



**Stockholm
University**

Bachelor Thesis

**Degree Project in
Geology 30 hp**

Sedimentation processes in Lake Sam Roi Yot, Prachuap Khiri Khan, Southern Thailand

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Stockholm 2019

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Abstract

Lake sediments are an excellent resource when investigating the evolution of a waterbody. The Sam Roi Yot (SRY) national park in southern Thailand holds a large wetland, which has evolved from a marine lagoon environment to the present-day brackish wetland. Studies in the SRY area suggest that this process can be linked to a decrease in Global Mean Sea Level (GMSL) which occurred in two steps: the first step around years (yr) 6500-6000 before present (BP) and then again from 3000 to 1000 yr BP. This study shows that a marine transition to lacustrine sedimentation occurred during the second regression, roughly 1900 calibrated age (cal) yr BP, instead of previously suggested 6000 cal yr BP (Koskelainen, 2013). Presently, the water depth in the SRY wetland varies by season, which has allowed salt water to intrude the basin. This may have caused a combination of both brackish and lacustrine sedimentation processes in SRY i.e from circa 1900 cal yr BP. For this study nine new lake-sediment cores were obtained from SRY in the Summer 2018 along with three transects. Loss-on-ignition (LOI) and grain size analysis (GSA) were combined with a detailed lithological description on core CP6. This investigation shows that SRY changed from a marine to lacustrine environment approximately around 1900 cal yr BP. From circa 1900 cal yr BP to 1600 cal yr BP, GSA and LOI detected increased accumulation of sand and a decrease in organic matter suggesting an oxygenic environment with increased soil erosion during the initial shoreline regression. The wetland condition occurred approximately around 600 cal yr BP followed by eutrophication. Induced eutrophication with increased soil erosion was detected near the water-sediment interface as an abrupt increase in LOI percentage (68%) and sand particles, which corresponds well with the recent change in land use seen in SRY.

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Introduction

Thailand has a total coastline of 2600 km. The coastal regions of Thailand are densely populated and economic activities such as tourism and fishery provide important income. Coastal biodiversity in Thailand is of great importance as it holds the majority of all mangrove species encountered globally. The ongoing degradation of Thailand's coastline together with coastal threats such as overexploitation and sea level rise recently became highlighted as beach erosion, coral bleaching, ground subsidence, saltwater intrusion and water-soil pollution are widely observed (Parr et al. 1993; Bupeng and Wattayakorn, 2008; Greenpeace, 2013; Sojisuorn et al. 2013; DMR, 2016).

The relative sea level rise along the Gulf of Thailand (GOT) varies by location and ranges from -0.8 to 12.7 mm yr⁻¹ between 1985 and 2009 (Sojisuorn et al. 2013). The future mean sea level rise is expected to accelerate (Sojisuorn et al. 2013; IPCC, 2013). Records from the past show that global mean sea level was 125-130 m below present-day sea level during the Last Glacial Maximum (LGM), which occurred between 26500 and 19000 years (yr) before present (BP) (Clark et al. 2009). Deglaciation subsequently triggered a global sea level rise, which submerged large parts of the continental shelf the so-called Sundaland (Hanebuth et al. 2000; Smith et al. 2011; Chabangborn, 2014).

The Holocene sea level rise can be studied along the east coast of Thailand, especially in the northwestern part of Sam Roi Yot (SRY) national park, which today is a large wetland. Eroded sea notches on limestone cliffs in SRY show that mean sea level reached a high stand of about 3-4 m above present-day sea level (a.s.l) around 6500 yr BP (Choowong et al. 2004; Dusitapirom et al. 2008; Surakiatchai et al. 2018). The sea level regression that followed was discontinuous and occurred in two steps: a first step between 6500 - 6000 yr BP and a second between 3000-1000 yr BP (Surakiatchai et al. 2018).

SRY has not been influenced by isostatic rebound after the last ice age as it is situated along the tropical Gulf of Thailand (GOT) which is considered tectonically stable with minor uplift (Bird et al. 2006; DMR, 2016) Therefore, the SRY wetland holds invaluable sediment records for investigating eustatic sea level changes during the Holocene, i.e. the past 11 700 years.

To study Late Holocene sea level changes, a series of sediment cores were obtained from the SRY wetland in summer 2018, carefully described and correlated with each other. Selected cores were further analyzed for grain size variations and organic matter content. The results show that the SRY wetland changed from a marine-influenced to a limnic-brackish sedimentation environment.

A brief climatologic background of Thailand

Thailand is extremely vulnerable to climate change, as its large agricultural sector employs 35% of the total workforce (FAPDA, 2018). Thailand's crop yields rely on stable seasonal precipitation, which is dictated by summer and winter monsoons. Seasonal flooding has devastated Thailand's crop yields and infrastructures several times. The worst flooding encountered for 50 years struck Thailand in 2011 leading to extensive damage and reconstruction costs of 96.5 billion USD according to the World Bank (2012).

Currently a combination of three monsoon system affect Thailand (Chawchai, 2014). First the Indian Summer Monsoon (ISM) that reaches Thailand between May to October, which contribute with warm and moisture air from the southwest. Meanwhile tropical cyclones associated with the southward movement of the Intertropical Convergence Zone (ITCZ) moves in over Thailand from the South China Sea from July to December. Therafter a winter monsoon brings in cold and dry air from the northeast during the dry season between November and January.

Evidently summer and winter monsoons have shifted both position and intensity during the past. Lake sediments from Lake Pa Kho and Lake Kumphawapi located in northeastern Thailand show for example that monsoon precipitation has greatly varied throughout the Holocene and that this influenced societies in the past (Chabangborn, 2014; Chawchai, 2014; Yamoah et al. 2016; Wohlfarth et al. 2016).

Study area

Sam Roi Yot (SRY) (12.08 to 12.31 N and 99.88 to 100.05 E) is located on the east coast of the Thai peninsula, about 183 km south of Bangkok (Fig. 1A, 1B). The SRY wetland is situated 0 m above mean sea level (a.s.l) (Google Earth, 2018). SRY was the first coastal area of Thailand to become established as a national park in 1966 (Parr et al. 1993). It is the largest fresh water wetland according to the Department of National Parks (DNP), although the water has distinct brackish characteristics when tasted. Dredging of river Khao Daeng (Fig. 2) was done in 1991 by the local Department of Irrigation which, according to Parr et al. (1993) may have allowed saltwater intrusion into the SRY wetland. Subsequently SRY National Park was listed in spring 1991, as one of the most threatened parks in the world by the International Union for Conservation of Nature (IUCN) Commission on National Parks and Protected Areas (CNPPA) (Parr et al. 1993). The boundaries of SRY national park have not yet been officially defined. Depending on which material or method used, the wetland covers an area of 162 km² or 98.8 km² (Fig. 1B, 3A; Appendix, Fig. A1 and A2), (Parr et al. 1993). SRY national park provides an important habitat for hundreds of wild birds, animals and rare threatened flora such as *Mallotus pallidus* (Airy Shaw), *Ornithoboea barbanthera* (Dicotyledonous, double-bladed plant) and *Premna repens* (Lamiaceae, mint family) (DNP, 2017). Fishery equipment and settled wood poles are observed throughout the study area suggesting ongoing anthropogenic alteration.

SRY belongs to the tropical-monsoon climate zone according to the Köppen-Geiger climate classification (Chen and Chen, 2013). At SRY precipitation is about 680 mm (rainy-season) between mid-May and mid-October, increases to 827.9 mm (winter-season) between mid-October and mid-February and decreases to 229 mm (summer-season) between mid-February and mid-May (TMD, 2015). The water depth at SRY currently varies with up to 0.5 m due to seasonal fluctuations in precipitation.

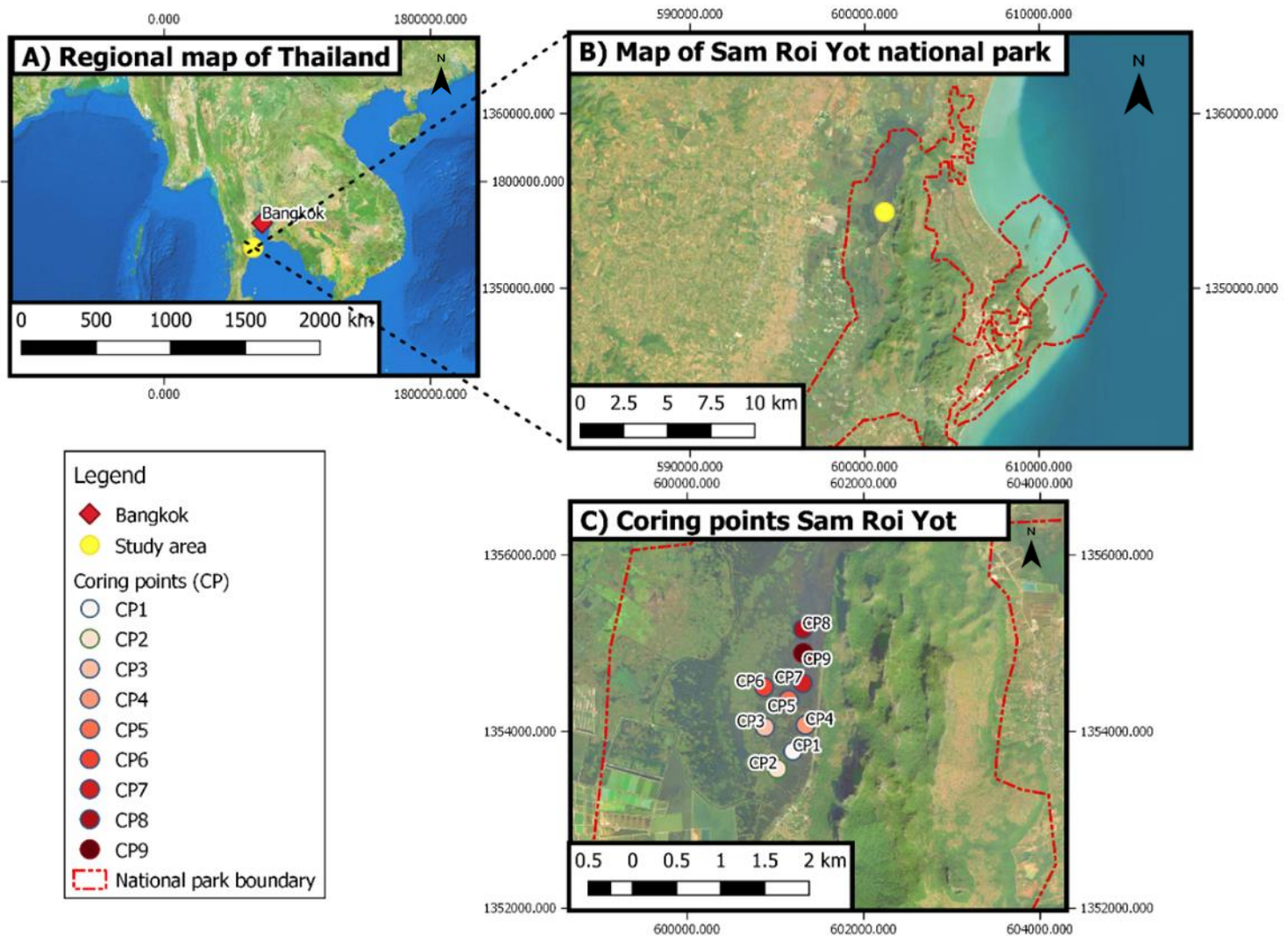


Fig 1 A. Regional map showing the location of Bangkok and of the study area which is located 183 km south of Bangkok, on the eastern part of the Thai Peninsula. B. Map of the Sam Roi Yot wetland showing the National Park boundaries. The yellow circle indicates the part of the wetland, where sediment cores have been investigated C. Zoom-in to the area where the nine sediment cores were obtained in July 2018. CP= coring point.

The best-preserved areas of the SRY wetland were chosen for this study. These are located in the north-western part of the park (Fig. 1B and 1C). Here the karst landscape of SRY is pronounced with steep uplifted Permian limestones reaching up to 605 m a.s.l (Fig. 2) (Choowong et al. 2004). Exposed outcrops of Silurian-Devonian sedimentary rocks are seen in the north-eastern part of SRY (Fig. 2). SRY national park is located immediately adjacent to the Ranong fault zone, seen on the uplifted western side of the Permian limestone as a dip slip normal fault (Fig. 2) (Geological Survey Division, 1985). Alluvial deposits such as beach sand, river gravel, silt, clay, mud and swamp or marsh sediments are frequent in the western lowland areas (Geological Survey Division, 1985).

Earlier studies at SRY

Elevated sea notches have been investigated along the eastern side of the SRY fault by Choowong et al. (2004), Dusitapirom et al. (2008) and Surakiatchai et al. (2018). Here sea notches displayed evidence that mean sea level (MSL) was around 3-4 m above present-day sea level at around 6500 yr BP (Choowong et al. 2004; Dusitapirom et al. 2008; Surakiatchai et al. 2018). Optically stimulated luminescence dating (OSL) done on SRY's Holocene beach barrier sand (Fig. 2) was recently undertaken by Surakiatchai et al. (2018). OSL dating shows that shore line regression which, according to Surakiatchai et al. (2018) is linked to a sea level regression that occurred discontinuously, first around 6500-6000 yr BP and then again from around 3000 to 1000 yr BP as shown in Table 1.

Sediment cores obtained in 2011 (BW 2011) were analyzed for macrofossil and loss-on-ignition (LOI) by Koskelainen (2013). Results from the macrofossil analysis show that the bottom sediments contained seashells such as *Macoma*, Elegant Dosinia, Channeled Duck Clam or Imperial Venus, and *Calico Scallop* (Koskelainen, 2013). Immediately above the marine sequence, the macrofossils show brackish environmental conditions. Fern *sporangia* and *Cyperaceae* appear, suggesting that a mix of aquatic and riparian plants were present in SRY around 6000 cal yr BP (Koskelainen, 2013). Aquatic macrofossils present were for example *Isoetes* (macrospores) and *Myriophyllum* (Koskelainen, 2013). After this phase, mites start to appear continuously throughout the sediment before increasing abruptly in the uppermost sediment, which was identified as limnotelematic. Mite larvae prefer stagnant water basins for hatching. Here *Juncus* and *Cyperaceae* become dominant together with *Nymphaea lotus* and *Nitella* oospores (Koskelainen, 2013). Charcoal particles show an initially increase after the transition from marine to lacustrine. The number of charcoal particles declines roughly from the middle of the lacustrine phase (Koskelainen, 2013).

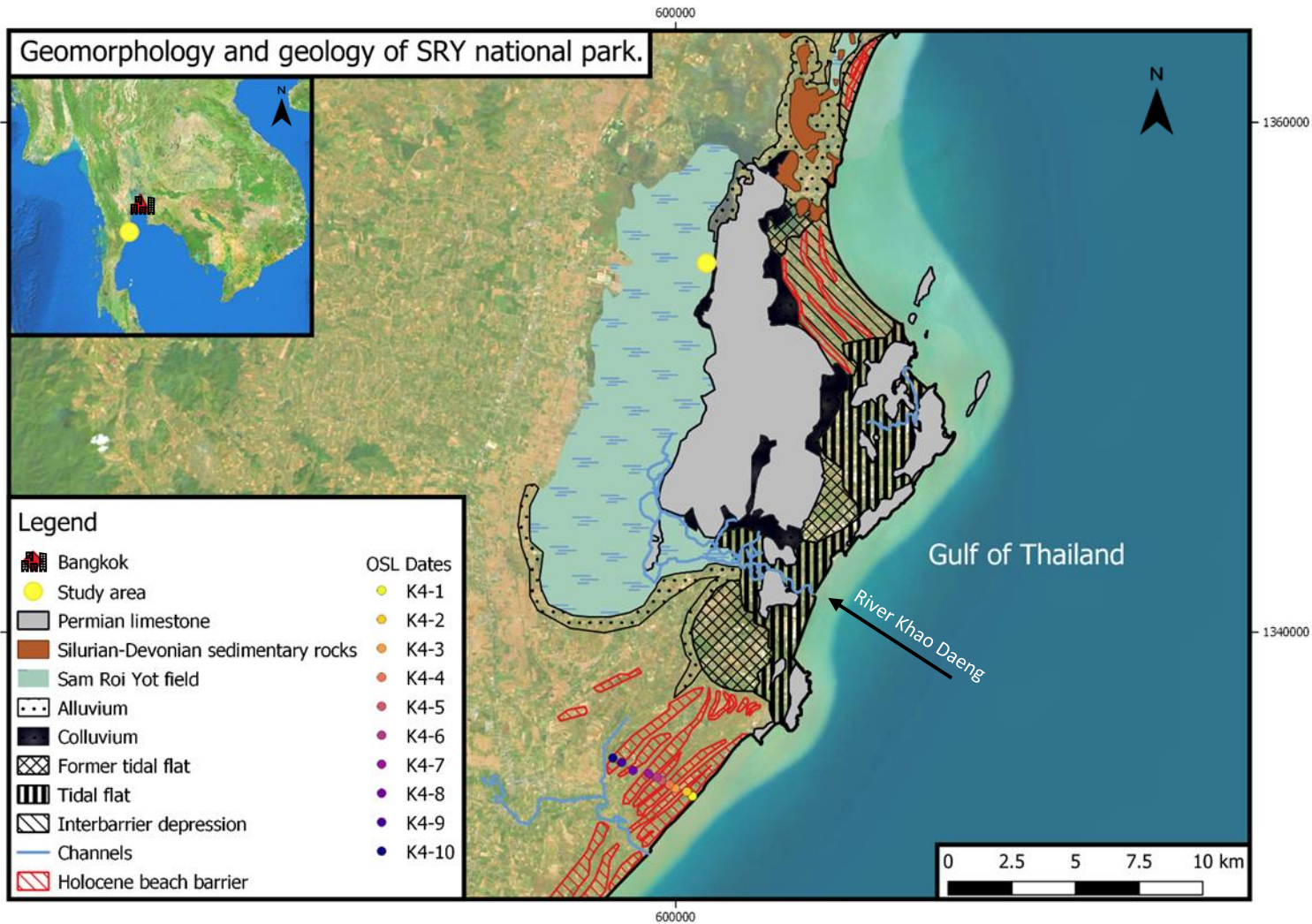


Fig. 2. Geomorphology and geology of SRY national park according to Choowong et al. (2004) and Surakiatchai et al. (2018).

