Field excursion through the Rhine delta and Holland coastal plain

A populated coastal-deltaic plain under threat of sea-level rise

iSLR 2018
28 August 2018

V1.2

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Contents

Rhine delta and Holland coastal plain full-day field trip by touring bus

Colofon

Field guide produced for iSLR2018 ECR conference Impacts of Sea-Level Rise - August 2018

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The excursion is sponsored by Utrecht University, faculty of Geosciences. The excursion is organised as part of the iSLR 2018 INQUA-PAGE ECR meeting organised at Utrecht Science Park 'De Uithof'. www.islr18.org

All graphic materials used are referenced to source publications and websites – see list section in last pages.

iSLR18

Logistic information

Three main stops:

Stop 1: UNESCO World Heritage site ‘Kinderdijk’ – ca. 30 minutes
Brisk morning walk along footpath in polder (1030 – 1100h)

Stop 2: Polder ‘De Vergulde Hand’ – Holocene geology and archaeology – ca. 2 hours
Field Lunch and 3 activities, rotations in subgroups (1230 – 1430h)

Stop 3: Mega-nourishment ‘Sand Engine’ and modern SLR – ca. 1.5 hours
Walk across coastal dunes to beach and sand-nourishment (1600 – 1730h)

Transfer to dinner location (Naaldwijk) with the same bus (1800 – 2130h)

Transfer back to Venue (Utrecht Science Park) with same bus (2230h arrival in Utrecht)

See front page map for approximate timing of arrivals of the various stops.

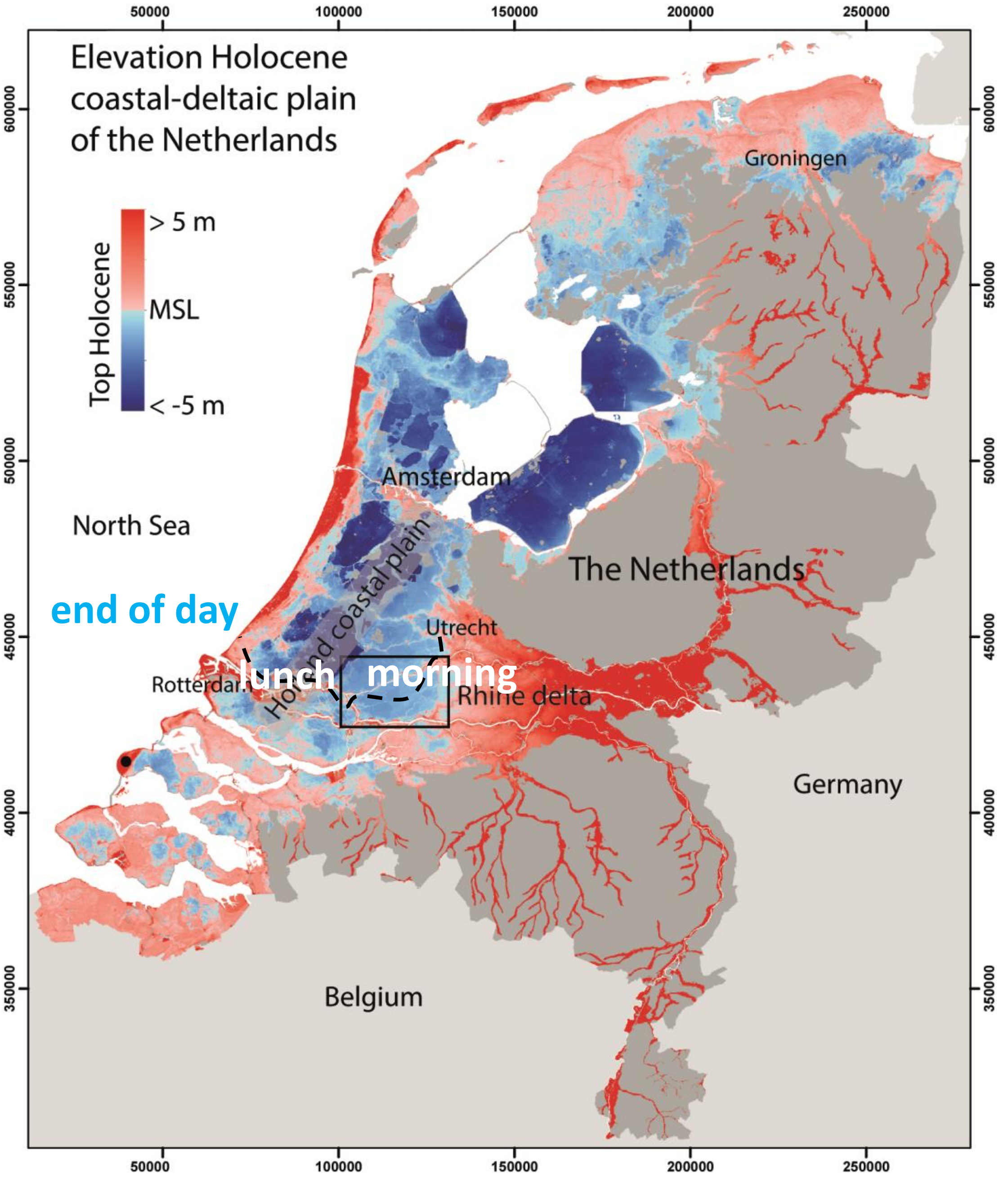


Fig. 1 - Digital elevation map of Holocene deposits in the Netherlands; c. 50 % of the surface area of the Netherlands consists of Holocene delta and coastal deposits, and c. 50 % of the Holocene surface is at present situated below mean sea level. Most of the areas that are situated below mean sea level have thick peat layers situated at shallow depths. The grey areas contain deposits of pre-Holocene age at the surface. Figure after Koster, 2017.

Excursion route during the day indicated with dashed black line.
The black square is the polder ‘Alblasserwaard’: morning drive to Kinderdijk Stop 1 – see Fig. 3.

Drive-by: Lek River and weir ‘Hagestein’

River Lek

The low lands of the Netherlands are the Rhine Delta and adjacent coastal plain which together comprise about half of the country (Fig. 1). Regulating surface water is therefore very important to ensure the viability and safety of the country. The Netherlands has approximately 1000 years of experience with adaptation and mitigation strategies to use the delta plain and its rivers economically, and meanwhile prevent the area from flooding. The dikes along the river and the weirs and groynes in the river are each measure to regulate river flow through the country and to deal with variable discharge. To ensure navigability of the river and safety of the polders on opposite sites of the dikes, works in the river and dike height and strength are regularly reassessed.

The River Lek is the middle one of three present day distributary branches of the Rhine. It carries 22% of the discharge of the Rhine River. In the 1950s, a series of weirs was constructed in this branch. The excursion passes the weir at Hagestein (Fig. 2a). The weirs serve to regulate division of discharge between the river branches. Hereto, at normal river discharge the weir is closed. At increased discharge, the weir is opened. During peak discharge the embanked floodplains between river and dike are allowed to flood (Fig. 2b). Opening of the weir happens c. 45 days/year. Rising relative sea level means that inland ‘backwater effects’ increase (besides tides) and the critical water levels for opening and closing the weirs may change.

Fig. 2a – The Hagestein weir in the Lek River. River flow is from right to left. The photo shows the weir closed at normal discharge. The weir is opened during river peak discharge. 2b – Inundation of the embanked floodplain of the Lek River in 1993 during peak discharge (source: RWS).

Drive-by: Polder ‘Albasserwaard’

Polder ‘Alblasserwaard’. Reclaimed 1100-1250 AD. Gently water managed since.

The Rhine Delta and coastal plains are fully reclaimed and compartmentalized into numerous regions or ‘polders’. Polders are areas enclosed by dikes, with water levels kept at artificial lows. Most polders are centuries old. The polder ‘Alblasserwaard’, reclaimed in the 12th and 13th cy, is situated between tidal-river reaches of main Rhine delta branches,

The subsurface of the polder primarily consists of peat and clay, intersected with former sandy fluvial channel belts. Centuries of artificial low water levels caused the peat to oxidize and compress. As a consequence, the polder experienced subsidence, and is almost entirely situated below mean sea level (Fig. 3). Only the former sandy channel belts and the dikes enclosing the polder are elevated above mean sea level. At present, the subsidence progressively continues, with rates between c. 1 – 2 mm/yr (Caro Cuenca et al., 2011). The low-lying polder has frequently been flooded; the most frequent flood was in 1953.

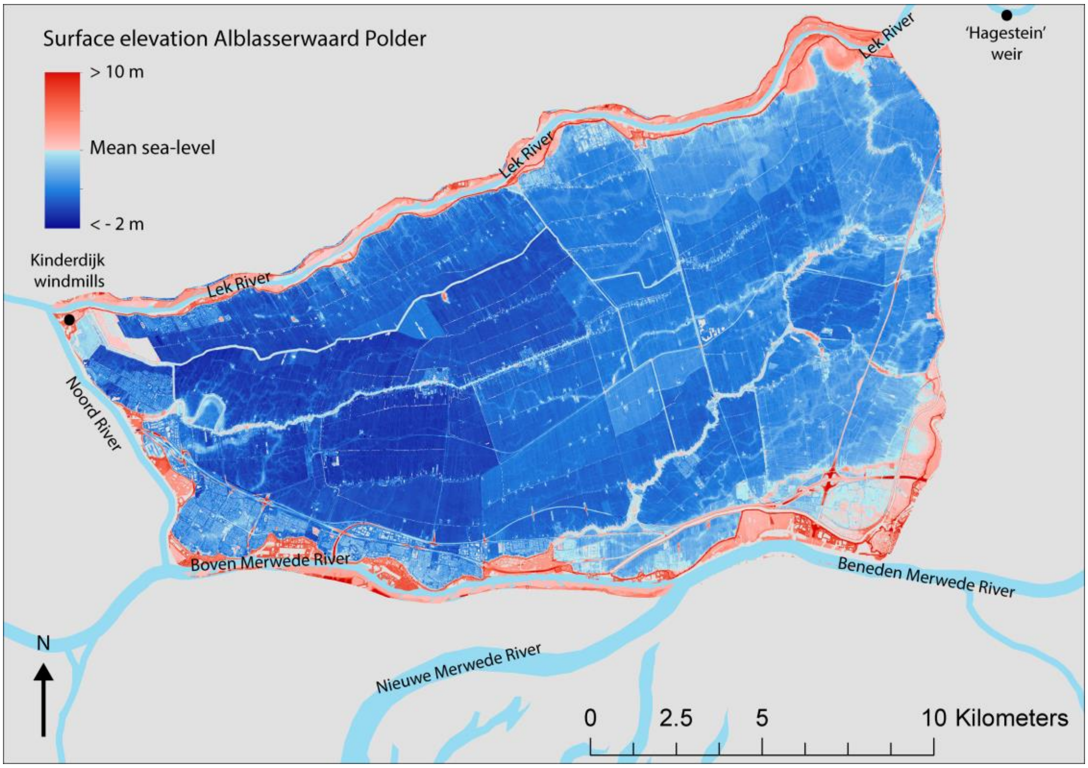


Fig. 3 - Digital elevation map of polder ‘Alblasserwaard’ shows that it is situated below mean sea level (TNO-GSN; compiled for this excursion guide). The river embankments are elevated up to 15 m above mean sea level

Stop 1: UNESCO World Heritage site 'Kinderdijk'

The windmills of 'Kinderdijk'

To maintain surface water levels in reclaimed polders in the delta and coastal plains at artificial lows, series of water pumping windmills were constructed throughout the Netherlands. The first windmills to serve this purpose were constructed in the 14th century. By then, the peat-rich reclaimed polders had subsided below sea- and river-water levels. Consequently, natural water gradients inside polders could not be used anymore for drainage. The windmills enabled the drainage of the polders. In parallel events, agricultural practices inside the polders changed from wheat growth to dairy farming, initiating the world famous Dutch cheese industry (e.g. Goudse-, Edammer cheese) (Van Dam, 2001).

The series of windmills of 'Kinderdijk' (Fig. 4) from the first half of the 18th century at the confluence of the Lek with the Rotterdam estuary tidal rivers (Noord, Nieuwe Maas). From 1740 to 1940 these functioned to keep ditch water levels and groundwater tables below surface in the 'Alblasserwaard' (Fig. 3): a medieval-reclaimed clay-covered deltaic peat land polder. At present, electricity driven pumping stations have this function. Since 1997, the 'Kinderdijk' windmills and supporting canals are a site with UNESCO World Heritage status.

14th cy – Polder water management formally organised

17th cy – wind-energy lowered polder water, bossom areas allocated

18th cy – two-staged wind-milling, using a low and a high bossom compartment

19th cy – wind mills replaced by steam-powered pumping stations

20th cy – pumping stations further modernized (diesel-electric, electric)

Fig. 4 – a) Series of windmills at 'Kinderdijk' (photo: Wikipedia), b) timeline of need for more milling / pumping capacity with aging of the medieval reclamation (Schengenga et al. 2013) . The polder side is behind the wind mills in the photo (left in panel b). The water in front of the mills is the 'bossom' (middle of panel b): the polder compartment used to collect the wind-milled waters and route and release them to tidal river and sea (at low tide, free flow).

Rhine-Meuse delta geological history

Last Glacial, Lateglacial, Early Holocene – Valley surface: buried by the younger delta

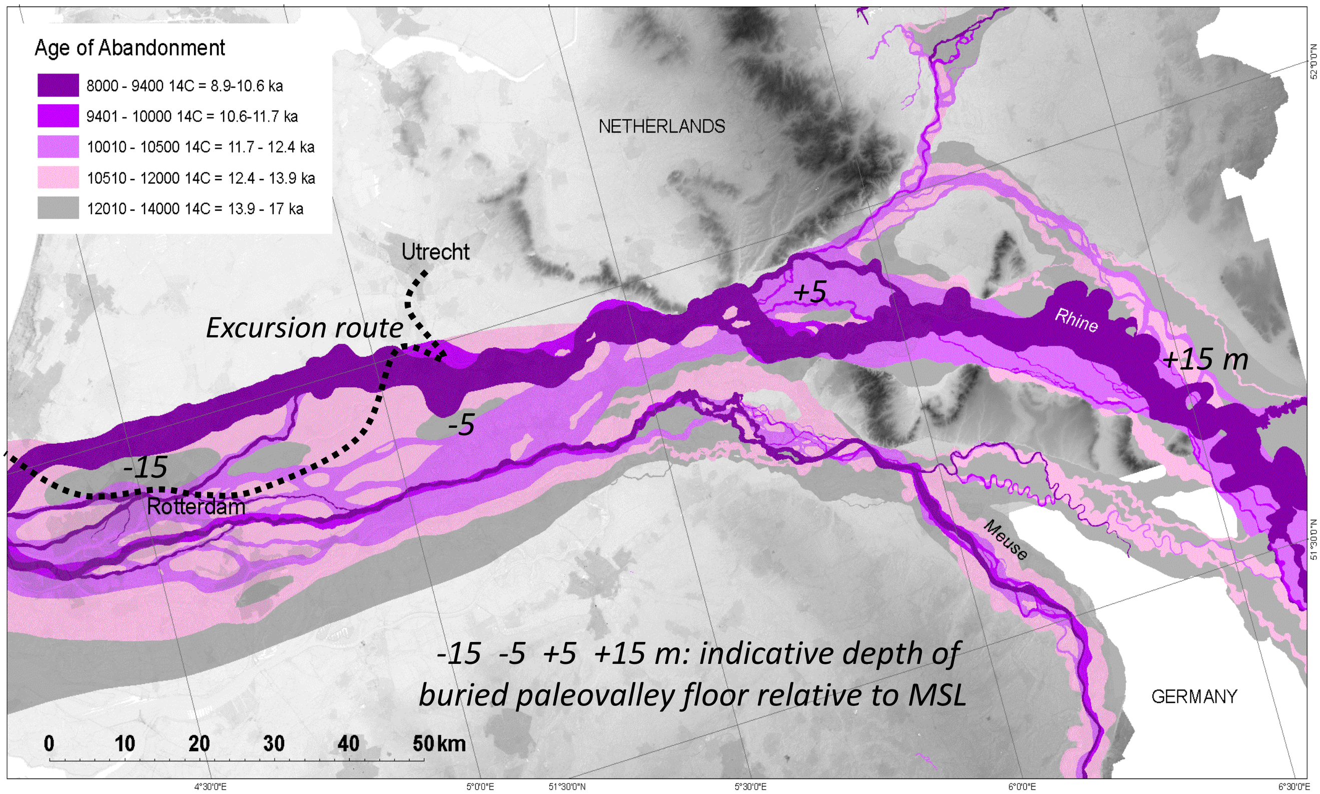


Fig. 5 – Geological map buried palaeovalley. Cohen et al. 2012

Middle Holocene, Late Holocene, Anthropocene – Avulsing channels of burying delta plain

