesolithic people who lived on the dune (Zeiler, 2012; Kubiak-Martens et al., 2013, 2014; Zeiler and Brinkhuizen, 2014) and the lithic tools they used (Niekus et al., 2014).

The Yangtze harbour is the first site from which *in-situ* Mesolithic archaeology has been uncovered on the lower Rhine-Meuse valley floor. Previously, *in-situ* early and middle Mesolithic archaeology in the Rotterdam region had been mainly uncovered from the very top of dunes (Zijl et al., 2011; Peeters et al., 2014), and from late Mesolithic and early Neolithic contexts where deltaic swamps had encroached onto the flanks of inland dune above the valley floor (e.g. Louwe Kooijmans, 2005; Amkreutz, 2013). In the uplands surrounding the Rhine-Meuse delta, sites with scattered remains of Mesolithic flint are more regularly found (e.g. Niekus, 2006; Peeters, 2007); but here organic remains are not as well-preserved as in wetland environments such as the Yangtze harbour. The preservation of bone (some of it predating the transgression of the site by 2000 years) may have been favoured by the damp conditions at and around the foot of the river dunes. Preservation may also have been enhanced by the abrupt drowning of the site around 6500 BC and the covering of the dune surfaces with protective peat-beds and sub-aquatic sediment in the centuries following that event.

3. Landscape reconstructions zooming in to site Yangtze Harbour West

With the help of the geological and palaeoenvironmental data, gathered together during phases 1–4, the Early Holocene landscape evolution of the study area has been reconstructed in relatively high detail. Around 9000 BC the study area was situated in a predominantly dry floodplain of the rivers Rijn and Maas (Vos, 2011).

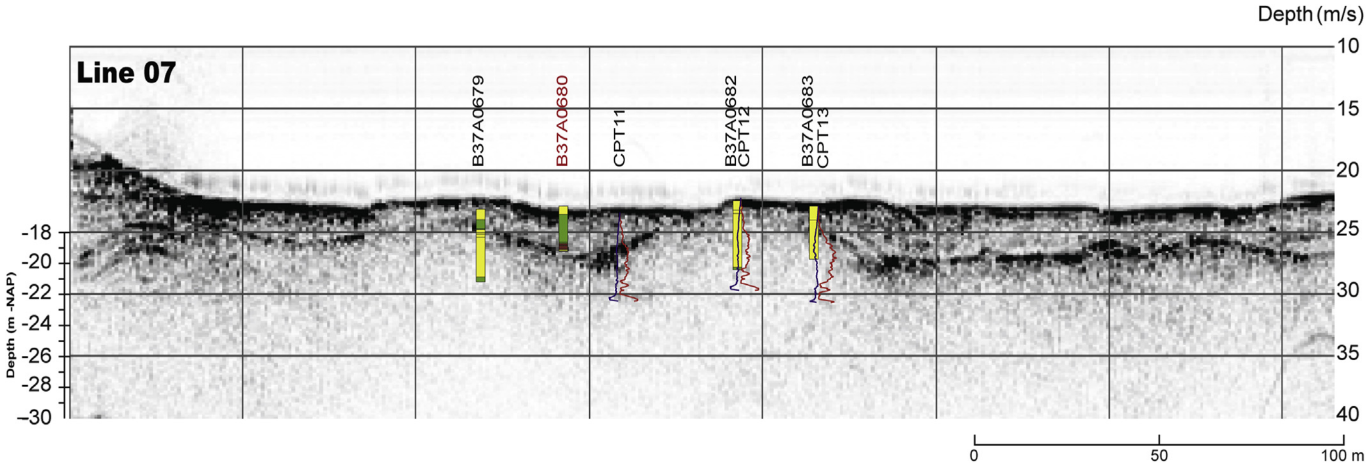


Fig. 20. Results of the seismic survey of line 07 of selection area West, including CPT and bore hole data. Borehole numbers in red are sampled for dating and palaeo-ecological analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