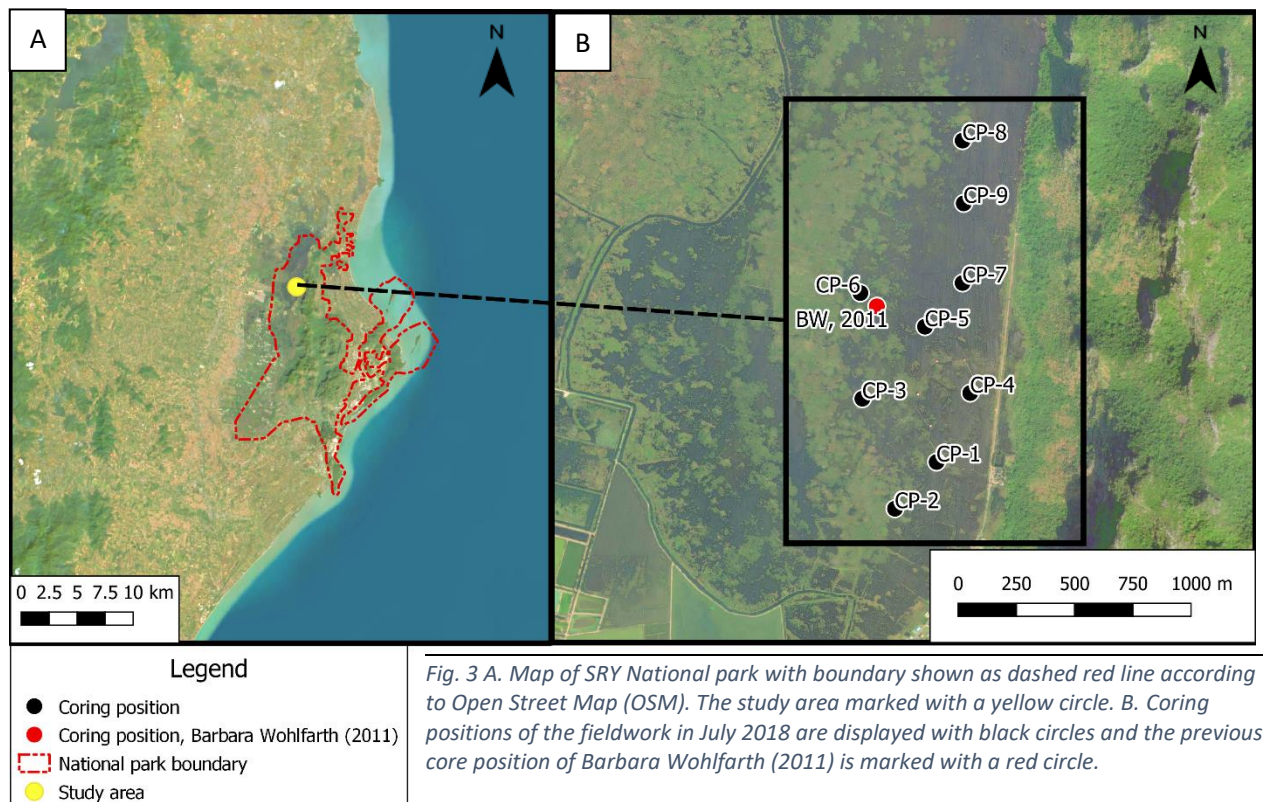
OSL dates (Surakiatchai et al. 2018)			
Sample ID	Distance from shore (m)	Year (BP)	error +/-
K4-1	170	844	80
K4-2	430	2284	220
K4-3	1180	2397	250
K4-4	1500	3914	200
K4-5	1900	8120	700
K4-6	2200	7204	450
K4-7	2480	6344	260
K4-8	3100	6216	340
K4-9	3500	6690	390
K4-10	3800	7273	390

Table 1. OSL dates obtained on Holocene beach barrier sand. The red line marks a hiatus in shoreline-regression, lasting between 3500-3000 years according to Surakiatchai et al. (2018). The error displays age uncertainty due to e.g spread in equivalent doses and assumptions.

Methods

Field method

Lake sediment cores from 9 different locations (CP1-CP9) were obtained from the SRY wetland using a modified Russian corer with a probing diameter of 7.5 cm and a core length of 100 cm. The overlap between cores was around 40 cm. Coring was performed from a raft. The depth was measured for each coring location. The coordinates for coring points CP4-CP9 were obtained with a handheld GPS device (Garmin), while the coordinates for CP1-CP3 were compiled using remote sensing onshore with the help of Google Earth (Google Earth, 2018). Plastic ribbons were used as visible markers for navigation through the narrow passages of vegetation. Core CP6 was extracted near the location of a core earlier obtained by Barbara Wohlfarth in 2011, which has been radiocarbon dated (Fig. 3B), (Table 2). The cores were carefully packaged on site with plastic foil and stored inside a protective PVC tube. All cores were labeled with the measured core depth in meters and the following abbreviations: Sam Roi Yot (SRY), Core Position (CP). Cores were then transported to Chulalongkorn University in Bangkok, Thailand.



Laboratory methods

Remote sensing of the SRY study area

Google Earth Maps and Open Street Map (OSM) were first used to define the extent of SRY National Park. Then two separate polygon shapefiles of the SRY national park border were created, using mapping tools such as QGIS and Google Earth. The digitalized extents of SRY National Park are shown in Fig. 3A and the Appendix (Fig. A1, A2). The geomorphology and geology of SRY national park were mapped using remote sensing and georeferencing and are based on earlier studies (Fig. 2) (Choowong et al. 2004; Surakiatchai et al. 2018). The coordinates for CP1-CP3 have been manually positioned after identifying the core location through Google Earth. Subsequently a GPS exchange format file (GPX-file) was retrieved from the GPS device (Garmin) and directly uploaded onto the map layer, which set the locations for CP4-CP9 (Fig 1C, 3B). The water depth was measured at 9 locations (CP1-CP9) during July 2018. All depths in this study used the water surface as a reference point. Water depths were also interpolated into a bathymetric map using the tile layer provided by ESRI as background map (Fig. 4).

Sediment description and transects

Nine sediment cores were unpacked and studied in the sediment laboratory of Chulalongkorn University in Bangkok, Thailand. Here the cores were first cleaned with a scraper and then carefully described. Overlapping sequences for each coring point were correlated with each other using specific marker horizons and a composite stratigraphy was established for each coring point. The sediments were assigned to sedimentary units to facilitate core correlations along transects (Table 3). Cores CP5 and CP6 were used as reference cores for the classification, mainly for two reasons: their detailed sediment description (Table 4 and 5) and their midpoint location (Fig. 3B). Four units and 10 sub-units were identified using changes in sediment composition, colour, shell content, organic matter content and bioturbation (Table 3; Appendix, Table A1 to A10).

Transect 1 was constructed from 4 selected cores oriented from south to north along a 1086.1 m cross-section line (Fig. 5). Transect 2 was drawn through 4 core locations oriented from northwest to southeast in a cross-section line extending 660.7 m (Fig. 6). Transect 3 was created from three core locations aligned 597.6 m from northeast to southwest (Fig. 7).

To compare the stratigraphy and the sediment properties of CP6 with the earlier obtained core BW 2011 (Wohlfarth, B., 2011), CP6 was sub-sampled for grain size analysis (GSA) and loss-on-ignition (LOI) analyses at Stockholm University. A tentative ^{14}C chronology is then presented.

Loss on ignition analysis

A total of 95 samples were analyzed for LOI in core CP6 to estimate the organic matter content and to correlate the new LOI profile to that of Koskelainen (2013) at core BW (2011), located 91 m to the southeast of CP6 (Fig. 3A and 6).

To clean the crucibles, they were heated to 105°C over night and then weighed. Sediment samples were then placed into the crucibles and dried at 105°C overnight. In the next step samples were milled to a powder and dried again at 105°C for 45 min to prevent water uptake that may have occurred during the milling process. The dried samples were then cooled in an exicator for 30 min before being weighed. The samples were subsequently placed in the furnace for heating to 550°C for 4 hours. The burned samples were stored in an exicator for 30 min before being weighted.

The following equation was used to calculate organic weight loss (Heiri et al. 2001):

$$LOI (\%) = \left(\frac{Dry\ weight_{105^{\circ}C} - Dry\ weight_{550^{\circ}C}}{Dry\ weight_{105^{\circ}C}} \right) \times 100$$

Grain size analysis

Ninety-five samples from core CP6 were analyzed for grain size with a laser granulometer (Mastersizer 3000) with a marginal error of <2%. Grain size analysis followed the procedure described by Blott et al. (2004).

Samples were first weighed to 200-300 mg before pretreatment. In a next step samples were pulverized, then 5 ml HCl (10%) was added to remove carbonates and 10 ml H₂O₂ (15%) was added to remove organic matter. After that, the samples were agitated and left overnight. To further accelerate oxidization samples were placed in a water bath set to 80 C°. More H₂O₂ (30%) and HCl (10%) were added until the reaction stopped. Thereafter the samples were washed and rinsed 3 times. Then 5 ml NaO₃P (0.05%) were added to prevent sediment aggregation. Samples were then placed into the laser granulometer (Mastersizer 3000) until obscuration level reached 5-15%. Here ultrasonic sound was used for 1 min with stirring for 2 min to keep the sediment disaggregated before measurement. After that, grain size data were collected from the laser granulometer (Mastersizer 3000) in two steps. First the average grain size diameter (10 x mm⁻³) was collected from the measurement file as D-values, and is explained as follows:

DX₁₀ = 10% of the bulk samples has a smaller grain size diameter.

DX₅₀ = 50% of the bulk sample has a smaller grain size diameter (median grain size).

DX₉₀ = 90% of the bulk sample has a smaller grain size diameter.

Particle size distribution (PSD) is sometimes referred to as grain size distribution or grain size variation and is often used as a sorting index to estimate sediment transportation distance (Blott et al. 2004).

Particle size distribution is defined by Blott et al. (2004) in the following equation:

$$\text{Particle size distribution} = \frac{DX_{90} - DX_{10}}{DX_{50}}$$

Grain size fractions were sampled within the grain size intervals of clay to very fine silt, fine silt to coarse silt and sand particles according to the grain size classification described by Wentworth (1922). A cumulative grain size diagram was then created.

Chronology from radiocarbon dating

The radiocarbon dates from core BW (2011), which was studied by Koskelainen (2013), are here compared to the ^{14}C dates obtained from core CP4 (Table 2). All radiocarbon dating was done using the Accelerator Mass Spectrometry (AMS) method. Radiocarbon ages were then calibrated with the Calib 7.10 program using the IntCal13 calibration curve (Reimer et al. 2013).

Age ranges (95.4 % confidence interval) for all ^{14}C dates were subsequently plotted against depth in Transect 2 for comparison.

BW, 2011					
Depth below water surface (m)	Depth mean (m)	Material	Lab ID	^{14}C date (BP)	error +/- (yr) 1σ
2.11-2.14	2.125	Small pieces of terrestrial material (also charred)	UBA-21603	5811	58
2.17-2.23	2.2	Small pieces of terrestrial material (also charred)	UBA-21604	5238	36
3.42-3.47	3.445	Pieces of wood	UBA-21605	5890	39
CP4, 2018					
Depth below water surface (m)	Depth mean (m)	Material	Lab ID	^{14}C date (BP)	error +/- (yr) 1σ
1.75-1.72	1.735	Charcoal	D-AMS 030465	1550	25
3.245-3.19	3.2175	Charcoal	D-AMS 030466	3090	30

Table 2. First collected depth and dated material from cores BW (2011) and CP4 are displayed from the middle to the left. Thereafter the given Lab ID with the resulting ^{14}C dates. Lastly error is 1σ (sigma 1), which is the two standard deviations in age within a confidence interval of 68.27%.

Results

Areal extent of SRY national park

The diverging information concerning the areal extent of SRY national park was first noted by Parr et al. (1993), who described a total area of 162 km² as compared to the 98.8 km² that are given by the Department of National Parks (DNP). The present study resulted in two different areal measurements: using the Google Earth Pro basic layer, the areal extent of SRY national park is 154.43 km²; according to the Open street map (OSM) layer the areal extent amounts to 147.74 km² (Appendix, Fig. A1 and A2). None of these new estimates however compare to those presented by Parr et al. (1993) and the Department of National Parks (DNP).

Water depth

Water depths measured in July 2018 varied between 0.8 – 1.40 m (Fig. 4). Overall the bathymetry appeared relatively flat and shallow throughout the extent of the study area. A minor decline in depth was measured towards the western and southern parts of SRY where vegetation becomes more pronounced (Fig. 4).

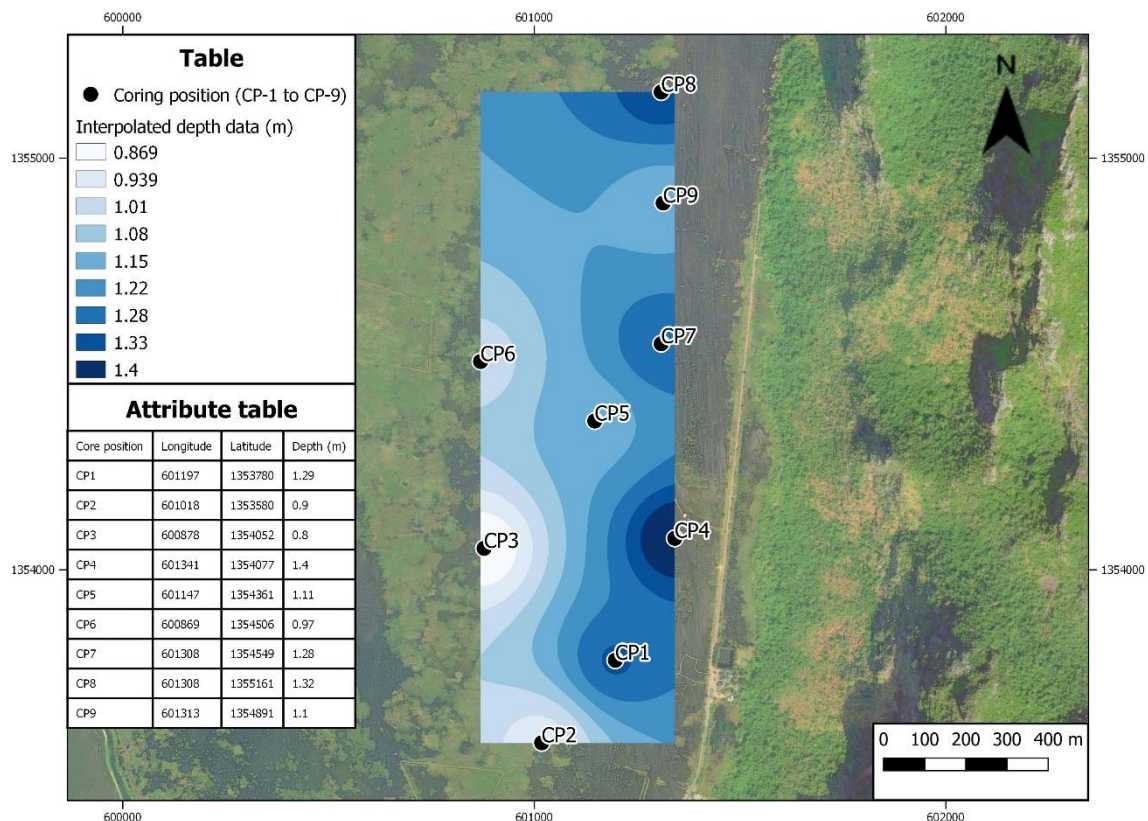


Fig. 4. Measured water depth (m) (see attribute table). Measurements were performed in July 2018.