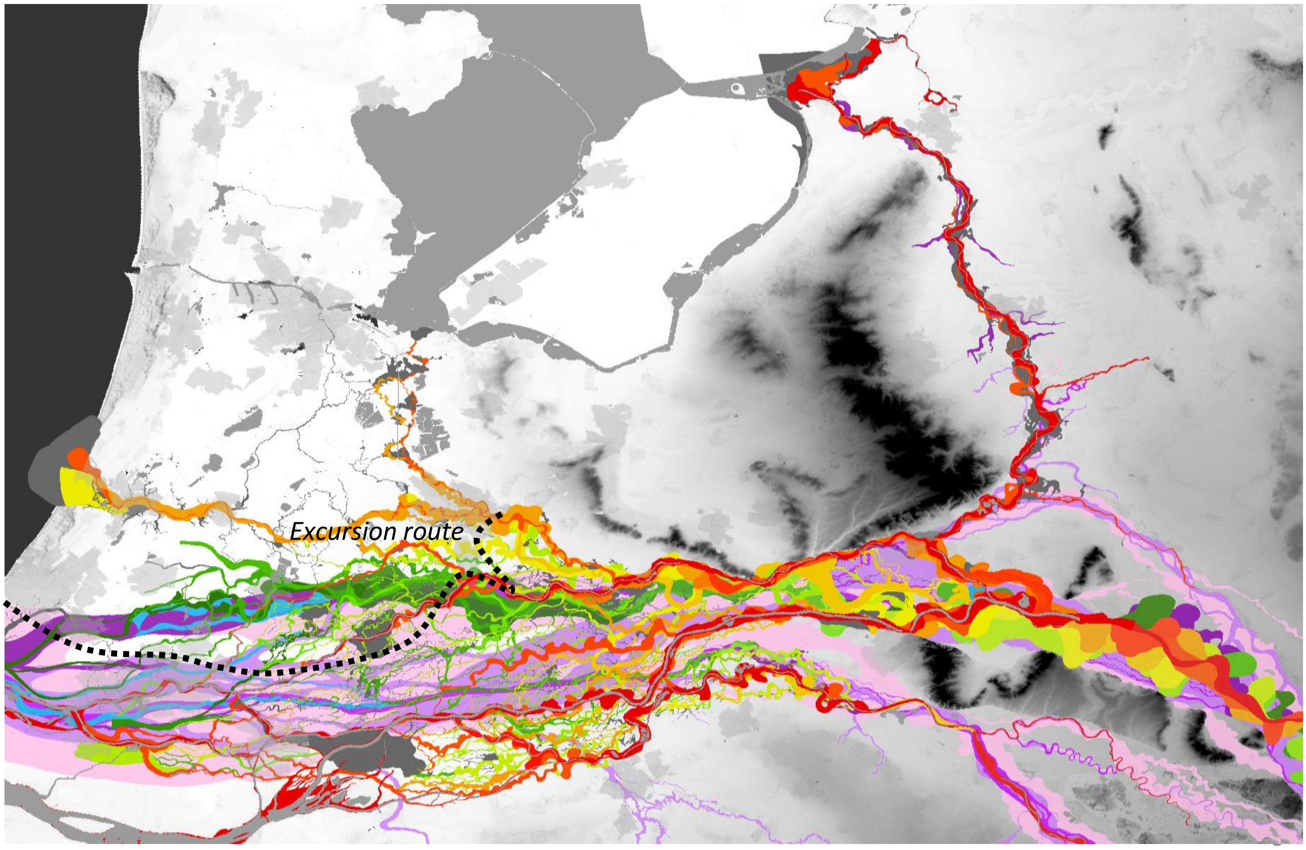


Fig. 6 – Geological map channel belt age Rhine-Meuse delta
Berendsen & Stouthamer 2001, Cohen et al. 2012

Netherlands coast and delta sea-level history

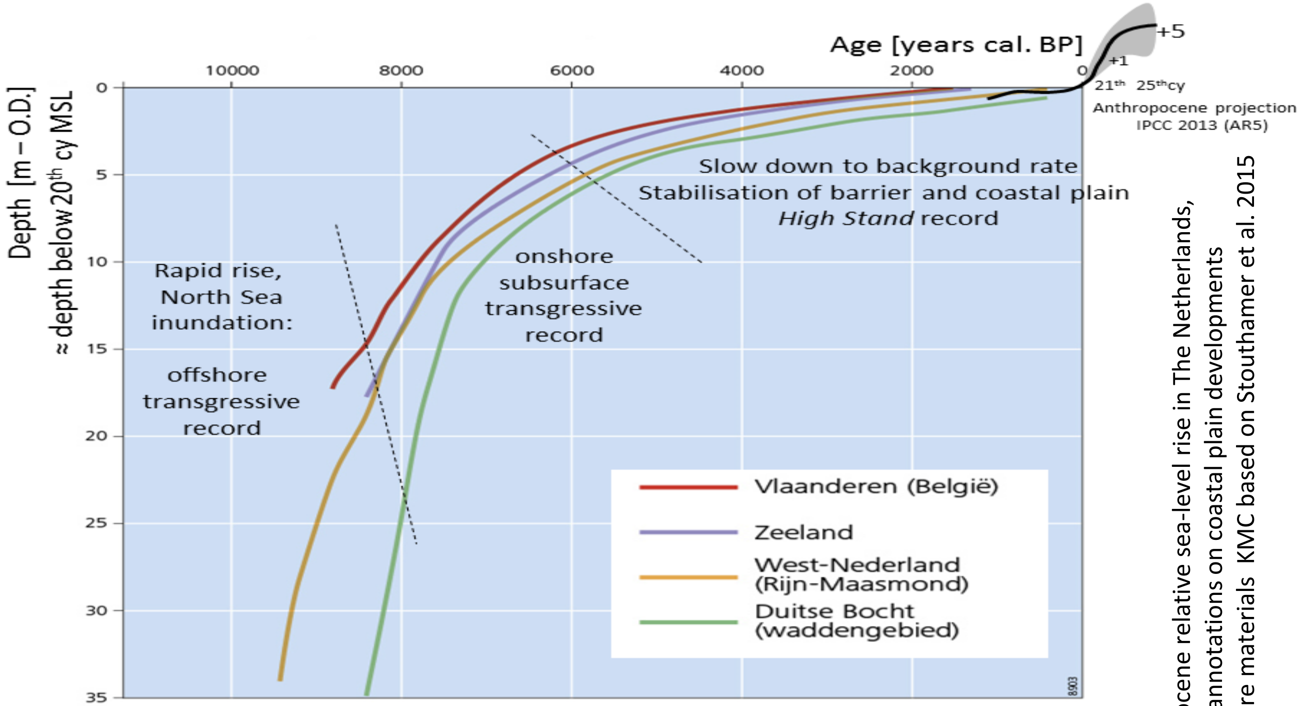


Fig. 7 – Holocene relative sea-level rise in The Netherlands, with annotations on coastal plain developments Lecture materials KMC based on Stouthamer et al. 2015

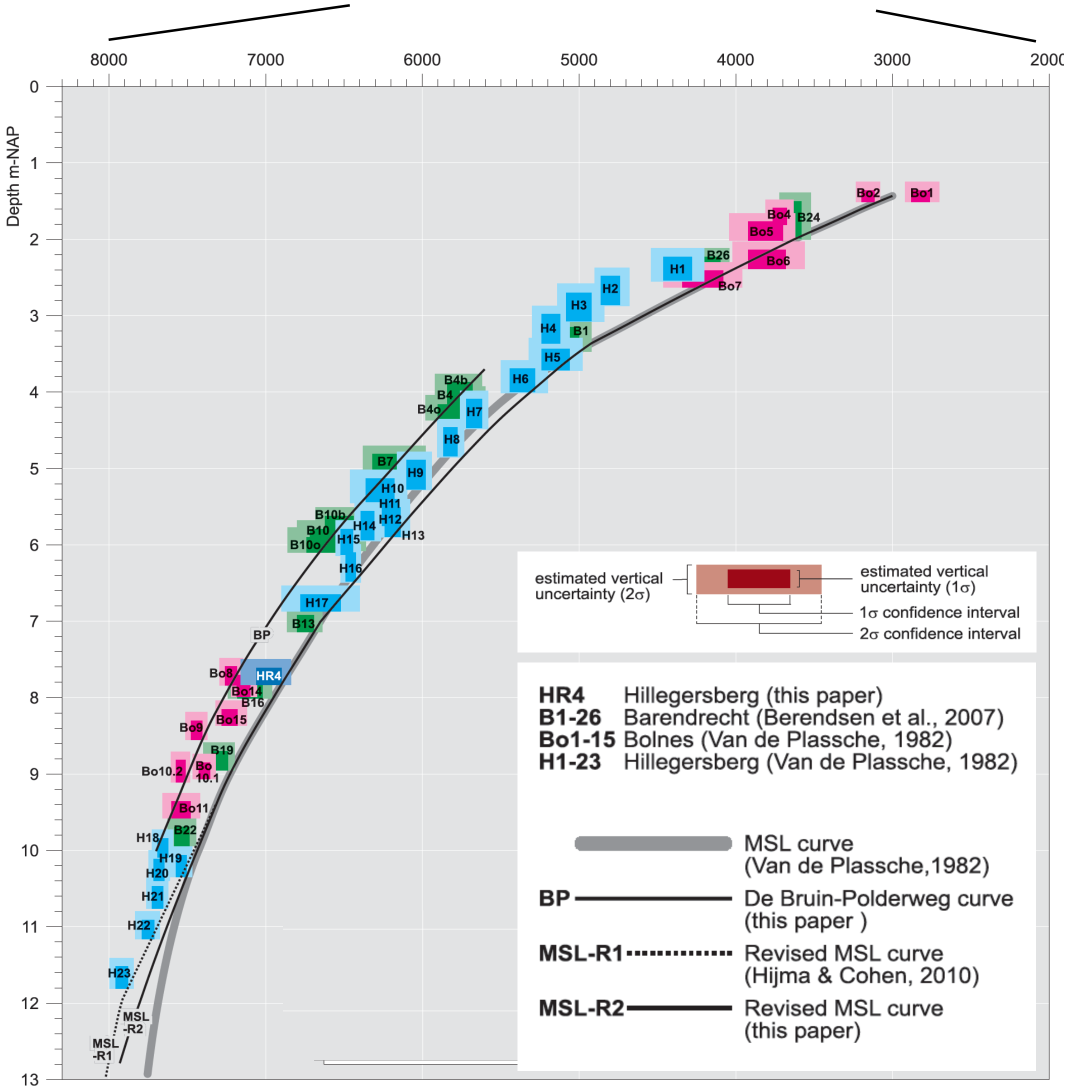
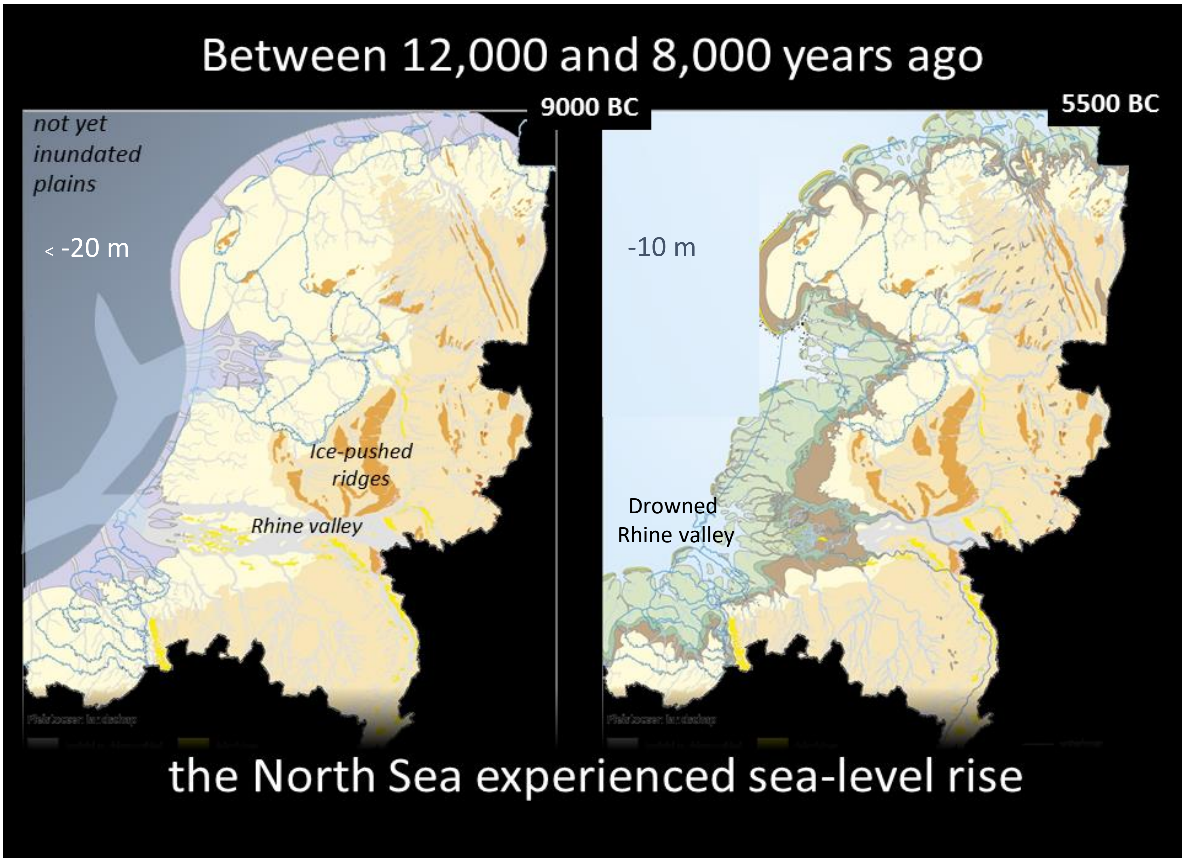
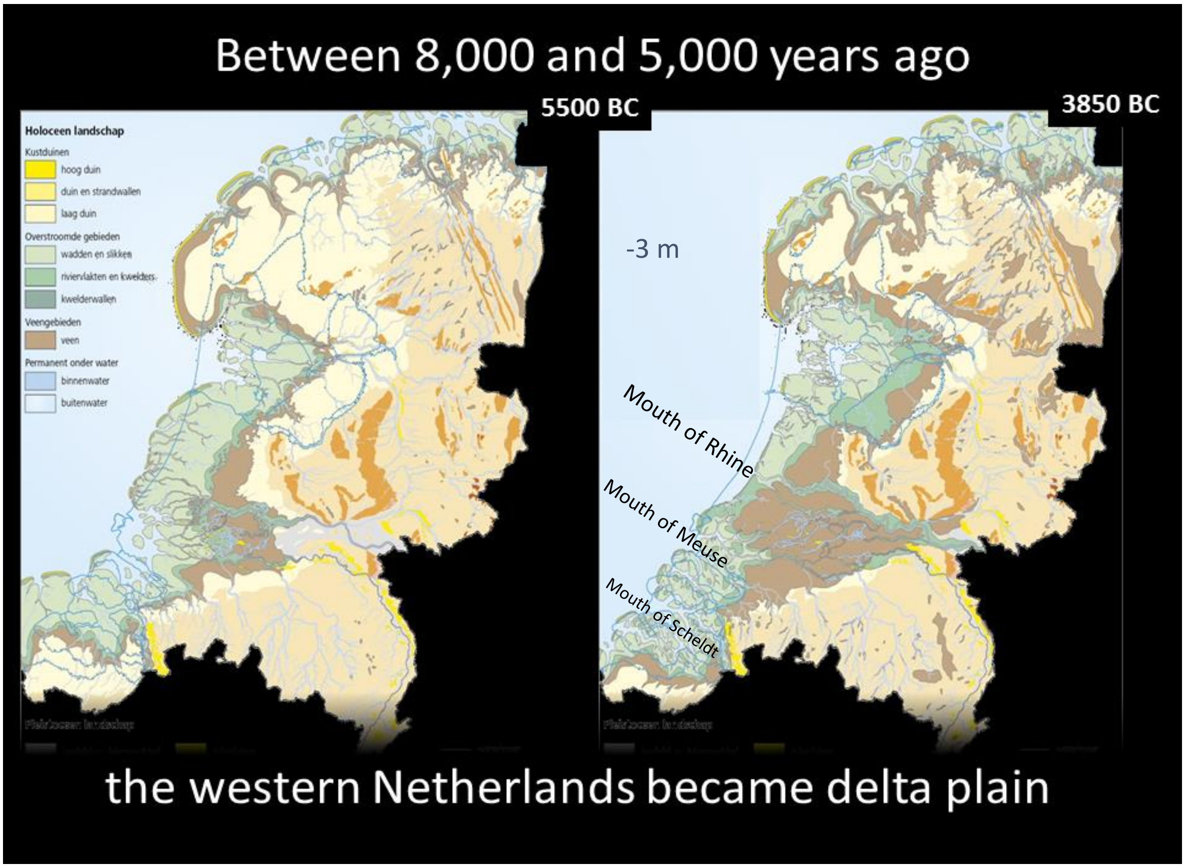