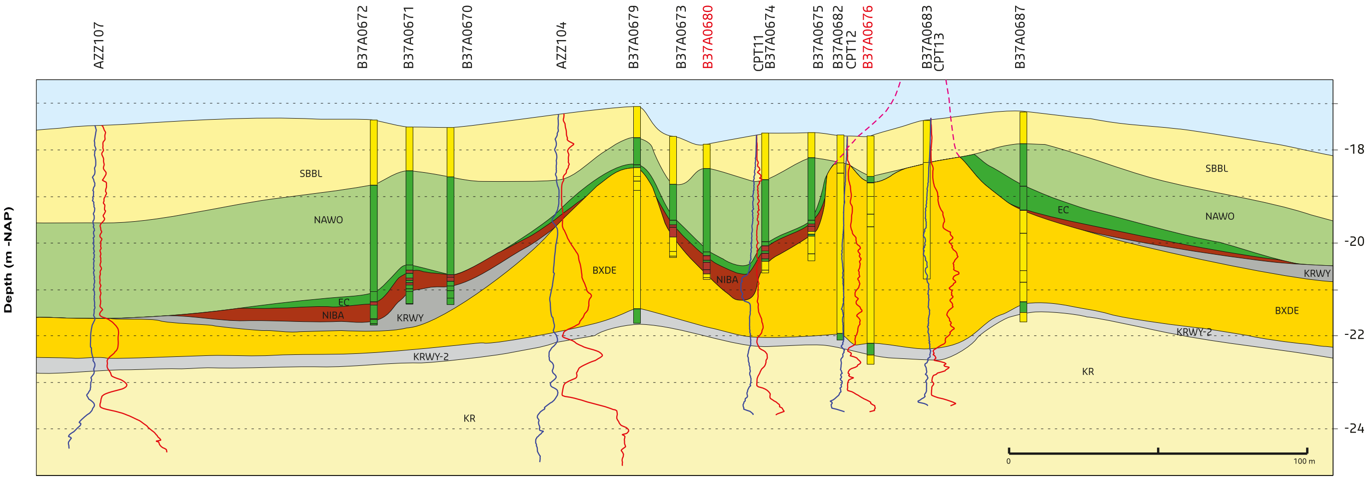


Fig. 21. East-west cross-section of selection area West, geological interpretation based on the data presented in Fig. 20. Legend, see Fig. 11. Borehole numbers in red are sampled for dating and palaeo-ecological analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The lower parts of the system (below 22 m −NAP) were occasionally flooded during periods of extremely high water, evidenced by the formation of a thin layer of silty clay (KRWY-2 layer). Vegetation in the river plain was scarce at this time and pollen evidence is dominated by pine (which was washed in by river floods though it initially blew in from areas known to be pine-dominated in the south, e.g. Hoek, 1997). The floodplain remained dry for long periods of the year and local sand drifts occurred, causing inland dunes to form. By 8400 BC, the dune field in Area West is estimated to have reached a height of 15 m −NAP (6 m above the surrounding plain). The absence of a noticeable palaeosol B-horizon in cores in the centre of the dune complex indicates that at least 1 m of dune top has been eroded as part of the marine truncation process. Therefore, the estimated height of the top of the dune is a projection based upon that of better-preserved dune morphologies from further inland in the delta plain. The highest occurrences of a clay cover on the dune flank indicate (thickness 10–20 cm; KRWY at highest encountered positions) occasional high water levels in the delta plain, due to river floods. The time-span of this (clay) unit is long, more than 1000 years (i.e. sedimentation rates less than 1 mm per year). The pedogenic development indicates that the floodplain was dry land, and suitable for occupation for most of the year. The findings of Phase 3 and 4 of this study confirmed the presence of such a landscape during the early Mesolithic and early middle Mesolithic and the results supported the decision to undertake detailed investigations of Area East, despite the fact that no archeological site was discovered.

The landscape situation changed after 7250 BC, when a large part of the area became wetland. It is assumed that Mesolithic communities did not stop visiting the study area but simply adapted their strategies to the wetland environment (as Mesolithic presence in the wider Western Netherlands suggests; e.g. Louwe Kooijmans, 2005; Amkreutz, 2013; Peeters et al., 2014); therefore, the potential area where archeological sites would be discovered (e.g. places where fire was used) is likely to have shrunk and finds would be concentrated into the remaining dryland zone.

As evidenced by the dates obtained from the Basal Peat covering the dune foot (Table 3), the water table rose at a rate of 0.2–0.3 m per century (7250–6500 BC). The geology shows that in the immediate vicinity of the dune, peat formation and distal clay sedimentation together could generally keep pace with the provision of accommodation space by the groundwater rise; however, in the surrounding local lakes too little sediment was received for organic matter to accumulate. Therefore, the landscape was a diverse mosaic of environments made up of shallow ponds and lakes with reed-sedge marsh around their rims, whilst the higher river dunes maintained terrestrial woodland cover. The tree vegetation on top of the dune shows the colonisation of broad-leaved tree species around 7000 BC, marking the Boreal/Atlantic transition. The proportion of *Pinus* reduced significantly whilst thermophilic tree species such as *Alnus*, *Corylus*, *Quercus* and *Ulmus* increased greatly in number. Around the dune, reed-sedge marsh, riparian and open water vegetation gained importance from this time. Around 6500 BC, with wetland sedimentation up to 18.75 m −NAP, the habitable area on the dune was at its smallest.