Lithological description and sub-division into lithological units

The most distinguishable lithologic changes seen in reference cores CP6 and CP5 were grouped into units A-D, starting with unit A at the deepest part and ending with unit D closest to the water-sediment interface (Table 3). Unit A was identified within the deepest part of all cores except for in CP8. Unit A is composed of a calcareous dark grey sandy to silty clay with shells and shell fragments, which became impenetrable at maximum depth. Four subunits were further identified in unit A based on the characteristics that are described in Table 3. A distinct change in colour is visible at the transition between unit A and B.

Unit B is present in all cores. The sediments are composed of sandy to silty clay without shells and have a ferric, beige brown color, which separates them from the underlying unit A and the overlying unit C. Unit B was divided into two subunits as shown in Table 3.

Unit C is present in 7 of the 10 cores, CP2, CP3, CP5, CP6, BW (2011), CP8 and CP9 and has a similar colour as unit A. Clear differences between units A and C are however the absence of shells in unit C. Moreover, the sediment in unit C oxidized rapidly, while this was not observed in unit A. Unit C was further divided into two subunits (Table 3).

Unit D is present in all cores except for in CP8. Unit D represents the water-sediment interface and is composed of either gyttja clay or clayey gyttja, which were divided into two subunits (Table 3).

	D:2	Gyttja or silty to clayey gyttja.
	D:1	Brown to grey, gyttja clay.
	C:2	Grey to dark grey, silty clay; contains more organic material than below.
	C:1	Grey to light grey, sandy or silty clay; contains organic material and sometimes rust.
	B:2	Beige brown, sandy or silty clay transition to grey silty clay with organic material.
	B:1	Beige brown to grey mixture of sandy or silty clay which sometimes contains organic material or appear distorted with gyttja infills and bioturbation with some occasional dark Fe-spots or yellow spots.
	A:4	Dark grey, sandy or silty clay; less organic material.
	A:3	Dark grey, sandy or silty clay; contains gravel.
	A:2	Dark grey, sandy or silty clay; comprised of more organic material and bioturbation.
	A:1	Dark grey, sandy or silty clay; contains seashells or sand.

Table 3. Units A-D with the 10 subunits in the column to the left and the sediment description displayed to the right.

Transects 1: core CP4, CP7, CP8, CP9 (Fig. 5; Appendix Table A4, A8, A9 and A10)

The deepest subunit present in CP9 and CP7, A:1, is composed of a calcareous, dark grey, sandy clay. The overlying subunit A:2 is composed of calcareous, dark grey sandy clay with a thin black layer in CP9. Limestone gravel (A:3) was occasionally spotted in CP4 and CP9, which are located close to the steep uplifted limestone cliffs of Permian age. Subunit A:4 is present in CP4, CP7 and CP9. It is composed of calcareous, dark grey sandy or silty clay with less organic material. It is thickest in CP4 and CP7 around 3.475-2.135 m depths, then thins out in CP9 and is absent in CP8. The overlying subunit B:1 is composed of a ferric, beige to brown, silty clay seen throughout transect 1, starting around depths of 2.25-2.1 m. Closest to the Permian limestone, at CP4 subunit B:1 contains numerous dark stains between 2.135-1.53 m depth (Fig. 5, Appendix, Table A4). Further to the north at CP7, dark stains were only observed in the upper part of subunit B:1 between 1.555-1.475 m depths (Fig. 5, Appendix, Table A8). Unit C is present in CP8 and CP9 around 1.535-1.325 m depth. At CP9, between 1.535-1.66 m depth, subunit B:2 marks the gradual transition from unit B:1 (brown sandy clay) to unit C:1 (light grey sandy clay). Here at CP9 subunit C:1 is composed of light grey sandy clay that subsequently grades into subunit C:2, which is composed of dark grey silty clay. In the northernmost location, CP8, subunit C:2 rests directly above subunit B:1. It is composed of grey clay and contains abundant organic matter that becomes darker at the water sediment interface. Finally, unit D encompasses gyttja or gyttja clay; it is present in CP4 and CP7, where it overlies unit B. In CP9 unit D rests directly on top of unit C and is absent in northernmost CP8.

Transect 2: core CP4, CP5, CP6 and BW (2011) (Fig. 6; Appendix, Table A4 to A7)

The deepest subunit A:1 is composed of calcareous, dark grey to grey, sandy to silty clay with imbedded fragmented and whole seashells; A:1 can be seen in BW (2011) and in CP5 around 2.925-3.56 m depth. The overlying subunit A:2 is made up of calcareous, dark grey to grey, silty clay, which is more bioturbated towards the inland, seen as a westward inclination from BW (2011) to CP6. Further away from land, in CP5, subunit A:2 is thinner and extends only between 2.73-2.96 m depths. In CP5, subunit A:2 is composed of dark grey, silty clay which contains organic matter, but no trace of bioturbation. In CP4, which is located near the Permian limestone cliff, subunit A:3 is a mixture of gravel and dark grey, sandy clay that appears between 3.455-3.505 m depth. Further away from the Permian limestone, in CP5 a local limestone pebble (2-3 cm) was embedded at 2.46 m depth right above subunit A:2. This extends the thickness of subunit A:3 at CP5. The overlying subunit A:4 is composed of less organic dark grey, silty clay; it is present at a deeper depth in CP4 and CP5, which are located further seawards; minor local bioturbation was observed in A:4 in CP4 around 2.545-2.485 m depth. Subunit B:1 is present throughout Transect 2 around 2.13-2.23 m depth. In subunit B:1 dark discoloration was seen in CP4 and to a lesser extent in CP5. Subunit B:2 is a transitional zone, in which the brown beige, silty clay turns into grey, silty clay; this unit is present in CP5, BW (2011) and CP6. In CP5, the overlying subunit C:1 is composed of light grey, silty clay which oxidized directly after the surface was scraped. Subunit C:2 follows in CP5 directly above C:1, whereas it overlies B:2 in BW (2011) and CP6. C:2 is composed of more organic material and does not show any sign of rapid oxidation. The top layer unit D is composed of gyttja and follows directly above unit C throughout transect 2, except for in CP4 where a brown, gyttja clay appears directly above unit B.

Transect 3: core CP1, CP2 and CP4 (Fig. 7; Appendix, Table A1, A2 and A4)

Three coring points are used to create transect 3. In CP1, which is in the middle of the transect, the deepest subunit A:1 between 3.225-2.91 m depth, is composed of calcareous dark grey silty clay with fragmented and whole seashells. The overlying subunit A:2 is composed of bioturbated calcareous dark silty clay, which can be seen in CP1, between 2.91-2.60 m depth. In CP4, which is close to the Permian limestone cliff, subunit A:3 contains gravel in the deepest part. Throughout Transect 3, subunit A:4 appears above different subunits in the following order: directly above subunit A:3 (gravel) in CP4 and close to the Permian limestone cliff; in CP1 above A:2 (bioturbation); and in the southernmost located CP2 it makes up the bottom layer. The overlying subunit B:1 is evenly deposited above subunit A:4 throughout Transect 3 around 2.135-2.23 m depth. In the southernmost CP2, subunit B:1 contains yellow spots and extends to between 2.23-1.265 m depth. In CP1 subunit B:1 is strongly bioturbated and occurs between 2.26-1.57 m depth. Lastly, in CP4, subunit B:1 contained numerous amounts of dark stains between 2.135-1.53 m depth. Subunit C:1 is composed of oxidized light grey, sandy clay and appears directly above subunit B:1 in CP2 between 1.265-1.11 m depth. The top unit D mainly contains gyttja at all locations and appears thickest at CP1.

Transect 1

Legend

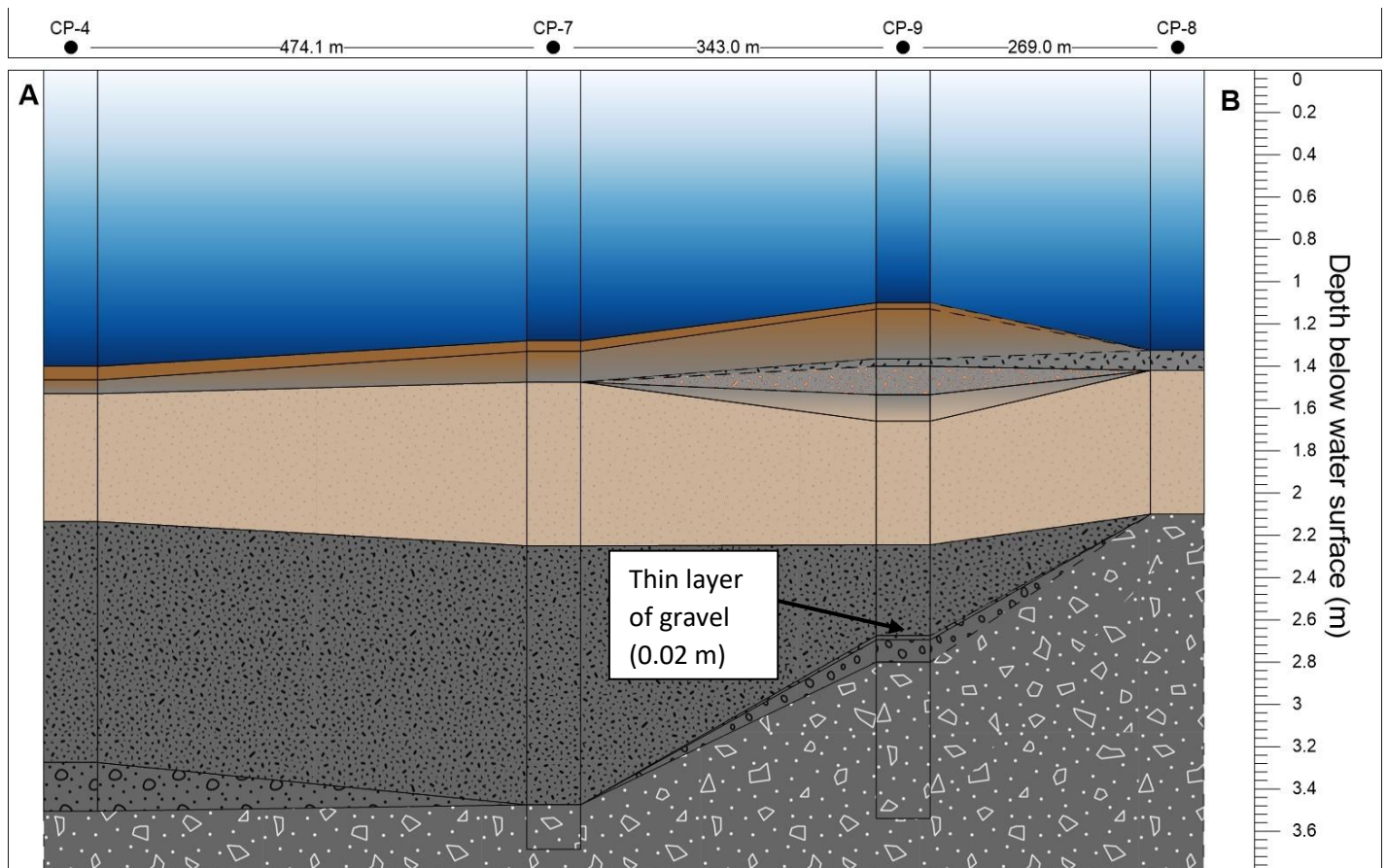
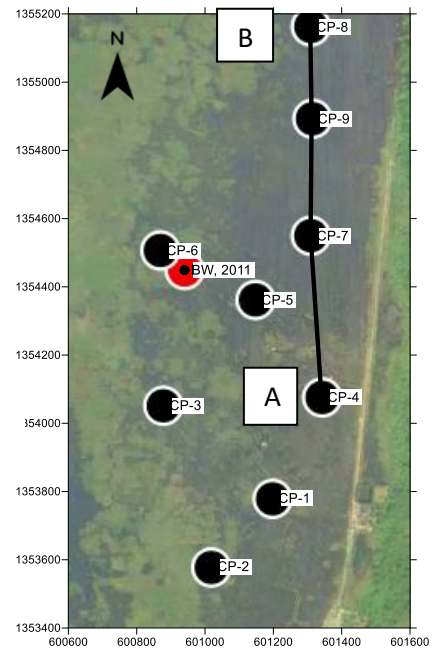
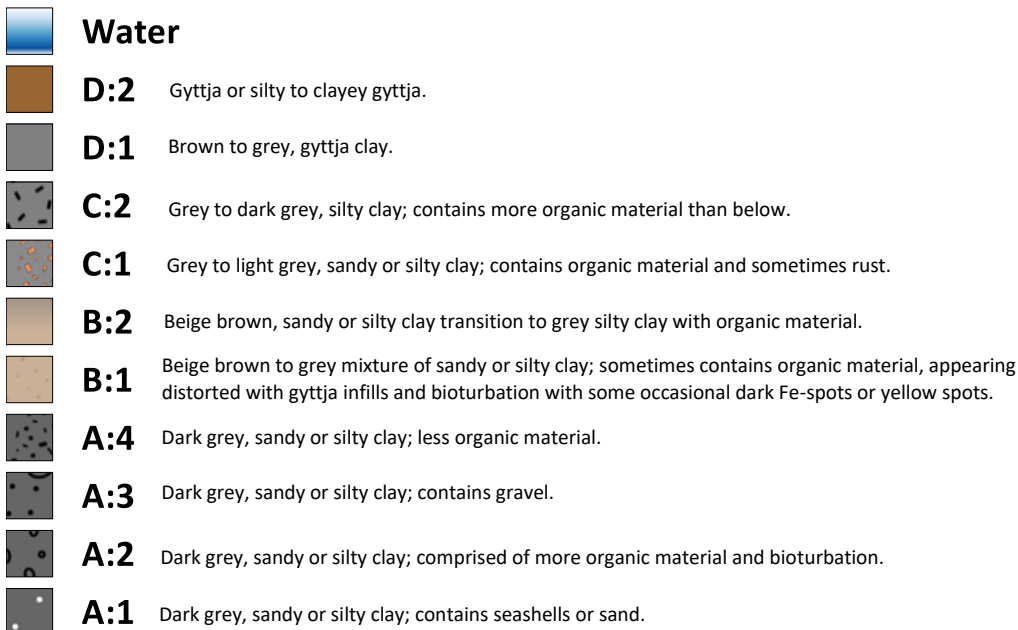


Fig. 5. Transect 1 with cores CP-4, CP-7, CP-9 and CP-8 in a south to north descend (left to right). Distances between core location varies between 269 m to 474.1 m.

