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Early Holocene environmental change in the Kreekrak area (Zeeland, SW-Netherlands): A multi-proxy analysis

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Abstract

Detailed botanical (microfossil and macroremain), zoological and geochemical analyses (major and trace elements including C, Al, S, Ca, Fe, P, As, Zn, U, Ba and Rare Earth Elements) of organic deposits provide new insights into Early Holocene environmental change in the Kreekrak area (southwestern Netherlands). The age assessment of the record is based on high resolution AMS ^{14}C wiggle-match dating (WMD). For the first time an AMS ^{14}C WMD based chronology covering the Late Glacial/Holocene transition and early Preboreal is introduced for a site in The Netherlands.

The Kreekrak botanical record reflects the end of the Younger Dryas to early Boreal and can be well correlated with pollen records from other sites in The Netherlands and Belgium. The palaeo-topography showed that the Kreekrak deposits formed in an abandoned channel of the River Schelde. Around ca. 11,490 cal BP, at the end of the Late Glacial/Holocene transition, infilling of the lake started with predominantly organic deposits in slowly running water. As a result of the warmer climate the area became forested with birch and poplar during the Friesland Phase (ca. 11,490-11,365 cal BP). Biological productivity of the lake and its surroundings increased. Aquatic vegetation developed in the lake, while shrubs of willow, reed swamps and grasslands fringed the shores. Precipitation increased, which caused a rise in the lake water table and an increase in the supply of oxic surface (=river) water into the Kreekrak lake. During this period, the Kreekrak lake was fed by inflowing river water, run-off, precipitation and seepage of Fe-rich groundwater. Around ca. 11,435 cal BP the water became stagnant probably as result of a total cut-off of the river channel. Inflow of river water ceased, while the supply of reduced Fe-rich groundwater became

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dominant. During the Rammelbeek Phase (ca. 11,365–11,250 cal BP), the climate was more continental and the abundance of grasslands and open herbaceous vegetation increased. Biological productivity remained high. In the lake, the supply of Fe-rich groundwater continued, the water level slightly decreased but aquatic vegetation remained present. At the end of the Rammelbeek Phase a sudden reduction in the supply of Fe-rich reduced groundwater caused a lowering of the groundwater level in the area, resulting in the development of a hiatus. Due to this hiatus, the Late Preboreal (11,250–10,710 cal BP) is absent from the record. During the early Boreal (10,710–10,000 cal BP) the landscape became densely forested and accumulation of peat in the former lake resumed due to a slowly rising groundwater level. The Boreal was a relatively stable period with low sedimentation rates.

The combination of palaeobotanical and geochemical analyses in the Kreekrak record shows a close interrelation between landscape development and geochemistry. It appears that the environmental development of this area during the Late Glacial/Holocene transition and Early Holocene was largely influenced (directly or indirectly) by major climatic changes that occurred during this period, which determined local phenomena such as the composition and density of the vegetation, occurrence of seepage and river activity. Further research of this type has the potential to develop the application of major- and trace element geochemistry in palaeoenvironmental reconstructions.

Keywords: Palaeo-environment; Palynology; Geochemistry; Groundwater seepage; Early Holocene; The Netherlands

1. Introduction

Early Holocene climate change has been frequently documented in The Netherlands (e.g., Wijmstra and de Vin, 1971; van Geel et al., 1981; Hoek, 1997a,b). However, most Dutch Early Holocene sites are located in the eastern Netherlands (Fig. 1a, b). The main reason for this is that due to the thick

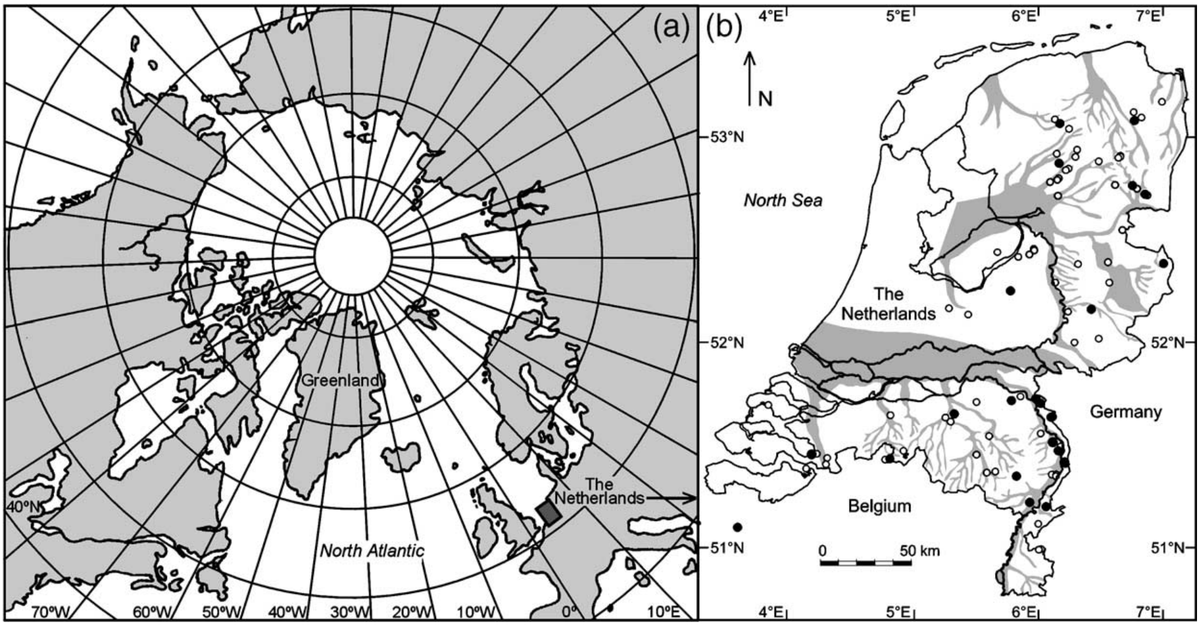


Fig. 1. a. Map of the Northern Hemisphere. b. Map showing the distribution of Preboreal records (open circles) and those with a Rammelbeek Phase (closed circles) in The Netherlands and Belgium. Furthermore, the stream and river valleys during the Preboreal are displayed. Data used are from Zagwijn (1986), van Gijssel and de Gans (1993) and Hoek (1997b). Note that almost all records with a Rammelbeek Phase are concentrated in the river valleys.

Holocene cover (>10 m, Fig. 2b), deposits of Late Glacial/Early Holocene age in the western part of The Netherlands are difficult to access with the standard coring equipment used by palaeoecologists. From the western part there are a few published pollen diagrams that date from the Late Glacial and Early Holocene (Hoek, 1997a). Of these, many are present in the archives of the Netherlands Geological Survey and were obtained in investigations for the construction of tunnels, waterworks and large buildings (Hoek, 1997b). Likewise, the Kreekrak borehole was originally cored by the Netherlands Geological Survey in relation to a sea-level research project. However, initial radiocarbon dating of the upper and lower part of the organic deposits at the base of the Holocene sequence showed that they were too old to be formed in relation to the Holocene sea-level rise. Although not suited for sea-level research, the availability of the Kreekrak record, nevertheless, created a unique opportunity to investigate environmental change in this area during the Early Holocene, about which little is known.

A very common setting in deltas such as in The Netherlands is seepage of reduced, oxygen-poor groundwater. In the Kreekrak area today seepage of groundwater occurs from the east where it exfiltrates at the foot of the Tiglian escarpment (Fig. 2b, c). Seepage was also an important factor in the past. This is evidenced by the existence of small lakes during the Early Holocene in this area. In lakes without inlets and outlets, the lake hydrology is in general controlled by precipitation, groundwater input, evaporation and inflow from adjacent wetlands. During prolonged climate shifts, especially drier and warmer periods, lakes can become disconnected from their catchments and groundwater flowpaths (Magnuson et al., 1997; Schindler, 1997). In seepage lakes, where groundwater is a prominent

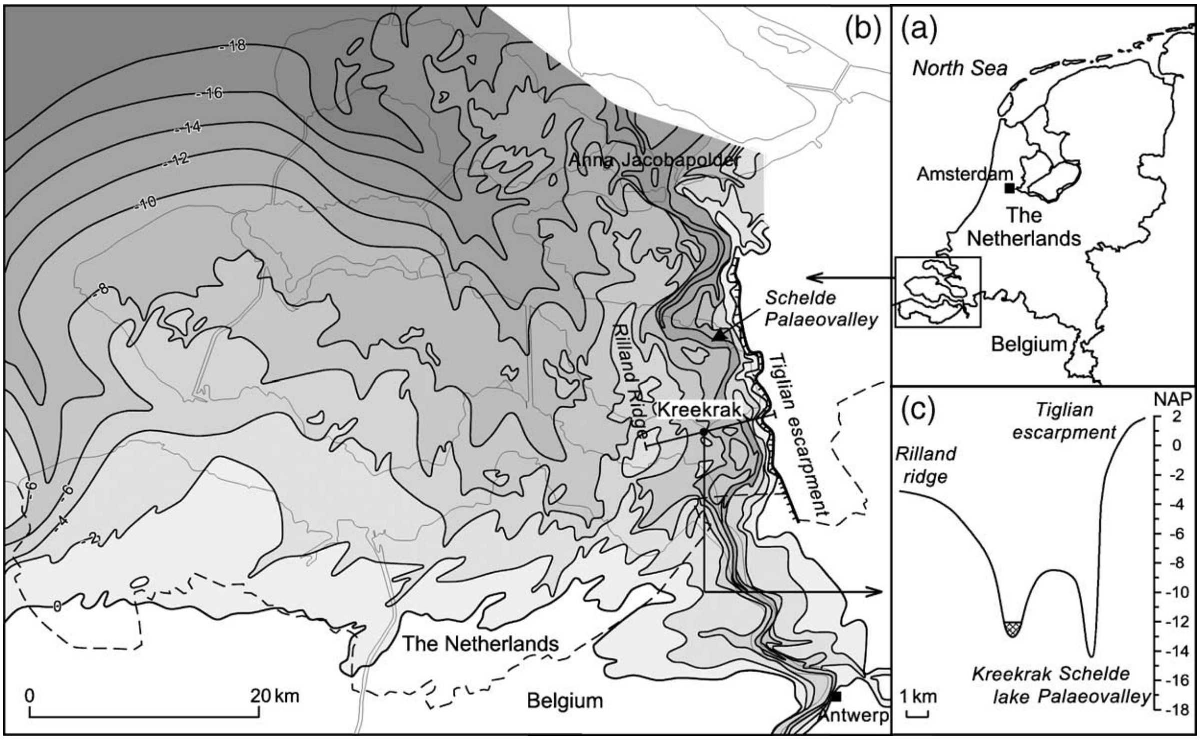


Fig. 2. a. Location of the Kreekrak site in the province of Zeeland, southwestern Netherlands. b. Detail of Zeeland and the adjacent River Schelde estuarine floodplain in Belgium showing a reconstruction of the topography of the Pleistocene substratum prior to the Holocene marine deposition and erosion. The contour interval is 2 m, no contours are given above NAP (after Kiden, 1995). c. Cross-section through the Rilland ridge, the Kreekrak lake, Schelde Palaeovalley to the Tiglian escarpment.

source of chemical inputs, small changes in precipitation and temperature can cause changes in the chemistry of lakes due to changes in the mixing rate between the various water sources. In some of these lakes, warmer and drier climate phases resulted in acidification, accompanied by declines in calcium and magnesium (Webster et al., 1990; Grimm et al., 1997). This close interaction between climate, lake hydrology and hydrochemistry can make seepage lakes to be sensitive indicators of climate change (Winter and Rosenberry, 1998; Fritz, 1996). This may add to the possibility that major climatic changes during the Late Glacial/Holocene transition and Early Holocene are reflected in the Kreekrak sediments. In this respect, also the combination of botanical analyses and geochemical analyses of the Kreekrak record is important. Previous research has demonstrated that organic-rich layers in The Netherlands systematically show elevated concentrations of trace elements (Huisman, 1998; Huisman et al., 1997; Huisman and van Os, 1998). Although the mechanisms behind these enrichments are as yet unknown, it stands to reason that the levels of enrichment are determined by: 1) water source, (2) amount of water supplied, (3) immobilised fraction of elements supplied and (4) sedimentation rate. This makes the study of trace elements in organic-rich sedimentary sections a potentially powerful tool for palaeoenvironmental reconstructions.

The aim of this paper is to reconstruct Early Holocene environmental change in the southwestern Netherlands and to investigate how the development of this area was influenced (directly or indirectly) by major climatic changes that occurred during this period. Also local phenomena, such as the occurrence of groundwater seepage and river activity in this area will be discussed.