The hydrological and palaeoenvironmental changes in the floodplain meant that, while dry habitable areas reduced in scale, conditions for hunting and gathering may have diversified and improved with the new environment of the late Boreal and earliest Atlantic providing an improved pallet of food resources (Kubiak-Martens et al., 2014). Therefore, within the remaining high-and-dry locations of the wetland, the odds of encountering Mesolithic archaeology may have increased relative to earlier periods (Amkreutz, 2013; Peeters et al., 2014).

The drowning history of Area West is visualized in a map and profile reconstruction (Figs. 23 and 24). The figures show both the run up to the drowning of the area around 6500 BC and the aftermath. At the critical moment, the drowning was rapid (sea-level jumping within in a few months or a year, possibly in two events of about a metre each; Hijma and Cohen, 2010; Törnqvist and Hijma, 2012).

The 6500 BC event transformed the floodplain wetland (zone 1 in Fig. 5) into shallow water rivermouth wetlands (zone 2 in Fig. 5) comprising and upper-estuarine' or 'fluvial deltaic' freshwater flood basin environment, which was part sub-tidal and part inter-tidal. With time, the environment became brackish, deepened further and became sub-tidal everywhere, before eventually became fully saline. In this environment the top of the dune was drowned and truncated by marine erosion. The (later eroded) dune top at 15 m −NAP would have been drowned by 6300 BC, based on sea-level data collected 20–30 km inland (Hijma and Cohen, 2010).

Coincidently and conveniently, the 6500 BC transgressive event matches the boundary between the Middle and Late Mesolithic in archaeological time division, as used on inland sites (Louwe Kooijmans, 2005). In the coastal Netherlands, the transgressive event(s) of 6500–6300 BC may have been instrumental in causing a change in Mesolithic site patterns.

Fig. 22. The underwater "excavation" recorded in pictures of the archaeological survey in 2012. Fig. 22a: Computer controlled sampling with a crane; Fig. 22b: Sampling en control of the digged up sediment; Fig. 22c: Transport of the big bags samples to sieving location; Fig. 22d: Sieving and archaeological selection of the sieved material.

From 6500 BC, the dune site Yangtze Harbour West rapidly became inhabitable. Successors of Middle Mesolithic people that had previously visited the area for its specific resources and hunting habitats, would have found that these environments had shifted further inland (e.g. Rotterdam and Alblasserwaard; Van der Woude, 1981, 1984; Bos, 2010), where indeed Late Mesolithic occupation is present and was exploited (Louwe Kooijmans, 2005; Amkreutz, 2013; Brouwer-Burg, 2013). From a palaeogeographical perspective, we recommend detailed archaeological inter-comparison of these deltaic Late Mesolithic sites and the submerged Middle Mesolithic equivalents. In such comparisons and evaluations, it should be considered that the inland shifting of environments not