Transect 2

Legend

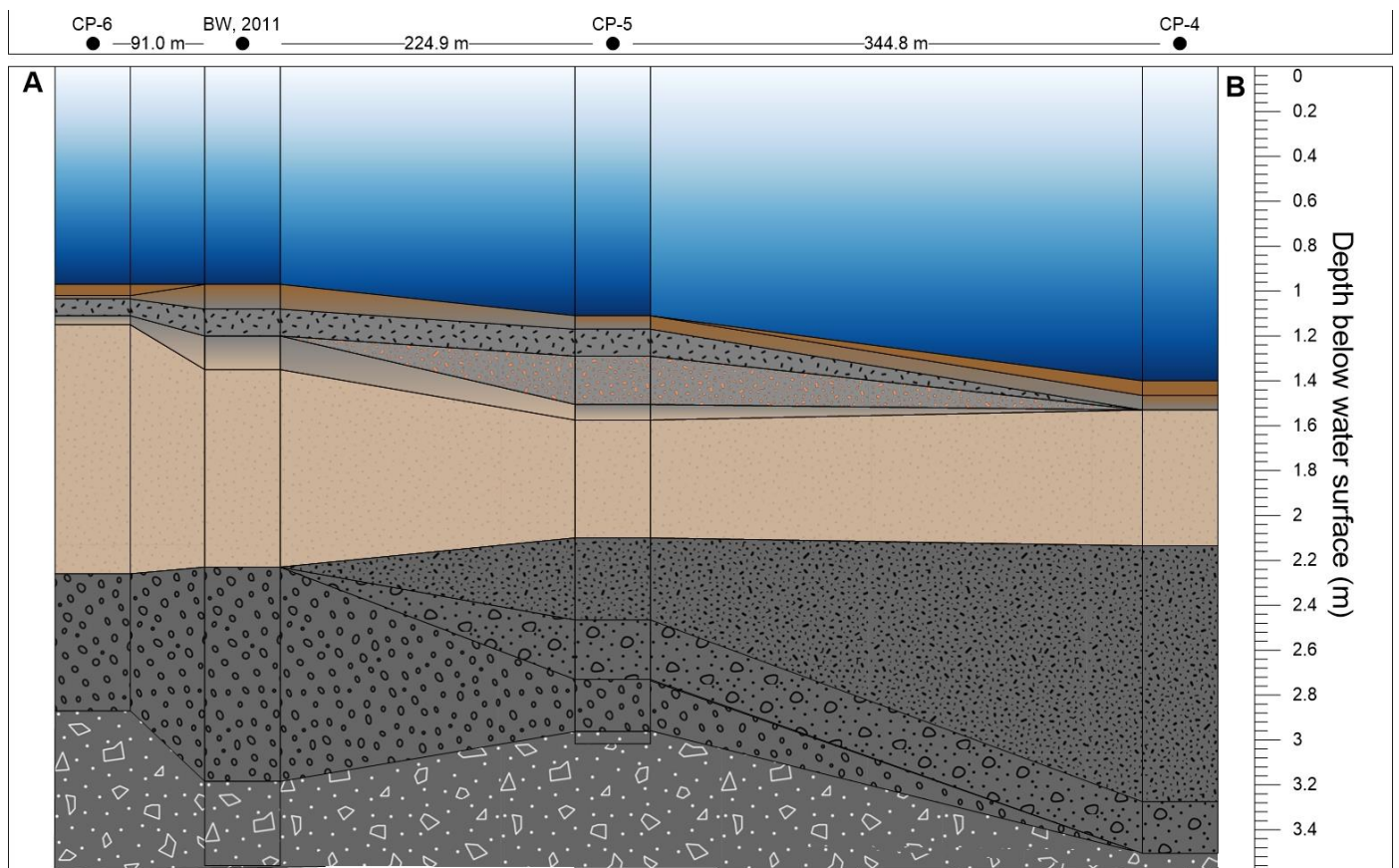
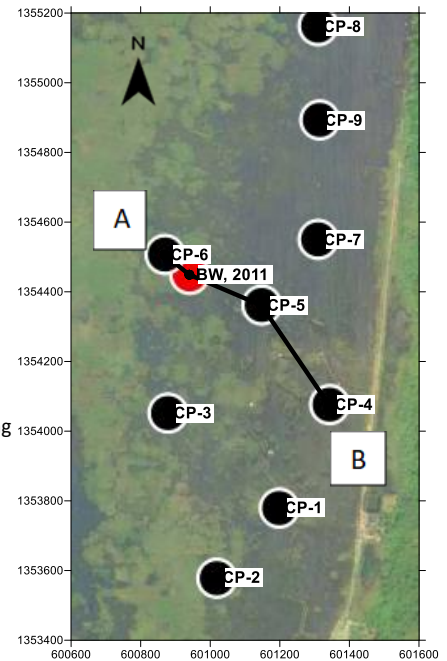
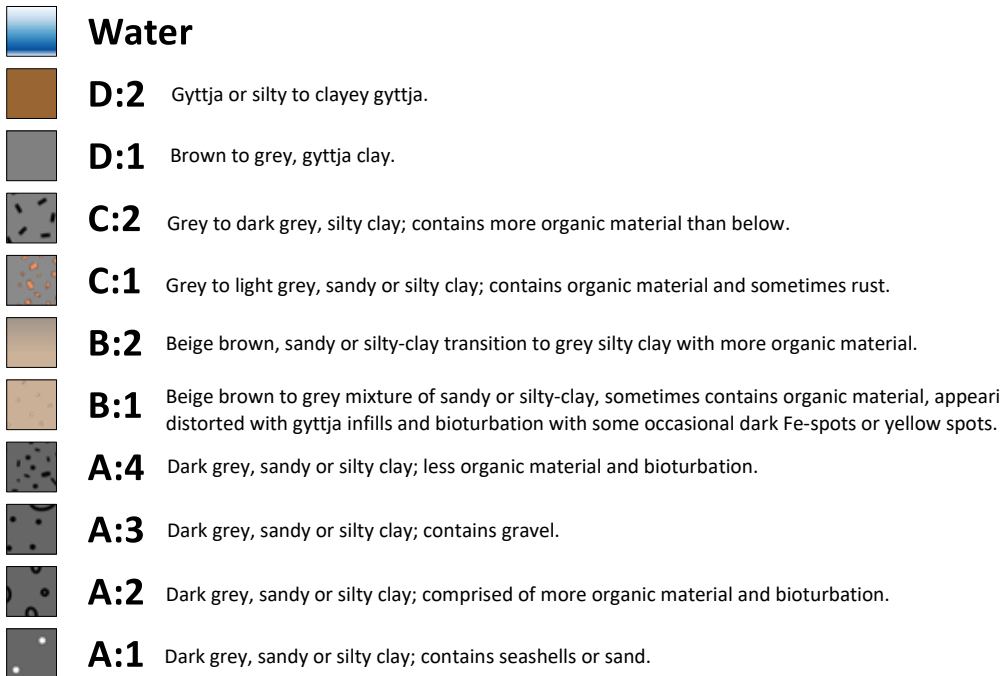


Fig. 6. Transect 2, made from the lithostratigraphic columns of CP-6, Barbara Wohlfarth (2011), CP-5 and CP-4. Transect 2 is oriented from northwest to southeast (left to right). Core depth of BW (2011) has been adjusted to equal the water depth of CP6 (2018). Distances between core location varies between 91 m to 344.8 m.

Transect 3

Legend

	Water
	D:2 Gyttja or silty to clayey gyttja.
	D:1 Brown to grey, gyttja clay.
	C:2 Grey to dark grey, silty clay; contains more organic material.
	C:1 Grey to light grey sandy or silty-clay; contains organic material and sometimes rust.
	B:2 Beige brown, sandy or silty clay transition to grey silty clay with organic material.
	B:1 Beige brown to grey mixture of sandy or silty clay, sometimes contains organic material, appearing distorted with gyttja infills and bioturbation with some occasional dark Fe-spots or yellow spots.
	A:4 Dark grey, sandy or silty clay; less organic material.
	A:3 Dark grey, sandy or silty clay; contains gravel.
	A:2 Dark grey, sandy or silty clay; comprised of more organic material and bioturbation.
	A:1 Dark grey, sandy or silty clay; contains seashells and sand.

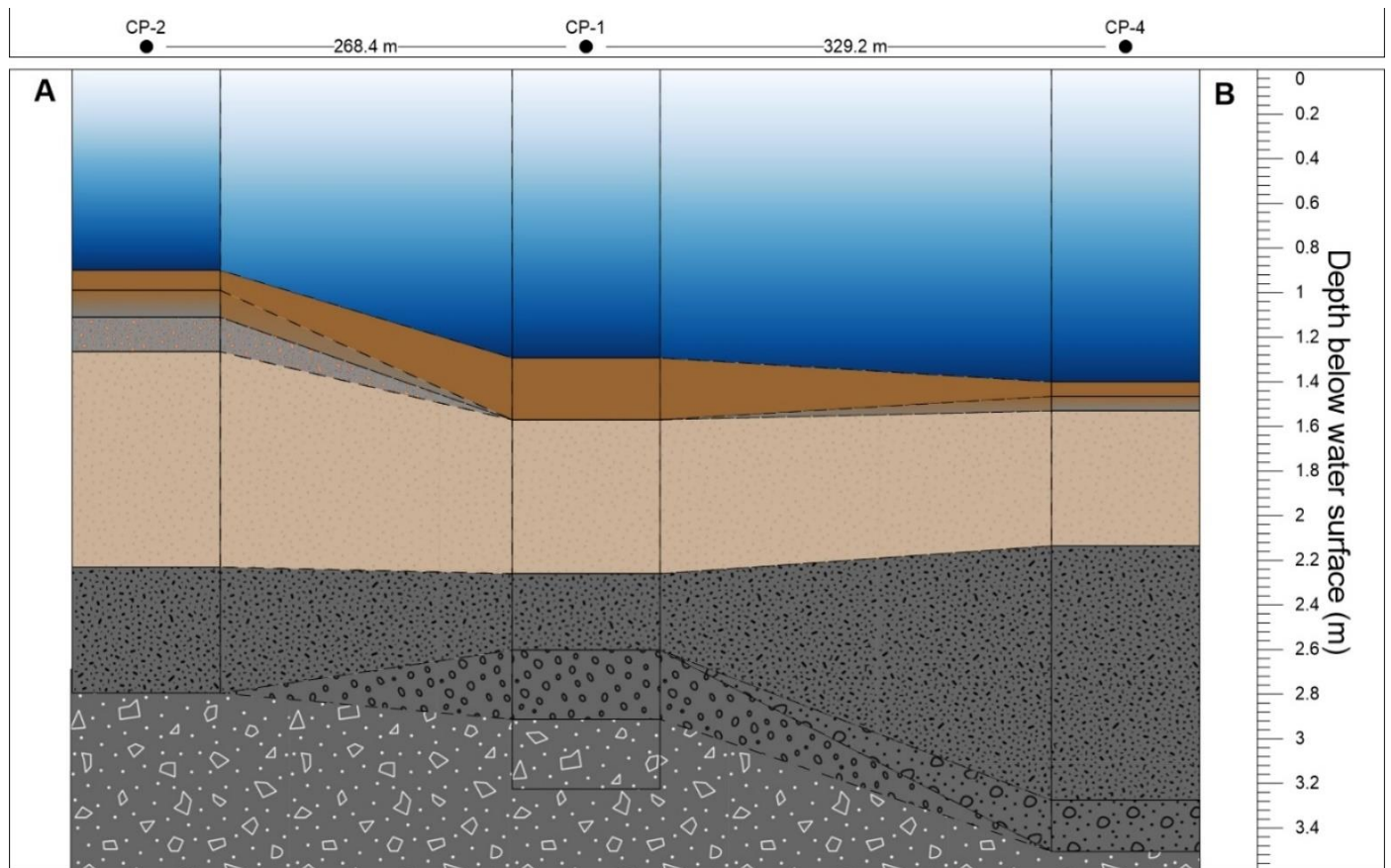
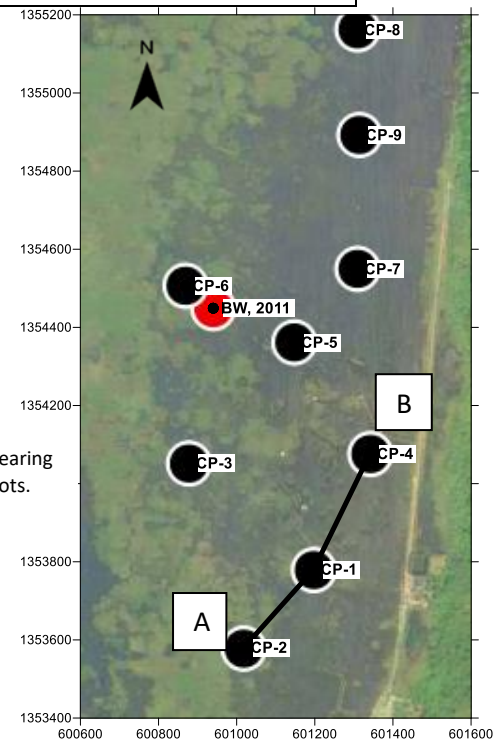


Fig. 7. Transect 3, using the lithostratigraphic columns of CP-2, CP-1 and CP-4. Transect 2 is oriented from northeast to southwest (left to right). Distances between core location varies between 268.4 m to 329.2 m.

Lithology of reference core CP5 (Table 4)

The lowermost unit A is as a compact dark grey, sandy clay with abundant of shell fragments, which suggests that it is of marine origin. The organic matter content increases in sub-unit A:2, where the number of shells decreases. Gravel was observed in subunit A:3 between 2.73 m and 2.46 m depth, ending with a limestone pebble (diameter 2-3 cm) embedded at 2.46 m depth. The organic material decreases in subunit A:3 between 2.46-2.10 m depth. Subunit B:1 is characterised by dark FeS-spots between 2.10-1.95 m depth and by beige silty clay with less organic matter between 1.95 m and 1.61 m depth. Plant remains were also observed in subunit B:1, between 1.61-1.575 m depth.

The transition between unit B and C (subunit B:2, between 1.575-1.505 m depth) is marked by a beige, silty clay, which grades into a light grey clay. Unit C is represented by two slightly different grey silty clay layers, C:1 and C: 2. The first subunit (C:1) between 1.505-1.305 m depth contains plenty of yellow spots and rusted immediately when exposed to air. The second unit (C:2) contained more organic material and had no signs of rapid rusting between 1.305-1.29 m depth. Further up, a gradual change from light grey to grey silty clay with dark spots can be seen between 1.29 m and 1.17 m depth. The uppermost unit D is made up of gyttja clay between 1.17-1.11 m depth and extends to the sediment-water interface.

Lithology of reference core CP6 (Table 5)

Sub-unit A:2 constitutes the lowermost layer in CP6 between 2.87-2.26 m depth. It is characterized by bioturbation and sand spots in a dark grey silty clay. The overlying unit B:1, a beige silty clay with less organic matter, starts at 2.26 m depth. It contains sand between 1.575-1.655 m depth and grades into a brown sandy clay, between 1.35-1.15 m depth. Sub-unit B:2 is a distinct transition layer between 1.15-1.11 m depth and composed of a dark grey silty clay. In the overlying sub-unit C:2, well preserved plant remains were observed. The uppermost unit D with its two sub-units D:1 and D:2 is composed of gyttja clay or gyttja between 1.035-0.97 m depth.

SRY-CP5		
Depth (m)	Description	Unit
1.11 - 1.17	Transition to gyttja clay.	D:1
1.17 - 1.21	Grey silty clay same as below.	C:2
1.21 - 1.29	Grey silty clay, dark spots.	
1.29 - 1.355	Light grey silty clay, no rapid oxidation, more organic materials.	C:1
1.355 - 1.505	Light grey silty clay with yellow spots, organic material; rust immediately after exposure.	
1.505 - 1.575	Light grey clay with organic material, transition to beige silty clay.	B:2
1.575 - 1.61	Beige silty clay, plant remains.	B:1
1.61 - 1.72	Beige silty clay lighter and more clay.	
1.72 - 1.80	Beige silty clay.	
1.80 - 1.90	Beige sandy silty clay.	
1.90 - 1.95	Beige silty clay.	
1.95 - 2.10	Beige sandy silty clay grading to more silty clay (less sand), dark spots throughout.	
2.10 - 2.13.5	Dark grey sandy silty clay transition to beige sandy silty clay.	A:4
2.135 - 2.175	Dark grey silty clay.	
2.175 - 2.24	Dark grey sandy silty clay (more sand than below).	
2.24 - 2.465	Dark grey sandy silty clay (less sand than below).	
2.465 - 2.58	Dark grey sandy silty clay less sand than below, large gravel occur local at 2.46 m.	A:3
2.58 - 2.73	Dark grey sandy clay contain gravel.	
2.73 - 2.8025	Dark grey sandy clay more organic material.	A:2
2.8025 - 2.9625	Dark grey silty clay with sand lenses, organic material.	
2.9625 - 3.0175	Dark grey sandy clay, compact, small shell fragment.	A:1

Table 4. Lithostratigraphy of master core CP5. The first column shows the depth (m) from the water-surface and the second column describes the lithology. The third column shows the different subunits.

SRY-CP6		
Depth (m)	Description	Unit
0.97 - 1.02	Gyttja.	D:2
1.02 - 1.035	Gyttja clay.	D:1
1.035 - 1.11	Dark grey sandy silty clay (plant remains).	C:2
1.11 - 1.15	Dark grey silty clay transition to brown sandy clay.	B:2
1.15 - 1.35	Brown sandy clay.	B:1
1.35 - 1.46	Beige silty clay (more silt).	
1.46 - 1.535	Beige silty clay.	
1.535 - 1.575	Beige sandy clay less sand.	
1.575 - 1.655	Beige sandy clay.	
1.655 - 1.81	Beige silty clay.	
1.81 - 1.84	Beige silty clay (more silt).	
1.84 - 2.10	Beige silty clay.	
2.10 - 2.26	Beige clay.	
2.26 - 2.47	Dark grey silty clay + piece of wood (<5%), 2.44 - 2.47 m, 2.33 - 2.36 m, bioturbation + sand spots.	A:2
2.47 - 2.87	Dark grey clay, (2.52 - 2.75 m. bioturbation root?).	

Table 5. Lithostratigraphy of master core CP6. The first column shows the depth (m) from the water-surface and the second column describes the lithology. The third column shows the different subunits.

Loss on ignition (LOI)

LOI results from CP6 (Table 5; Fig. 8; Appendix, Table A11)

In core CP6, LOI values range around 4.6-8.6 % in the strongly bioturbated unit A. LOI percentages decrease in unit B from 5 to 3.5 %, coinciding with the transition from the bioturbated dark grey silty clay to less organic, beige silty clay at 2.15 m depth. LOI further decreases to 1.4 % in the middle of unit B at 1.59 m depth. Thereafter LOI increases slightly and remains around 2-4 % between 2.15-1.15 m depth. At the transition from unit B (brown, sandy clay) to unit C (dark grey, silty clay) between 1.15-1.09 m depth, LOI values increase again to 9.4%. The organic matter content increases in unit C and LOI percentages are steady around 10 %. In the uppermost unit D, LOI values increase rapidly from 10.5 to 67 % and are around 54.8 % to 59 % just below the sediment- water interface between 1.03-0.97 m depth.