Fig. 8 –Sea-level data collected in the Rotterdam area (selected sites) Van de Plassche et al. 2010

Netherlands coastal plain and delta palaeogeography


Between 12,000 and 8,000 years ago

the North Sea experienced sea-level rise


Between 8,000 and 5,000 years ago

the western Netherlands became delta plain

Figures 9-12: Map series Vos (2015) – annotations KMC – Legend on page 21

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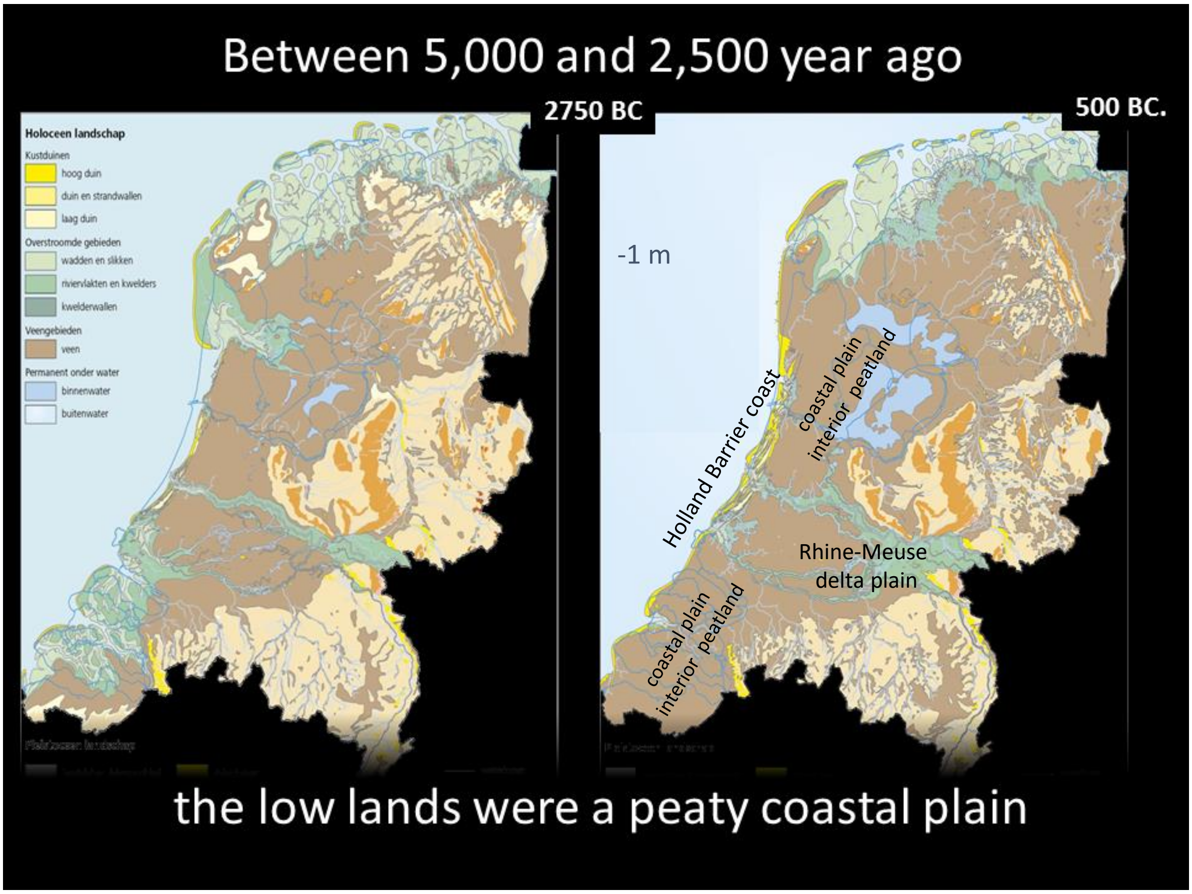
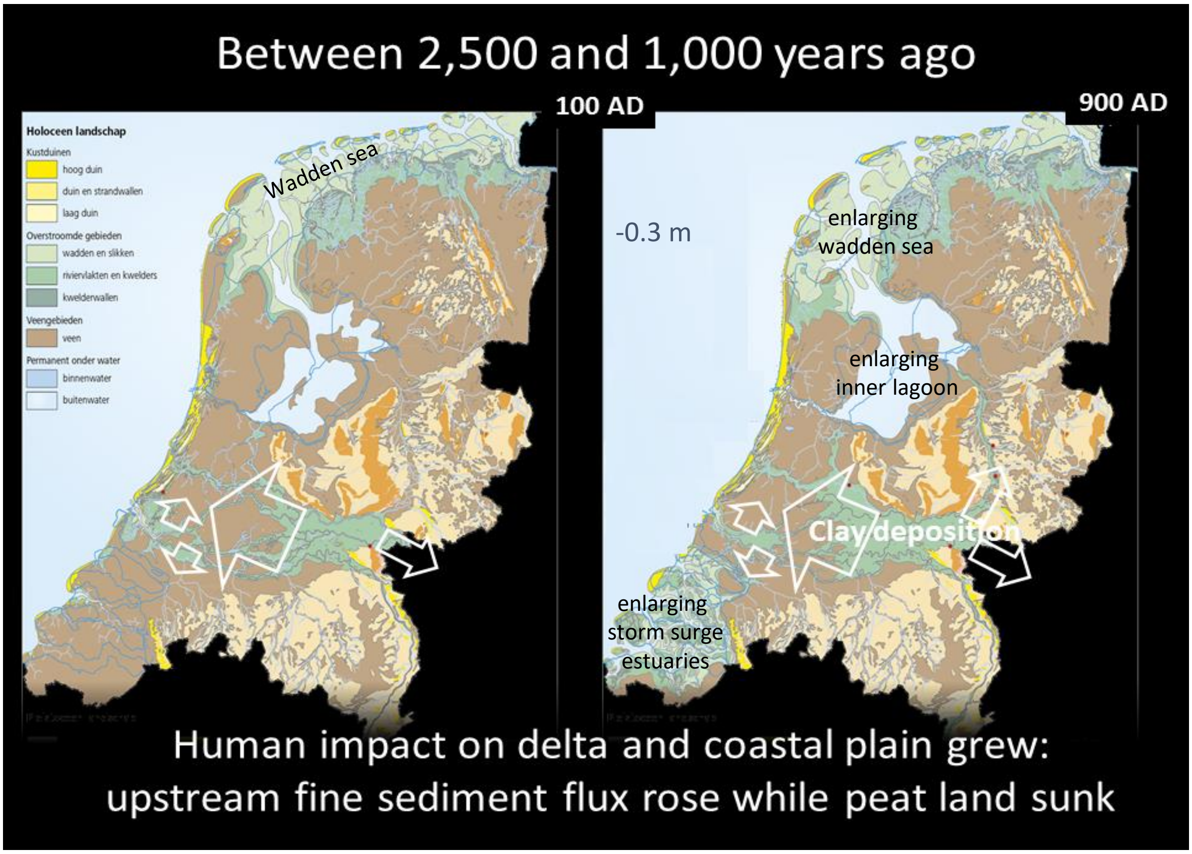
Netherlands coastal plain and delta palaeogeography



Between 5,000 and 2,500 year ago

the low lands were a peaty coastal plain



Between 2,500 and 1,000 years ago

Human impact on delta and coastal plain grew: upstream fine sediment flux rose while peat land sunk

Figures 9-12: Map series Vos (2015) – annotations KMC – Legend on page 21

Have an ANDROID smartphone? Search google play for “Deltares Paleomaps”

Drive-by: Rotterdam large delta-city and harbour

The Port of Rotterdam

Rotterdam as a town was founded in the 13th century at the confluence of the Meuse river and the Rotte tidal creek into northerly peat land. The toponym Rotterdam means ‘dam in the Rotte’ and reflects a measure of occupants against relative sea-level rise. The people along the Rotte were forced to dam their creek because of peat land subsidence, that they had triggered themselves by draining it. The dam prevented saline water to enter the hinterland and allowed the Rotte channel to be used as a ‘bossom’ (similar to the system shown at Kinderdijk). In the 19-20th cy (compare Figures 13 and 14), Rotterdam became the largest harbour of Europe (present global top 5).

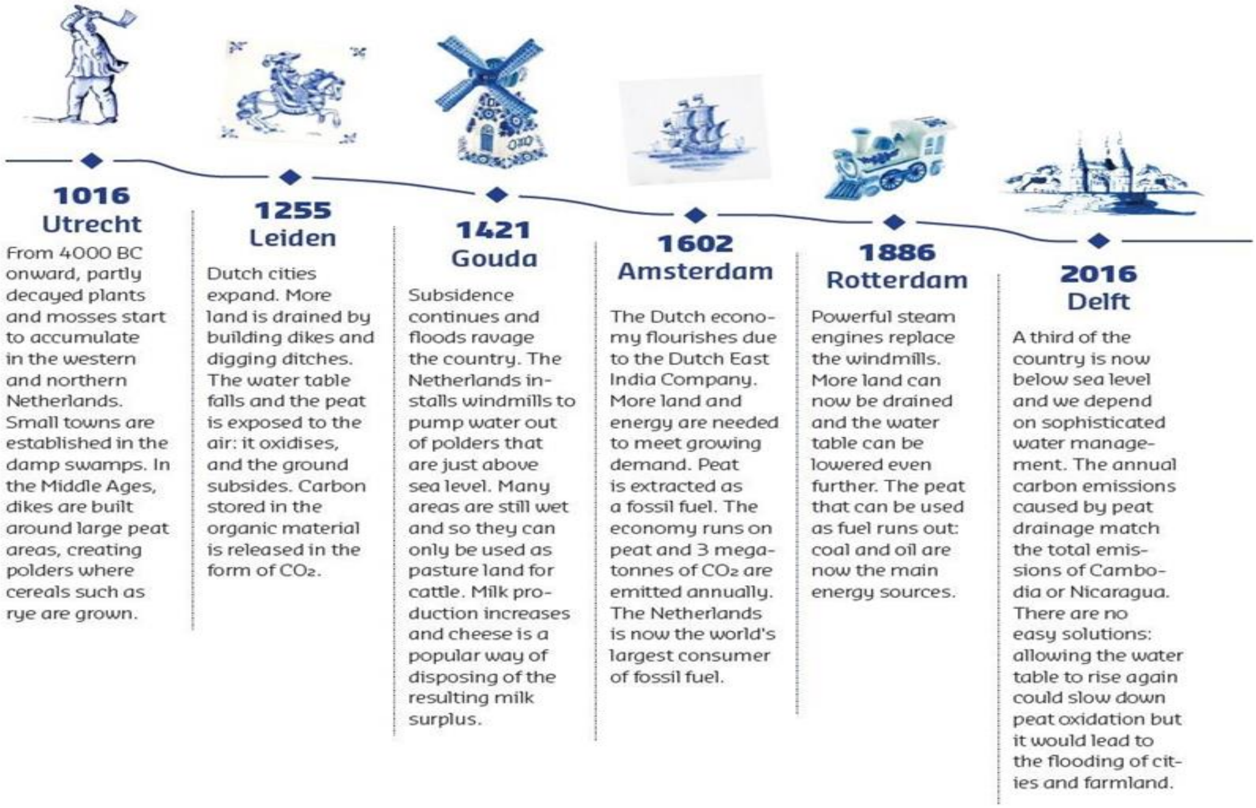
The bearing capacity of the Rotterdam shallow subsoil is low, and requires deep foundations for most constructions. Also, great volumes of man-made ground have been brought-up locally. Older natural peaty subsoils, have been compressed and pushed down below groundwater levels. Applying such overburdens, with hindsight has mitigated the impacts of peat oxidation and surface subsidence. Areas that have not received antropogene overburdens, occur north of the city and at present experience 1–2 mm/yr surface lowering (Van de Borne et al. 2016). As a consequence, Rotterdam is at present an elevated height in a low-lying coastal plain (Koster, 2017) – See Figures 15 and 16.

Fig. 13 – Satellite image of Rotterdam and its harbor (NASA World Wind engine).

Lower Rhine-Meuse delta - Historic situation 1850

Fig. 14 - Manuscript maps 'veldminuten' of Topographic Military Map series of the Netherlands (1850), sheets Rotterdam, Delfland, Voorne-Putten [...]

Holland Human-Induced Land Subsidence



1016
Utrecht
From 4000 BC onward, partly decayed plants and mosses start to accumulate in the western and northern Netherlands. Small towns are established in the damp swamps. In the Middle Ages, dikes are built around large peat areas, creating polders where cereals such as rye are grown.