2. Study area

The Kreekrak site nowadays is located near the eastern edge of the coastal plain in the province of Zeeland (Fig. 2a, b). The coastal plain is about 50 km wide and is bordered at the eastern side by a pronounced escarpment up to 20 m high, which consists mainly of Early Pleistocene (Tiglian) deposits (Kasse, 1988).

In Zeeland the original topography of the Pleistocene subsoil (Fig. 2b) prior to Holocene marine erosion was reconstructed based on a large number of borehole data, collected by the Geological Survey of The Netherlands (Vos and van Heeringen, 1993). The reconstruction shows the continuation on Dutch territory of the Late Pleistocene valley of the River Schelde, which has previously been identified further upstream in Belgium (Kiden, 1991; Kiden and Verbruggen, 1987). The palaeovalley of the River Schelde is cut in the gently undulating sandy substratum; down to depths of − 12 m NAP (Dutch Ordnance Datum) at the Belgian–Dutch border and − 16 m NAP at Anna Jacobapolder (Kiden, 1995; Vos and van Heeringen, 1993). In The Netherlands, the palaeovalley lies at the foot of the Tiglian escarpment, which is mainly made up of sand with discontinuous but strongly compacted and impervious clay layers of half a meter to a few m thick. The palaeovalley is bordered on its western side by a low north–south trending ridge in the Pleistocene topography, the Rilland ridge (Fig. 2b, c).

Near the end of the Weichselian Pleniglacial the River Schelde, occupying the palaeovalley, had a braided pattern (Kiden, 1991). As a result of changes in the climatological and hydrological regime, a transition to a large-scale meandering river pattern took place at the beginning of the Late Glacial. This meandering regime probably persisted until the start of the Holocene, when a general decrease of river activity heralded a period of relative stability and slow aggradation in the river channels. Seepage of carbonate-rich groundwater at the foot of the Tiglian escarpment locally led to the formation of shallow marl lakes in small depressions beyond the river floodplain. During the first half of the Holocene the rapid sea-level rise raised the regional groundwater level and initiated widespread basal peat growth on the Pleistocene surface. However, the peat was quickly drowned and covered by clayey lagoonal deposits. Subsequently, a typical Holocene coastal sedimentary sequence was formed, consisting of clastic tidal deposits with one or more intercalated peat beds, i.e., Holland peat (compare Table 1). In many places, large tidal channels have eroded the basal peat and the underlying deposits, including the sediments in the Schelde palaeovalley. This Holocene tidal erosion, combined with the fact that in the Kreekrak area the Late Glacial

Table 1
Lithological description of the Kreekrak core (NITG ref.-no.: 49D0324)

Depth (m)	Lithology	Lithostratigraphy	Depositional environment
0.00–1.00	Medium fine sand (160 μm), greyish black	Naaldwijk formation,	Tidal (estuarine)
1.00–3.00	Very fine sand (140 μm), grey, well sorted, some shells and shell fragments	Walcheren member	
3.00–4.200	Very fine sand (120 μm), very silty, greyish brown, well sorted, some plant fragments		
4.20–5.6	Sandy clay, dark grey, stiff, some root fragments		
5.60–6.35	*Phragmites* peat, dark brown	Nieuwkoop formation, Holland peat	Terrestrial
6.35–8.00	Sandy clay, dark grey, slightly organic, stiff, some *Phragmites* roots	Naaldwijk formation,	Tidal (estuarine)
8.00–8.56	Very sandy clay, dark grey, stiff, lower part organic, some burrowings and plant and peat fragments	Wormer member	
8.56–9.48	Very fine sand (120 μm), clayey, brownish grey, well sorted		
9.48–9.50	Peat, brown		
9.50–10.46	Very fine sand (120 μm), dark grey, well sorted, slightly organic, some plant fragments		
10.46–13.45	Medium fine sand (160 μm), greyish brown, well sorted, with thin organic laminae and some shell fragments in upper part, many plant fragments and oblique bedding in lower part		
13.45–13.73	Medium fine sand (170 μm), greyish brown, strongly organic, some shells and shell fragments, oblique bedding		
13.73–13.78	Very amorphous peat, dark brown	Nieuwkoop formation,	Terrestrial
13.78–13.80	Disturbed during coring (=small hiatus)	Basal peat	↑ ↑
13.80–14.08	Amorphous peat, dark brown, some plant fragments	Nieuwkoop formation,	↑
14.08–14.16	Gyttja, light yellowish brown, laminated, some plant, wood and shell fragments	Basal peat	↑
14.16–14.22	Dark greyish brown gyttja, some plant, wood and shell fragments		↑
14.22–14.27	Very sandy gyttja, light yellowish brown, some plant and shell fragments (*Bithynia tentaculata*)		Limnic
14.27–15.16	Medium fine sand (170 μm), slightly silty, greyish brown, well sorted, some shell fragments	Boxtel formation	Aeolian and fluvial
15.16–15.21	Slightly sandy silt, greyish green, stiff, slightly organic, many plant fragments, weak bedding		
15.21–16.10	Medium fine sand (170 μm), greenish grey, well sorted		

Location National grid (RD) in m: *X*: 75110, *Y*: 383240 and Geographic coordinates: 51°26′21″.72 N, 4°14′25″.14 E. Surface level was at +1.34 m NAP (Dutch Ordnance Datum, approx. mean sea level). Lithostratigraphic units refer to Weerts et al. (2000) and de Mulder et al. (2003). The present study concentrates on the shaded area, or more precisely between 13.80 and 14.30 m.

and Early Holocene deposits are buried beneath approximately 14 m of younger sediments, makes that only the main outlines of the Late Glacial/Early Holocene fluvial landscape in the Schelde palaeovalley are known.

The Kreekrak borehole was drilled a few kilometres west of the River Schelde palaeovalley between the Rilland ridge and the Tiglian escarpment (Table 1; Fig. 2c). Cross-sections through the area (Fig. 2c) show that the Kreekrak sediments were located at a comparatively deep level (ca. −13.00 m NAP) relative to the depth of the palaeovalley itself. Therefore, it is likely that the Kreekrak deposit was formed in a residual channel of the River Schelde, which was probably active during or at the end of the Late Glacial.

3. Material and methods

3.1. Sampling

The core segments were taken with a sampler with plastic liners in an encased borehole and drilled with a Stihl mobile drilling rig, equipped with a mechanised bailer drilling unit (compare Oele et al., 1983). The segments were 1 m in length and 10 cm in diameter. Due to the coring method there is no overlap in depth range between successive segments and it is possible that a few centimetres of sediment are disturbed or missing at the transition of two segments.

The core segments were cut in two halves along their length. The sediments were photographed and a lithological description was made with special emphasis on the organic deposits at the base of the Holocene tidal sequence (Table 1). From the organic sediments and from the directly under- and overlying deposits, 1 cm thick horizontal slices were cut. These were sealed in plastic bags and stored at 4 °C waiting further subsampling for palaeobotanical and geochemical analyses.

3.2. Botanical analysis

From the 1 cm thick slices pollen samples were taken using a small corer of defined volume (~280 mm^3). The samples were prepared for pollen analysis following Fægri and Iversen (1989) in addition with heavy liquid separation to remove minerogenic components. Sieving was done over a 215 μm sieve. To estimate pollen concentrations *Lycopodium* spores were used (Stockmarr, 1971). The pollen residues were mounted in glycerine. A Leica light microscope with a magnification of 400× and 1000× was used for microfossil analysis. Preservation of pollen and spores was excellent. Pollen types were identified using modern reference material for comparison and identification keys of Moore et al. (1991) and the NEPF (Punt, 1976; Punt and Clarke, 1980, 1981, 1984; Punt and Blackmore, 1991; Punt et al., 1988, 1995, 2003) for classification and verification. Nomenclature follows these keys. Other microfossils such as algae, fungi etc. were identified using Komárek and Jankovská (2001), van Geel (1978), and van Geel et al. (1981, 1984, 1989).

The macroremain samples were taken from the same sediment slices as the pollen samples and varied in general between 15 and 25 ml sediment. Core slices were boiled in 5% KOH for ca. 5 min and then washed over a 75–80 μm sieve. Macrofossils were picked out manually from the recovered fraction held on the sieve and stored at a temperature of 4 °C for future check-ups. A Leica dissection microscope with a magnification of 8–100× was used for macroremain analysis. Special slides were prepared for the identification of *Juncus* seeds and wood under high magnification. Fruits of *Betula* recorded in the samples were referred to as *Betula* sect. *Albae* and include both *B. pubescens* and *B. pendula*. Plant macrofossil identifications were made by comparison with modern reference material and identification keys of Bertsch (1941), Körber-Grohne (1964), Berggren (1969, 1981), Anderberg (1994), Beijerinck (1976), Nilsson and Hjelmqvist (1967), and Schweingruber (1978). Nomenclature follows van der Meijden (1996).

Combined microfossil and macroremain diagrams were constructed using the TILIA, TILIA.GRAPH and TG.VIEW computer programs (Grimm, 1992). Combined AP (arboreal pollen) and NAP (non-arboreal pollen) totals were employed for percentage calculations. The average number of terrestrial pollen and spores included in the pollen sum is 820. Pollen and spores of the local aquatic- or mire vegetation (incl. Cyperaceae) and redeposited palynomorphs of thermophilous taxa were excluded (compare Janssen, 1973; Bos, 1998). Inwash of palynomorphs of thermophilous taxa occurred in the more minerogenic sediments in the lower part of the record. The combined microfossil and macroremain diagrams were arranged stratigraphically and divided into ecological groups. Zonation of the diagrams is based on changes in the AP/NAP ratio and trends in the percentages of dominant arboreal taxa (*Betula*, *Pinus*, *Corylus*) that dominate the Late Glacial–Early Holocene pollen records of NW Europe.

3.3. Geochemical analysis

Subsamples for geochemical analyses were taken from the same levels as the pollen samples, but also at more shallow depths (between 13.80 and 14.06 m depth). No samples were available for geochemical analyses from depths between 14.17 and 14.20 m and from 13.82 to 13.85 m. The samples were freeze-dried and ground using a Herzog tungsten-carbide swing-mill. Small subsamples were used for measuring total sulphur (S), total carbon (C_{tot}) and organic carbon (C_{org}; after HCl-treatment), by combustion and IRdetection using a LEKO CS element analyser. The rest of the subsample was dissolved in a mixture of concentrated $HClO_4$, HNO_3 and HF, and analysed by ICP-MS (Agilent 7500) for in total 55 major- and trace elements. For some of the elements (Fe, Zn, Ba) additional calculations were made (see Huisman et al., 1997; Huisman, 1998) to estimate the amount of the elements that were not incorporated in clay minerals or other phyllosilicates. They represent the elements that immobilised in the sediment after transport by surface- or groundwater, and are therefore considered to reflect aspects of the hydro-environmental conditions. Only a relevant selection of elements will by presented in this paper.

As part of the ICP-MS analyses, the concentrations of the so-called Rare Earth Elements (REE) were measured. The REE are the elements with atomic number 58 to 71 (Lanthanum; La to Lutetium; Lu) and form a group of elements that behave very similar. However, in certain environments some elements are fractionated. In order to study these fractionations, plots are made of normalised REE-patterns. For surface water and groundwater studies, normalisation is usually done relative to a clay standard (North American Shale Composite, NASC; Taylor and McLennan, 1985). The most important fractionations are (1) Ce due to immobilisation by oxidation (2) the light REE (LREE; La to Sm) due to preferent immobilisation by carbonate complexation and (3) relative increase in Eu due to feldspar weathering (cf. Huisman et al., 1999; Brookins, 1989; Shiller, 2002).

The loss-on-ignition (LOI) samples were ashed within crucibles to remove any organic matter. The latter were first heated to 550 °C to remove organic contamination, cooled in a dessicator and weighed. Then the samples were dried overnight in the crucibles at 105 °C, cooled in a dessicator and weighed. The sample plus crucible were then put back into the furnace at 550 °C for 4 h for the ashing of organic matter. Once the ashing was complete the crucibles were cooled in a dessicator and re-weighed to provide a measure of LOI.

3.4. Radiocarbon dating

Eight samples of macroremains (Table 2) were selected for ^{14}C dating in order to provide an accurate chronology for the Kreekrak record. Organic material reflecting atmospheric ^{14}C concentrations, e.g., seeds and fruits from terrestrial plants, was preferred in order to reduce the likelihood of contamination by older or younger carbon (Marcenko et al., 1989; Törnqvist et al., 1992). Two samples were dated at the Van de Graaff AMS Laboratory in Utrecht and six at the AMS facility (CIO) in Groningen. Two initial samples dated in Utrecht also contained aquatic macroremains; the other six consisted of *Betula* remains only (Table 2).