Correlation between core BW (2011) and CP6 using LOI

LOI values obtained on the sediments from cores BW (2011) and CP6 were correlated with each other using 4 tie points (Fig. 8, line 1-4). One tie point is in unit A, where LOI percentages remain steady in BW (2011) and CP6 (Fig. 8, line 1). The transition between unit A and B, where LOI values decrease concurrently in both cores was taken as a second tie point (Fig. 8, line 2). The third tie point was placed at the LOI minimum in BW (2011) and CP6, roughly in the middle of unit B at 1.51 m (BW, 2011) and 1.59 m (CP6) (Fig. 8, line 3). In unit C and D, LOI increases abruptly to 5.35 % (BW, 2011) and 6.56 % in CP6 (Fig. 8, line 4) and marks the fourth tie point.

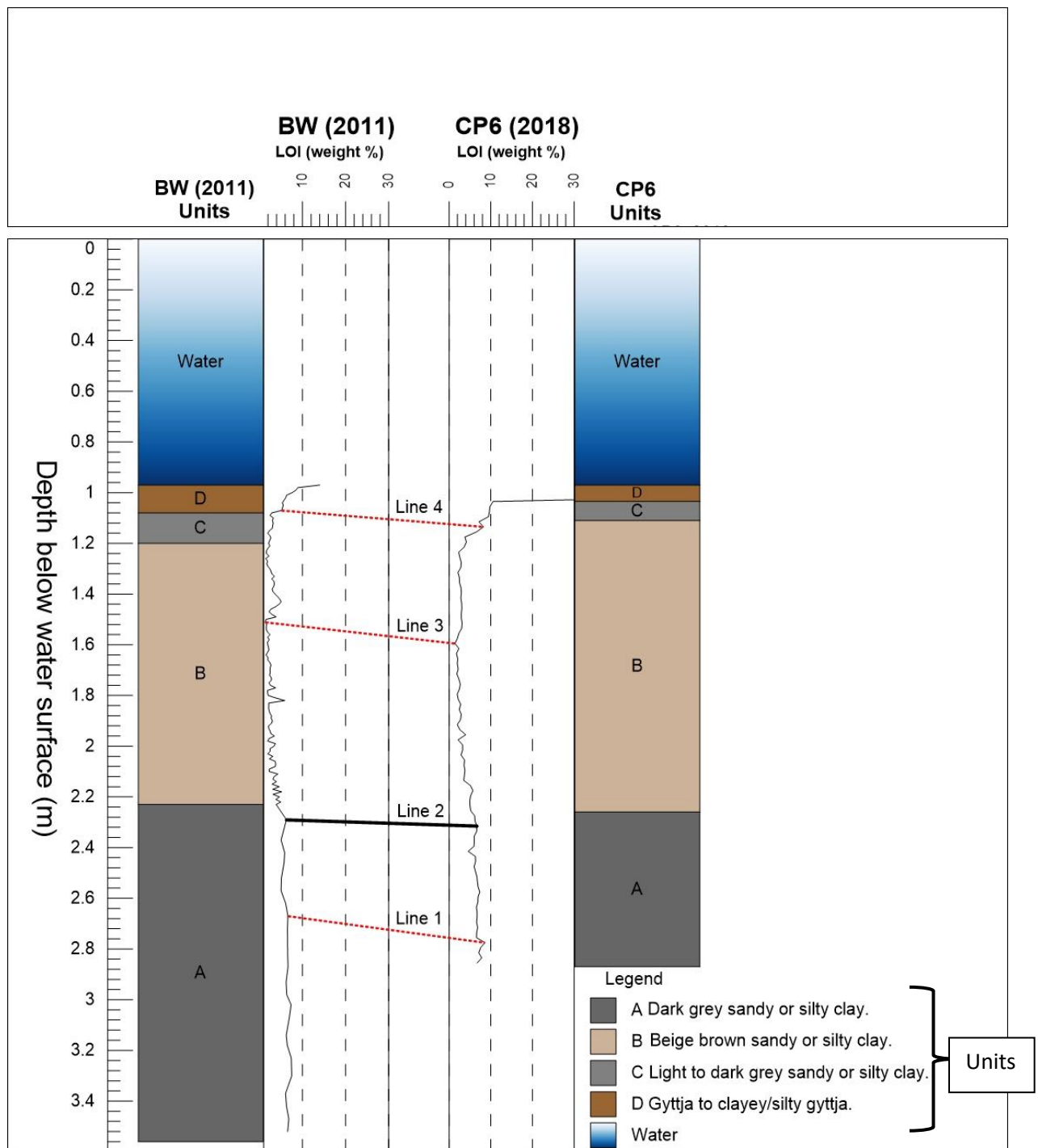


Fig. 8 Correlation between cores BW (2011) and CP6 (2018) using the respective LOI curves and four tie points. Line 2 (black solid) shows a clear transition between unit A and B. The dashed red line marks line 1, 3 and 4 which compares distinct changes in LOI values seen in both cores. The increase in LOI from 10.5 to 68%, near the water sediment interface is not shown here as the scale is set to 30%.

Grain size analysis (GSA)

Grain size distribution (Fig. 9; Appendix, Table A11)

Clay (45-50%) and silt (45-50%) are equally distributed in unit A. Sand particles however increase briefly to 32.5 % where sand lenses had been observed. In unit B, the sand fraction initially increases and reaches a maximum of 73.9 % in the middle of unit B. Thereafter the relative amount of sand decreases to 30% and clay and fine silt particles increase up to 42.8 %. In the upper part of unit B sand and clay to fine silt dominate with 30.6-53.2 % and 27.6-67.2%, respectively, while coarse silt becomes less abundant with around 18.7-27.9 %. In unit C clay and fine silt increase at first and thereafter remain around 52.9-72.8 % (Fig 9).

Particle size distribution (PSD) used as a sorting index (Fig. 9; Appendix, Table A11)

The particle size distribution (PSD)* is display in unit A appears intermediately sorted around 3.5-6.1 mm⁻³ and sorting only increases briefly to 9 mm⁻³ where sand lenses occur. At the transition between unit A and B, PSD fluctuates between 2.3 and 8.9 mm⁻³. Thereafter the sediment is well sorted (1.8-4 mm⁻³) up to the middle of unit B. However, in the middle of unit B, PSD increases rapidly to 8.2 mm⁻³. Throughout the upper part of unit B PSD displays large variations ranging between 2.7 and 11.3 mm⁻³. Roughly at the end of unit B, the sediment is again well sorted as PSD briefly stagnates between 2.3 and 3.1 mm⁻³. At the transition between unit B and unit C PSD fluctuates again between 2.3 and 9.9 mm⁻³. The sediment in unit C is mainly composed of poorly sorted clay as seen in the increase in a PSD of around 14-23 mm⁻³. In unit D PSD decreases to 9.2 mm⁻³ as the sediments became increasingly sorted just before the sediment-water interface. Required sample size for PSD was too small in the uppermost samples between 0.99 m and 0.97 m depth to be analyzed.

* Unit for PSD is micrometer written with 10 x mm⁻³ and here simplified to mm⁻³.

Comparison of LOI and GSA in relation to lithology (Fig. 9; Appendix, Table A11)

In unit A, both LOI and GSA display homogenous and steady curves in the beginning; the decrease in LOI values is linked to a brief increase in the sand fraction, which relates to sand spots that had been identified during the lithological description.

In unit B LOI percentages decrease when the sorted sand fraction increases; LOI reaches minimum values in the middle of unit B, where the sand fraction has a maximum and the particle size distribution indicates increased sorting. Thereafter LOI percentages increase again in concert with a rise in clay particles and less sorting. The sediment becomes more sorted in the upper part of unit B, where LOI increases and the fraction of clay particles remain steady. LOI percentages and the clay fraction increase gradually at the transition between unit B and C and remain high throughout unit C. In unit D, LOI and the sand fraction increase.

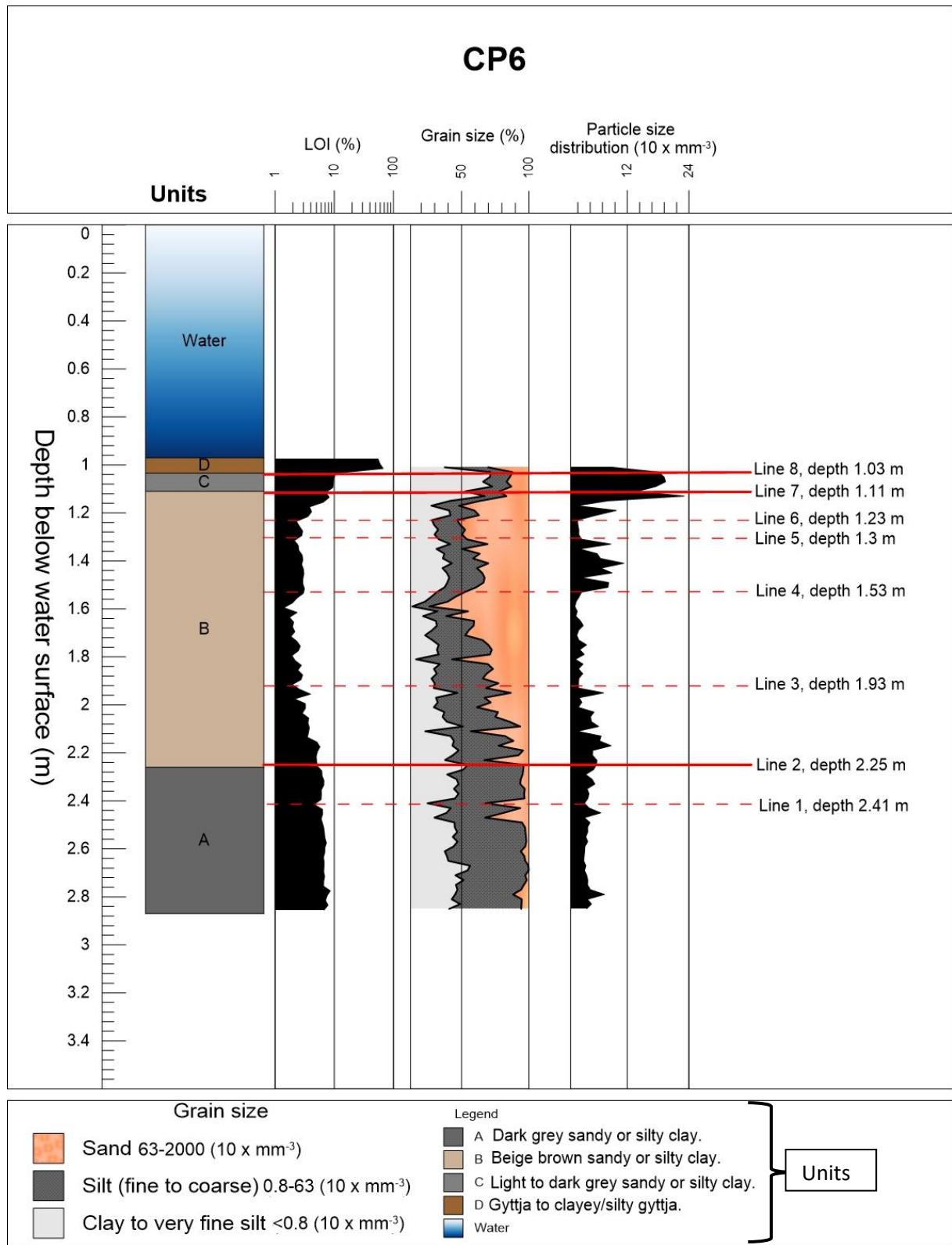


Fig. 9 LOI and GSA graphs for CP6 is based on 95 sampled in 2 cm intervals. The LOI scale is logarithmic. Each correlation point is numerically labeled (1 to 8), marked with a thick red-line (transition); or a dashed redline (sedimentation change).

Chronology of the sediments

The three radiocarbon dates obtained on core BW (2011) between 2.11-3.47 m depth contained charred fragments of terrestrial material and a piece of wood (Table 6). Calibrated ages for these three dates range between 5900 and 6800 cal yr BP. Two additional samples from CP4 were selected and dated within the frame of this study. These samples contained charcoal (Table 6). The oldest ^{14}C date in CP4 (3225-3376 cal yr BP) was from unit A and the next oldest date (1385-1524 cal yr BP) was obtained roughly where LOI percentage are lowest and grain size reaches a maximum in unit B (Fig. 9; Table 6). The new dates provide different results as compared to the earlier obtained dates in core BW (2011). While the three ^{14}C dates from core BW (2011) suggest more or less constant ages between 3.47 and 2.11 m depth (units A and B), the new dates indicate a much younger age for the upper part of unit A and for unit B (Table 6; Fig. 10). These contradicting ^{14}C dates presently only allow establishing a tentative chronology. This tentative chronology uses the three ^{14}C dates, which are marked in green colour in Table 6: one radiocarbon date from subunit A:1 (UBA-21605) in BW (2011) with a ^{14}C age of 5890 yr BP $\pm$ 39 yr (6634-6797 cal yr BP) (Table 6; Fig. 10); two radiocarbon dates from CP4, one from subunit A:4 (D-AMS 030466) with a ^{14}C age of 3090 yr BP $\pm$ 30 yr (3225-3376 cal yr BP) and one from subunit B:1 (D-AMS 030465) with a ^{14}C age of 1550 yr BP $\pm$ 25 yr (1385-1524 cal yr BP) (Table 6; Fig. 10).

The two contradicting ^{14}C dates, which are marked in red in Table 6, were excluded for the following reasons: first these two ^{14}C dates display similar ages as the ^{14}C date below 1.36 m in the same core (Table 6; Fig. 10). Secondly the new ^{14}C dates obtained on CP4 show that the older ^{14}C dates from BW (2011) appear above the younger ^{14}C dates in CP4 (Fig. 10). Lastly, grain size analysis made on CP6 located 91 m northwest of BW (2011) detected coarser sediment (33-43.1 % sand) at equal depths of the excluded ^{14}C dates (BW, 2011), suggesting that the rejected ^{14}C dates from BW (2011) are composed of reworked material (Fig. 9, 10). Therefore, only the oldest date in BW (2011) with the two additional dates from CP4 has been taken into account for the construction of a tentative linearly interpolated age-depth curve seen in Figure 11. For this curve a constant sedimentation rate was assumed.

BW, 2011									
Depth below water surface (m)	Mean depth below water surface (m)	Unit	Lab ID	Material dated	¹⁴ C date (yr BP)	error +/- (yr) (1σ)	Calibrated age range (yr BP)	Median probability age (yr BP)	Calibrated error (yr)
2.11-2.14	2.125	B	UBA-21603	Small pieces of terrestrial material (also charred)	5811	58	6472 - 6744	6610	+134 -138
2.17-2.23	2.2	B	UBA-21604	Small pieces of terrestrial material (also charred)	5238	36	5917 - 6029	5985	+44 -68
3.42-3.47	3.445	A	UBA-21605	Pieces of wood	5890	39	6634 - 6797	6711	+86 -77
CP4, 2018									
Depth below water surface (m)	Mean depth below water surface (m)	Unit	Lab ID	Material	¹⁴ C date (yr BP)	error +/- (yr) (1σ)	Calibrated age range (yr BP)	Median probability age (yr BP)	Calibrated error (yr)
1.72-1.75	1.735	B	D-AMS 030465	Charcoal	1550	25	1385 - 1524	1466	+58 -81
3.19-3.245	3.2175	A	D-AMS 030466	Charcoal	3090	30	3225 - 3376	3296	+80 -71

Table 6. First three columns (to the left) show the depth range and the mean depth below the water surface for each radiocarbon date. The four middle columns show the lab ID of the samples and the dated organic material and all ¹⁴C dates age with a 1σ error. The last three columns (to the right) display the calibrated age range and median probability age and the calibrated error, which is the difference between median probability and the calibrated maximum/minimum age. The calibrated age interval is based a 95.4 % confidence interval. Radiocarbon dates not used for the tentative chronology are marked in red and those that were are marked in green.