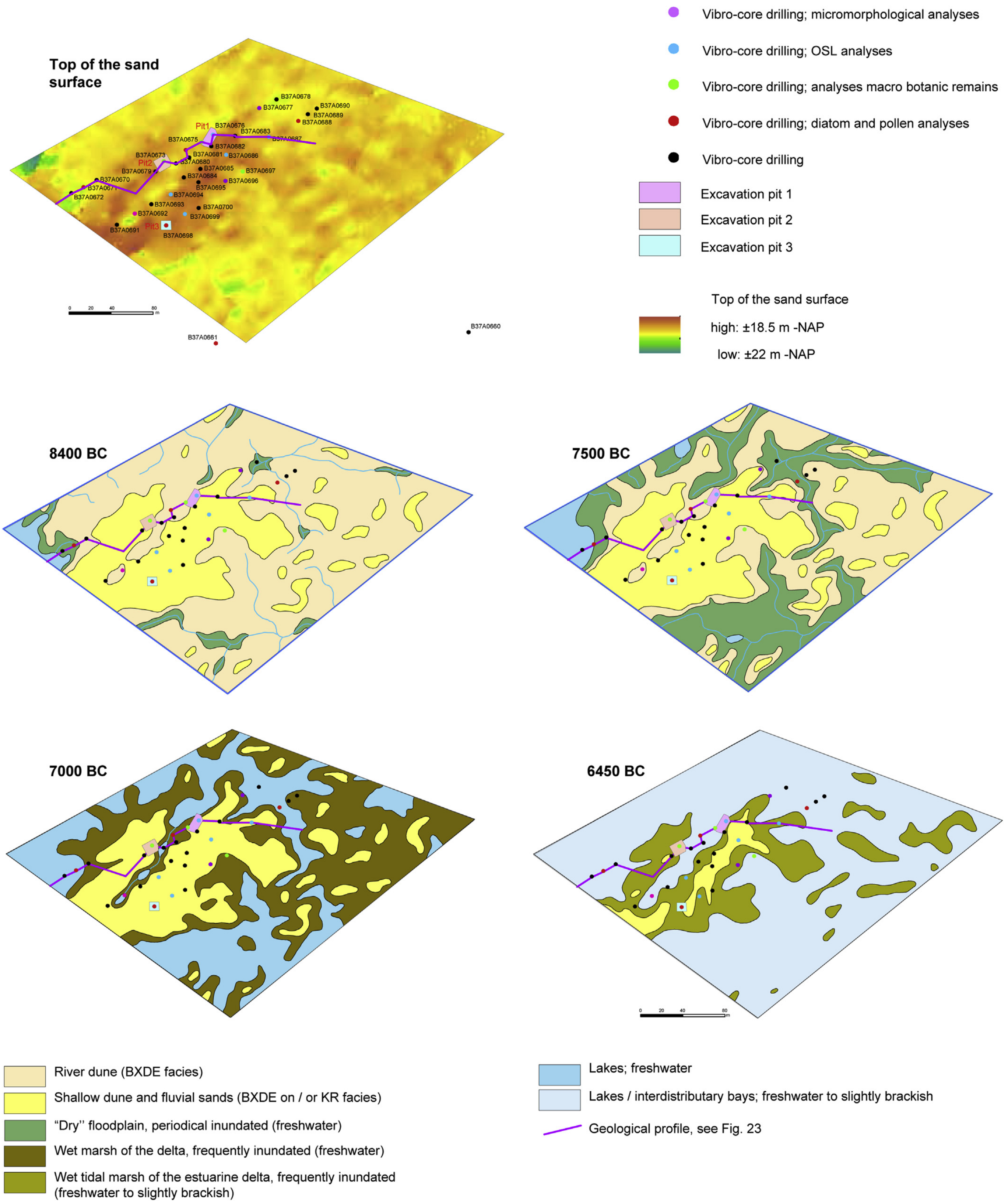


Fig. 23. Map reconstruction of the drowning of the landscape of selection area West for the time steps: 8400, 7500, 7000 and 6400 BC.