1255
Leiden
Dutch cities expand. More land is drained by building dikes and digging ditches. The water table falls and the peat is exposed to the air: it oxidises, and the ground subsides. Carbon stored in the organic material is released in the form of CO₂.

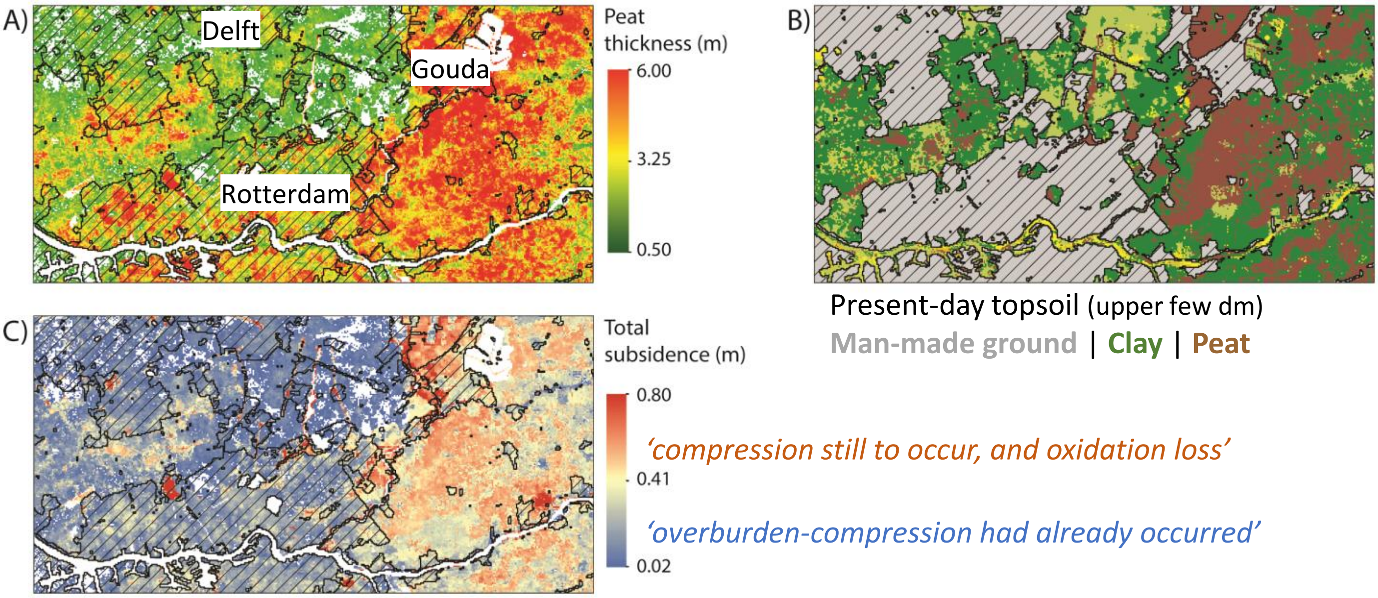
1421
Gouda
Subsidence continues and floods ravage the country. The Netherlands installs windmills to pump water out of polders that are just above sea level. Many areas are still wet and so they can only be used as pasture land for cattle. Milk production increases and cheese is a popular way of disposing of the resulting milk surplus.

1602
Amsterdam
The Dutch economy flourishes due to the Dutch East India Company. More land and energy are needed to meet growing demand. Peat is extracted as a fossil fuel. The economy runs on peat and 3 megatonnes of CO₂ are emitted annually. The Netherlands is now the world's largest consumer of fossil fuel.

1886
Rotterdam
Powerful steam engines replace the windmills. More land can now be drained and the water table can be lowered even further. The peat that can be used as fuel runs out: coal and oil are now the main energy sources.

2016
Delft
A third of the country is now below sea level and we depend on sophisticated water management. The annual carbon emissions caused by peat drainage match the total emissions of Cambodia or Nicaragua. There are no easy solutions: allowing the water table to rise again could slow down peat oxidation but it would lead to the flooding of cities and farmland.

Fig. 15 – Tiled historic time line - Erkens et al. 2016



Present-day topsoil (upper few dm)
Man-made ground | Clay | Peat

'compression still to occur, and oxidation loss'

'overburden-compression had already occurred'

Fig. 16 – Subsidence and peat near Rotterdam, with a) Accumulated thickness of Holocene peat, b) Present-day topsoil composition and c) Anticipated subsidence in the area owing to combined peat compression and oxidation, under continued groundwater-table lowering (business as usual). Urban areas are less prone to subsidence than agricultural areas. From Koster (2017).

Stop 2: Polder ‘De Vergulde Hand West’ - Vladingen

Outline of program (two hour stop)

Hand out of field lunch

Split up the group – rotation of activities C-B-A / A-C-B / B-A-C

A. Impact of SLR at present, delta land use change, managing soft soils, new vs. legacy occupation
  - *Growth of Vlaardingen, urban and commercial*
  - *Growth of Rotterdam harbour, deeper harbours* - Figures 17-21
  - *Subsurface infrastructure (e.g. tunnels)*

B. Impact of SLR (pre)historic: loss and regain of land, Iron Age, Roman Age, Medieval reclamation.
  - *hand corings along ditch (Edelman auger and gauge)* - Figures 22-28
  - *top sections of mechanical corings*

C. Impact of SLR: Holocene transgression. Drowning of valleys to become delta. Basal Peat.
  - *Middle sections of mechanical corings (post-drowning tidal)*
  - *Lower sections of mechanical corings (pre-drowning fluvial)* - Figures 29-31

Fig. 17 - Vlaardingen c.1550 AD,
Map by Jakob van Deventer.
Madrid Spanish royal library

Stop 2

Map Series Stop 2

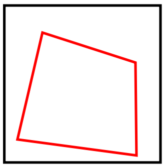


Fig. 18 **Situation 1905** *(highway and future Blankenburg tunnel for reference)*

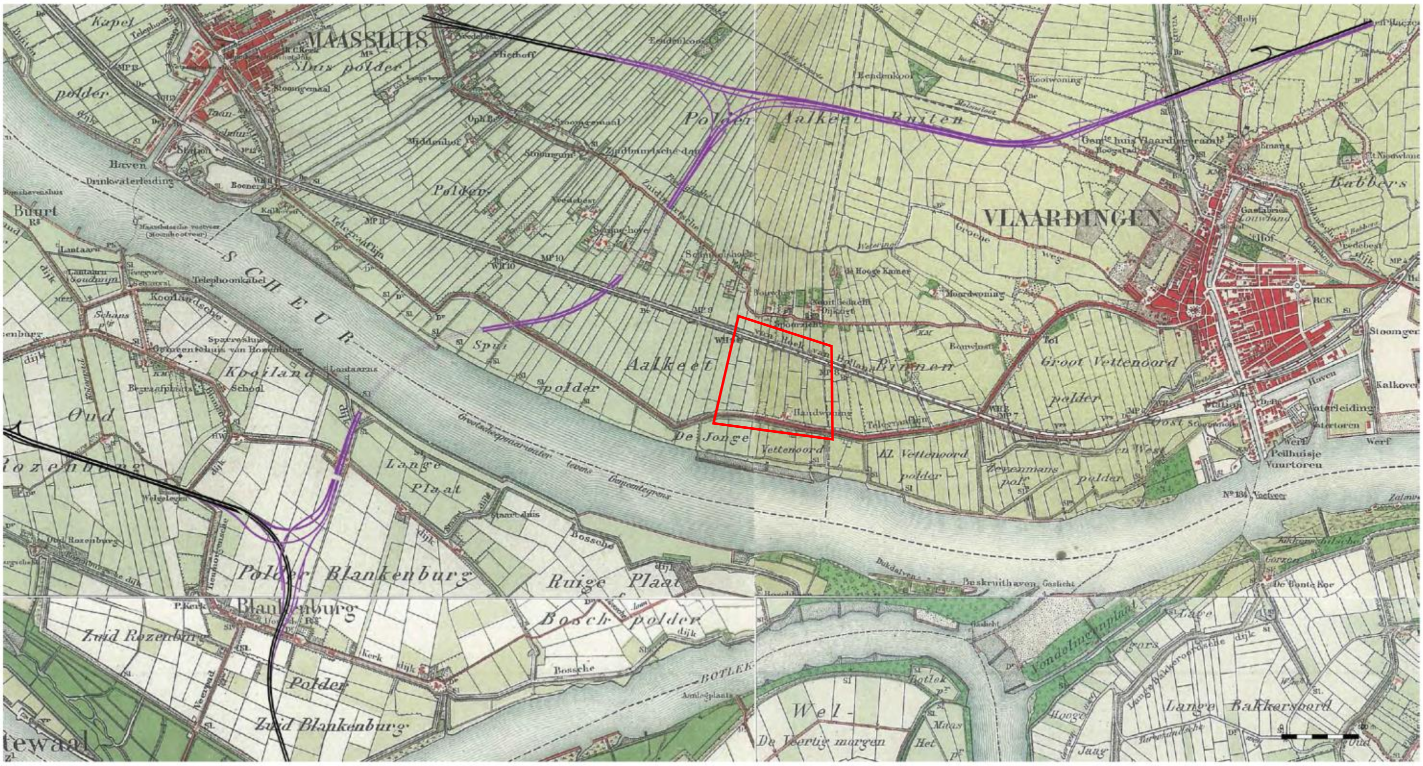
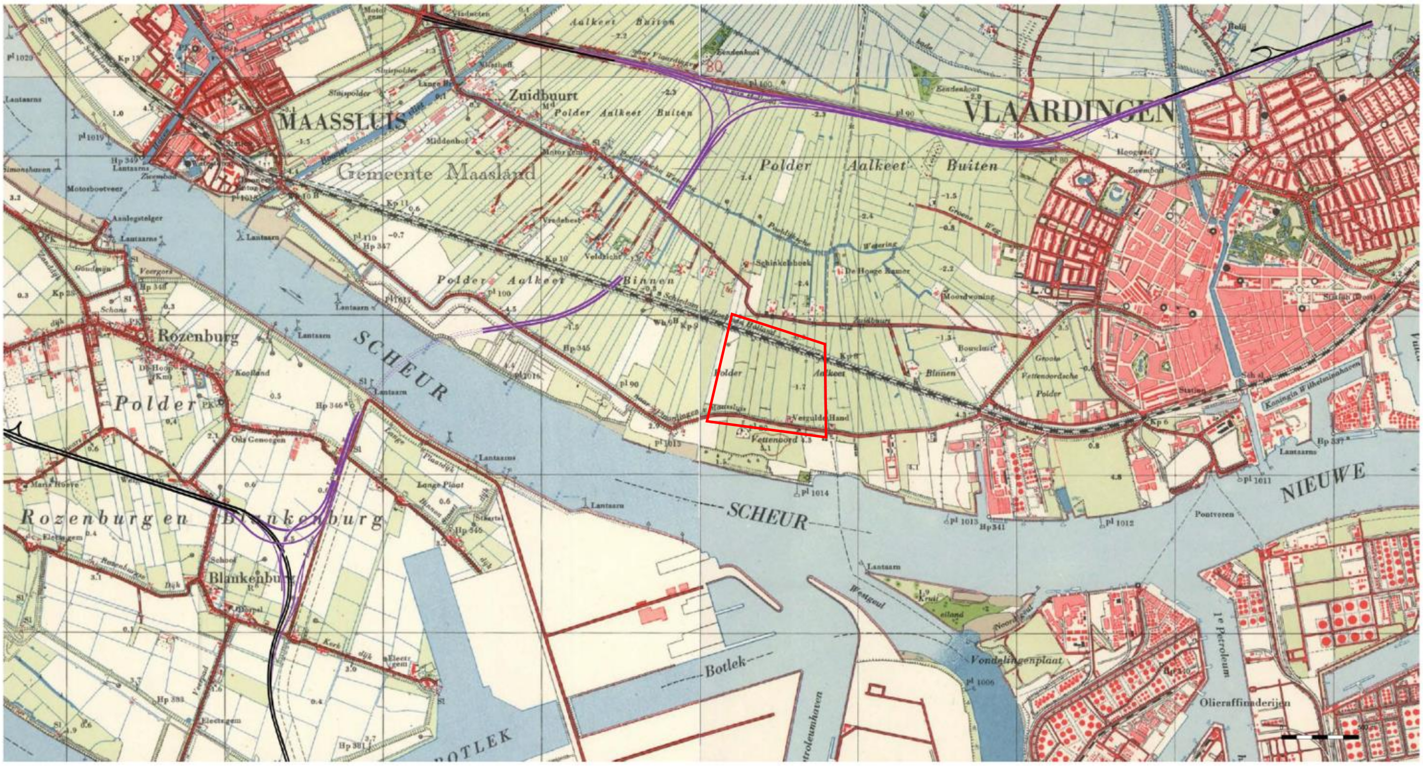


Fig. 19 **Situation 1948** *(highway and future Blankenburg tunnel for reference)*



Source: Ontwerp-Tracebesluit Blankenburgertunnel (RWS 2018: Bijlage A Vormgevings- en inpassingsplan). National topographic map series.

Map Series Stop 2

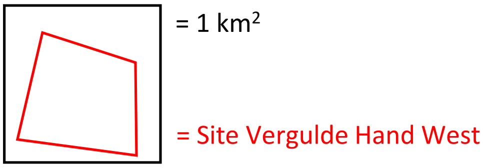


Fig. 20 **Situation 1974** *(highway and future Blankenburg tunnel for reference)*