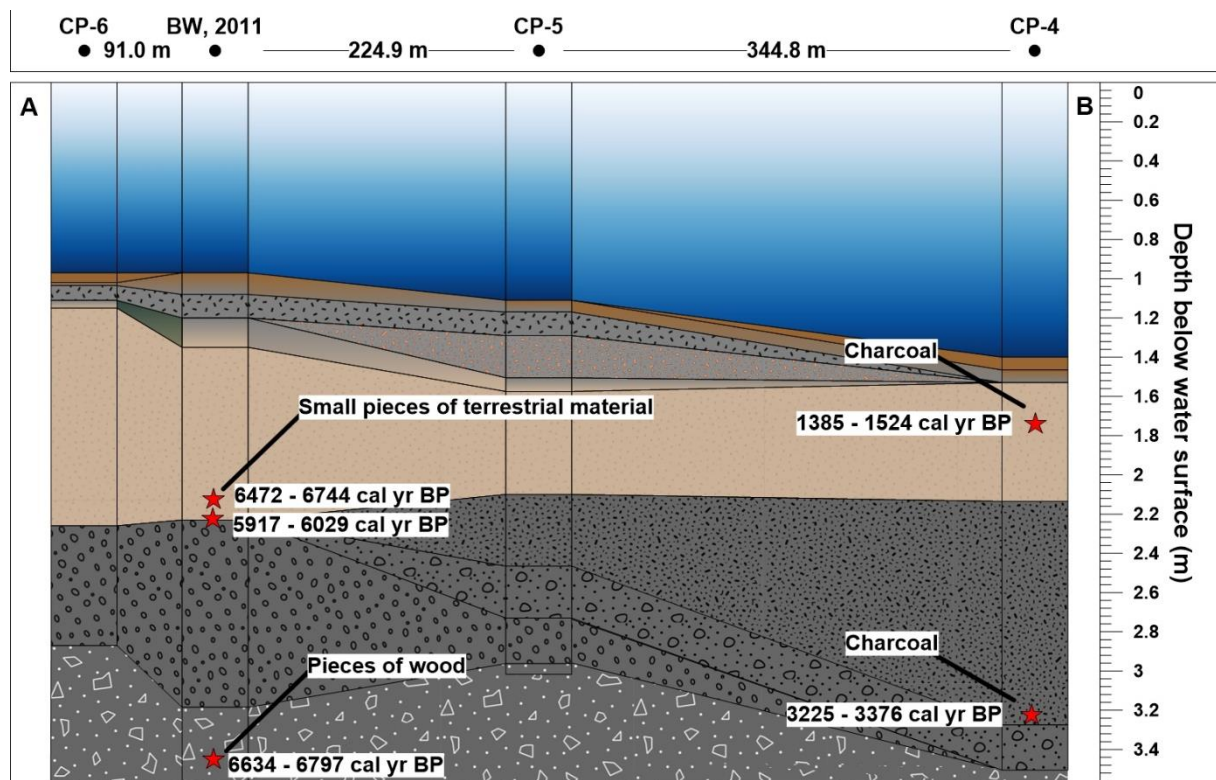


Fig. 10. Calibrated radiocarbon dates from the two cores BW (2011) and CP4 shown according to lithological unit and depth.

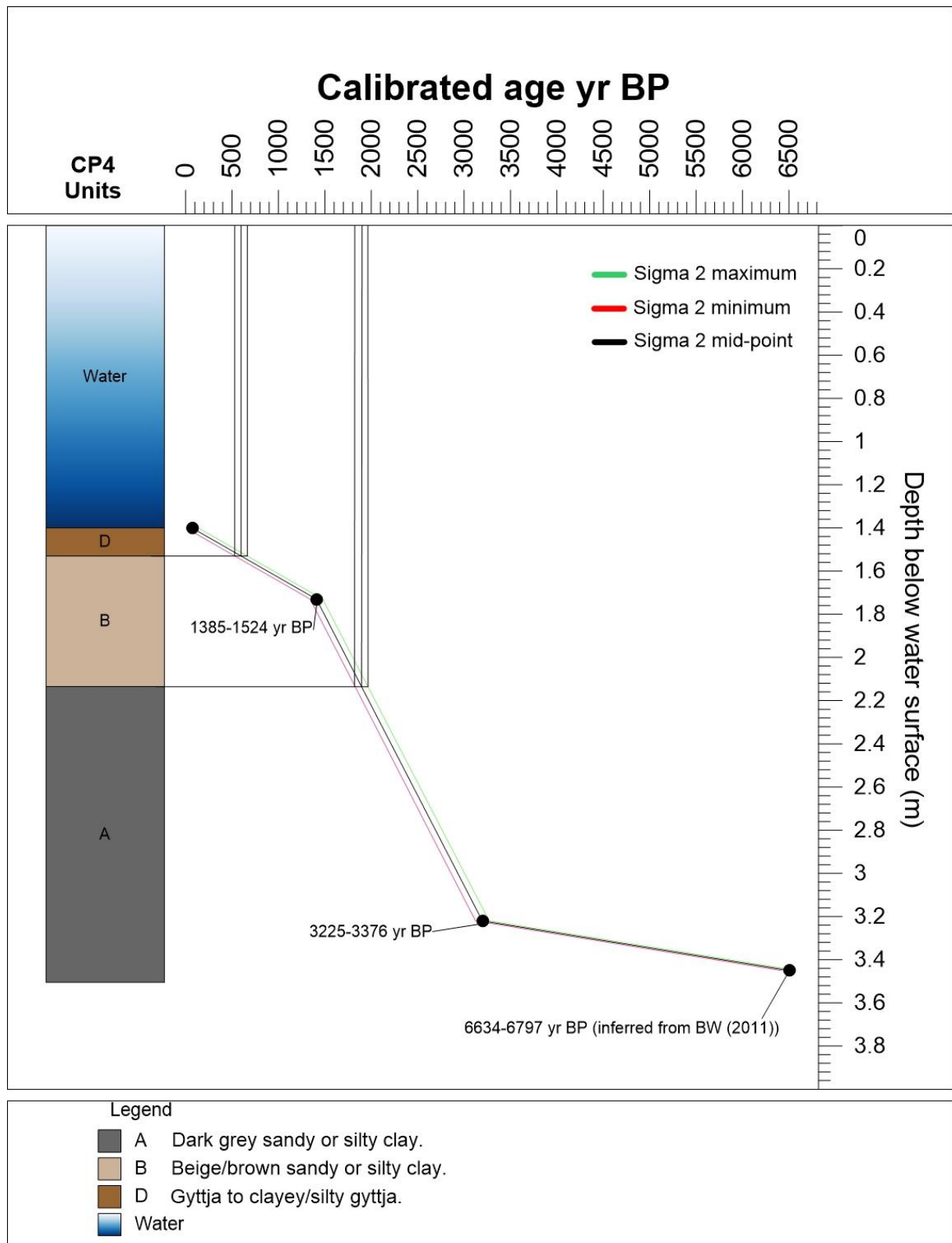


Fig. 11. A linear interpolation made with the two calibrated dates obtained from CP4 and the deepest calibrated age inferred from BW (2011). The oldest and youngest ages within the age range are marked as "sigma 2 maximum" and "sigma 2 minimum". The "sigma 2 mid-point" is the median value between "sigma 2 maximum" and "sigma 2 minimum". At the water sediment interface "sigma 2 minimum" was set to 0 yr BP. All ^{14}C dates are plotted on the depth scale of CP4.

Discussion

Seasonal changes in water depth

Fieldwork for this study was done during the rainy season (July 2018), while the older cores were obtained during the dry season (January 2011), when the water level in SRY was lower. Comparison between the field notes of B. Wohlfarth (2011) and the work by Koskelainen (2013) and the water depth during July 2018 suggests that the water table in SRY was around 0.43 m lower in January 2011. To align the two cores with each other, the original depth of core BW (2011) (Koskelainen, 2013) was therefore adjusted by adding 0.43 m. The top most loose gyttja with plant remains in CP4, CP5, CP6 and CP9 was lost during extraction of the cores. The total thickness of the lost top material is between 0.05-0.1 m, which contributes to some minor depth deviations. The offset seen in the correlation between the LOI curves of BW (2011) and CP6 is likely due to loss of the uppermost sediment during extraction (Fig. 7).

Chronology of SRY

One of the goals of this study was to establish a tentative chronology for the sediments in SRY. This partly failed because only three ^{14}C dates could be used to construct a chronology. The age of each lithologic unit (A-D) was determined using linear interpolation between the calibrated ^{14}C dates: the oldest unit A accumulated roughly between 6800 and 1900 cal yr BP, unit B between 1900 and 600 cal yr BP and unit C and D are younger than 600 cal yr BP. These estimates are based on the assumption that sediment accumulation was uniform between each calibrated ^{14}C date (Fig. 11).

Using LOI and GSA to support the lithostratigraphy of CP6

The organic matter measured by LOI can be used to classify lacustrine sediments such as gyttja clay (LOI 3-6 %) and clay gyttja (LOI 6-30%) according to Matthews et al. (2001). If LOI alone is used, the marine bioturbated silty clay in unit A would be a clay gyttja, which indicates that the common classification using LOI is not applicable for marine sediments. The LOI method is widely used for estimating the organic matter content, as it is time efficient, inexpensive and easy to reproduce. Organic matter generally originates from vascular and fibrous plants, which grow near the shoreline or from non vascular plants e.g., photosynthetic algae and other aquatic plants (Meyers and Teranes, 2001). LOI does not give an answer on the provenance of the organic matter but it could indicate both run-off and aquatic productivity (Meyers and Teranes, 2001). However, here is a known risk that non-organic volatiles e.g. structural water within the clay may increase the LOI values artificially with up to 20% (Heiri et al. 2001), which could have been the case here. In this study LOI is therefore mainly used to correlate core CP6 with BW (2011), which has been analysed for macrofossils.

The observed changes in lithology suggest that four distinct shifts in sedimentation occurred in SRY (Fig. 9). The three constructed transects (Fig. 5, 6 and 7) show that these lithologic changes are present throughout SRY and that the resulting LOI and GSA values compare well to these lithologic changes (Fig. 9).

In unit A clay and silt with organic matter are deposited homogeneously with the exception of local sand lenses. In horizons with sand lenses LOI decreases from 6 to 4.5% and the sand fraction increases significantly from 6 to 32%. This suggests that non organic volatiles e.g. structural water in the clay may have contributed to a minor increase in LOI values (Heiri et al. 2001).

Initially in unit B, LOI decreases concurrently as the sand fractions increase and become more sorted. In permeable sand the environment is generally oxygenic which, according to De Beer et al. (2005) rapidly degrades organic matter through aerobic activity. This would explain why LOI values are low (down to 1.4 %) where sand is more abundant (up to 73%) unit B (Fig. 9). Accumulation of coarser sediment with less organic matter content could also suggest that finer material i.e. clay and silt mobilized in suspension and were transported further, which would be consistent with an oxygenic environment caused by stronger runoff or wave action. A concurrent increase in LOI (from 1.4% to 4%) and clay and silt particles (from 30% to 70%) is seen from the middle of unit B (Fig. 9) which suggests a

combination of higher aquatic production or weakened degradation of organic matter, as the loss of non organic volatiles in clay during combustion cannot account for the doubling affect seen in LOI.

Here, from the middle of unit B, mite remains become more abundant according to Koskelainen (2013), which, together with the increase in clay and silt fractions suggest, that the water became more stagnant as mites require calmer water to hatch.

The abrupt increase in LOI values in unit C coincides with the occurrence of well-preserved plant remains (Table 5) and with a decrease in sand, which could indicate a decrease in runoff. This suggests a combination of high organic production and anoxic conditions, which would have favored the preservation of plant remains. In the upper most unit D LOI and sand particles increase. This could indicate increased soil erosion from recent changes in land use allowing nutrient rich inflow to accelerate eutrophication in SRY, which is consistent with observations made in North American lakes (Wetzel, 2001).

Sedimentation history of SRY

The “calcareous marine” unit A, >6800-1900 cal yr BP

The oldest sediment in unit A (>6800 yr BP) was identified as marine because of the occurrence of sea shells that are imbedded in the dark grey calcareous, sandy to silty clay. To the east of the SRY study area, cliffs composed of Permian limestone form a natural barrier island and create an ideal location for a back-barrier lagoon (Fig. 1B, 1C, 2, 3A and 3B). Dating of sea notches at the base of these Permian limestone cliffs by Dusitapirom et al. (2008) suggests that sea level was at 2.67 m a.s.l between 7000 and 5000 yr BP. In cores that are located close to the former barrier island subangular limestone gravel was found embedded in the calcareous marine, dark grey, silty clay. This could suggest increased weathering during the early to mid-marine phase.

In the upper part of unit A, bioturbation by roots, which is otherwise absent in the overlaying unit B was observed in BW (2011) and CP6. This suggests that vegetation became established along the former shoreline between circa 6000 to 1900 cal yr BP. The top of unit A is more or less flat and reminds of a tidal flat (Fig. 5, 6 and 7). Further evidence supporting a tidal influenced lagoon can be derived from the sand lenses in CP6 (Table 5; Fig. 9).

Comparably high LOI percentages in unit A (4.6-8.6 %) could be due to the strong bioturbation seen throughout unit A (Table 5; Fig. 9). The near uniform accumulation of sorted silt and clay in unit A further points to a steady accumulation in a low energy environment, typical of a tidal influenced lagoon where mangrove vegetation stabilizes the sediment (Taylor, 2012).

The “ferric lacustrine” unit B, ~1900 to 600 cal yr BP

In unit B the sediment changes distinctly into a ferric, beige brown, silty clay. This lithologic change has been described as a transition from marine to lacustrine in previous studies (Koskelainen, 2013). No conclusive evidence describing the water in SRY basin as either brackish or lacustrine could be found in unit B, therefore this phase should be considered as a combination of both brackish and lacustrine influences. The sediment in unit B is generally ferric (oxidized) and contains less organic matter, indicating that SRY turned into an oligotrophic state (high oxygen concentration) during the combined lacustrine phase which was unfavorable for organic preservation.

In an oligotrophic basin the primary source of organic matter stems from phytoplankton production according to Wetzel (2001). Rapid initial accumulation of nutrient poor and coarse sediment into the basin could presumably have preceded and perhaps limited the phytoplankton production after the transition from marine to lacustrine conditions, which would further explain the low LOI percentage (1.4-5%) seen in unit B (Fig. 8). Furthermore, dark iron sulfide (FeS) stains in unit B were only seen in CP4, CP5 and CP7, i.e. furthest away from any potential source of fresh water inflow (Appendix, Table A4, A5 and A8). Their occurrence suggests an oxygen-poor environment, so-called hypoxia. Hypoxia is common in coastal areas especially where strong freshwater influx meets standing salt water. Fresh water lenses then develop above denser sea water and block oxygen from diffusing into the saltwater below. This allows marine organisms to deplete oxygen in the underlying saltwater lenses (Stickney, 2016). Oxygen depletion produces hydrogen sulfide (H₂S), which reacts with ferrous iron (Fe⁺²) and precipitates iron sulfide (FeS) as dark stains in the sediment.

The new data set suggests that sedimentation in SRY changed from marine to lacustrine approximately 1900 cal yr BP (Fig. 11). The start of this time interval compares well to the

second shoreline regression (~3000-1000 yr BP) described by Surakiatchai et al. (2018).

Influence from the sea most likely occurred during a combined brackish lacustrine phase (1900 to 600 cal yr BP) as typhoons are known to influence SRY occasionally (Surakiatchai et al. 2018).

Furthermore the seasonal change in water depth (0.43m) allows saltier water to intrude during the dry season, which most likely occurred in the past when the shoreline was further inland.

Initially in unit B (~1900 to 1600 cal yr BP) organic matter content decreases steadily concurrently with an increase in sorted sand particles (Fig. 9). Charcoal particles counted in this unit by Koskelainen (2013) show higher numbers until about 1.55 m depth (middle of unit B). The co-occurrence of low organic matter content, abundance of charcoal particles and increased accumulation of sand could be explained by desiccation or ensuing soil erosion and sediment transport by streams as the shore line regression exposed new land areas, which lacked stabilizing vegetation. The plausible desiccation seen in unit B (~1900 to 1600 cal yr BP) coincides with a period of drier climate between 1900-1600 cal yr BP (Wohlfarth et al. 2012) and roughly with another period of drier climate conditions between 2050-1300 cal yr BP, according to Yamoah et al. (2016). However, these paleoclimate records are from lake sediments located 640 km northeast of SRY.

Between circa 1600 and 600 cal yr BP, sediment organic matter increased slightly and thereafter stagnated around (2-4.1 %), concurrently with a decrease in charcoal particles (Koskelainen, 2013) and sand particles (Fig. 9). A decreased influx of sand and charcoal particles could be associated with weaker soil erosion and fewer or less intense forest fires, suggesting that the vegetation that had become established could prevent soil erosion 1600 to 600 cal yr BP. This time interval could relate to a period of stronger monsoon rains occurring around 1150-980 cal yr BP (Chawchai, 2014) and wetter climate condition between 1300-1000 cal yr BP (Yamoah et al. 2016). By tentatively using the particle size distribution together with the coarser grain fractions as an indicator for stronger runoff, one interpretation would be that two periods of shifting monsoons affected the sedimentation in SRY.