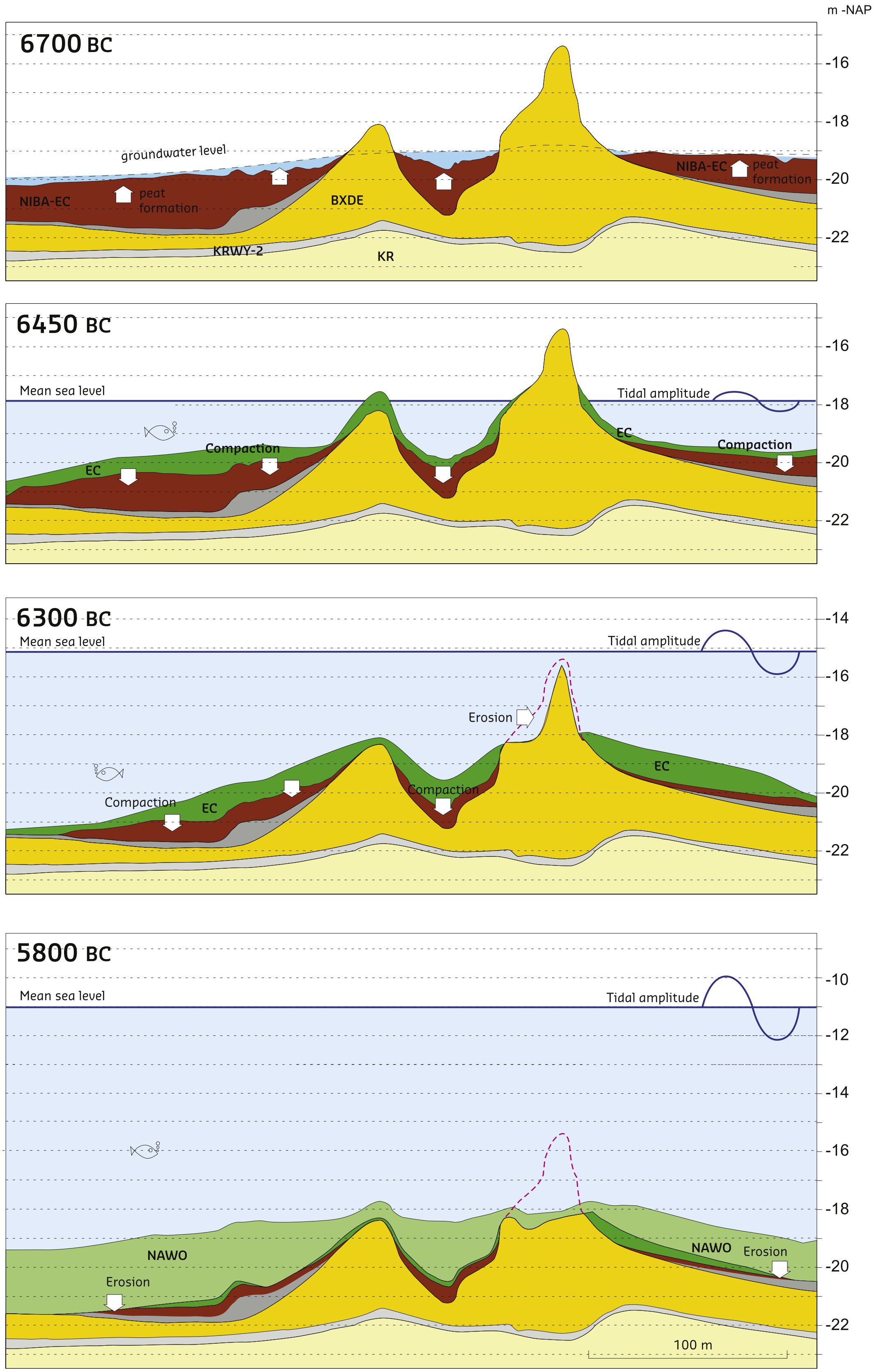


Fig. 24. Profile reconstruction of the drowning of the landscape of selection area West for the time steps: 6700, 6500, 6350 and 5800 BC. Location profile, see Fig. 23. Legend, sediment layers, see Fig. 11; and water types, see Fig. 23.

only considers fluvial and estuarine wetlands, but also (embryonic) coastal barrier and spit systems at the estuary mouth (at the boundary of zones 3 and 4 in Fig. 5). These environments may have been part of Mesolithic land use strategies too, but unfortunately these Mesolithic remain and associated structures are not preserved because of coastal erosion.

4. Discussion

The staged, geogenetic approach, which employs detailed geophysical and geological surveying and sampling strategies, provided high-resolution insights into the location of local features in the palaeolandscape. Such an approach is needed to systematically screen a study area and to target locations that have the highest chances of having been prehistoric habitation sites. The staged strategy allowed for flexible project planning within this large engineering operation, particularly since initial geological interpretations had to be revised when new data was collected. The approach made adjustments to the outset concept of the project possible (e.g. revision of methodologies, specialist disciplines to be consulted, and variations in allocated budgets of time and money). Because the geoarchaeological investigations were incorporated into the overall scheme, the impact of change upon the harbour engineering works itself was negligible and in turn, the cost for the archaeological research was reduced.

The geotechnical data collected as part of the engineering work was beneficial for the geoarchaeological investigation. The reverse is also true; the improved local geological insight for the Maasvlakte 2 area can be of value in the design of the next infrastructural works and operation activities. Of course, it can also benefit future archaeological prospection projects related to works in the other harbour basins and their associated canal systems.

The staged geogenetic approach can be applied in comparable underwater areas elsewhere in the world where large engineering projects are taking place and the deeper subsurface of the seafloor will be disturbed. It is especially applicable in marine areas where transgressive sediment layers cover former landsurfaces – which is the case in the coastal zones of many of the world's present-day deltas. Of course, the effectiveness of the methodology cannot be assessed based on this single case study, but at least future underwater archaeological investigations can follow our approach, and where necessary, modify it for local conditions.

Whilst this study was a local mapping and archeological prospection activity, the geogenetic approach generates high-quality information that feeds back into the regional paleogeographical knowledge framework. This means that the results are not just useful for discovering and managing archeology locally, but can be used in geological and archaeological desk studies deployed in the wider region.

In the North Sea area, submerged prehistoric archaeology is present, which is buried under a variable thickness of young, shallow marine sediments (e.g. Tizzard et al., 2011; Hijma et al., 2012; Bicket et al., 2011 All of these remains are discovered more-or-less by chance and by accident, due to seabed mineral extraction and beam trawling. To find more buried underwater sites, preferably before they are destroyed, it is advised that a staged geogenetic approach is adopted around selected areas prior to major disturbance.

Also in cases where former Palaeolithic and Mesolithic landscape surfaces are naturally eroding, prospection of the seafloor for prehistoric sites using a staged geogenetic approach is suggested. Part of the approach should include the adaption of deployed geophysical techniques to select the most efficient sampling and excavation strategies. Side-scan sonar surveys, for example, would be useful to chart the seafloor bathymetry of sites with very limited sediment cover. The use of divers for sampling and for underwater excavations may also be feasible in such cases. The submerged archaeological site of Boulder Cliff in the Solent in southern Britain, which is monitored by the Maritime Archaeology Trust (MAT), stands as an example of this approach (Momber, 2000, 2011).