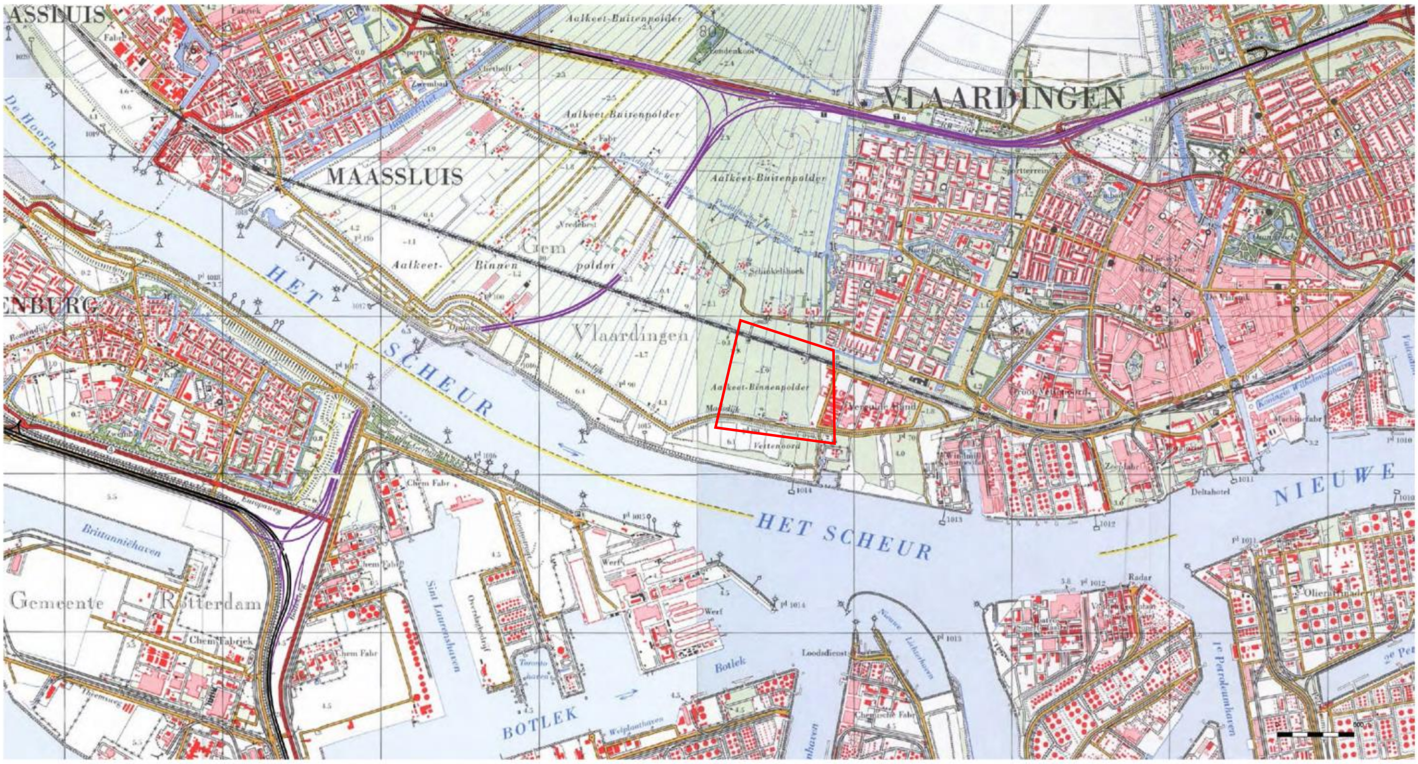
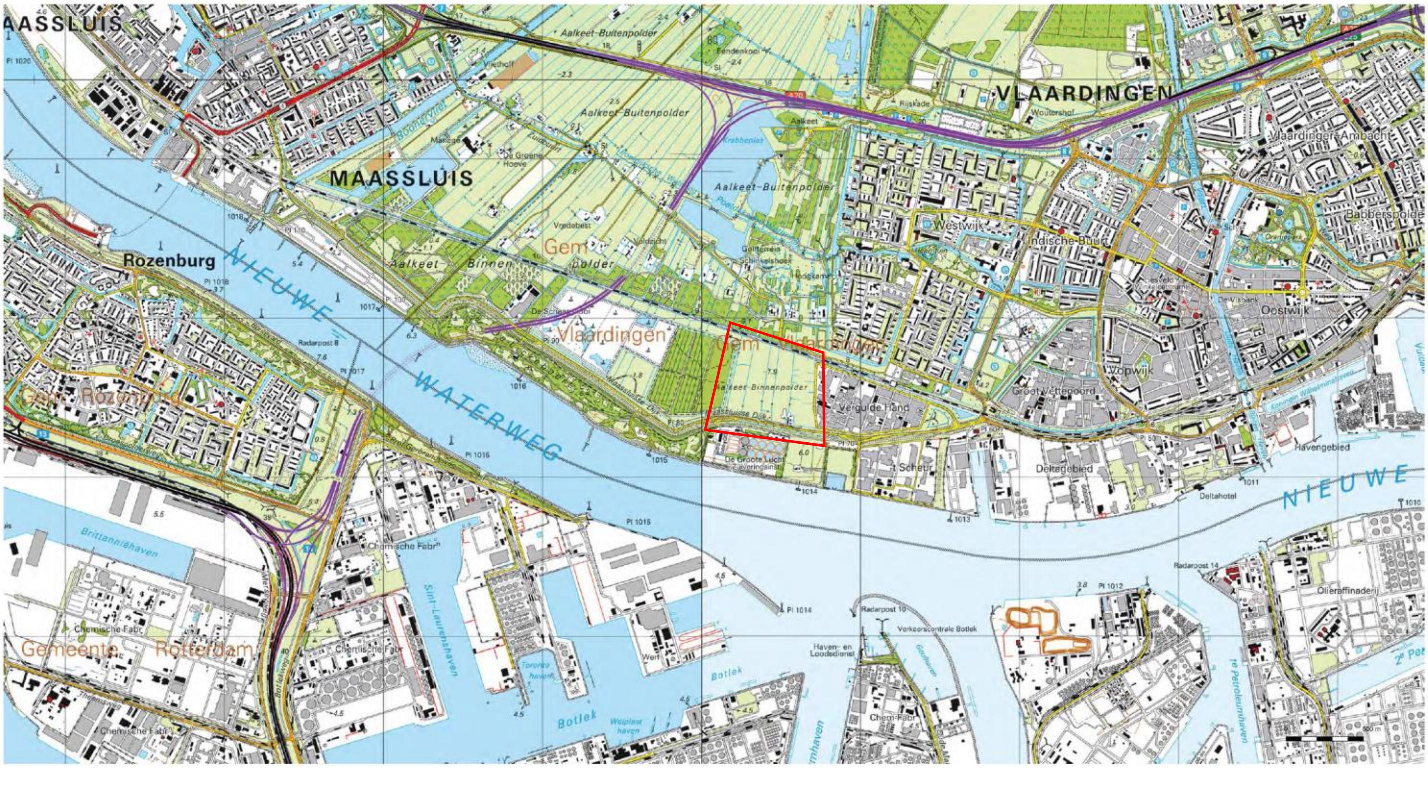


Fig. 21 **Situation 2009** *(highway and future Blankenburg tunnel for reference)*



Source: Ontwerp-Tracebesluit Blankenburgertunnel (RWS 2018: Bijlage A Vormgevings- en inpassingsplan). National topographic map series.

Stop 2: Polder ‘De Vergulde Hand’ - Vlaardingen

Drained, drowned and reclaimed polder landscape

The polder ‘De Vergulde Hand’ is situated on the border of the Meuse Estuary flood lands and medieval-reclaimed peatlands of the coastal plain interior. The site offers a prime example of how the impacts of relative sea-level rise have affected humans in prehistoric, historic times, and are affecting at present. The area has a very rich, multi-phased archaeological occupational record that was systematically excavated and studied in multidisciplinary project between 2000 and 2010 (Eijskoot et al., 2011). Figure 22 on the next page illustrates the reconstruction, further summarized below (Vos & Eijskoot 2011).

The area was inhabited from the Late Bronze Age to the Middle Ages. During the Bronze Age (2000 – 800 yr BCE) and the Early Iron Age (2800 – 2500 yr BCE), the peatlands were only sporadically inhabited. This changed however during the Middle- to Late Iron Age and onwards (500 – 12 yr BCE). During this early period of habitation, the peat swamps were periodically flooded during storms. From this period, the oldest water management infrastructures in the area are known: dams to regulate the surface water in the peatlands.

The peat in the swamps could eventually form several meters above sea-level. In this period, the peat was partially drained to facilitate agriculture and was invaded by water from the estuary. This caused the peat to rupture and transform into floating islands. Eventually, the peat was entirely flooded and covered with a clay layer. The overburden of the clay caused further compression of the peat, resulting in land subsidence. The sunken area remained modestly inhabited during Roman times (12 yr BCE – 250 yr CE), and appears fully abandoned in the Dark Ages (Late Roman and Early Medieval times; 250 – 900 yr CE). In absence of humans, a new phase of peat formation commenced.

Then, in the 11th or 12th century CE, the re-established peatland was reclaimed. New ditches were cut to transform the area into a polder for agricultural purposes, protected from the Meuse estuary flood waters by the Maassluisse Dijk dike. These ditches and dike are still present today. As in iron-age and Roman times, the drainage induced substantial land subsidence. The polder surface nowadays is maintained at 2 m below mean sea level.

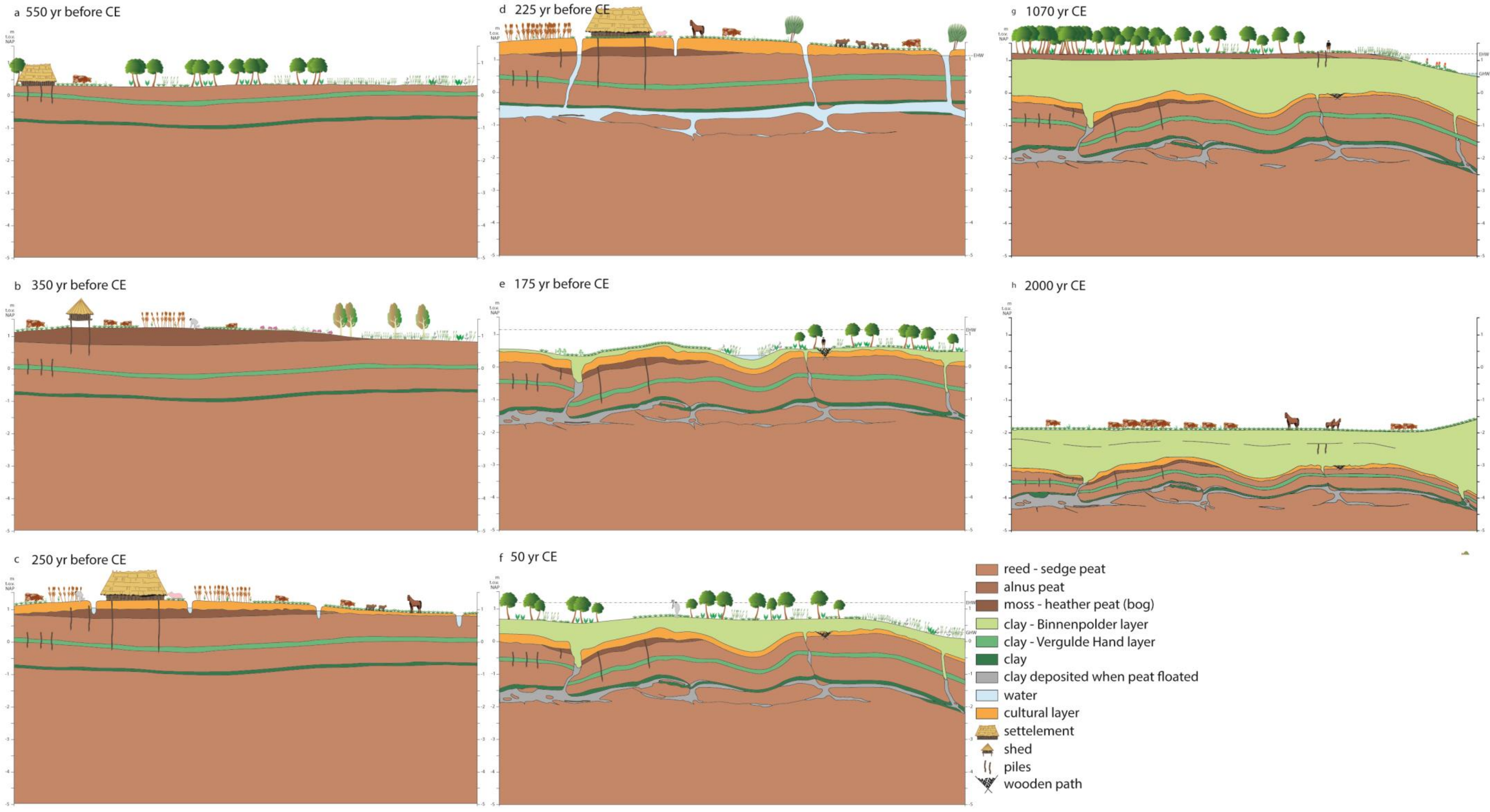
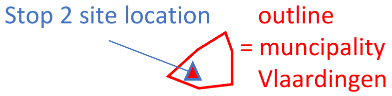


Fig. 22 – Overview of the impacts of sea-level rise for inhabitants of the peat swamps at the ‘Vergulden Hand’ archaeological site (after Vos & Eijskoot, 2011)



Map Series Palaeogeography

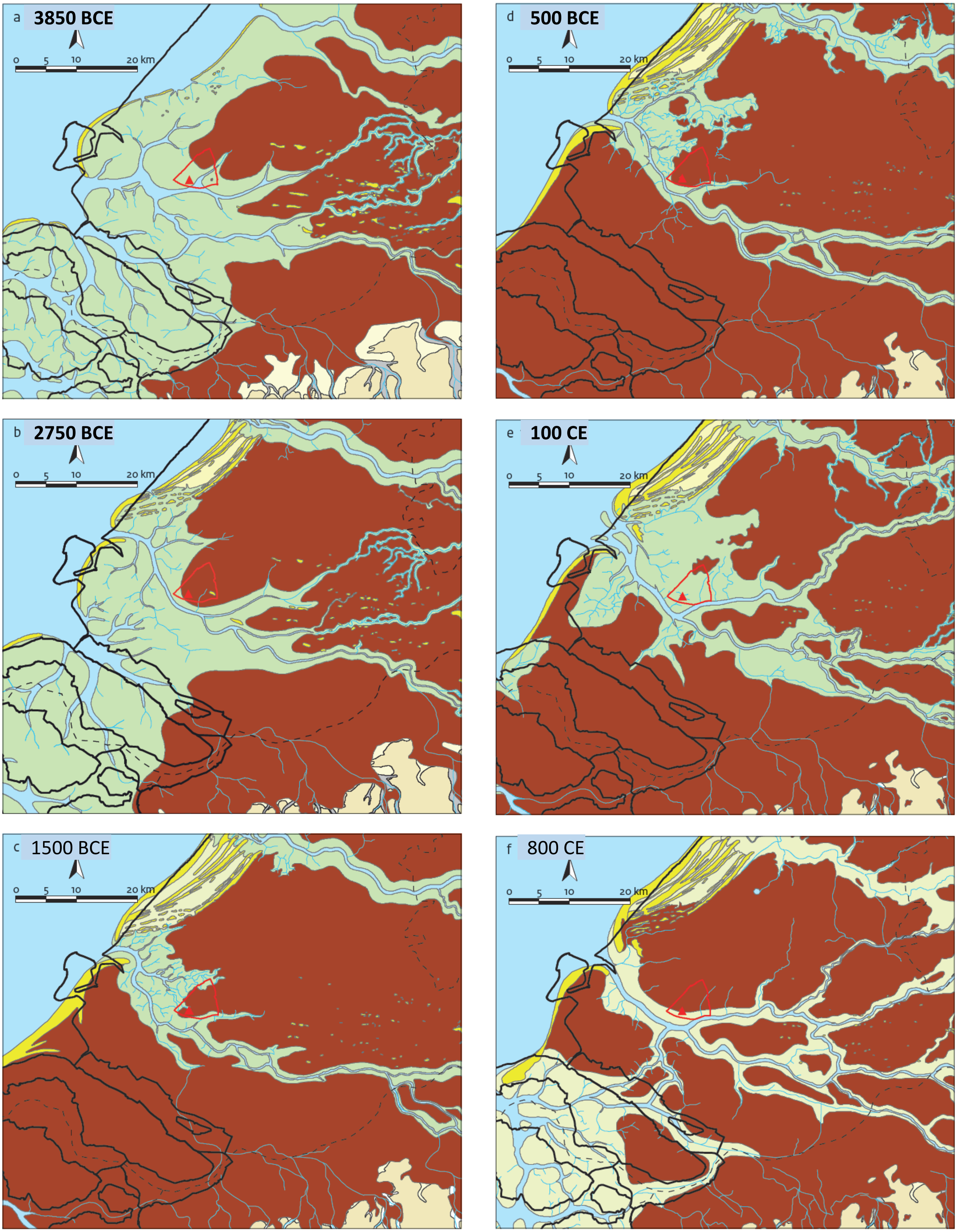


Fig. 23 – Zoomed in crops from paleogeographical map series Figs 10-12. From: Vos & Eijskoot, 2011