The wetland unit C and D, ~600 cal yr BP to present

Around 600 cal yr BP (Fig. 11), the sediments became more organic and clayey, suggesting that wetland condition had become established in the shallower part of SRY, while the area around CP1, CP4 and CP7 was still covered by deeper water. The sediments of the wetland stage are also characterized by a distinct change in color from beige brown to grey, sometimes rapid oxidation and well-preserved plant remains. These latter could indicate anoxic bottom water condition caused by high organic production. The sediment commonly changes color from red or brown to black or grey when iron oxides convert into sulfides (Drever, 1997). The macrofossil analysis in core BW (2011) (Koskelainen, 2013) displays an increase in riparian wetland vegetation such as *Juncus* and *Cyperaceae* together with some small amounts of *Nymphaea lotus* and *Nitella oospores* and a larger amount of charcoal particles and mites. The organic matter content and clay particles increase in unit C, which suggests a low energy environment and high organic production, which would further support wetland condition. The lowering of the water table and the ensuing change from a lake to wetland conditions in unit C, roughly coincide with a period of drier climate between 700-500 cal yr BP according to Yamoah et al. (2016) and between 650-500 cal yr BP according to Chawchai (2014).

Anthropogenic influences, uppermost unit D

SRY is today no longer in its natural state (Parr et al. 1993; Koskelainen, 2013) and anthropogenic influences must be considered when evaluating the results from the uppermost part of unit D. Evidently increased eutrophication can be inferred from the gyttja sediments in unit D. The high organic matter content implies high aquatic productivity in SRY, which can not be detected anywhere else in the core (Fig. 9). Presently, several aquacultural compounds (shrimp farms) connect and surround the SRY wetland area (Fig. 1B, 1C and 3B) (Parr et al. 1993) and contribute to the ongoing eutrophication. Moreover, the abrupt increase of sand particles and organic matter may be related to an increase in soil erosion, which has accelerated during the last 80 years due to deforestation. Before 1930 forests covered 70% of Thailand as compared to roughly 15% today (Delang, 2005). In a vegetated drainage basin (e.g. forests) about one-third of the precipitation is discharged as runoff or groundwater seepage which, according to Wetzel (2001) increases organic production in basins surrounded by land clearances.

Further studies

To establish a better chronology of the SRY sediments more radiocarbon dates would be needed. A better chronology would then allow to connect the environmental changes seen in the sediments of SRY with Holocene climate shifts described by Wohlfarth et al. (2012), Chabangborn (2014) Chawchai (2014) and Yamoah et al. (2016). Moreover, diatom analysis on new cores could provide a better assessment of when SRY was subject to marine and lacustrine conditions and future pollen and macrofossil analysis could give information on changes in local and regional vegetation. Investigating lipid biomarkers could potentially explain the change in organic production seen at SRY. The observed acidity and the FeS content of the lake sediments would need further examination so that costly land reclamation projects on the SRY wetland can be prevented. The geology of the area is still poorly understood and the age estimation of the Silurian sedimentary rock is done without good identifications of the rock type (Fig. 2). No soil maps over the area are available, which could help identifying areas prone to erosion. Moreover, seismological surveys need to be conducted at SRY to exclude regional uplift as a potential cause for shore line regression and the connection between neoglaciation and shoreline regression needs further investigation.

Conclusion

Marine conditions most likely prevailed at SRY after the first shoreline regression 6500 yr BP (Surakiatchai et al. 2018). Thereafter SRY became a tidally influenced lagoon with mangrove vegetation along the shoreline until isolation from the sea occurred around 1900 cal yr BP, i.e. much later than previously suggested by Koskelainen, (2013). Between 1900 cal yr BP and 1600 cal yr BP, the sediment shows increased accumulation of sand particles and lower organic matter content, suggesting initially higher levels of soil erosion after the isolation from the sea. Wetland conditions occurred approximately around 600 cal yr BP and were followed by eutrophication. Human-induced eutrophication and possibly also an increase in soil erosion occurred during the last decades and is detected near the sediment-water interface as an abrupt increase in LOI percentages and sand particles, presumably caused by nutrient rich influx from nearby farms and large scale deforestation seen in the surroundings.

Acknowledgments

I would like to thank my family, wife and son for staying put through all the absence during this study. Especially thanks to both my supervisors, first Barbara Wohlfarth with her sharp scientific mind which gave me the structural thinking and language aid I needed, then to my big bro Akkanewut Chabangborn aka (P'Nut) who made this study possible by allowing my participation in his fieldwork and the laboratory description of the sediment cores. A big thanks to my co-student Worakamon Nudnara aka (Nong Bam) which has been working hard by doing the majority of the core descriptions in this study. Then to Carina Johansson who made the laboratory moment possible by giving me valuable advice on how to conduct the precise measurements needed and further helping me at the start of each analysis. Thanks to my friends and classmates from the distance program, Ben Jonkman, Iliyan Deskov and Stefan Bjursäter who has helped me with proofreading and giving me important feedback on this text. Lastly, I would like to thank everyone that I have encountered so far at Stockholm University and Chulalongkorn University for helping me with everything from holding up a door to giving me their advice and valuable time.

Appendix

Fig. A1

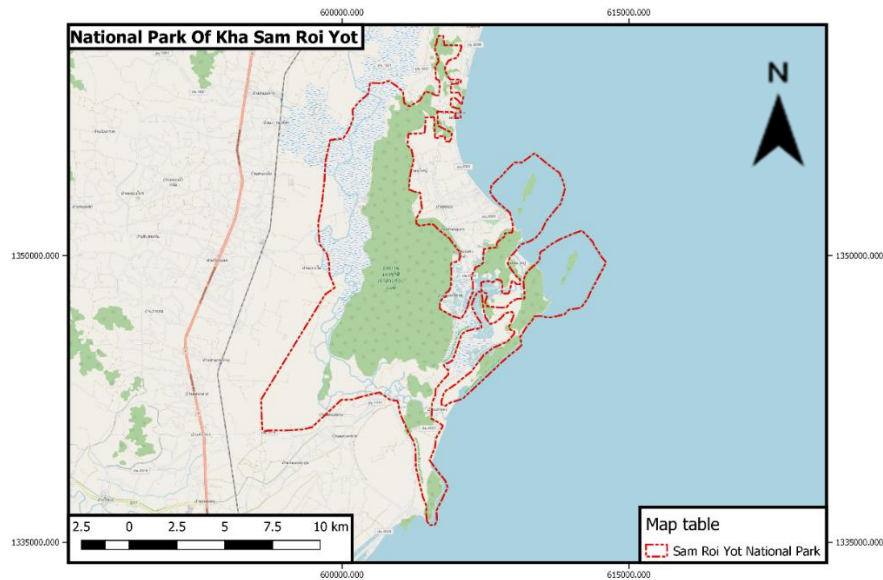


Fig. A1 The OSM base map is used for better understanding the extent of SRY. OSM is an open license map layer which is obtained through OpenStreetMap.org. The OSM standard base map is considered reliable and defines the area of SRY national park clearly.

Fig. A2

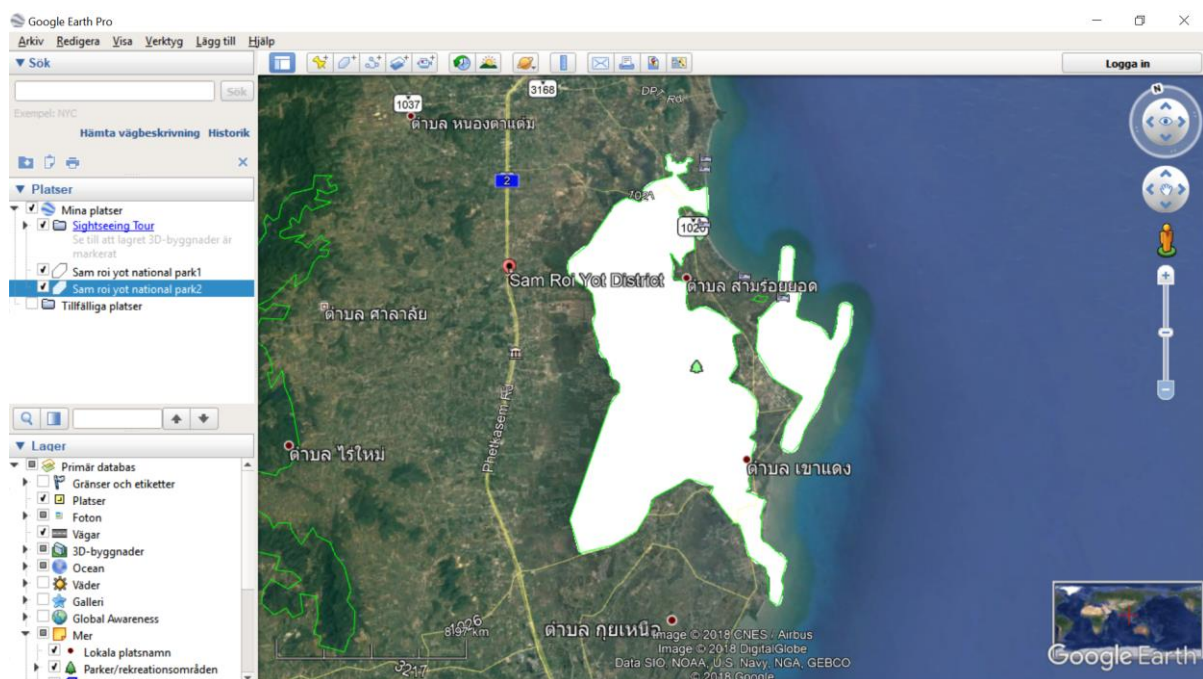


Fig. A2 The boundaries of SRY National park according to Google Earth (2018). These divert slightly from the boundaries set in the OSM tile layers in Fig. A1.

Table A1

SRY-CP1		
Depth (m)	Description	Unit
1.2925 - 1.5375	Gyttja.	D:2
1.5375 - 1.57	Transiton gyttja clay.	
1.57 - 1.5975	Beige silty clay, bioturbation infilled with clayey gyttja.	B:1
1.5975 - 1.6175	Beige clay.	
1.6175 - 1.7525	Beige silty clay (more silt) more silt at top.	
1.7525 - 1.9325	Beige silty clay (more silt on top), bioturbation infilled with gyttja, some light brown clay pocket.	
1.9325 - 1.9925	Beige silty clay (less silt than below), bioturbation infilled with gyttja.	
1.9925 - 2.1725	Transition to beige silty clay, 1.9925 - 2.0725 m, less silt than below.	
2.1725 - 2.26	Transition from beige sandy silty clay to dark grey sandy silty clay.	A:4
2.26 - 2.28	Dark grey sandy silty clay, more sand than below, some beige mixture.	
2.28 - 2.33	Dark grey silty clay less beige than above.	
2.33 - 2.4125	Dark grey silty clay more organic materials, some mixture of beige patches.	
2.4125 - 2.5225	Dark grey sandy silty clay, some sand lenses.	
2.5225 - 2.56	Dark grey silty sandy clay (more sand than below).	
2.56 - 2.6025	dark grey sandy silty clay (less sand below).	A:2
2.6025 - 2.9125	Dark grey silty sandy clay to sandy silty clay more organic material, 2.607 - 2.56 m, bioturbation.	
2.9125 - 2.9775	Dark grey silty sandy clay (more sand), oxidized rapidly, less shell fragments, organic materials.	A:1
2.9775 - 3.08	Dark grey sandy silty clay (less sand), large shell (well preserved), organic material slightly increasing.	
3.08 - 3.1525	Dark grey silty sandy clay (more sand) sand pockets, shell fragments and more organic materials.	
3.1525 - 3.225	Grey silty sandy clay (shell fragments and organic materials).	

Table A1 Lithologic description of CP1 and different units.

Table A2

SRY-CP2		
Depth (m)	Description	Unit
0.9 - 0.935	Gyttja.	D:2
0.935 - 0.965	Dark grey gyttja clay.	
0.965 - 0.99	Gyttja.	
0.99 - 1.085	Dark grey gyttja clay.	D:1
1.085 - 1.11	Transition from dark grey gyttja clay to light grey sandy clay.	
1.11 - 1.265	Light grey sandy clay (oxidized).	C:1
1.265 - 1.325	Beige sandy clay some yellow spots and more sand.	B:1
1.325 - 1.385	Beige sandy clay (yellow spots).	
1.385 - 1.45	Beige silty clay.	
1.45 - 1.495	Beige sandy clay.	
1.495 - 1.78	Beige clayey sand (yellow spots).	
1.78 - 1.845	Beige sandy clay (yellow spots).	
1.845 - 2.08	Beige clayey sand.	
2.08 - 2.23	Beige sandy clay.	
2.23 - 2.32	Transition from beige sandy clay to dark grey silty clay.	A:4
2.32 - 2.605	Dark grey silty clay.	
2.605 - 2.645	Dark grey silty clay (less silt).	
2.645 - 2.675	Dark grey silty clay.	
2.675 - 2.695	Dark grey silty clay (less silt).	
2.695 - 2.795	Dark grey silty clay.	

Table A2 Lithologic description of CP2 and different units.

Table A3

SRY-CP3		
Depth (m)	Description	Unit
0.8 - 0.845	Gyttja.	D:2
0.845 - 0.95	Dark grey gyttja clay.	D:1
0.95 - 1.05	Dark grey silty clay.	C:2
1.05 - 1.155	Brown silty clay.	B:2
1.155 - 1.41	Beige sandy clay (less sand) (oxidized).	B:1
1.41 - 1.58	Beige silty clay.	
1.58 - 1.715	Beige sandy clay (less sand).	
1.715 - 1.74	Beige sandy clay.	
1.74 - 1.80	Beige sandy clay (oxidized on top).	
1.80 - 1.885	Beige silty clay.	
1.885 - 1.965	Beige clayey sand.	
1.965 - 2.05	Beige sandy clay.	
2.05 - 2.19	Transition from beige sandy clay to dark grey sandy clay.	A:4
2.19 - 2.53	Dark grey sandy clay (more sand).	
2.53 - 2.675	Dark grey sandy clay.	
2.675 - 2.91	Dark grey silty clay.	
2.91 - 3.44	Dark grey clay.	

Table A3 Lithologic description of CP3 and different units.

Table A4

SRY-CP4		
Depth (m)	Description	Unit
1.40 - 1.465	Clayey gyttja.	D:2
1.465 - 1.53	Brown gyttja clay.	D:1
1.53 - 1.645	Beige sandy clay with dark spots.	B:1
1.645 - 1.81	Beige silty clay (more silt).	
1.81 - 2.015	Beige clay with dark spots.	
2.015 - 2.135	Beige silty clay with dark spots.	
2.135 - 2.235	Beige silty clay transition to dark grey silty clay.	A:4
2.235 - 2.30	Dark grey clay transition to beige clay.	
2.30 - 2.35	Dark grey silty clay.	
2.35 - 2.615	Dark grey clay, 2.545 - 2.485 m, bioturbation (root?).	
2.615 - 2.70	Dark grey clay with light grey clay spots.	
2.70 - 2.80	Dark grey clay (oxidized).	
2.80 - 2.97	Dark grey silty clay.	
2.97 - 3.245	Dark grey clay (some sand spots).	
3.245 - 3.275	Dark grey sandy clay.	
3.275 - 3.455	Dark grey sandy clay (less gravel).	A:3
3.455 - 3.505	Dark grey sandy clay with gravel.	

Table A4 Lithologic description of CP4 and different units.

Table A5

SRY-CP5		
Depth (m)	Description	Unit
1.11 - 1.17	Transition to gyttja clay.	D:1
1.17 - 1.21	Grey silty clay same as below.	C:2
1.21 - 1.29	Grey silty clay, dark spots.	
1.29 - 1.355	Light grey silty clay, no rapid oxidation, more organic materials.	C:1
1.355 - 1.505	Light grey silty clay with yellow spots, organic material; rust immediately after exposure.	
1.505 - 1.575	Light grey clay with organic material, transition to beige silty clay.	B:2
1.575 - 1.61	Beige silty clay, plant remains.	B:1
1.61 - 1.72	Beige silty clay lighter and more clay.	
1.72 - 1.80	Beige silty clay.	
1.80 - 1.90	Beige sandy silty clay.	
1.90 - 1.95	Beige silty clay.	
1.95 - 2.10	Beige sandy silty clay grading to more silty clay (less sand), dark spots throughout.	
2.10 - 2.135	Dark grey sandy silty clay transition to beige sandy silty clay.	A:4
2.135 - 2.175	Dark grey silty clay.	
2.175 - 2.24	Dark grey sandy silty clay (more sand than below).	
2.24 - 2.465	Dark grey sandy silty clay (less sand than below).	
2.465 - 2.58	Dark grey sandy silty clay less sand than below, large gravel occur local at 2.46 m.	A:3
2.58 - 2.73	Dark grey sandy clay contain gravel.	
2.73 - 2.8025	Dark grey sandy clay more organic material.	A:2
2.8025 - 2.9625	Dark grey silty clay with sand lenses, organic material.	
2.9625 - 3.0175	Dark grey sandy clay, compact, small shell fragment.	A:1

Table A5 Lithologic description of CP5 and different units.