Table 2
Radiocarbon dates (AMS) from the Kreekrak site

Depth (cm)	Lab. nr.	^{14}C age BP	WMD age cal BP	Dated material	$\delta^{13}C$ values
13.82–13.85	UtC-9217	9080 ± 60	10,230	*Cornus mas*, 2 nut fragments; *Carex rostrata*, 1 nutlet; *Carex* sp., 5 nutlets; *Urtica dioica*, 8 seeds; *Menyanthes trifoliata*, 2 seeds; *Oenanthe aquatica*, 1 seed; unidentified leaf remains	−28.1
14.04–14.05	GrA-23040	9450 ± 60	10,650	*Betula*, 37 fruits, 2 bud scales, 3 male catkin scales	–
14.07–14.08	GrA-23039	9490 ± 50	10,710	*Betula*, 57 fruits, 15 female catkin scales, 14 male catkin scales	−28.53
14.08–14.09	GrA-23030	9950 ± 50	11,259	*Betula*, 50 female catkin scales	−28.01
14.15–14.16	GrA-23031	10,030 ± 50	11,346	*Betula*, 50 female catkin scales	−28.53
14.19–14.20	UtC-9125	9930 ± 50	11,396	*Betula*, 512 fruits, 105 female catkin scales, 1 bud, 3 bud scales; *Atriplex*, 1 seed; *Lycopus europaeus*, 1 seed; *Nymphaea alba*, 13 seeds; *Ceratophyllum demersum*, 4 seeds	−27.7
14.22–14.23	GrA-23032	10,060 ± 50	11,434	*Betula*, 40 female catkin scales	−28.54
14.27–14.28	GrA-23029	10,140 ± 60	11,496	*Betula*, 2 small twigs, 19 fruits, 5 female catkin scales, 2 male catkin scales, 1 bud scale	–

For calibration, the wiggle-match dating method and INTCAL98 calibration curve (Stuiver et al., 1998) is used. Laboratory Nr. Utc: Van de Graaff Laboratory, Utrecht, The Netherlands, GrA: Radiocarbon Laboratory of the Centre for Isotope Research in Groningen, The Netherlands.

Radiocarbon dates were transferred into calendar years by using the wiggle-match dating (WMD) method (e.g., van Geel and Mook, 1989; Kilian et al., 2000; Speranza et al., 2000; Mauquoy et al., 2002; Blaauw et al., 2003, 2004). In this method the wiggles in the ^{14}C calibration curve are used to obtain a more accurate chronology. High-resolution series of uncalibrated AMS radiocarbon dates can be matched to the ^{14}C INTCAL98 calibration curve (Stuiver et al., 1998) by using the stratigraphical position of the ^{14}C dated samples. The WMD method is especially used for the steep parts of the calibration curve, which correspond to periods of fast increasing atmospheric ^{14}C concentrations. Calendar ages are reported in cal BP, i.e., calibrated or calendar age relative to 1950.

4. Results

4.1. Microfossil and macroremain diagram

In the lowest spectra of the Kreekrak record (Figs. 3 and 4), between 14.30 and 14.27 m, relatively high pollen values of *Betula* (20–40%), and NAP (25–35%, especially Poaceae, *Artemisia*, Asteraceae, *Helianthemum* and *Saxifraga*) and lower values of *Pinus* (7.5–25%) are recorded. *Juniperus* pollen was recorded in values between 7.5–10%. *Salix* pollen was recorded in values between 7.5–15% and macroremains were present. Pollen of *Empetrum nigrum*, *Calluna vulgaris* and *Betula nana* type was present in low percentages. Furthermore, macroremains of *Betula* and seeds of *Minuartia rubella* and *Campanula* cf. *rotundifolia* were recorded. The total microfossil concentration is relatively low in the sandy deposits (Fig. 4). High numbers of various reworked palynomorphs (Fig. 3) and fruits and a cone of *Alnus glutinosa*, *Glomus* chlamydospores and sclerotia of *Cenococcum geophilum* are recorded.

Between 14.27 and 14.17 m the pollen concentration and percentages of *Betula* (to ca. 70%) and numbers of macroremains increase. NAP percentages (especially *Artemisia* and Poaceae) decrease to 10% and taxa such as *Helianthemum*, *Sedum*, *Saxifraga*, and *Polemonium* disappear, while others such as *Heracleum sphondylium*, *Chaerophyllum hirsutum/temulum*, *Daucus carota*, *Sanguisorba officinalis* and *Pulsatilla* appear. *Pinus* pollen is recorded in low percentages (<10%). In this part of the diagram also *Populus* pollen and macroremains were recorded in combination with ascospores of *Amphisphaerella amphisphaerioides* (T.310). *Salix* pollen is recorded in relatively high values (ca. 15–35%) in combination with large numbers of macroremains. The pollen values of *Juniperus*, *Betula nana* type decrease, while Ericales disappear. Some *Alnus incana* fruits were recorded (Plate I). However, pollen of *Alnus* was only recorded occasionally. Furthermore, pollen of *Epilobium angustifolium* type, macroscopic charcoal, charred macroremains of *Betula* and ascospores of *Gelasinospora* (T.1, van Geel, 1978) and *Bombardioidea* type (T.575, Bos et al., in press) were recorded. Between 14.27 and 14.17 m the microfossil concentration increases first slowly, but later very strongly. The change in pollen concentration is coincident with the change from light yellow-brown sandy gyttja to dark grey gyttja. The amount of reworked palynomorphs, *Glomus* chlamydospores and *Cenococcum geophilum* sclerotia also strongly decreases during this interval.

Between 14.17 and 14.08 m the diagram shows a distinct peak in the pollen values and concentration of Poaceae and *Artemisia*. Furthermore, *Rumex*, *Plantago*, Apiaceae, *Saxifraga* and *Campanula* contribute to the NAP. Lower pollen percentages are recorded of *Betula* (ca. 55%). The pollen concentration and number of *Betula* macrofossils remain high, but slightly decrease. Relatively high pollen percentages are recorded of *Populus* together with high amounts of macroremains and ascospores of *Amphisphaerella amphisphaerioides*. The pollen values of *Juniperus*, *Betula nana* type decrease, while Ericales disappear. Also some *Alnus incana* fruits were recorded. Furthermore, macroscopic charcoal, ascospores of *Gelasinospora* (T.1 and T.2) and charred remains of *Betula* are recorded. Just below 14.17 m the deposit changes from dark grey into light yellow-brown gyttja. The total microfossil concentration in this interval is high. At 14.08 m there is a very abrupt change from gyttja to peat, which suggests the presence of a hiatus.

From 14.08 m on the *Pinus* pollen values, concentrations and number of macroremains show high values. *Corylus*, *Quercus* and *Ulmus* are present with continuous pollen curves. The percentages of *Corylus* increase to around 15%. The values of *Betula*, *Populus*, and *Salix* pollen decrease, although

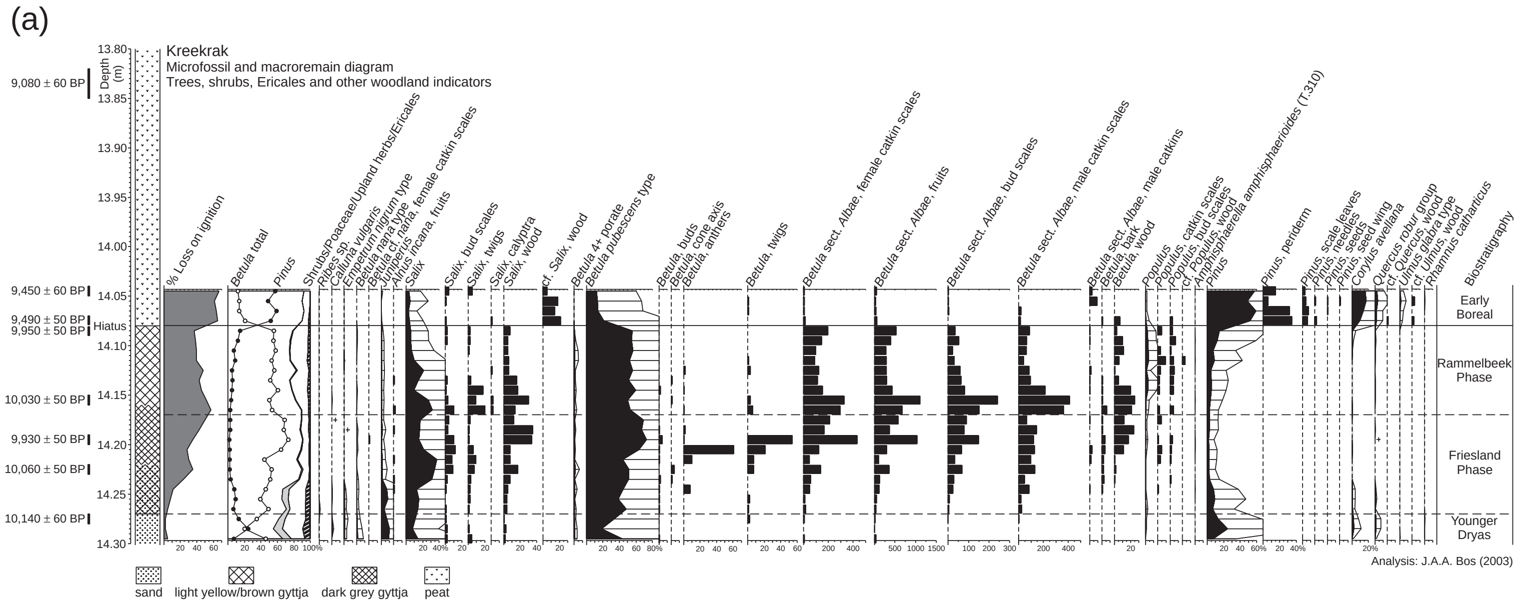


Fig. 3. Combined microfossil and macroremain diagram of the Kreekrak record. Microfossils (e.g., pollen, spores) are displayed by curves (%), macroremains by histograms giving total amounts, presence (+) or abundance (+=present, ++=abundant and +++=very abundant). Exaggeration of pollen curves 5×. In the different ecological groups (e.g., trees, shrubs, reed swamps etc.) also fungi are included that are indicative for this group or which have host species included in this specific ecological group. Depth in metres below surface (surface at +1.34 m a.s.l.). The curve of total reworked palynomorphs includes *Alnus*, *Abies*, *Picea*, *Pinus haploxylon*, *Carpinus*, *Engelhardtia*, *Ilex*, *Nyssa*, *Carya cordiformis* type, *Juglans*, *Tilia*, pre-Quaternary spores and Dinoflagellate cysts.