Map Series Palaeogeography

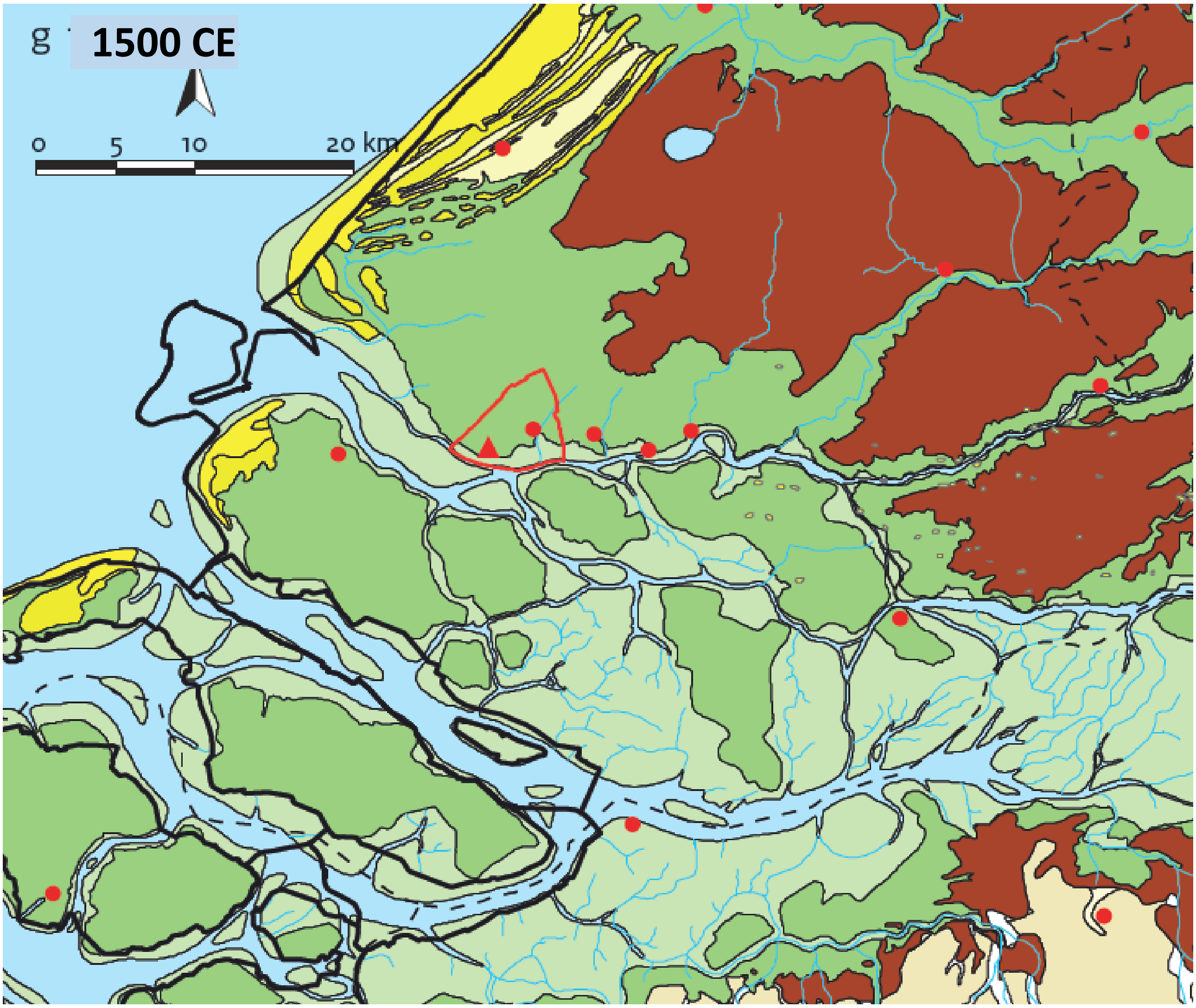
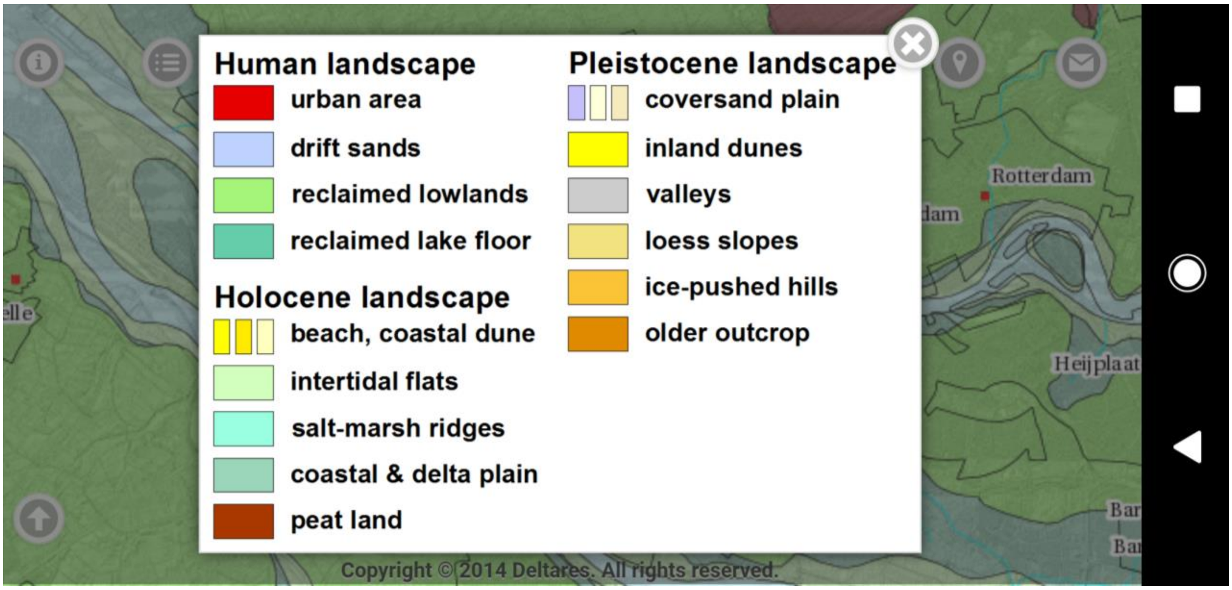


Fig. 24 – Vlaardingen and surrounding c. 1500 AD - From: Vos & Eijskoot, 2011. Legend in English provided below



Human landscape
- 🟥 urban area
- ▭ drift sands
- 🟩 reclaimed lowlands
- 🟩 reclaimed lake floor

Holocene landscape
- 🟨🟨▯ beach, coastal dune
- ▭ intertidal flats
- ▭ salt-marsh ridges
- 🟩 coastal & delta plain
- 🟫 peat land

Pleistocene landscape
- ▯▯▯ coversand plain
- 🟨 inland dunes
- ▭ valleys
- 🟨 loess slopes
- 🟧 ice-pushed hills
- 🟧 older outcrop

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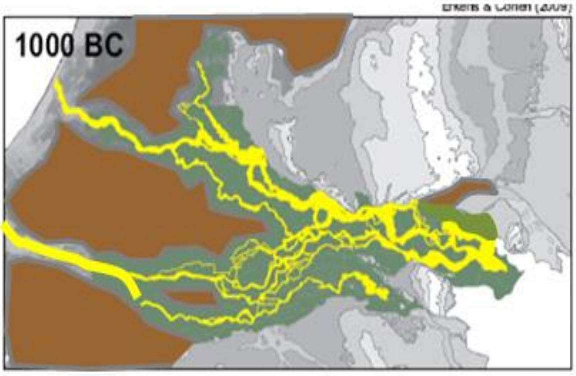
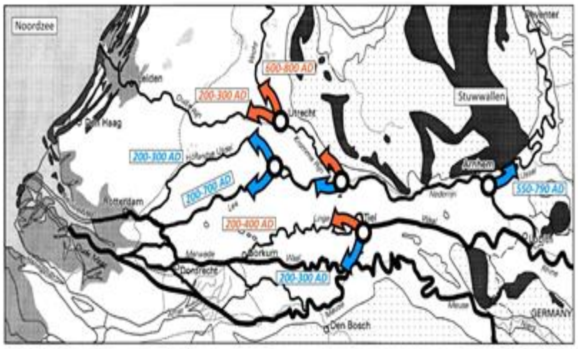
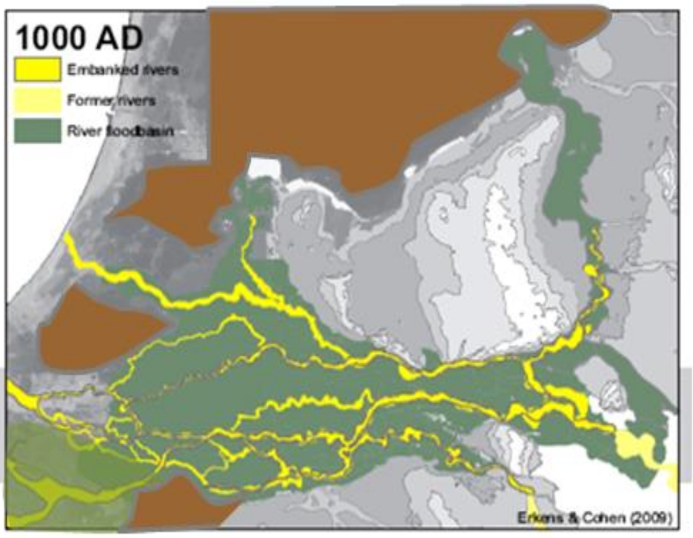
Stop 2 – Activity B - Materials

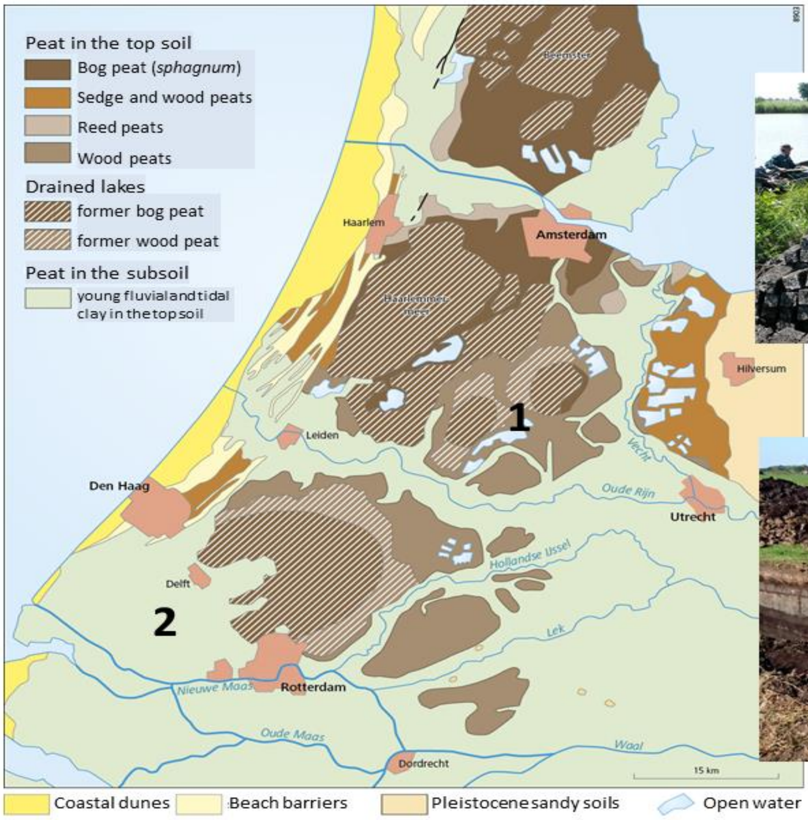


Owing to deforestation and erosion in the German hinterland, overbank deposition of fine sediment (clay, silt) in the delta increased. This allowed new river branches to avulse, spreading the overbank mud cover even more.





Clay cover from rivers and estuaries expanded over peat land – in some places *following* prehistoric early reclamations



1: Nieuwkoop
Peat topsoil, peat subsoil

2: Vlaardingen
Clay top soil, peat subsoil

Vlaardingen picture shows
1) Oxidation and 2) Compression

Figs. 25 and 26. Lecture materials KMC, based on Erkens and Cohen 2009; Stouthamer et al. 2015; Erkens et al. 2016

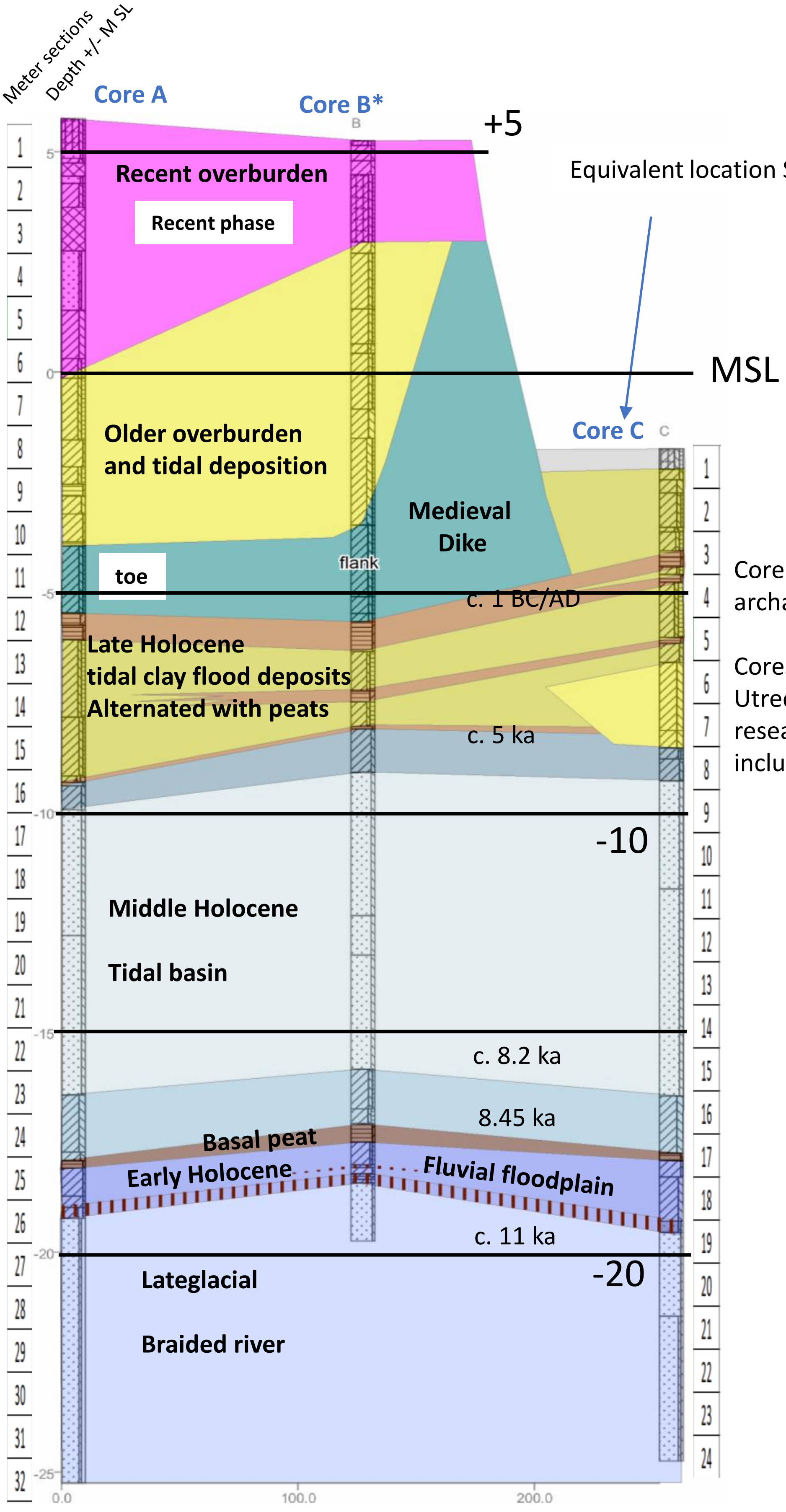
Stop 2 – Activity B – Materials

2006-2008 archaeological excavation pictures Vlaardingen De Vergulde Hand West – Eijskoot et al. 2011