Other successful, but less sophisticated methods used to recover flint and faunal remains from the seabed are trawling and clamshell grabbing. However, using these seabed sampling techniques means that the archaeological heritage of the deeper underwater subsurface remains “unseen”. From an archaeological standpoint, it might be wise to map the geology of heavily trawled or mineral-extracted areas of the seabed, to help assign a context for archaeological discoveries in future trawled areas.

In less dynamic underwater areas away from river mouths, such as in the micro-tidal Mediterranean and Baltic Seas, archaeology often lies on the seafloor or covered by a thin layer of sediment. Geological investigations play a less prominent role in palaeolandscape investigations of these sites, and the bathymetry might better be interpreted as a palaeolandscape using geomorphological, rather than geological techniques (Cohen and Lobo, 2013). The palaeobathymetry, related to Holocene sea-level change (drowning history), seabed morphology and erosion, are the main issues of interest in the palaeoenvironmental research of these sites (e.g. Schmölcke et al., 2006; Scicchitano et al., 2008; Dolukhanov et al., 2010; Fischer, 2011; Benjamin et al., 2011; Bailey and King, 2011; Passaro et al., 2013; Cohen et al., 2014).

In the Yangtze harbour study, the activities leading up to the eventual discovery of the archaeology were those that identified and mapped river dunes in the submerged environment. The presence of these dunes and their previously known attractiveness for prehistoric humans, at least for dune sites that were frequented in late Mesolithic and Neolithic times after 6500 BC (e.g. Louwe Kooijmans, 2005; Amkreutz, 2013), provided the starting point for this project. The results of the Yangtze harbour excavation seem to indicate that, at least in the area west of Rotterdam, dune sites that drowned before 6500 BC contain rich archaeology, restricted to early and middle Mesolithic times. It suggests that the high densities of archaeological material on those sites is intimately related to the landscape changes that such sites undergo due to the approaching sea and submergence of the valley plain (Fig. 25).

The sediments at the interface of the dune foot and the surrounding ‘basal peat’ wetland at depths of 18.5–20 m –NAP were the focus of excavation in area West and these were particular rich in archaeology. The character of the unit and its known location made it possible to identify the site in the extensive drilling program of Phase 3, and explains the success in collecting archaeological information by sieving the large-grab samples in Phase 4. Furthermore, as part of future prospection strategies the feet of river dunes at more inland positions, could be targeted to see whether Middle Mesolithic find concentrations along dune foot areas are a westerly phenomenon only, or occur inland too (Peeters et al., 2014).

However, there were other suitable habitats for settlement than river dunes alone in the drowning fluvial delta, for instance, along the river banks of palaeochannels. These features were widespread however, and proving a human presence in those environments may be more appropriately dubbed ‘finding a needle in a haystack’ (Weerts et al., 2012). Such watercourses existed in the wetland environment that existed in the middle Mesolithic period, and in the valley floodplain environments of the early Mesolithic. Also off-site archaeology related to hunting, gathering and ritual activities are wide spread, and they can be found in many different habitats of the drowned floodplain. In such environments, finding positive indications in a vibrocore stands a much lower chance of success than on the dune flanks. The samples are simply too small and their