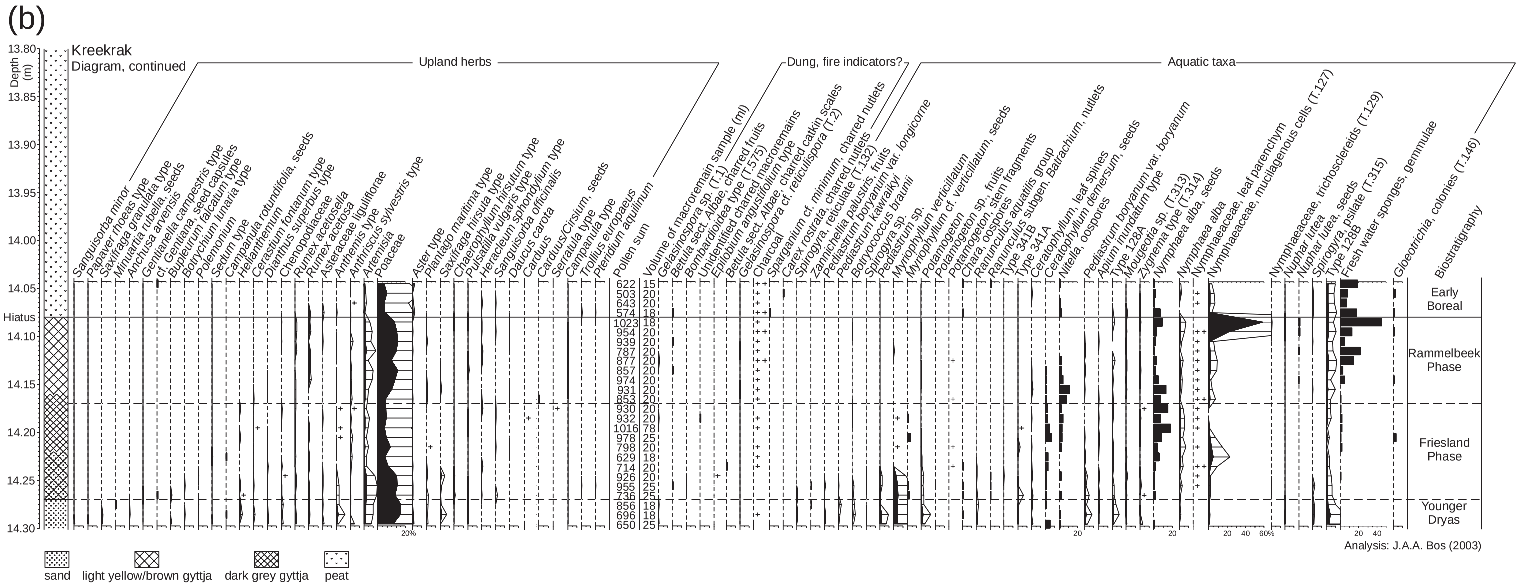
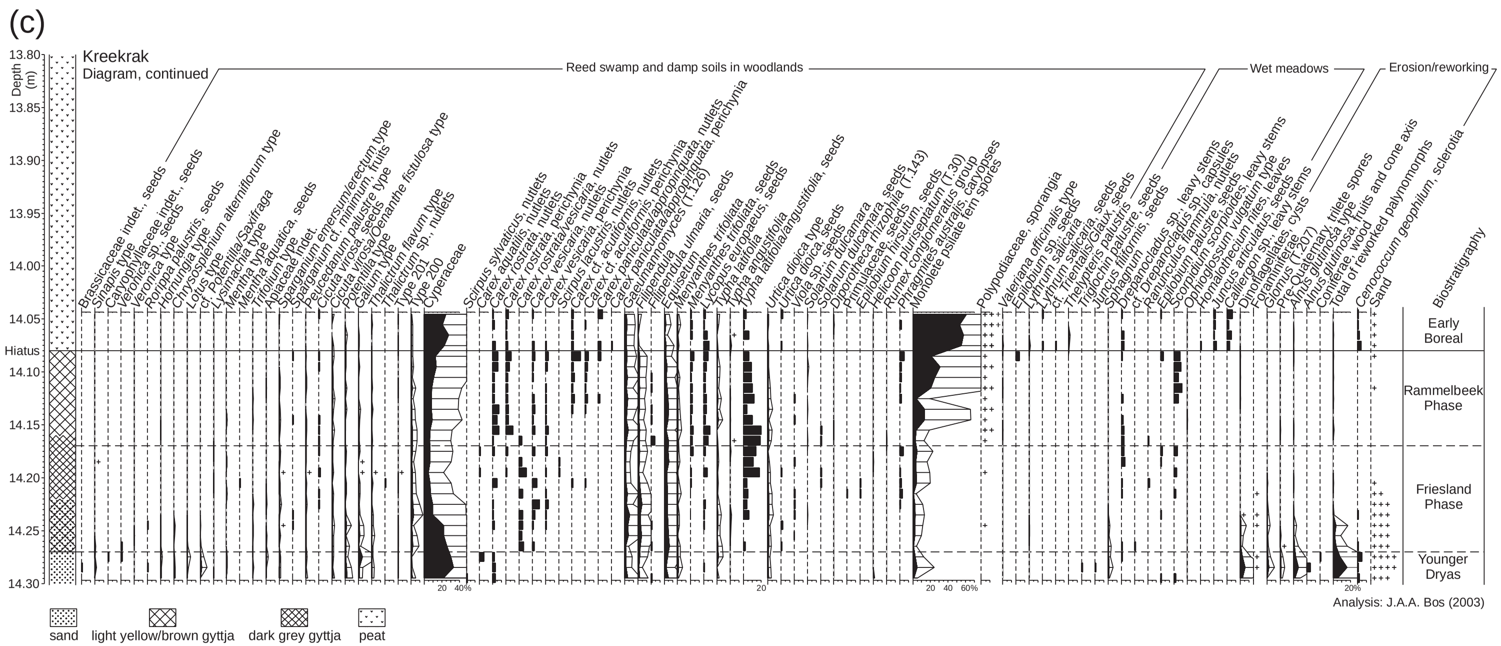


Fig. 3 (*continued*).



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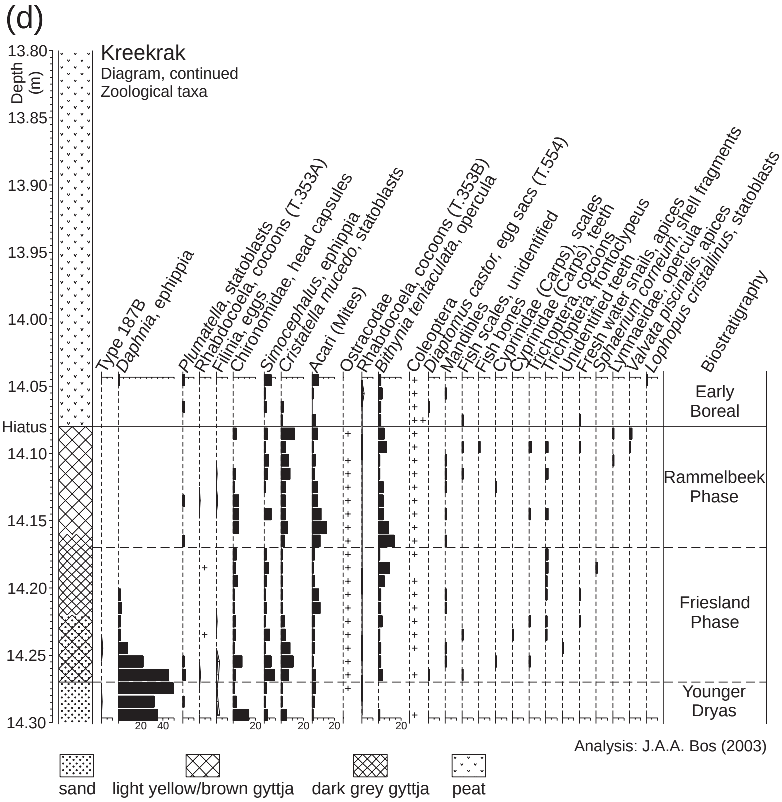

Fig. 3 (*continued*).

low numbers of macroremains of these taxa are still recorded. NAP values decrease to a minimum of ca. 10%. Furthermore, macroscopic charcoal and charred macroremains of *Betula*, *Sparganium* and *Carex rostrata* are recorded. The total microfossil concentration within this peaty interval is high.

Between 14.04 and 13.80 m the pollen spectra (not counted in detail and therefore not displayed in Fig. 3) show relatively high percentages of *Pinus, Corylus, Quercus* and *Ulmus* and low percentages of NAP. Pollen of *Tilia* is not recorded in this interval. Above 13.78 m, the pollen association contained *Alnus* pollen, while anthropogenic indicators were absent.

4.2. Geochemistry

Based on the geochemical analyses, the record can be subdivided into two parts: Between 14.30 and 14.08 m, a more or less gradual change occurs in many geochemical components in comparison to the upper part of the record (Fig. 6a, b). The Al content shows high, fluctuating values between 14.30 and 14.20 m. Above 14.17 m low values are recorded. The curves of organic carbon (C_{org}) and LOI show considerable changes (Figs. 3, 6a). At 14.27 m, at the transition from sand to sandy, light yellow-brown gyttja, both curves show a slight increase. Between 14.27 and 14.17 m both values increase more or less continuously, but again show a slight decrease between 14.17 and 14.08 m. This decrease is coincident with a change to a lighter coloured deposit. The sulfur (S_{tot}) curve remains constant, except for two minor peaks. The contents of reactive Fe (Fe_{reac}) and P show a distinct gradual increase and reach a maximum around 14.135 m. However, the levels drop again considerably at a depth of 14.085 m. Ca shows two distinct peaks, one at 14.225 and one at 14.085 m. From the trace metals, the distribution of excess barium (Ba*) shows a close similarity to that of Fe

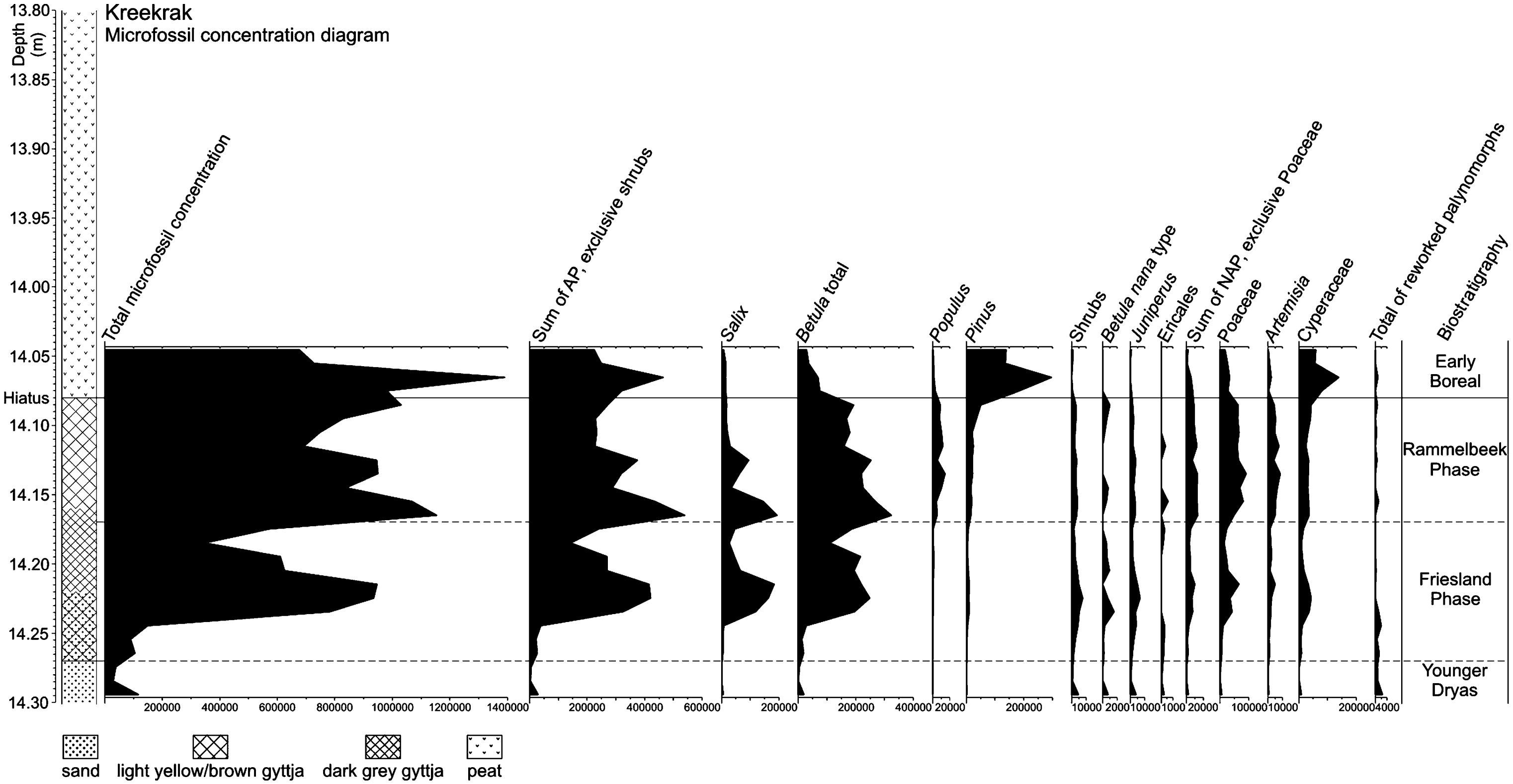

Fig. 4. Microfossil concentration diagram of the Kreekrak record, showing a selection of taxa. Depth in metres below surface (surface at +1.34 m a.s.l.).

and P. Zn* also seems to show a similar but less distinct pattern. Arsenic (As) starts with a similar increase as Fe and P, but reaches a maximum at 14.145 m, and then decreases. U starts at relatively high levels, which decrease to a low constant value around 14.165 m. The decrease seems to be more stepwise than gradual, but the resolution of the data is too low to draw further conclusions.