Fig. 27 - **Example evidence of oldest phase of ditch cutting (c. 1 BC/AD), with later clay fill**

Fig. 28 - **Example excavated structures: Roman Age last house on subsiding peaty top soil**

Stop 2 – Activity C – Site Geology



Equivalent location Stop 2

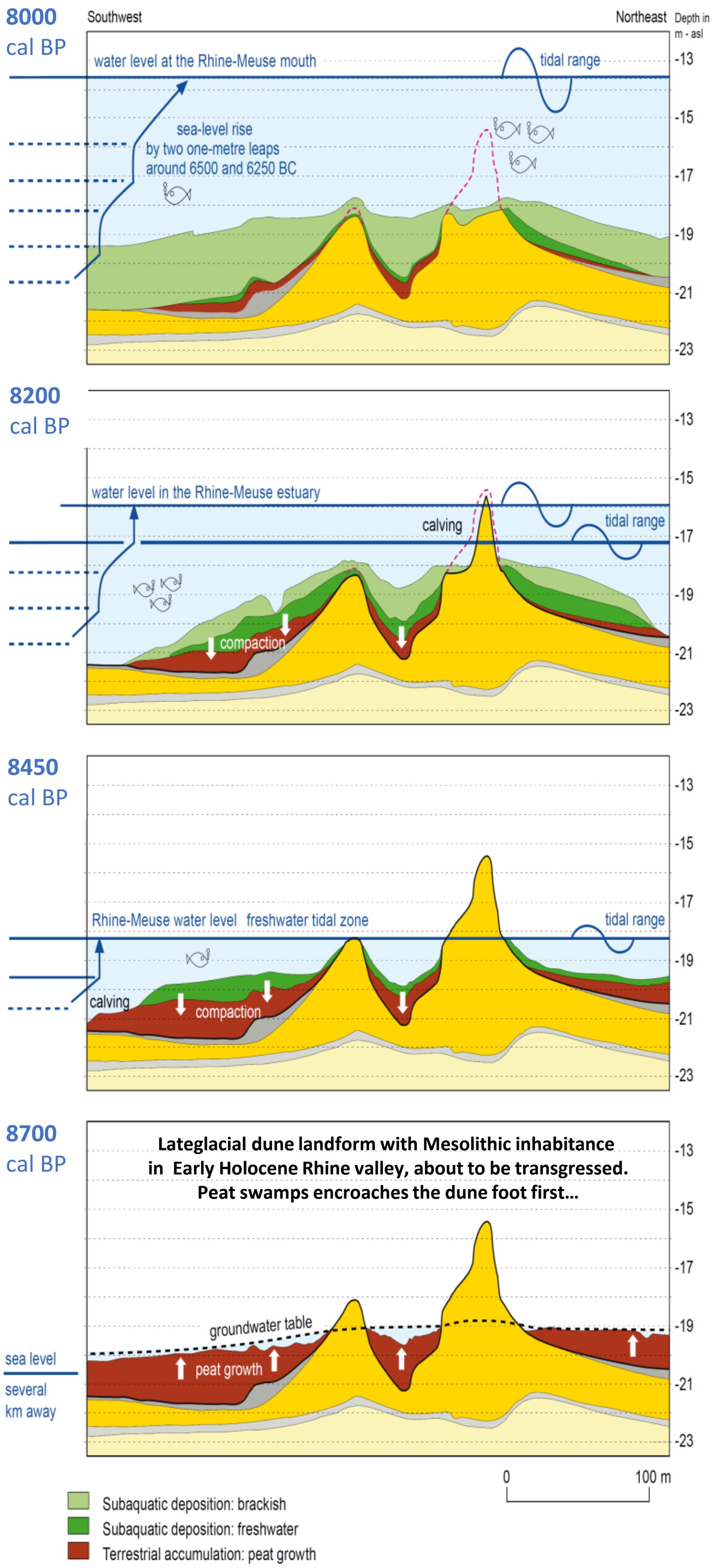
Core B was selected for further archaeological prospective research

Cores A and C were handed over to Utrecht University for research/education purposes – including this excursion

Figure 29
Build up of Holocene delta at the Maassluisse Dijk. From Huijzer 2017, with excursion annonations.

Section location: 1 km west of Stop 2, future location Blankenburg tunnel, to be constructed 2018-2022

Rotterdam sea-level jump 8.45-8.2 ka BP



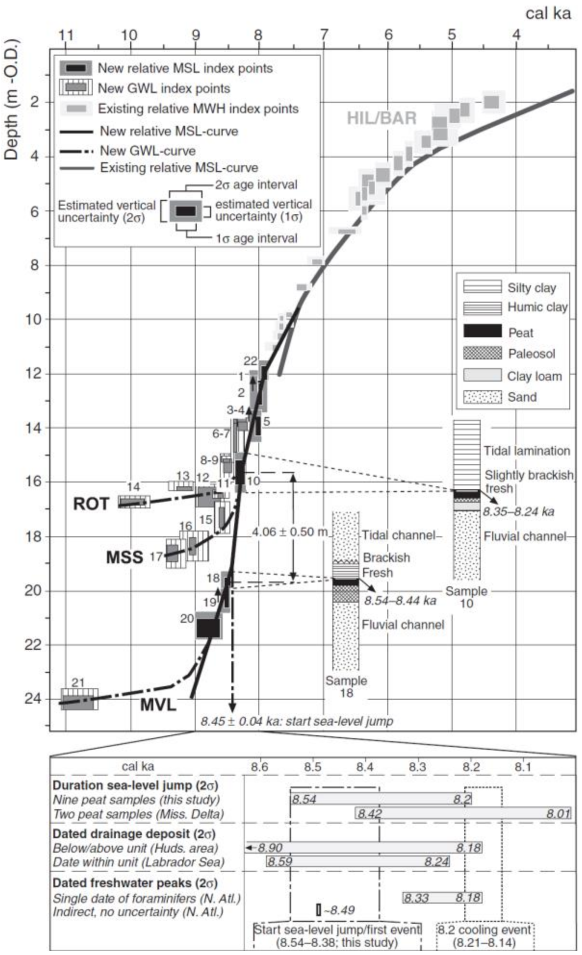


Figure 1. Relative sea-level rise in western Netherlands based on geological data (9–7.5 ka, this study; 7.5–4 ka, Van de Plassche, 1982; Berendsen et al., 2007). Upper panel plots age-depth index points and shows that sea-level jump commenced ca. 8.45 ka (calendar years ago, cal). Sedimentological (lithology, structure) and paleoenvironmental (pollen, diatoms) indicators are plotted as core logs for two sites with transgressed basal peat that most closely bracket jump magnitude. Groundwater-level (GWL) rise (depicted for sites ROT, MSS, and MVL) is plotted as sigmoidal curves that show initial fluvial-controlled groundwater levels graded to paleovalley floodplain level (dipping from 17 to 24 m between ROT and MVL), then gradual establishment of sea-level control in coastal zone and eventual full pick-up of mean sea-level (MSL) rise (20–18, 10, 5, 1–2, 22). Arrows above index points indicate that their depths are possibly overestimated, because of uncertain amounts of compaction. Lower panel compares timing of Rotterdam jump with other published sites. End of jump coincides with start of 8.2 ka event; onset appears to have been two centuries before. Dates from Hudson (Huds.) area (Barber et al., 1999; postdate southeast Hudson Bay and predate East Hudson Strait) were recalibrated using Marine04-curve (Hughen et al., 2004) using reservoir effects defined in original publications. The 2σ interval of Labrador Sea date (Hillaire-Marcel et al., 2007) was obtained by calibrating original radiocarbon date (7950 ± 80 ¹⁴C yr B.P.). Miss.—Mississippi; N. Atl.—North Atlantic; O.D.—Dutch Ordnance Datum; MHW—mean high water.

Fig. 31 Relative sea-level rise at base of Holocene based on sites ROTterdam, MSS Maassluis (= Stop 2) and MVL Maasvlakte (= Figure 30). From Hijma & Cohen 2010. Original figure caption included.

Fig. 30 Landscape reconstruction of drowning of Mesolithic site 'Yangtzehaven' (location: Maasvlakte seaward harbour extension, 10 km west of Stop 2. See also Figs. 32-33). From Moree & Sier 2015, incorporating Hijma & Cohen 2010 and Vos et al. 2015.

Stop 2 – Activity C - Materials

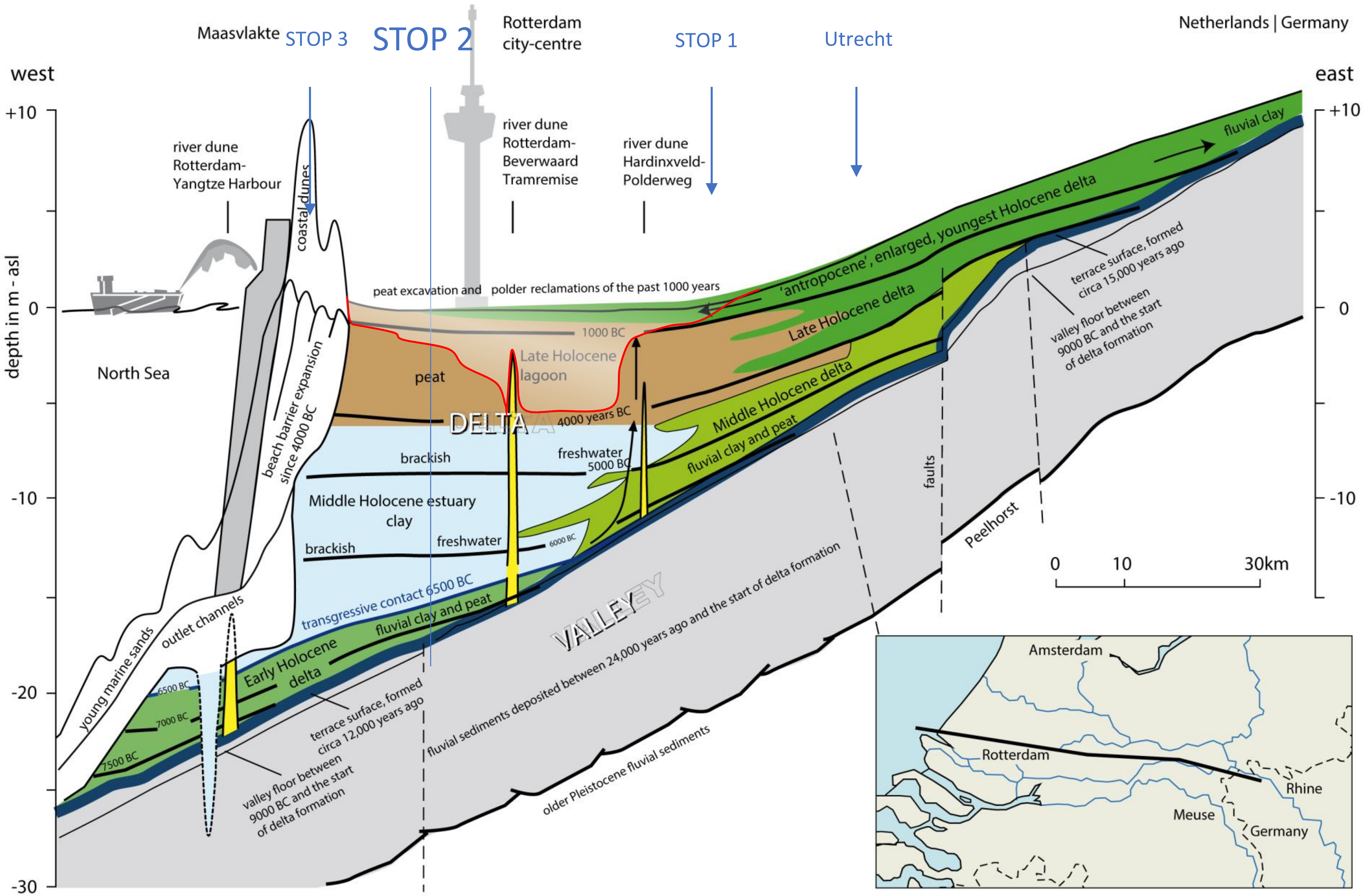


Fig. 32 – Schematic cross-section showing the accommodation of the Rhine delta and Holland coastal plain up to 1000 years ago, after Cohen and Hijma 2014; Moree & Sier 2015. Red line shows the present surface elevation – including for peat mining and polder reclamation activities. **Excursion stop locations also indicated**

Drive-by: Mega storm surge barrier ‘Maeslantkering’

Coastal protection

To protect the Rotterdam harbour against storm surge induced flooding, the ‘Maeslantkering’ was constructed in the 1990s. Due to the economic importance of the harbour, a permamently closed barrier was not an option. Instead, a barrier was constructed that could be closed during storms causing an increase in water level height of 3 m above mean sea level, and kept open during normal weather conditions. The barrier is one of the world’s largest moving structures.

The barrier consists of two gates, that are floated in and then are sunk to close the barrier. They are 22 m high and 210 m long. The arms of the gates are attached to shore with a ball shaped joint that allows the gate to move freely under influence of wind, water, and waves. The total construction costs were 660 million Euro. Add maintenance costs to this.

Since its construction finished twenty years ago (1997). It has been operated twice because of a large storm surge: 8 November 2007 and 3 January 2018 (Figure 33). Test closures of the Maeslantkering are performed once a year.

Fig. 33 ‘Maeslantkering’ storm surge barrier closed in anticipation of storm surge 3 January 2018 (photo ANP).