Table A6

SRY-CP6		
Depth (m)	Description	Unit
0.97 - 1.02	Gyttja.	D:2
1.02 - 1.035	Gyttja clay.	D:1
1.035 - 1.11	Dark grey sandy silty clay (plant remains).	C:2
1.11 - 1.15	Dark grey silty clay transition to brown sandy clay.	B:2
1.15 - 1.35	Brown sandy clay.	B:1
1.35 - 1.46	Beige silty clay (more silt).	
1.46 - 1.535	Beige silty clay.	
1.535 - 1.575	Beige sandy clay less sand.	
1.575 - 1.655	Beige sandy clay.	
1.655 - 1.81	Beige silty clay.	
1.81 - 1.84	Beige silty clay (more silt).	
1.84 - 2.10	Beige silty clay.	
2.10 - 2.26	Beige clay.	
2.26 - 2.47	Dark grey silty clay + piece of wood (<5%), 2.44 - 2.47 m, 2.33 - 2.36 m, bioturbation + sand spots.	A:2
2.47 - 2.87	Dark grey clay, (2.52 - 2.75 m. bioturbation root?).	

Table A6 Lithologic description of CP6 and different units.

Table A7

BW (2011)		
Depth (m)*	Description	Unit
0.97 - 1.08	Dark brown silty gyttja, bioturbated base.	D:1
1.08 - 1.20	Light grey fine sand, strongly bioturated; dark organic material from top layer has moved down.	C:2
1.20 - 1.35	Light brown and reddish/orange grey silty fine sand, gLB.	B:2
1.35 - 1.47	Same color as below, maybe more light brown, but oxidized to reddish/orange/beige; fine sand pockets, clayey silt; gLB.	B:1
1.47 - 1.56	Brown and orange-beige mix of fine sand and to a lesser extent of clay silt/silty clay; coarse material than below; gLB.	
1.56 - 1.76	Same as below, but higher sand content; gLB.	
1.76 - 2.08	Mixture of sediment: brown clayey silt and orange-beige fine sand; no clear structure.	
2.08 - 2.14	Brown sandy clayey silt, thin fine sand lenses; gLB.	
2.14 - 2.23	Mix of dark grey silty sandy clay, beige fine sand, light brown silty clay. Beige fine sand oxidizes rapidly to orange brown. LB looks gradual, but the transition is still very obvious.	A:2
2.23 - 2.29	Dark grey silty sandy clay, strongly bioturbated, contains pockets of the overlying orange-beige sand; gLB.	
2.29 - 2.46	Dark grey silty clay, surface oxidizes to reddish grey; some light grey ?fine sand lenses; this layer contains more fine sand lenses in the overlapping core; gLB.	
2.46 - 2.795	Dark grey silty clay; surface oxidizes rapidly (Fe) & becomes orange-grey; much less plant remains than below; FeS stains/spots; gLB.	
2.795 - 2.98	Grey silty clay, fine plant remains, strongly bioturbated; dark plant/root layer cuts through core 2.88-2.92; gLB.	
2.98 - 3.14	Grey silty clay, some fine plant remains, salt crystals; not bioturbated, gLB.	A:1
3.14 - 3.185	Grey silty clay, some fine plant remains, shell fragments; bioturbated; gLB.	
3.185 - 3.23	Grey silty clay with less fine plant remains than below; not bioturbated, gLB.	
3.23 - 3.30	Grey silty clay with finer plant remains than below (mosses?), gLB, strongly bioturbated.	
3.30 - 3.56	Grey silty clay with fine and coarse plant remains; gastropd shell at 3.44 m; salt crystals appear when sediment dries.	
* water depth aligned to that of CP6, July 2018		

Table A7 Lithologic description of BW (2011) and different units.

Table A8

SRY-CP7		
Depth (m)	Description	Unit
1.28 - 1.33	Gyttja (shell fragment).	D:2
1.33 - 1.38	Light grey clay (gyttja spot).	D:1
1.38 - 1.475	Dark grey gyttja clay (bioturbation).	
1.475 - 1.555	Beige to brown silty clay (dark spots).	B:1
1.555 - 1.64	Beige silty clay.	
1.64 - 1.695	Beige sandy clay.	
1.695 - 1.875	Beige silty clay.	
1.875 - 2.25	Beige clay.	
2.25 - 2.305	Dark grey silty clay transition from beige clay (charcoal).	A:4
2.305 - 2.645	Dark grey silty clay (less silt).	
2.645 - 2.73	Dark grey silty clay.	
2.73 - 2.785	Dark grey sandy silty clay.	
2.785 - 2.815	Dark grey sandy clay (less sand).	
2.815 - 2.935	Dark grey silty clay.	
2.935 - 3.09	Dark grey sandy clay (less sand).	
3.09 - 3.12	Dark grey silty clay (less silt).	
3.12 - 3.16	Dark grey silty clay.	
3.16 - 3.31	Dark grey sandy clay (less sand).	
3.31 - 3.475	Dark grey silty clay.	
3.475 - 3.605	Dark grey sandy clay (less sand).	A:1
3.605 - 3.685	Dark grey sandy clay.	

Table A8 Lithologic description of CP7 and different units.

Table A9

SRY-CP8		
Depth (m)	Description	Unit
1.325 - 1.35	Dark grey clay with organic matter.	C:2
1.35 - 1.42	Grey clay with organic matters.	
1.42 - 1.46	Dark brown clay.	B:1
1.46 - 1.515	Dark brown sandy clay.	
1.515 - 1.69	Beige sandy clay (more sand).	
1.69 - 1.76	Beige sandy clay.	
1.76 - 1.925	Beige silty clay.	
1.925 - 2.05	Brown sandy clay (less sand).	
2.05 - 2.10	Brown sandy clay.	

Table A9 Lithologic description of CP8 and different units.

Table A10

SRY-CP9		
Depth (m)	Description	Unit
1.10 - 1.13	Gyttja.	D:2
1.13 - 1.22	Dark grey gyttja clay.	D:1
1.22 - 1.485	Light grey clay.	D:1?
1.485 - 1.365	Dark grey gyttja clay.	D:1
1.365 - 1.40	Dark grey silty clay.	C:2
1.40 - 1.535	Light grey sandy clay.	C:1
1.535 - 1.66	Brown sandy clay transition from light grey sandy clay.	B:2
1.66 - 1.72	Brown sandy clay (more sand).	B:1
1.72 - 1.865	Brown sandy clay.	
1.865 - 1.915	Beige sandy clay transition from brown sandy clay.	
1.915 - 2.145	Beige silty clay.	
2.145 - 2.22	Beige sandy silty clay.	
2.22 - 2.245	Beige silty clay.	A:4
2.245 - 2.28	Dark grey silty clay.	
2.28 - 2.35	Dark grey silty clay (more silt).	
2.35 - 2.41	Dark grey silty clay.	
2.41 - 2.47	Dark grey silty clay (more silt).	
2.47 - 2.675	Dark grey silty clay.	A:3
2.675 - 2.695	Dark grey sandy clay (less sand) (gravel).	
2.695 - 2.80	Dark grey sandy clay (2.745 - 2.735 m black layer).	A:2?
2.80 - 2.96	Dark grey clayey sand.	A:1?
2.96 - 2.98	Dark grey sandy clay (less sand).	
2.98 - 3.055	Dark grey sandy clay.	
3.055 - 3.095	Dark grey sandy clay (less sand).	
3.095 - 3.54	Dark grey sandy clay.	

Table A10 Lithologic description of CP9 and different units.

Table A11

First columns (to the left) shows the depths below water surface (m) in which samples was collected and the given sample ID. The middle columns display LOI weight percentages, grain size intervals in unit micrometer ($10 \times \text{mm}^{-3}$) according to Wentworth (1922) and particle size distribution in micrometer ($10 \times \text{mm}^{-3}$). Last two columns (right) show skewness and laboratory remarks. The GSA result from the two uppermost samples is marked red and excluded because samples was too small to provide an acceptable obscuration level.

CP6								
Depth below water surface (m)	Sample ID	LOI (w %)	Clay to very fine silt (%) <0.8 ($10 \times \text{mm}^{-3}$)	Fine silt to coarse silt (%) 0.8-63 ($10 \times \text{mm}^{-3}$)	Sand (%) 63-2000 ($10 \times \text{mm}^{-3}$)	Particle size distribution average diameter ($10 \times \text{mm}^{-3}$)	Skewness (0-3)	Remarks
0.97	1	54.80	44.06	48.93	7.02	5.02	1.99	GSA excluded
0.99	3	59.03	18.38	33.22	48.41	4.15	1.36	GSA excluded
1.01	5	67.04	37.53	32.29	30.17	9.21	2.28	GSA sample was measured twice*
1.03	7	10.55	71.60	16.26	12.14	18.24	2.62	
1.05	9	9.79	71.14	14.83	14.03	19.15	2.65	GSA sample was measured twice*
1.07	11	9.66	65.94	17.61	16.46	19.46	2.04	
1.09	13	9.43	72.75	14.35	12.90	17.58	2.74	GSA sample was measured twice*
1.11	15	7.16	52.86	25.31	21.83	13.98	1.50	
1.13	17	8.26	67.19	16.14	16.67	23.05	2.35	GSA, slightly increased obscuration (16.5%)
1.15	19	6.56	41.48	22.29	36.23	8.16	0.98	
1.17	21	3.79	27.58	20.53	51.90	2.26	0.50	
1.19	23	4.15	40.85	18.71	40.43	9.89	1.03	GSA, slightly increased obscuration (17%)
1.21	25	3.59	41.73	21.22	37.05	5.93	1.06	GSA sample was measured twice*
1.23	27	2.29	27.95	18.83	53.23	2.33	0.57	
1.25	29	2.56	29.67	19.38	50.95	2.39	0.58	
1.27	31	2.91	32.56	20.11	47.33	2.57	0.85	GSA sample was measured twice*
1.29	33	2.82	29.91	20.48	49.62	2.55	0.64	
1.31	35	2.12	33.10	20.76	46.15	3.14	0.77	
1.33	37	2.45	41.49	27.88	30.64	8.82	1.11	
1.35	39	2.50	31.30	19.13	49.57	2.71	0.67	
1.37	41	2.85	37.24	26.28	36.48	6.15	0.93	
1.39	43	2.94	36.13	22.42	41.45	6.82	0.89	
1.41	45	2.81	42.78	27.21	30.02	11.35	1.39	
1.43	47	3.00	35.82	25.66	38.51	6.87	0.94	
1.45	49	3.06	39.06	26.30	34.63	9.06	1.06	
1.47	51	2.94	40.86	26.32	32.82	3.08	1.33	GSA sample was measured twice*
1.49	53	2.93	39.43	26.95	33.62	8.39	1.01	LOI sample flipped before weighing
1.51	55	3.12	37.43	23.49	39.07	8.24	0.99	
1.53	57	3.01	31.59	20.72	47.68	3.14	0.82	
1.55	59	2.34	27.44	17.87	54.69	2.63	0.79	GSA sample was measured twice*
1.57	61	1.97	22.71	16.92	60.37	2.06	0.41	
1.59	63	1.40	13.39	12.72	73.90	1.80	0.18	

Depth below water surface (m)	Sample ID	LOI (w %)	Clay to very fine silt (%) <0.8 (10 x mm ⁻³)	Fine silt to coarse silt (%) 0.8-63 (10 x mm ⁻³)	Sand (%) 63-2000 (10 x mm ⁻³)	Particle size distribution average diameter (10 x mm ⁻³)	Skewness (0-3)	Remarks
1.61	65	2.35	32.09	22.79	45.12	2.28	0.79	GSA sample was measured twice*
1.63	67	1.75	21.37	17.26	61.38	2.01	0.35	GSA sample was measured twice*
1.65	69	2.06	30.88	28.45	40.67	2.91	0.64	
1.67	71	1.96	31.71	27.28	41.00	3.45	0.77	
1.69	73	2.16	27.82	27.42	44.77	2.53	0.63	
1.71	75	1.85	22.86	29.94	47.20	2.19	0.55	
1.73	77	2.33	28.29	37.38	34.32	2.58	0.71	
1.75	79	2.67	33.00	36.92	30.08	4.09	0.94	
1.77	81	2.47	31.71	40.78	27.51	2.77	0.66	
1.79	83	1.93	32.93	38.26	28.81	3.66	0.88	
1.81	85	2.17	16.17	26.73	57.10	1.90	0.30	
1.83	87	2.78	33.91	35.67	30.42	3.41	0.76	
1.85	89	2.43	29.49	43.90	26.61	2.53	0.63	
1.87	91	2.91	31.50	37.11	31.39	3.37	0.85	
1.89	93	2.74	27.67	38.07	34.26	2.57	0.68	
1.91	95	1.95	30.02	47.39	22.59	2.50	0.59	
1.93	97	2.57	29.36	38.75	31.89	2.52	0.63	
1.95	99	3.97	47.01	39.63	13.36	7.40	1.16	
1.97	101	2.14	31.00	36.10	32.90	2.67	0.68	
1.99	103	3.24	32.29	39.46	28.25	3.19	0.82	
2.01	105	3.24	29.37	31.90	38.74	2.47	0.60	
2.03	107	2.88	37.29	39.85	22.86	5.55	1.37	
2.05	109	3.70	35.88	39.30	24.82	4.85	1.03	
2.07	111	3.58	39.05	46.53	14.43	5.05	1.08	GSA sample was measured twice*
2.09	113	3.78	51.06	42.58	6.36	6.45	1.85	GSA sample was measured twice*
2.11	115	3.66	22.98	33.92	43.10	2.32	0.63	
2.13	117	3.50	41.82	40.50	17.68	6.92	1.38	
2.15	119	5.10	44.31	44.31	11.38	6.60	2.15	
2.17	121	5.72	43.21	34.39	22.40	8.87	1.59	GSA sample was measured twice*
2.19	123	5.18	47.91	47.90	4.20	5.28	1.63	
2.21	125	4.94	43.48	48.92	7.60	5.24	2.04	
2.23	127	5.01	37.70	29.28	33.03	6.10	1.00	GSA sample was measured twice*
2.25	129	5.19	54.55	41.69	3.76	5.98	2.01	

Depth below water surface (m)	Sample ID	LOI (w %)	Clay to very fine silt (%) <0.8 (10 x mm ⁻³)	Fine silt to coarse silt (%) 0.8-63 (10 x mm ⁻³)	Sand (%) 63-2000 (10 x mm ⁻³)	Particle size distribution average diameter (10 x mm ⁻³)	Skewness (0-3)	Remarks
2.27	131	6.15	51.26	44.68	4.05	5.45	2.01	
2.29	133	6.20	39.35	56.06	4.59	3.93	1.28	
2.31	135	6.65	46.36	47.64	6.00	5.18	2.05	GSA sample was measured twice*
2.33	137	6.63	47.77	45.90	6.33	5.71	1.87	
2.35	139	6.02	44.30	52.74	2.96	4.21	1.48	
2.37	141	6.04	47.79	48.76	3.45	4.55	2.05	
2.39	143	5.96	45.14	51.66	3.20	4.36	1.62	GSA sample was measured twice*
2.41	145	4.57	24.72	42.91	32.37	3.69	1.04	GSA sample was measured twice*
2.43	147	6.31	41.95	51.74	6.31	4.60	1.72	
2.45	149	6.34	38.85	42.45	18.70	6.87	1.55	
2.47	151	6.00	29.81	37.67	32.52	3.67	1.35	GSA sample was measured twice*
2.49	153	6.34	44.76	50.22	5.01	4.76	1.66	
2.51	155	6.66	44.99	52.19	2.83	4.30	1.50	
2.53	157	6.79	46.76	50.76	2.48	4.33	1.63	GSA sample was measured twice*
2.55	159	6.95	43.45	54.46	2.09	3.93	1.31	
2.57	161	7.36	46.98	51.18	1.83	4.33	1.50	
2.59	163	6.93	44.01	53.36	2.63	3.77	1.26	GSA sample measured three times*
2.61	165	6.89	37.54	56.52	5.94	3.72	1.61	
2.63	167	6.55	39.07	57.63	3.30	3.62	1.17	
2.65	169	6.71	40.20	57.15	2.65	3.54	1.47	GSA sample was measured twice*
2.67	171	6.68	56.33	43.42	0.24	3.96	1.76	
2.69	173	6.60	54.47	45.53	0.00	3.70	1.41	GSA sample was measured twice*
2.71	175	6.85	45.42	51.91	2.67	4.12	1.78	GSA sample was measured twice*
2.73	177	6.61	51.49	47.01	1.49	4.34	1.81	GSA sample was measured twice*
2.75	179	6.56	45.81	50.57	3.62	4.29	2.26	
2.77	181	8.59	46.98	47.26	5.76	4.84	2.76	GSA sample was measured three times*
2.79	183	7.55	45.22	43.09	11.70	7.60	2.87	GSA sample was measured twice*
2.81	185	7.11	42.70	52.10	5.20	4.29	2.23	GSA sample was measured twice*
2.83	187	7.84	48.97	45.61	5.43	5.07	2.83	
2.85	189	6.73	40.86	53.54	5.60	4.11	2.24	GSA sample was measured twice*
*Remeasurments was done several times during GSA. A certain technique is required as coarser grains sometimes settle on the bottom of the test tube before sample has been placed in the device. In this case the sample was portioned into the device during several measurments and an average was counted from the total result.								

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