A major change in the geochemical composition occurs at 14.08 m. In the peat above 14.08 m, the contents of all elements change (Figs. 3, 5, 6a). The overlying interval (14.08–13.80 m) shows different distribution patterns and element associations than below. This also suggests the presence of a hiatus at 14.08 m. The Al content first slightly increases, and then it remains more or less constant, but finally shows a slight decrease to 13.85 m. At 14.08 m the LOI and C_{org} first increase considerably, but then remain more or less constant. S shows constant low values. Fe_{reac}, P and Ca show a sharp decrease followed by low contents, similar to Ba*. As shows no change at 14.08 m, and decreases slightly with decreasing depth. Zn* and U first show a marked increase at 14.08 m, U then shows a slight decrease, while the concentration of Zn gradually increases.

The Rare Earth Element (REE)-patterns (Fig. 6b) also show a depth-related variation. In the deepest layers, the NASC-normalised patterns are more or less horizontal. Between 14.09 and 14.17 m — the interval with the high contents of Fe_{reac}, P and Ba* — the contents are lower. Moreover, the pattern changes and now shows lower values for the Light REE (LREE) relative to the Heavy REE (HREE). After the transition at 14.08 m, the pattern reverts to more shale-like (horizontal) up to 13.80 m depth.

4.3. ^{14}C wiggle-match dating

All eight samples that were radiocarbon dated provide ^{14}C ages compatible with the expected ages using biostratigraphical correlation with the regional pollen zonation scheme and chronostratigraphy (in radiocarbon years BP) for The Netherlands and Belgium (compare Hoek, 1997a). In order to transfer the radiocarbon dates to calendar years by using the WMD method, the record was divided into two sections based on the position of the hiatus at 14.08 m (Blaauw et al., 2004). Subsets of ^{14}C dates from these two sections were then wiggle-matched separately (Fig. 5). For the lower part of the record, the five radiocarbon dates of subset 1 show a good match on the 10,000 ^{14}C BP plateau. For this section an accumulation rate of 15.6 yr/cm was assumed, which is rather high but partly due to the accumulation of sand in the basal part of the record. In the upper part, the higher total microfossil concentrations (Fig. 4) indicate that the accumulation rate was lower. For this section an accumulation rate of 25 yr/cm was assumed. Despite the low number of radiocarbon dates available in subset 2, the three radiocarbon dates could be matched well with the calibration curve, especially because the uppermost date could be pinpointed on a steep part of the calibration curve. WMD shows that the hiatus at 14.08 m covers ca. 530 calendar years (Fig. 5).

5. Discussion

5.1. Biostratigraphy

Based on changes in the forest composition and herbaceous vegetation, the Kreekrak microfossil and macroremain diagram can be well correlated with pollen records from other sites in The Netherlands (e.g., van Geel et al., 1981; Hoek, 1997a) and Belgium (Verbruggen et al., 1996). The diagram can be subdivided into four zones.

Based on the co-dominance of birch and pine and relatively high NAP and Poaceae pollen values together with the presence of shrubs (*Juniperus*, *Betula nana* and *Salix*), Ericales (*Empetrum nigrum*, *Calluna vulgaris*) and other taxa indicative for open environments (e.g., *Artemisia*, *Helianthemum*, *Saxifraga*, Chenopodiaceae, *Plantago* and *Rumex*), the lower part of the record between 14.30 and 14.27 m can be correlated with the later part of the Younger Dryas (compare van Geel et al., 1981; Hoek, 1997a).

Between 14.27 and 14.17 the increasing values of *Betula*, the decreasing values of NAP (including

Plate I. *Alnus incana* (grey alder) fruits. Samples 14.24–14.25 m (1), 14.18–14.19 m (2 and 5) with a detail of the characteristic inflated cells on the fruit wing (5), and 14.21–14.22 m showing a detail of the top of the fruit with the characteristic hairs surrounding the style (3–4). Size bar is 0.2 mm.

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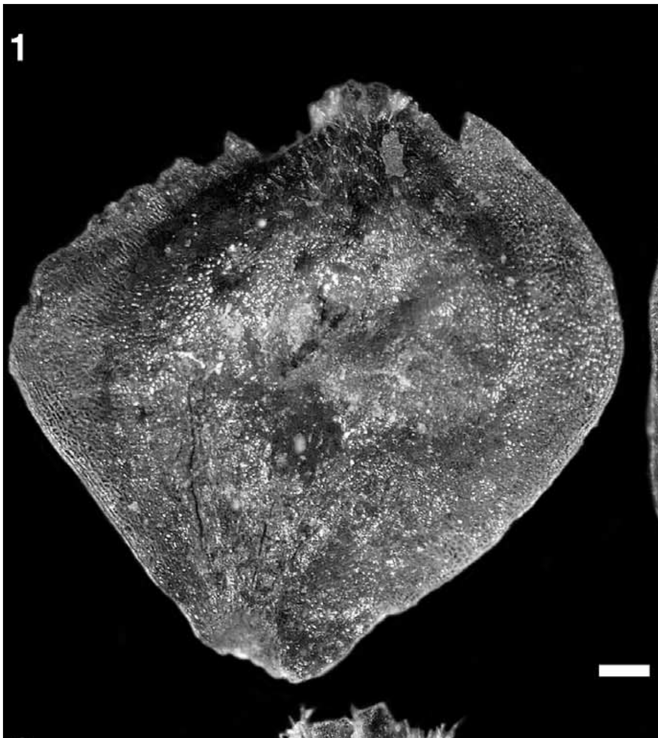

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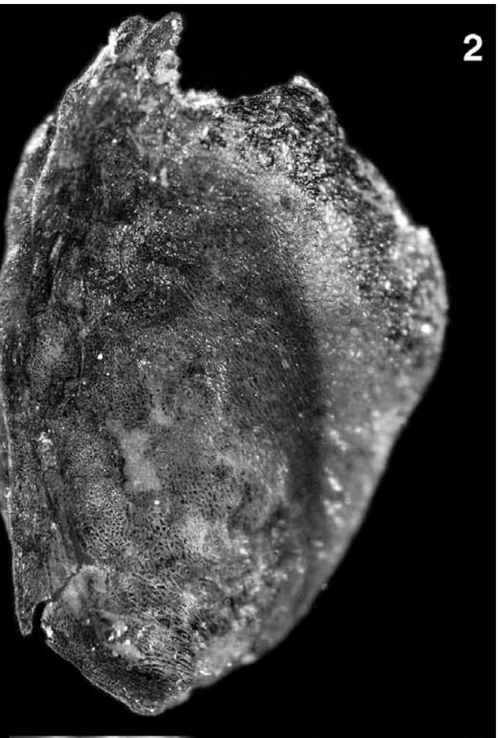

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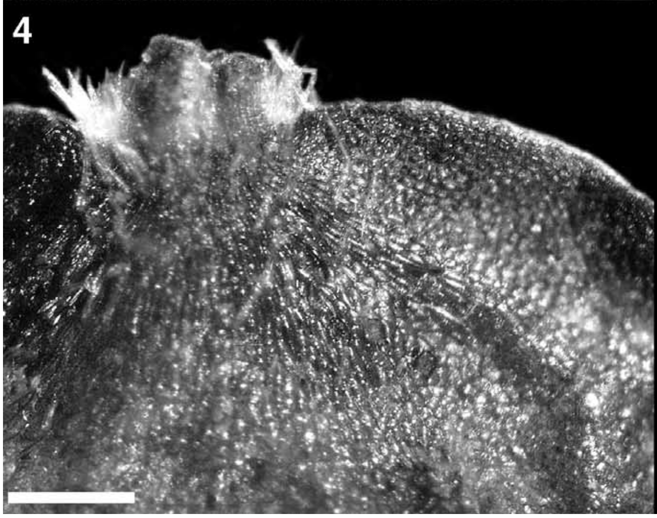

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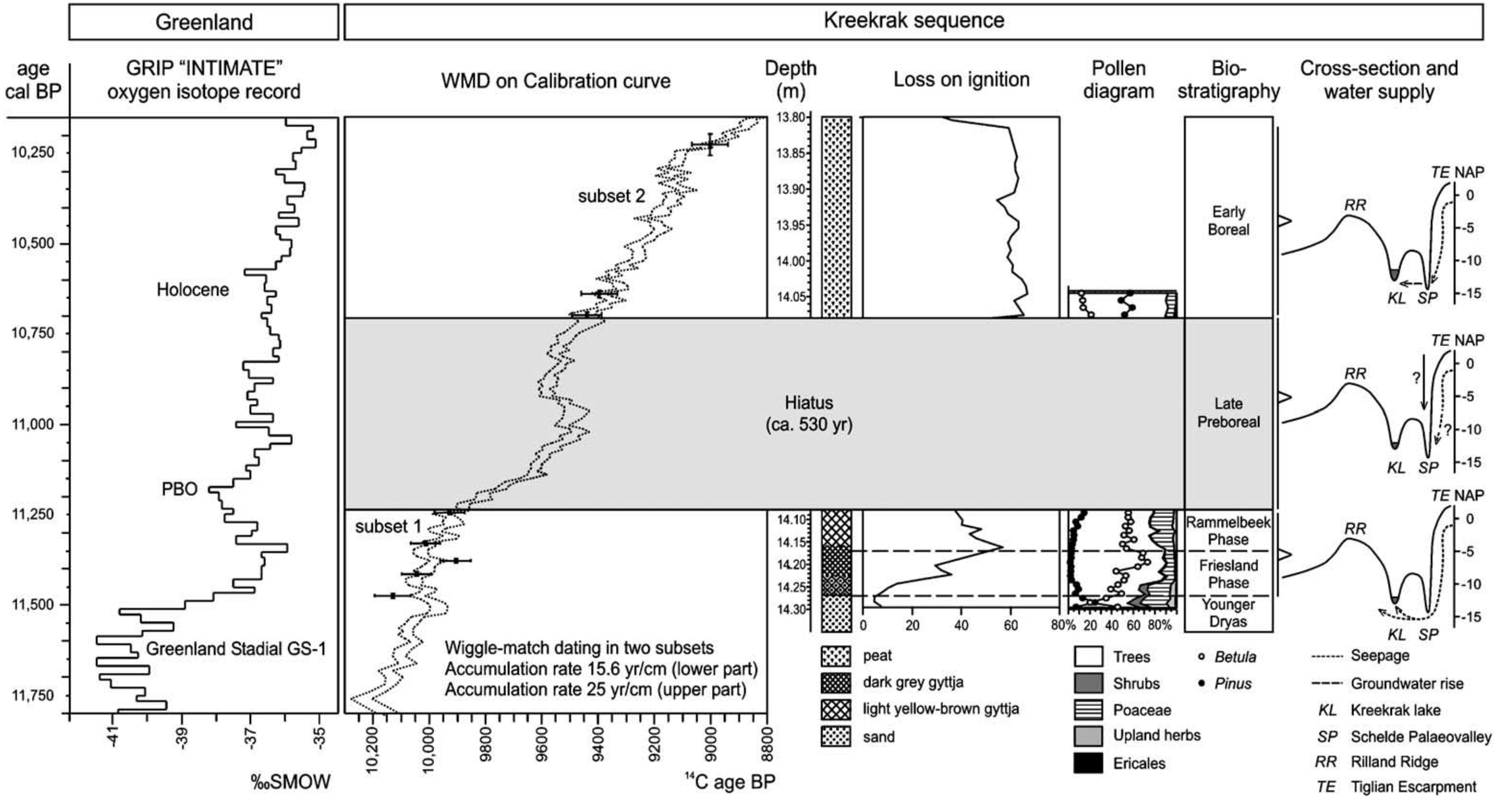

Fig. 5. Series of ^{14}C AMS dates from the Kreekrak record are wiggle-matched to the INTCAL98 ^{14}C calibration curve (Stuiver et al., 1998). Furthermore, the lithology of the record is displayed with depth in metres below surface (surface at +1.34 m a.s.l.). The summary pollen diagram of the Kreekrak record is tentatively compared with the GRIP Greenland ice-core record. At the right a cross-section from the Rilland ridge through the Tiglian escarpment is given with the main directions of water supply (seepage and groundwater rise) for the Early Preboreal (Friesland and Rammelbeek Phase), Late Preboreal and Early Boreal.