Stop 3: Mega-nourishment ‘Sand Engine’

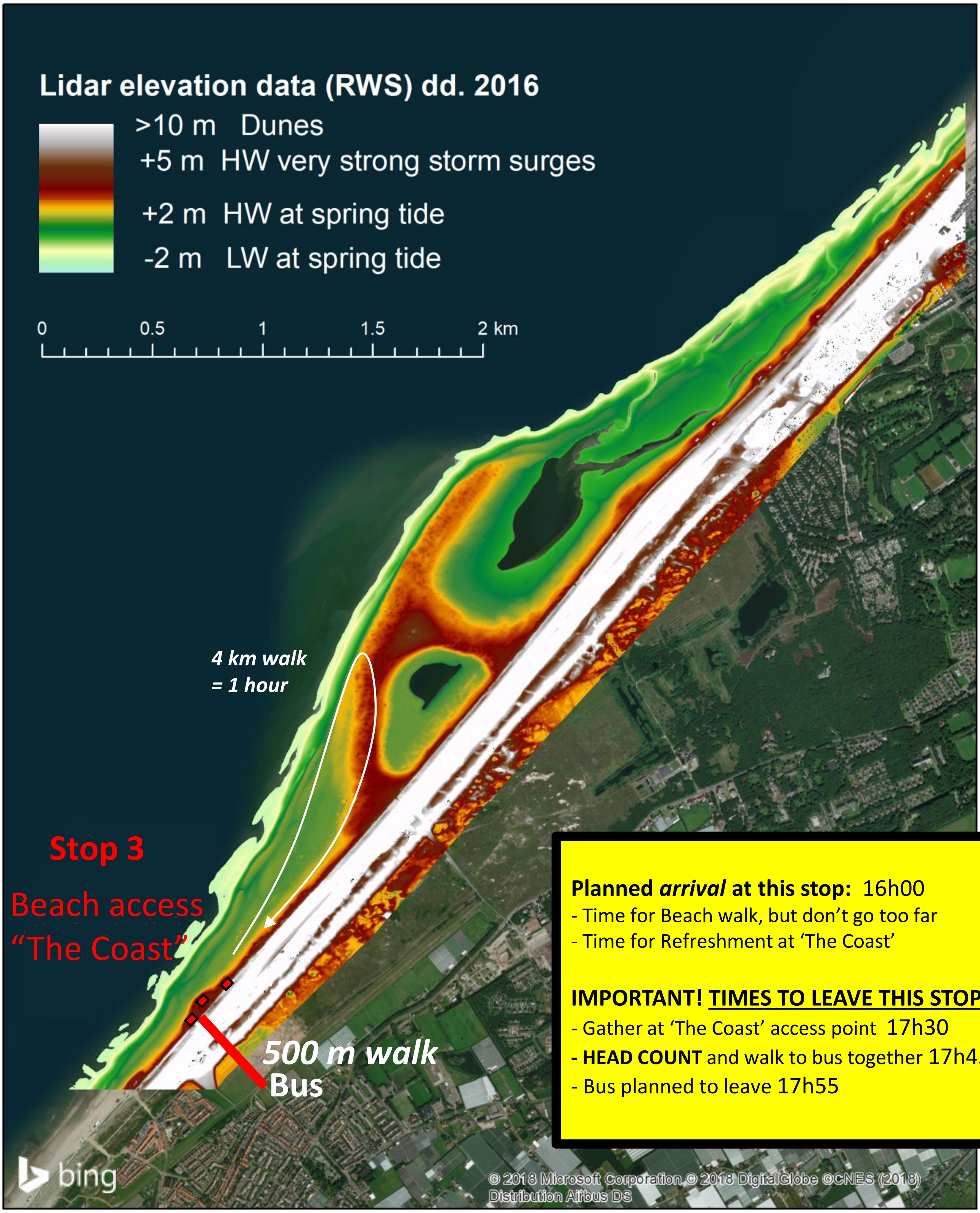
Mega-nourishment of the Holland beach barrier system

Historically, the storm surge flood defence in the Netherlands has made use of the natural beach and dune geomorphology. In places, engineered artificial structures were added. Such hard structures are costly in construction and maintenance and have negative impacts on eco-systems and water-sediment balances. Softer coastal engineering solutions would be an alternative and large scale experiments to test this are conducted. Behold the ‘Sand Engine’.

The ‘Sand Engine’ was created in 2011 as a sandbar-shaped peninsula. Waves and wind will rework the ‘Sand Engine’, transport and spread the sand along the adjacent coast, supplying the original beach and coastal dune system. Creating the ‘Sand Engine’ required to move 21.5 million m^3 of sand dredged from a few km offshore - beyond 20 meter depth, to not disturb the natural beach system - at a cost of 70 million Euros. A cheap deal because the 2008-2010 financial crisis had kept a fleet of hopper-dredge ships stand-by in the nearby Rotterdam harbour. The supplied volume should last until c. 2031. The Sand Engine’s dynamics are monitored by a consortium of institutes in the Netherlands (Figs. 34 & 35).

Fig. 34 – Sand Engine from the air (RWS commissioned photo series – views to the south) in 2011 (a,b), 2012 (c,d), 2013 (e), 2014 (f), 2015 (g), 2016 (h), and 2017 (i). Compilation: Rutten (2018).

Stop 3: Mega-nourishment 'Sand Engine'



Planned *arrival* at this stop: 16h00
- Time for Beach walk, but don't go too far
- Time for Refreshment at 'The Coast'

IMPORTANT! TIMES TO LEAVE THIS STOP
- Gather at 'The Coast' access point 17h30
- **HEAD COUNT** and walk to bus together 17h45
- Bus planned to leave 17h55

Predicted tides at 28 Aug 2018 [Scheveningen]
Low Water 12h45 -0.45 m
High Water 17h39 +1.15 m

Fig. 35 – Lidar elevation data dd. 2016 of the Sand Engine mega nourishment area. Figure produced by KMC using RWS data and BING maps background data.

Stop 3: Mega-nourishment ‘Sand Engine’

Sea-level change at the Dutch coast

The purpose of the ‘Sand Engine’ is to strengthen the Dutch coast against sea-level rise. In the past century, observed sea-level rise was in the order of 1.5-2.0 mm/yr. In the next century, these rates are projected to increase as a result of climate change (Fig. 36).

The projected sea-level rise scenarios for the Dutch coast range between 0.2 and 1.2 m by 2100, depending on the amount of greenhouse gas emitted (Vermeersen et al, 2018). These projections include changes in: 1) ocean density and dynamics; 2) ice sheet and glacier mass changes, 3) groundwater extraction and 4) glacial isostatic adjustment. For the Dutch coast, the changes are projected to be around or slightly above the global mean sea-level change. The projections *exclude* potential rapid changes in Antarctica causing additional sea-level rise of several decimeters up to a meter. The projections also do not include local coastal land subsidence, which would also amplify the effect of sea-level rise.

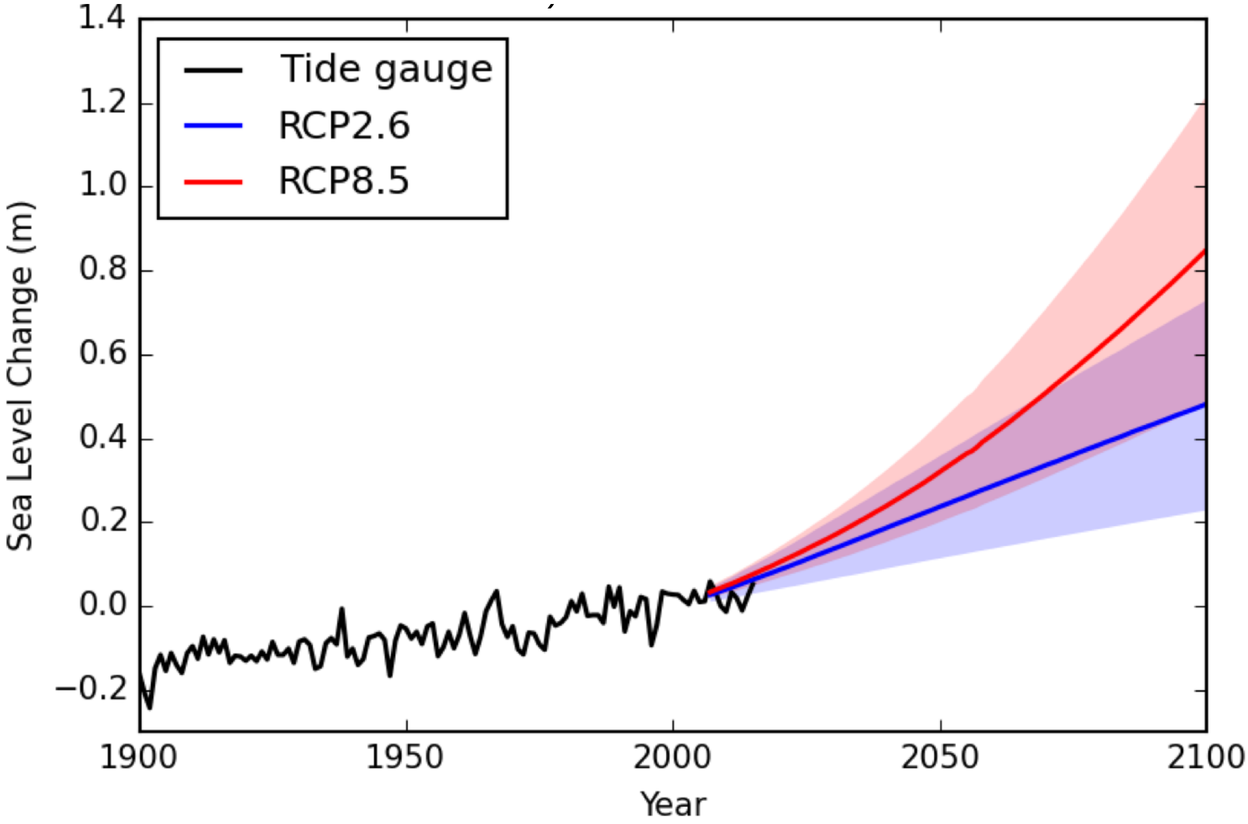


Fig. 36 – Observed (black; based on tide gauges) and projected sea-level change (m) for two scenarios, for site Den Helder, NL (Vermeersen et al., 2018). Shading indicates the 5-95% uncertainty range.

References, i.e. sources of figure material

ANP Algemeen Nederlands Persbureau [Netherlands' General Press office]

Berendsen, H.J.A., Stouthamer, E. (2001). Palaeogeographic development of the Rhine-Meuse delta, the Netherlands. Koninklijke Van Gorcum. [Book + maps]

Caro Cuenca, M., Hanssen, R., Hooper, A., Arikan, M. (2011), Surface deformation of the whole Netherlands after PSI analysis, Proc. 'Fringe 2011 Workshop' Italy, pp. 8

Cohen, K.M., Stouthamer, E., Pierik, H.J., & Geurts, A.H. (2012). Digitaal Basisbestand Paleogeografie van de Rijn-Maas Delta / Rhine-Meuse Delta Studies' Digital Basemap for Delta Evolution and Palaeogeography. Dept. Fysische Geografie. Universiteit Utrecht. [Digital Dataset. DOI 10.17026/dans-x7g-sjtw]

Cohen, K.M., & Hijma, M.P. (2014). The Transgressive Early–Middle Holocene Boundary: The Case for a GSSP at Rotterdam, Rhine Delta, North Sea Basin. In STRATI 2013 (pp. 925-929). Springer.

Eijskoot, Y., Brinkkemper O., De Ridder T. (2011), Vlaardingen – De Vergulde Hand-West (in Dutch), RCE Rapportage Archeologische Monumentenzorg 200, pp. 590. [Archaeological book report, in Dutch]

Erkens G. & Cohen, K.M. (2009).Quantification of intra-Holocene sedimentation in the Rhine-Meuse delta: a record of variable sediment delivery. Chapter 6 in: Erkens, G. (2009). Sediment dynamics in the Rhine catchment: quantification of fluvial response to climate change and human impact. Utrecht University. Pp 117-171.

Erkens, G., van der Meulen, M. J., & Middelkoop, H. (2016). Double trouble: subsidence and CO 2 respiration due to 1,000 years of Dutch coastal peatlands cultivation. Hydrogeology Journal, 24, 551-568.

Hijma, M.P., Cohen, K.M. (2010). Timing and magnitude of the sea-level jump preluding the 8200 yr event. Geology, 38. 275-278.

Huizer, J. (2017), Maassluissedijk, Blankenburgverbinding Noordoever (gemeente Vlaardingen), ADC Rapport 4342, pp. 20 [archaeological report, in Dutch]

Koster, K. (2017), 3D characterization of Holocene peat in the Netherlands – Implications for coastal-deltaic subsidence (PhD dissertation), Utrecht Studies in Earth Sciences 140, 185 pp.

Moree, J.M. and Sier, M.M. (Eds.) Twenty metres deep! The Mesolithic period at the Yangtze Harbour site – Rotterdam Maasvlakte, the Netherlands. Early Holocene landscape development and habitation. BOOR reports 566. pp 7-350. [Book Report. Municipality of Rotterdam & Harbour Authorities Rotterdam].

Rutte, J. (2018), Sandbar behaviour along a man-made curved coast, Utrecht Studies in Earth Sciences 156, pp. 96 [Published PhD-thesis, Utrecht University]

RWS Rijkswaterstaat – Netherlands national governmental agency responsible for civil works (road and water infrastructure, navigability, flood and storm safety).

Schengenga, P., Brouwer-te Molder, M., Vanagt, T., Kooiman, M. (2013). Gebiedsvisie Kinderdijk. H+N+S Landschapsarchitecten and Beek & Kooiman Cultuurhistorie. 112 pp. [Advisory Report, in Dutch]

Stouthamer, E., Cohen, K.M., Hoek, W.Z. (2015) De vorming van het land. Van Gr [Text book on Geology and Geomorphology of the Netherlands, in Dutch]

Van de Plassche, O., Makaske, B., Hoek, W. Z., Konert, M., & Van der Plicht, J. (2010). Mid-Holocene water-level changes in the lower Rhine-Meuse delta (western Netherlands): implications for the reconstruction of relative mean sea-level rise, palaeoriver-gradients and coastal evolution. Netherlands Journal of Geosciences, 89, 3-20.

Van den Born, G. J., Kragt, F., Henkens, D., Rijken, B., Van Bemmel, B., Van der Sluis, S., Polman, N., Bos, E.J., Kuhlman, T., Kwakernaak, C, van den Akker, J. (2016). Dalende bodems, stijgende kosten (No. 1064). Planbureau voor de Leefomgeving. [Government agency advisory report, in Dutch]

Vermeersen, L., Slangen, A., Gerkema, T., Baart, F., Cohen, K.M., Dangendorf, S., Duran-Matute, M., Frederikse, T., Grinsted, A., Hijma, M.P., Jevrejeva, S., Kiden, P., Kleinherenbrink, M., Meijles, E., Palmer, M., Rietbroek, R., Riva, R., Schulz, .E., Slobbe, D., Simpson, M., Sterlini, P., van de Wal, R., van der Wegen, M. (2018), Sea-level change in the Dutch Wadden Sea. Netherlands Journal of Geosciences (in press).

Vos P.C., Eijskoot, Y. (2011) Hoofdstuk 3: Geologie. In: Eijskoot et al. (2011), p. 69-146. [chapter in archaeological book report, in Dutch]

Vos, P.C. (2015). Origin of the Dutch coastal landscape: long-term landscape evolution of the Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series. Barkhuis. [Published PhD-thesis, Utrecht University]

Vos, P.C., Bunnik, F.P., Cohen, K.M., & Cremer, H. (2015). 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. Quaternary International, 367, 4-31.

Wikipedia – The Free Encyclopedia [online www.wikipedia.org; www.wikipedia.nl]

End of Excursion - Dinner location – Home journey

Back to bus at end of Stop 3
Gather at 'The Coast' at latest 17h30. We do a head count.
We walk back to the bus together. Leaving the beach at The Coast at 17h45
We are back at the bus, all aboard at 18h00 to drive to the Dinner location

Conference dinner
The conference dinner, sponsored by TU Delft, takes place at
Restaurant Leonor Fini, at the Fletcher Hotel-Restaurant Carlton **in Naaldwijk**
We will enjoy a 3-course menu.

Home journey
After the conference dinner, the touring bus will drive us
from the restaurant to Utrecht Science Park 'De Uithof',
where we plan to arrive around 22.30.

PAGES PAST GLOBAL CHANGES
INQUA International Union for Quaternary Research
NESSC NETHERLANDS EARTH SYSTEM SCIENCE CENTRE
TNO
Utrecht University
TU Delft
Deltares Enabling Delta Life
IMAU Institute for Marine and Atmospheric research Utrecht
Universiteit Leiden
UNIVERSITY OF EXETER
UNIVERSIDAD CENTRAL CARACAS - VENEZUELA
NIOZ
SESYNC NATIONAL SOCIO-ENVIRONMENTAL SYNTHESIS CENTER