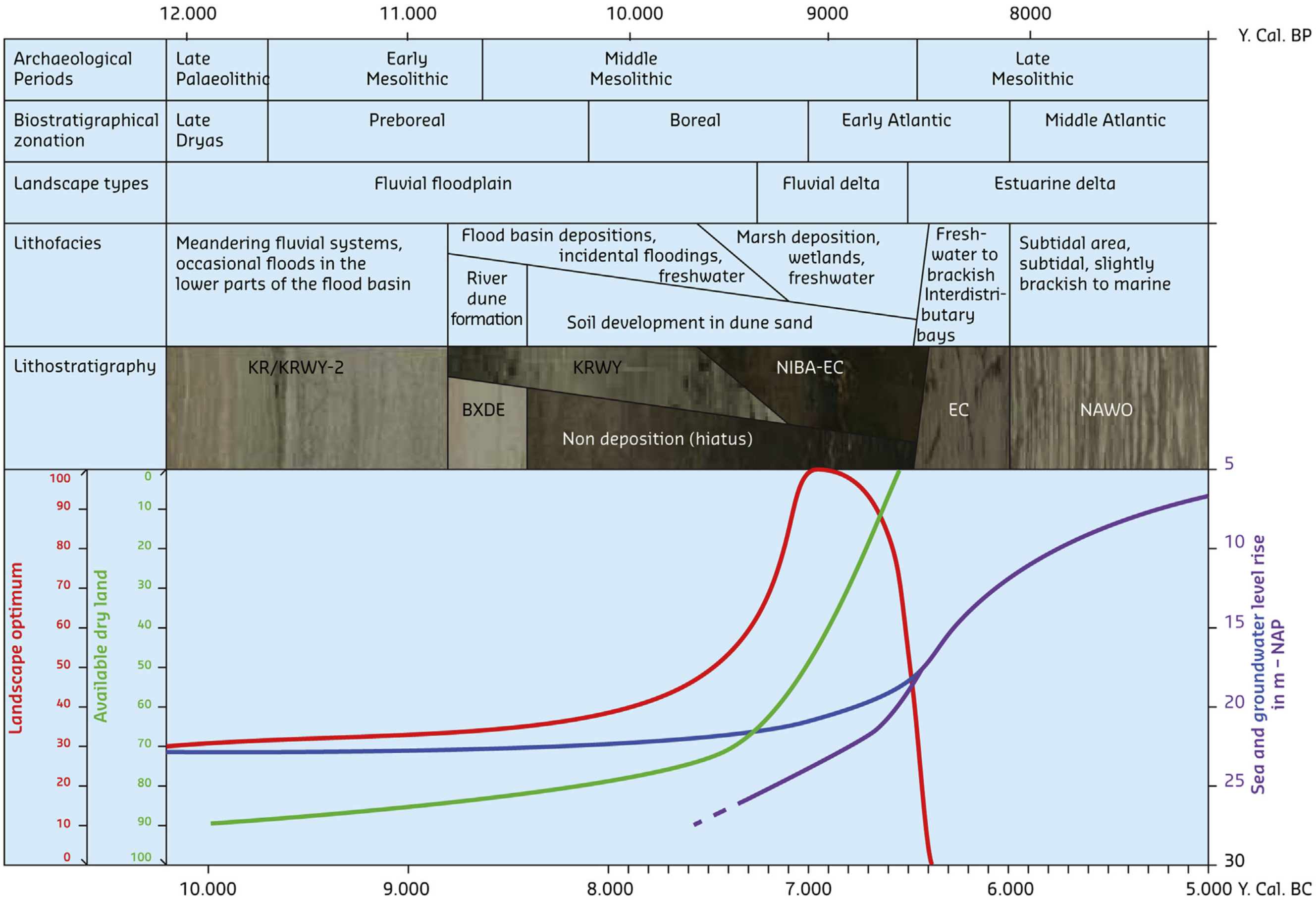


Fig. 25. Synthesis of the lithostratigraphy, sedimentary environments, and dry/"optimal" land surface in time, related to ground- and sea-level rise. Stratigraphy, see also Figs. 10–12 and 21; sea- and groundwater-level curves, see Fig. 13; salinity reconstruction, Figs. 14 and 15; available dry land/"landscape optimum" reconstruction, see Fig. 23.

numbers too low. To harvest data on off-site archeology from early Holocene delta deposits, the taking "bulk samples" is an alternative to coring and should be considered for future projects reaching Phase 3. This can be done using a similar pontoon crane that was deployed for the excavation of the dune in Phase 4, or perhaps by making use of the dredging vessels that would remove the sediment during construction anyway.

Sand nourishments to beaches and dredged stockpiles of gravel and sand from the seabed can be seen as large "bulk samples". Palaeolithic and Mesolithic material and palaeontological remains (e.g. mammoth bones) have been found on the sand supplied beaches of the Maasvlakte (Louwe Kooijmans, 1975; Verhart, 1988). Also in the northern Netherlands Palaeolithic artefacts are found in nourishment deposits on the beaches of The Wadden Sea islands. These supplied sands originated from the Pleistocene seabed about 10–15 km offshore (Stapert et al., 2013a, 2013b).

The problem with the nourished beach sample finds is that the palaeoenvironmental context where the material is coming from is not precisely known. This differs for the large grab samples of the archaeological excavation during Phase 4 of the Yangtze harbour investigations (Moree and Sier, 2014), where the geological work of Phases 1–3, provided a secure context for each grab sample.

In the last few years, Wessex Archaeology has carried out a survey in the North Sea, about 11 km off Great Yarmouth on the coast of Norfolk. The work was undertaken in conjunction with Hanson Aggregate Marine Ltd in consultation with English Heritage. Assessment of targeted loads of dredged mineral sediment at wharves is undertaken in order to mitigate the effects of aggregate dredging on cultural heritage and is undertaken as part of extraction license agreements (Dr. Louise Tizzard, Wessex Archaeology, pers. com.). Geophysical, coring and dating techniques were used to understand the Pleistocene depositional environments and provide contextual information for Palaeolithic materials recovered from this area. Lithic artefacts, including handaxes, flakes, cores and faunal remains were discovered in 2007/2008 in stockpiles of gravel from that area (Tizzard et al., 2011). To trace these stockpile finds back to a geological source unit, a geophysical survey was carried out, seabed sampling methods were applied, and targeted coring executed to obtain complete samples of the sedimentary sequence from the vicinity of the site. The sediment cores were used to carry out palaeoenvironmental assessments and analysis, using amongst others methods, ^{14}C and OSL dating (Bicket et al., 2014). During a survey in 2011, large bulk samples were taken by recovering around 1000 tons, from a known Pleistocene fluvial sediment unit (based on geological interpretation). Firstly, archaeologists assessed the cargoon the vessel, but they found that the best place to assess the sediment was at the wharf where the oversize fraction (>63 mm) could be routinely sieved and examined. This proved successful in identifying the "larger" archaeological material such as hand axes, flakes and faunal remains. These remains would never have been found in the analysis of samples from boreholes (the "needle in a haystack" approach).