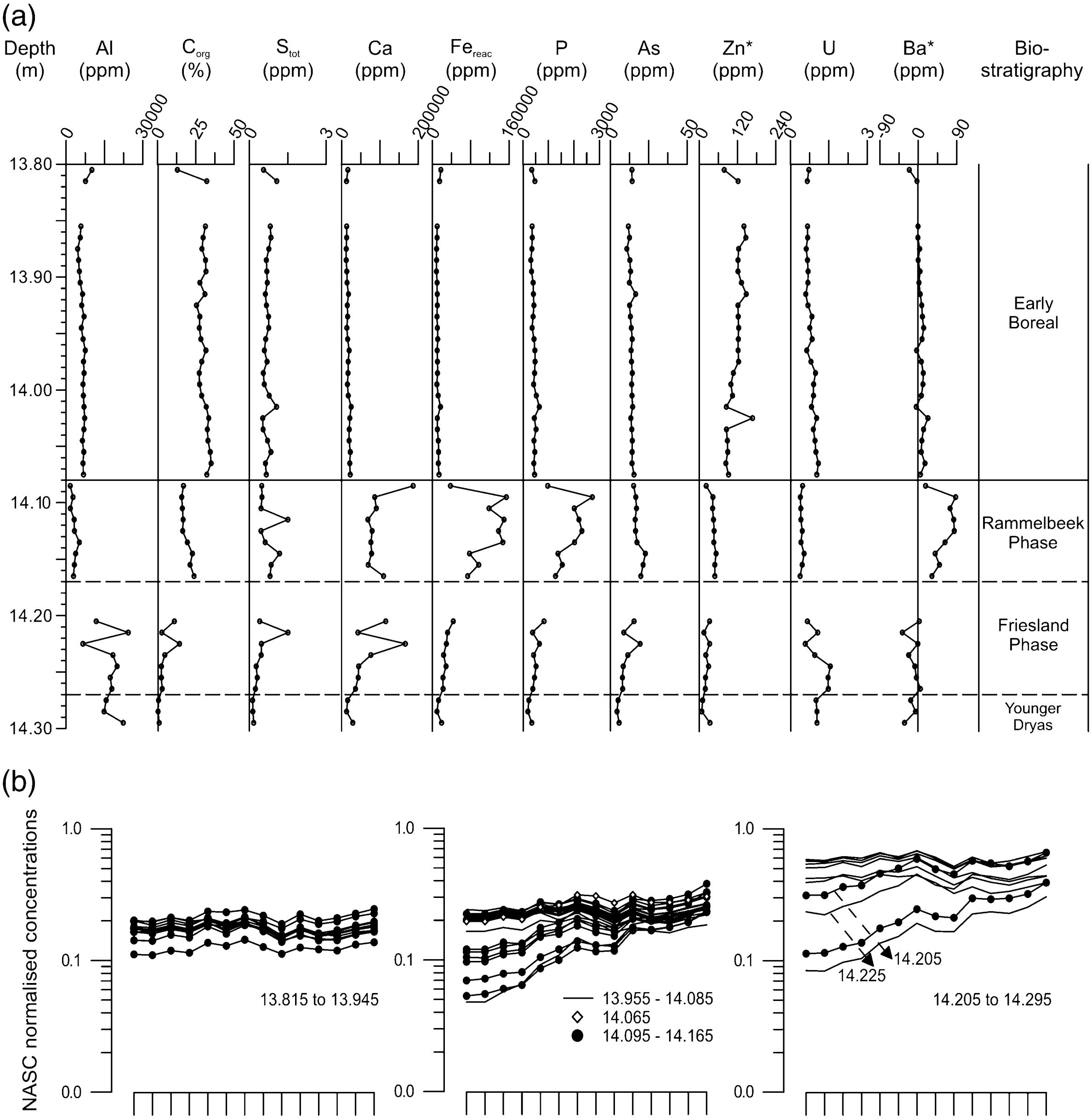

Fig. 6. a. Geochemistry. The following formulas were used: $Fe_{reac}=(Fe_2O_3-(Al_2O_3*0.25))*(56/80)*10000$, $Ba^*=Ba-(K_2O*130.25+51.5)$, $Zn^*=Zn-(Al_2O_3*3.78+6.84)$ with Fe_2O_3, Al_2O_3 and K_2O in percentages and Ba, Ba*, Zn, Zn* and Fe_{reac} in ppm. Depth in metres below surface (surface at +1.34 m). b. Plots of Rare Earth Elements (REE) patterns for all the analysed samples, normalised to NASC (North American Scale Composite). The plots show the REE-elements from light to heavy on the *X*-axis, and the normalised REE-contents on the (logarithmic) *Y*-axis. Each line represents one sample, and connects the normalised concentrations for all REE. REE derived from weathering of clays would show a more or less horizontal line, with fractionation processes causing deviations.

Poaceae), and disappearance of typical "Late Glacial" shrubs and herbs (e.g., *Betula nana*, *Empetrum*, *Helianthemum*, *Saxifraga* and *Polemonium*) suggest correlation with the Friesland Phase of the Preboreal (compare van Geel et al., 1981; Hoek, 1997a). The Younger Dryas–Preboreal transition in this record is thus simultaneous with the transition from sand to sandy, light yellow-brown gyttja.

The relatively high Poaceae values in the diagram between 14.17–14.08 m suggests that here the grass-dominated Rammelbeek Phase of the Preboreal (cf. Wijmstra and de Vin, 1971; e.g., Behre, 1966, 1978; van Geel et al., 1981) is recorded. Lower AP percentages are recorded and taxa indicative of open environments show higher values (e.g., *Artemisia*, *Rumex*) or return in the pollen assemblage (*Saxifraga*, *Plantago*). During this interval the gyttja that was deposited turned lighter again.

After 14.08 m, the high pollen values of *Pinus* and *Corylus*, low values of NAP and presence of *Quercus* and *Ulmus* suggest correlation with the Boreal (compare van Geel et al., 1981). The abrupt transition to peat and sudden changes in the pollen taxa and geochemical data (see Sections 4.2 and 5.3.4) indicate that at 14.08 cm a hiatus is present that covers the period between the end of the Rammelbeek Phase and the start of the Boreal. The Late Preboreal is thus absent from the record.

Between 14.04 and 13.80 m the pollen spectra were not analysed in detail, but the relatively high percentages of *Pinus*, *Corylus*, *Quercus* and *Ulmus* and low percentages of NAP and continued absence of *Tilia* suggests an early Boreal age.

Between 13.78 and 13.80 m a small hiatus is present at the overlap between two cores, due to the coring procedure. Above 13.78 m the pollen association with *Alnus* points to the Atlantic.

5.2. Chronology

The Kreekrak record is the first one in The Netherlands where a WMD based chronology could be obtained that covers the Late Glacial/Holocene (LG/H) transition and the early Preboreal (e.g., Friesland and Rammelbeek Phase). Up to now WMD only proved reliable for the Late Preboreal between ca. 11,250 and 10,700 cal BP, while WMD failed before 11,250 cal BP (compare van der Plicht et al., 2004; Bos et al., 2004).

WMD of the Kreekrak series of AMS ^{14}C dates suggests that the LG/H lithostratigraphic and biostratigraphic boundary in the Kreekrak record could be dated to ca. 11,490 cal BP. This age is in agreement with the LG/H transition of 11,530–11,470 as defined in the dendrochronology curve based on an increase in the ring width observed in German pines (Björck et al., 1996; Spurk et al., 1998). It is also in agreement with ages for the LG/H boundary that were derived from other wiggle-match dated records, such as at Lake Gośiąz (14,460 cal BP), Holzmaar (11,490 cal BP), and Kråkenes Lake (11,530 +40, −60 cal BP) (e.g., Goslar et al., 1995; Hajdas et al., 1995 and Gulliksen et al., 1998 with a summary in Table 2). The date of the transition at Kreekrak is slightly younger than the defined LG/H boundary of 11.5/11.6 k ice-core yr BP in the GRIP and GISP2 ice-core records (compare Lowe et al., 2001). However, the dendrochronological time-scale (in dendro yr BP) and Greenland ice core time-scale (in ice-core yr BP) are based on different proxy records and therefore do not have to be equal. Assuming that the northern hemisphere temperature changes were recorded without a time-lag, the best way to compare terrestrial and Greenland ice-core chronologies probably remains by comparison of δ^{18}O in lake carbonates with the δ^{18}O record in Greenland ice (oxygen-isotope wiggle matching, e.g., Lotter et al., 1992; Hammarlund et al., 1999; Schwander et al., 2000; Hoek and Bohncke, 2001).

Nevertheless, highly detailed terrestrial records from Kråkenes, Gerzensee and Leysin show that the start of the LG/H transition could be dated at 11,530/11,535 cal BP, while the end of the transition in the latter two records was dated at 11,487 cal BP (Birks and Ammann, 2000). The date of ca. 11,490 cal BP for the LG/H boundary in the Kreekrak record therefore may suggest that here the end of the LG/H transition is recorded.

The start of the Rammelbeek Phase in the Kreekrak record was dated at ca. 11,365 cal BP, and shows a good fit with the start of the Preboreal oscillation (PBO) as defined in the GRIP ice core record (Fig. 5; compare Björck et al., 1996; Lowe et al., 2001). Also the start of the Preboreal Oscillation (PBO) recorded in the Gerzensee and Leysin δ^{18}O records of 11,363 cal BP (Schwander et al., 2000; Birks and

Ammann, 2000) corresponds with the start of the Rammelbeek Phase in the Kreekrak record. The earlier published tentative correlation of the Rammelbeek Phase in the Borchert record (van der Plicht et al., 2004) with the Preboreal Oscillation in the Greenland ice cores is thus confirmed.

Comparison of the Kreekrak and Borchert records (van der Plicht et al., 2004) shows that the Late Preboreal encompasses the period from 11,250 to 10,710 cal BP, and that the Boreal thus started around 10,710 cal BP.

5.3. Environmental synthesis

The integration of the palaeobotanical and geochemical records enables the reconstruction of environmental changes in the Kreekrak region. The botanical record reflects changes in the vegetation of the lake itself (local), on the lake shore (extra-local) and in the area surrounding the Kreekrak lake (regional). The microfossil and macroremain assemblages thus consist of an autochthonous (local pollen and macroremains) and an allochtonous (regional pollen) component (Janssen, 1973, 1984). The concentrations of the various geochemical elements in the Kreekrak core reflect the interaction of different processes. The driving force is the deposition of sediment with a specific chemical composition combined with the supply of elements by water and immobilisation by diagenetic processes. In organic-rich layers, such as in the Kreekrak record, the amount of diagenetically immobilised elements is most important. Assuming that post-sedimentary enrichments are negligible, factors influencing the concentration of diagenetically immobilised elements are (1) source — and hence composition — of water, (2) amount of water supplied, (3) immobilised fraction of elements supplied and (4) sedimentation rate. The variations recorded in the Kreekrak record can to a large extent be explained by these factors. A general interpretation of the elements as applicable in the settings discussed here is given in Table 3.

5.3.1. Late Glacial/Holocene transition (ca. 11,525–11,490 cal BP)

During the LG/H transition the vegetation in the Kreekrak area was rather open. On sand dunes scattered shrubs of *Juniperus*, Ericales (*Calluna*, *Empetrum*), and herbaceous vegetation with *Artemisia*, Poaceae, *Campanula rotundifolia*, *Saxifraga*, *Anchusa arvensis*, *Helianthemum*, *Plantago*, *Minuartia rubella*, Chenopodiaceae, and *Rumex acetosella* was present. *Betula* copses and shrubs of *B. nana* and *Salix* were present on wetter substrates. In this open landscape erosion was still an important process (e.g., reworked palynomorphs, *Glomus* and *Cenococcum geophilum*, Fig. 3).

During this period, a lake was formed. In the lake, aquatic vegetation became present with both submerged and floating taxa, e.g., *Potamogeton*, *Myriophyllum verticillatum*, *Zannichellia palustris*, *Ceratophyllum demersum*, *Ranunculus* subgen. *Batrachium* and various algae, such as Characeae (e.g., *Nitella*, *Chara*), *Botryococcus braunii*, *Spirogyra* and *Pediastrum* (Fig. 3). Furthermore, a fauna with mites (Acari), waterflees (*Simocephalus*, *Daphnia*), larvae of non-biting midges (Chironomidae), Bryozoa (*Cristatella mucedo*, *Plumatella repens* type), Ostracoda, rotifers (*Filinia*) and flatworms (Type 353A, B) was present. The abundance of *Spirogyra* and presence of Characeae, *Zannichellia palustris*, Ostracoda, Type 128A and 128B suggests that the water was shallow, carbonate-rich and mesotrophic to eutrophic (e.g., Frey, 1964; Weeda et al., 1985, 1987, 1988, 1991, 1994; Runhaar et al., 1987). The aquatic and zoological taxa also suggest stagnant to slowly running water. Furthermore, the relatively high concentrations of U, Al and low C_{org} and LOI (Fig. 6a) point to a depositional environment with reduced sediments where inflowing water supplied both oxygen and minerogenic sediment. The generally flat NASC-normalised pattern is consistent with clay minerals derived REE (Fig. 6b). Here, the elements are either present in clay, or they are supplied by the inflowing water.

Willow shrubs and taxa such as *Cicuta virosa*, *Carex*, *Epilobium palustre*, *Equisetum*, *Sparganium*, *Typha latifolia*, *Lycopus europaeus*, *Menyanthes trifoliata*, *Mentha aquatica*, *Filipendula ulmaria*, *Thalictrum*, *Triglochin palustris*, and *Urtica dioica* formed the vegetation around the lake. Both the aquatic and swamp taxa indicate mesotrophic to eutrophic conditions. More acid, calcareous-poor conditions are indicated by *Botrychium*, *Juncus filiformis*, and mosses (e.g., *Sphagnum*, *Drepanocladus* and *Scorpidium*

Table 3
General interpretation of the geochemical elements as applicable in the discussed settings

Elements	Occurrence	Indicative for
Al	Clay minerals, micas and feldspars	Amount of non-organic sediment
LOI/C_{org}	Organic matter	Amount of organic matter
S	Organic matter	C_{org}/S ratio ~100 related to amount of organic matter
	Sulphides (especially pyrite; FeS_2)	C_{org}/S ratio >100 additional S in sulphides (e.g., pyrite)
Fe_{reac}	(a) in oxic environments: hydroxides or oxides (Fe_2O_3 or FeOOH)	High concentrations:
	(b) in reduced sulfate-rich (e.g., marine-influenced) environments: sulphides (e.g. pyrite)	(1) supply of dissolved Fe(II); either through reducing conditions in Fe(III)oxide-bearing sediments, or through supply by (reducing) groundwater
	(c) in reduced sulfate-poor (mostly freshwater) environments: carbonates (siderite; $FeCO_3$)	(2) potential of immobilisation by (a) oxygen, (b) sulphate or (c) carbonates
P	(a) organic matter (b) adsorbed onto Fe(hydr)oxides (oxic environments) (c) as vivianite ($Fe_3[PO_4]_2 \cdot 8H_2O$; reducing, siderite-forming sediments) (d) in primary minerals especially apatite ($Ca_5[PO_4]_3[OH,F,Cl]$) and monazite ($[Ce,La,Th]PO_4$)	High concentrations usually relate to iron (hydr)oxides (b) or siderite (c)
Ca	Calcium carbonate	Calcium carbonate indicative for biological activity or supply of lime-rich water
As	As trace element in Fe(hydr)oxides and pyrite (Dellwig et al., 2002; Huerta-Diaz and Morse, 1992; Gunnink, 2003; Huisman et al., 2000)	High concentrations related to Fe(hydr)oxides or pyrite; supply of As by (reducing) groundwater
Zn*	As trace element in sulphides and Fe(hydr)oxides (Huerta-Diaz and Morse, 1992; Huisman et al., 1997; Huisman, 1998)	?
U*	Trace element: mobile in oxic environments but adsorbs onto organic matter in reducing environments (cf. Spirakis, 1996)	Accumulation in settings where oxic water enters reduced organic-rich environments
Ba*	Trace element; high concentrations in Fe(hydr)oxides; especially bog iron ore (Huisman et al., 1997; Zuurdeeg et al., 1988) Ba contents in seawater<fresh water due to precipitation of barite ($BaSO_4$)	High concentrations in Fe(hydr)oxides; may also indicate supply of (fresh) water from reducing Fe(hydr)oxides

scorpioides). *Rorippa palustris* was present as a pioneer on fresh newly formed substrates.

5.3.2. Friesland phase (ca. 11,490–11,365 cal BP)

During the Friesland Phase the area became forested with *Betula* and *Populus*. These formed swamp woodlands around the lake, while the parasitic fungus *Amphisphaerella amphisphaerioides* infected the poplar trees. The shape of the recorded *Betula* fruits and female catkin scales suggests that both *Betula pubescens* and *B. pendula* were present. *B. pendula* may have grown on drier and poorer soils, such as on sand dunes, in open woodlands with *Anthriscus sylvestris* and *Chaerophyllum temulum*. On open spots herbaceous vegetation remained present with *Artemisia*, *Carduus*, *Rumex acetosella*, and *Pulsatilla*. Records of macroscopic charcoal, charred remains of *Betula* and *Gelasinospora* ascospores indicate that during this period fire occurred in the birch woodlands. *Epilobium angustifolium* appeared in localities where the woodland vegetation was burned down (van der Hammen, 1951; van Geel et al., 1981; Bos and Janssen, 1996).

Salix shrubs became abundant around the lake. Along the shores also reed swamps and wet meadows were present with taxa such as *Phragmites australis*, *Typha*, *Carex*, *Cicuta virosa*, *Equisetum*, *Sparganium*, *Lycopus europaeus*, *Menyanthes trifoliata*, *Mentha aquatica*, *Filipendula ulmaria*, *Thalictrum*, *Epilobium*, *Urtica dioica*, *Sanguisorba officinalis*, *Ranunculus flammula*, *Rumex acetosa*, *Heracleum sphondylium*, *Galium* and *Potentilla*. However, a number of these taxa also may have grown in other vegetation types.

In the Kreekrak lake, *Nymphaea alba*, fresh water sponges and *Gloeotrichia* colonies (cyanobacteria) appeared in the aquatic vegetation, and indicate a gradual increase in the water level. Furthermore, also cyprinid fish, molluscs (*Bithynia tentaculata* and *Sphaerium corneum*) and Trichoptera larvae appeared. Both the botanical and zoological taxa indicate that during this period the lake became deeper. With the increasing water depth, taxa preferring shallow water disappeared, e.g., *Zannichellia palustris*, *Ranunculus* subgen. *Batrachium* and many algal species.

During the early Friesland Phase, sandy gyttja accumulated in the lake. Also the high Al, low C_{org} and LOI contents and generally flat NASC-normalised pattern (Fig. 6a, b) indicate that the deposits that accumulated contained sand and clay minerals. This, together with the relatively high U contents, suggests that inflow of oxygenated water continued into the lake, which also supplied minerogenic sediment.

Furthermore, the steady increase in the Fe and P contents suggest that the supply of reduced, Fe-rich, water (probably seepage of groundwater) in the lake gradually increased. Since the chemistry of the seepage water is determined by the reduction capacity and Fe and P availability in de aquifer it proceeds from, it is unlikely that other processes than an increase in the relative influx of seepage water are relevant. Given the environment and the low S_{tot} values, it is assumed that Fe was present as siderite ($FeCO_3$) with additional vivianite ($Fe_2[PO_4]_3 \cdot 8H_2O$). The correlation between Fe_{reac} and Ba* shows that the iron in this water was probably derived from the reduction of ironhydroxides, in which barium was concentrated. The lack of a strong increase in As — which would be expected with bog iron ore as a source (cf. Huisman et al., 1997; Pierce and Moore, 1982) — is because As cannot be incorporated into siderite, so there is no immobilisation process to retain the available As. In the deposits also a large number of botanical taxa were recorded that are typical for situations in which seepage of groundwater occurs. Examples are *Myriophyllum verticillatum*, *Menyanthes trifoliata*, *Carex aquatilis*, *Epilobium palustre*, *Triglochin palustre*, *Scirpus sylvaticus*, *Chrysosplenium alternifolium*, Characeae, and in some cases also *Lycopus europaeus* (compare Weeda et al., 1985, 1987, 1988, 1991, 1994). A very common setting in coast-near deltas such as in The Netherlands is seepage of reduced groundwater. The most likely source for this water is groundwater from the east, were it exfiltrates at the foot of the Tiglian escarpment (Fig. 2b, c). Given the Pleistocene topography at the start of the Holocene (Fig. 2b), an additional source of exfiltrating groundwater may also have been the Rilland ridge, or the higher Pleistocene grounds towards the southwest.

During the later part of the Friesland Phase the sand content in the deposits and the total amount of reworked palynomorphs decreased, indicating less erosion in the hinterland and less redeposition. A decrease in the supply of minerogenic sediment and an increase in the biological productivity (producing both organic matter and calcium carbonate) were also suggested by a combination of a drop in Al, a rise in Ca and C_{org} and LOI, the higher pollen concentration and larger amount of macrofossils in the samples. Furthermore, the drop in the U content points to a gradual shift from oxic water to a more reduced water supply. The botanical data also suggest a contemporaneous shift from slowly running to stagnant water. This shift was simultaneous with a change to less eutrophic conditions. The overall change can be interpreted as a general quieting of the environment and a disconnection of the site from a surface water source.

5.3.3. Rammelbeek phase (ca. 11,365–11,250 cal BP)

In the Netherlands and northwestern Belgium the Rammelbeek Phase was characterised by the regional expansion of grasslands (van Geel et al., 1981, Hoek, 1997a; Verbruggen et al., 1996). It is assumed that the maximum of Poaceae pollen in the Kreekrak record was also caused by regional deposition of grass pollen. Between 14.12 and 14.08 m a few caryopses of *Phragmites australis* were recorded, but here and also at lower levels (between 14.17–14.23 m), finds of *Phragmites* caryopses did not correspond with high values of Poaceae pollen. This suggests a predominantly regional origin of grass pollen. Furthermore, the higher percentages and concentrations of NAP (especially *Artemisia* and *Rumex*) and re-occurrence of taxa indicative for open grounds (Chenopodiaceae, *Plantago*, *Saxifraga*, *Campanula* and *Pulsatilla*) suggest an increase in the abundance of herbaceous vegetation.

In woodlands on moist soils around the lake *Populus* became more important (Figs. 3 and 4). Records of macroscopic charcoal, charred remains of *Betula* and *Gelasinospora* (including *G. retispora*) indicate that fires occurred in these woodlands. Both the geochemical (high Ca content) and botanical data suggest that biological productivity remained high.

During the Rammelbeek Phase substantial amounts of iron were deposited in the sediments. Irrespective of the environment, these amounts can only form with a large supply of iron, i.e., by seepage of Fe-rich groundwater. The relative depletion of LREE in this interval (Fig. 6b) points to a major supply to the system by a carbonate-rich water source, with pH roughly between 7 and 8.1; as the LREE are more prone to form positively charged complexes with carbonates, they are more susceptible to immobilisation by absorption under these circumstances. The water becomes depleted in LREE as a result. In acidic water and water with $pH>9$ no such fractionation occurs (Johannesson and Hendry, 2000; Åström, 2001). Also the presence of "seepage indicators" (see Section 5.3.2.) indicates the contribution of seepage water and calcareous-rich conditions in the lake.

The higher numbers of swamp taxa, Type 128B, Polypodiaceae spores, leafy stems of *Scorpidium scorpioides* and appearance of *Ophioglossum* spores suggest that there was an expansion of swamp vegetation and wet meadows around the lake. Here, *Carex acutiformis*, *C. paniculata/appropinquata*, *Valeriana officinalis* s.l. and *Diporotheca rhizophila* (Type 143), as a parasite on *Solanum dulcamara*, appeared. *Salix* shrubs became less abundant around the lakes and depressions. In the lake, submerged taxa (*Ceratophyllum demersum*, *Myriophyllum verticillatum* and *Nitella*) were gradually replaced by nymphaeid taxa (*Nymphaea alba*, *Nuphar lutea*) and swamp vegetation, partly as a result of the hydroseral succession process. The botanical data indicate that during this period the water depth changed from a few meters to less than 1 m (compare Hannon and Gaillard, 1997).

At the end of the Rammelbeek Phase (sample 14.085 m, Fig. 6a) the Ca content strongly increases, while the Fe, P and Ba* contents show a very strong decrease. The high Ca content may be the result of an increased biological activity producing biogenic calcium carbonate, or it represents a strong decrease in the sedimentation rate. The increase in the Fe, P and Ba* contents suggests a sudden reduction in the supply of iron-rich reduced groundwater. At this time also a large number of botanical "seepage indicators" have disappeared, which confirms that the influence of groundwater seepage decreased. A sudden disconnection from a local groundwater source and/or a distinct lowering of the groundwater level may have occurred (see Section 6.).

5.3.4. Late Preboreal (ca. 11,250 to 10,710 cal BP)

The Late Preboreal period is missing from the record due to a depositional hiatus. The major changes after the hiatus suggest that several interrelated changes in the environment occurred: the drop in calcium probably indicates a lack of supply of calcium to the system. The increase in C_{org} and LOI is probably counterbalancing the decrease in carbonate content. The increase in Al suggests — in combination with the increases in Zn* and U and higher total microfossil concentrations — that the sedimentation rate decreased.