Some might argue that bulk sampling by dredging or taking grab samples is a 'coarse' way to undertake underwater archaeological prospection and/or excavation compared with approaches to archaeological surveys on land. However, for areas such as the North Sea, in most cases there is no alternative considering the depth and cost of investigations. Therefore, it is important that before any significant quantity of sampling and disturbance of the seafloor is carried out, the subsurface geology of the area is investigated with geophysical and coring (including grab sampling) techniques and that the palaeoenvironment and age of the sediments are determinated. In this 'geologically controlled approach' the landscape context of the bulk samples is known and the technique can be referred to as 'controlled dredging' or 'controlled grab sampling'. Controlled bulk sampling can be timetabled into construction works that engineers are undertaking anyway to deepen harbours or water-related infrastructure. So, in many cases, this approach is a win–win situation created between the construction engineers and the archaeological investigators. However, in practice these opportunities are often not taken into account because of the lack of communication, understanding or tradition of working together between the engineering managers, archaeologists and geologists. It is hoped that the approach outlined in this paper will go some way to addressing these problems and provide a template for future collaborative investigations in the field of underwater archaeology.

5. Summary and conclusions: lithofacies, palaeolandscapes and prospection

From findings in the western Netherlands (Louwe Kooijmans, 2005), and also from investigations of offshore dredged sands used to further extend and reclaim land of the Maasvlakte, the presence of Mesolithic archaeology in the region has previously been known (Louwe Kooijmans, 1975; Verhart, 1988, 2005; Van Ginkel et al., 2014). This existing knowledge was the impetus to dedicate archaeological prospection efforts to surfaces from the Mesolithic period in the Yangtze Harbour area in the Port of Rotterdam, which was carried out using a geogenetic approach. As a result, this paper has helped elucidate: 1) early and middle Holocene landscape development; 2) potential Mesolithic use of the reconstructed landscapes and; 3) understanding what localities in the landscape have the highest potential to find archaeological evidence for human presence.

For the Yangtze Harbour area, the insights are:

- Up to 7250 BC the whole floodplain and inland dune complex was suitable for (seasonal) settlement (i.e. make use of fire to cook food, make tools). Locations along local drainage lines are regarded to have been frequented most, but in the rest of the floodplain suitable locations will have existed too. It is hard to differentiate and chances of actually finding archaeology are to be considered low.
- Between 7250 and 6500 BC, the area suitable for settlement was reduced to higher parts of the inland dunes. The surrounding wetlands (swamps, marshes, lakes) were part of a rich habitat, but not good locations for settlement. The geological context is easy to differentiate and the chances of finding archaeology on the top of the dune are great. Chances are equally high at the dune foot and around the fringe of swampland surrounding the dunes. The state of preservation and the opportunities to also collect contextual palaeoenvironmental information are high. Finds at the dune foot may have been colluvially displaced by a few metres.
- After 6500 BC, the study area was submerged. No Mesolithic archaeological sites are expected to be found, since there was further sea level rise of many metres during later millennia.

The contrast between the archaeology of the period before and after 7250 BC is the result of the connection between drowning of the landscape due to groundwater rise (in advance of sea-level rise) and habitat changes associated with the hydrological change (besides climatic developments and vegetation succession). In combination, this creates a Mesolithic 'prospection optimum' centred around inland dunes that have wetland deposits blanketing their lower slopes (capping their feet). For the study area, this relationship is visualized in Fig. 25, together with trend lines for groundwater and sea-level rise, and the decline of available land. Understanding how this optimum affected middle Mesolithic human activity, and hence archaeological preservation in the subsurface, is a starting point of evaluating the benefits and pitfalls of the deployed survey method. One can discuss whether coring or grab sampling would be optimal in later stages of prospection. The main point of this paper is emphasizing the need to establish the geological context prior to major disturbance of the seabed, which is what the geogenetic approach does. Deciding whether to focus on a known (true site) discovery, or to undertake more random screening for off-site archaeology is a secondary matter.

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