The Late Preboreal is present in other nearby palynological records (compare Verbruggen et al., 1996; Hoek, 1997a), where it is characterised by the expansion of *Pinus*. The hiatus in the Kreekrak record, therefore, must be a local phenomenon.

5.3.5. Early Boreal (ca. 10,710–10,000 cal BP)

During the early Boreal mixed deciduous woodlands with *Quercus* and *Ulmus* and herbs (*Heracleum sphondylium* and *Anthriscus sylvestris*) had largely replaced the swamp woodlands with *Betula pubescens* and *Populus*. On drier and poorer soils (i.e., sand dunes), open *Pinus sylvestris* woodlands with *Corylus avellana* shrubs developed and *Pteridium aquilinum* formed part of the undergrowth. *Rhamnus catharticus* shrubs were present on moist, humus-rich soils. The botanical data (Fig. 3 and scanned samples) suggest a densely forested environment.

The homogeneous distribution of geochemical elements (Fig. 6a) indicates that little changed in the water supply and overall geochemical setting during a prolonged period of time. The flat REE-patterns (Fig. 6b) indicate carbonate-poor, maybe slightly acidic water (Huisman et al., 1999; Johannesson and Hendry, 2000). During this period the hydroseral succession process in the lake advanced further and aquatic communities were present in deeper parts of the lake. At the sample site peat was formed (also indicated by the fungus *Cenococcum geophilum*). Here, *Salix* shrubs, reed swamps and meadows were present in which *Lythrum salicaria*, *Juncus articulatus*, *Thelypteris palustris* and *Calliergon* appeared. The swamp taxa, Type 128B and *Spirogyra* indicate that the water was shallow and that more or less mesotrophic conditions prevailed. Records of macroscopic charcoal, charred remains of *Betula*, *Sparganium* and *Carex rostrata* indicate that fires occurred in the swamps and swamp woodlands.

5.3.6. Local presence of *Alnus incana*?

In the Kreekrak record a number of *Alnus incana* fruits were recorded from levels that date to the Friesland and Rammelbeek Phases (Plate I, Fig. 3a). However, pollen of *Alnus* was only recorded occasionally and sometimes at corresponding levels as the *A. incana* fruits. The fruits are substantially different, e.g., smaller and thinner wings with very characteristic rounded cells (compare also Jacomet, 1986; Berggren, 1981), from the *A. glutinosa* fruits that were recorded in the lower sandy part of the deposit between 14.28–14.29 m. Their presence may have been the result of reworking and redeposition of older material, which is the case with macroremains of *A. glutinosa* recorded in the Younger Dryas deposits between 14.28–14.29 m (Fig. 3c). However, the fruits were found in a part of the Friesland and Rammelbeek Phase when erosion was diminished. Local presence of *A. incana* in Europe during the Early Holocene was suggested earlier by Firbas (1949). Early Holocene pollen records of *A. incana* are known from fluvial settings such as the northern Upper Rhine Rift valley (central-west Germany) where the species probably occurred locally in meadows on the floodplain of the River Rhine during the early Boreal (Dambeck and Bos, 2002). Furthermore, *A. incana* was present during the Eemian and Early Weichselian in Europe (compare Litt, 1994; Caspers and Freund, 2001). The occurrence of *Alnus* pollen in other Late Glacial diagrams of The Netherlands without indications of reworking from older deposits also may suggest local occurrence of *Alnus* during the Late Weichselian.

6. Climatic signal

The analysed part of the Kreekrak record reflects a period, i.e., the LG/H transition and early Preboreal, in which major climatic changes occurred on a global scale. The LG/H transition is characterised by abrupt warming, followed by a climatic oscillation, the Preboreal oscillation (Björck et al., 1996). These events are recorded in detail in the oxygen isotope records of the Greenland ice cores (e.g., Dansgaard et al., 1993; Johnsen et al., 1997; Grootes et al., 1993). In order to determine how the vegetation development in the Kreekrak area was influenced by these global climatic changes the wiggle-match dated regional pollen diagram was tentatively correlated with the δ^{18}O curve of the GRIP ice-core (Fig. 5). Here, the GRIP-ss08c chronology adopted by the INTIMATE group is used (Björck et al., 1998; Walker et al., 1999; Lowe et al., 2001). Ice core years and dendro years are taken as identical. It appears that trends recorded in the Kreekrak record and in the δ^{18}O curve are approximately synchronous, which suggests that environmental change in the Kreekrak area was primarily influenced by major, global climatic changes that occurred during this period.

Furthermore, minimum mean July temperatures can be inferred from the botanical data (preferably macroremains) of the Kreekrak record by using the climate indicator plant species method (sensu Iversen, 1954; Kolstrup, 1980). In the record a large number of taxa are present that can be used for palaeotemperature reconstructions. However, only a few of them were present that indicate minimum mean July temperatures of at least 13 °C.

At ca. 11,490 cal BP (LG/H transition) near Kreekrak a lake was formed in which accumulation of organic deposits started. The lake was formed in an abandoned channel of the River Schelde that had been active during the Late Glacial. The geochemical and botanical data suggest that with the warmer climate, there was a transition to a less energetic environment and the channel became less active. A similar decrease of fluvial activity at the beginning of the Holocene was also observed further upstream along the River Schelde (Kiden, 1991). As a result, infilling with predominantly organic deposits started in slowly running water and the biological productivity of the lake and lake surroundings increased. Also precipitation increased. This is suggested by a combination of both a rise of the lake water table and an increase in the supply of oxic surface water into the lake by inflowing water. The rise of the lake water level was also a result of a larger supply of Fe-rich groundwater due to seepage.

Comparison with the GRIP record (Fig. 5) shows that there was a small time lag between the vegetation response and the climate warming at the LG/H transition. After the climate warming the area became forested with birch and poplar during the Friesland Phase (ca. 11,490–11,365 cal BP). During this period biological productivity in the lake and lake surroundings further increased. During the Friesland Phase, the water depth of the lake gradually increased. However, around ca. 11,435 cal BP a shift occurred in the water supply of the lake. At this time there was a disconnection from a local surface (oxic) water source, while the supply of reduced Fe-rich groundwater (i.e., seepage) became more important. This disconnection was probably the result of a total cut-off of the river channel, which caused a shift from running to stagnant water in the Kreekrak lake. The botanical data, including *Ceratophyllum demersum* (13+: °C, Isarin and Bohncke, 1999; 15 °C, Litt, 1994), *Lycopus europaeus* (16 °C, Bell, 1970) and later also *Scirpus lacustris* (13 °C, Iversen, 1954), *Typha latifolia/angustifolia* (13–14 °C, Kolstrup, 1979, 1980; Isarin and Bohncke, 1999) and *Solanum dulcamara* (13 °C, Iversen, 1954) suggest that during the LG/H transition and Friesland Phase minimum mean July temperatures were at least 13–16 °C.

During the Rammelbeek Phase (ca. 11,365–11,250 cal BP) the supply of Fe-rich groundwater continued and biological productivity in and around the Kreekrak lake remained high. During this period the abundance of grasslands and open herbaceous vegetation increased. The Rammelbeek Phase reflects a period with a more continental climate with dry, warm summers, cold winters and relatively low groundwater levels (van Geel et al., 1981; Hoek and Bohncke, 2002). The botanical data of the Kreekrak record (e.g., *Ceratophyllum demersum*, *Lycopus europaeus*, *Solanum dulcamara* and *Typha latifolia/angustifolia*) suggest no decline in the mean July temperatures. This is in agreement with the botanical data of the Borchert record, which suggested minimum mean July temperatures of 13–15 °C (van Geel et al., 1981). The Rammelbeek Phase is not always present or recognisable in Preboreal pollen diagrams of The Netherlands (see low number of records in Fig. 1). As a consequence of the lower groundwater levels it is at many localities represented by a hiatus (Hoek, 1997a; Hoek and Bohncke, 2002). The position of the depositional hiatus at the Kreekrak site, covering the Late Preboreal, in this respect seems strange. One would rather expect the Rammelbeek Phase to be absent. In the Kreekrak record this drier period is reflected in a decrease of the lake water level, while records of Poaceae, *Artemisia*, Chenopodiaceae, *Rumex acetosa* and *Gelasinospora* also indicate more open landscapes and drier conditions. Nevertheless, aquatic vegetation remained present in the lake, while accumulation of gyttja continued. Also the high Ca content in the last sample before the hiatus is probably the result of increased biological activity producing biogenic calcium carbonate. Since calcium carbonate is susceptible to weathering and there are no indications for pollen degradation due to oxidation, it is unlikely that this layer was exposed during the hiatus. It is therefore assumed that the position remained waterlogged with an extremely low sedimentation rate. There are thus no indications — botanical, lithological or geochemical — that the lake water level lowering during the Rammelbeek Phase and following Late Preboreal continued to the point that the lake dried out. A possible cause for the hiatus can be found in the geochemical data, which indicate a sudden reduction in the supply of iron-rich reduced groundwater. The major source for this groundwater comes from the east, where it wells up at the foot of the Tiglian escarpment (Fig. 2c). A secondary source may have been the Rilland Ridge to the west of the Schelde palaeovalley (Fig. 2b and c). However, its contribution was probably only minor, as this ridge is much smaller and lower than the Tiglian escarpment (ca. −4 m vs. +20 m NAP), so that the groundwater volume involved will have been much lower. The sudden decrease in the supply of iron-rich seepage water indicates a lowering of the groundwater level in the area. As a consequence a hiatus developed in the record. Two hypotheses are postulated to explain the hiatus:

It is possible that the lowering of the groundwater table could have been induced by a renewed incision of the River Schelde, which caused a cut-off from the local groundwater source from the east. Such a renewed incision phase of the river may have been a reaction to a sudden change to a cooler and wetter climate at the start of the Late Preboreal (van der Plicht et al., 2004). However, although both the Maas and Rhine Rivers show a phase of incision during the early Preboreal (Berendsen et al., 1995; Kasse et al., 1995), there is no evidence for renewed incision of the River Schelde during this period (Kiden, 1991). Moreover, it is unlikely that a river incision would be sufficiently deep to have a considerable effect on the groundwater flow.

An alternative, and in our opinion a more likely hypothesis, is that the drier climate during the preceding Rammelbeek Phase caused a decreased recharge of the groundwater aquifers, which only manifested itself in the exfiltration area at the foot of the Tiglian escarpment with some delay. This was influenced by the particular hydrogeological conditions in the area of the Tiglian escarpment. The palaeo-relief was relatively high; the difference in altitude between the crest and the foot of the escarpment was approximately 30 m. Therefore, the groundwater table had a steep slope in a westerly direction, towards the exfiltration area at the foot of the escarpment near the Kreekrak lake. Because of this, the unsaturated zone above the groundwater table was unusually thick underneath the escarpment, probably in the order of 20 m (it is still relatively thick today, although the relief is only about half of that at the beginning of the Holocene) (R. Stuurman, pers. comm. 2005). The effect of any climatic change first had to propagate downward through this thick unsaturated zone before the groundwater table itself would be affected. In fact, in the first part of a drier period, the groundwater even would still be recharged fully by the water from the preceding wetter period which percolated gravitationally downward through the unsaturated zone. Only after the effect of the desiccation had reached the groundwater table, it would start to be lowered. Even then, seepage in the Kreekrak lake would still continue, until the hydraulic head in the exfiltration area at the foot of the escarpment fell below the level of the lake itself. This required an equivalent drainage from the whole aquifer underneath the Tiglian escarpment. As the aquifer is relatively large and the sediments fine grained, this introduced another major delay in the transmission of the effect of a climatic dessication to the exfiltration area at the foot of the escarpment. As a result, the total time lag of the reaction of the groundwater system underneath the Tiglian escarpment to a climatic desiccation at the beginning of the Holocene may be estimated to be in the order of 50 to 100 years (R. Stuurman, pers. comm. 2005).

Comparison with the GRIP ice-core record (Fig. 5) shows that the start of the Rammelbeek Phase is synchronous with the start of a negative excursion in the δ^{18}O isotope values, the Preboreal Oscillation or PBO (Björck et al., 1996). In the ice cores the PBO is a phase of diminished snow accumulation that has been attributed to a meltwater pulse, caused by the melting of the Scandinavian ice sheets, including the drainage of the Baltic Ice Lake (e.g., Björck et al., 1997; Hald and Hagen, 1998; Husum and Hald, 2002) and Lake Agassiz (e.g., Fisher et al., 2002; Teller et al., 2002). This resulted in a temporary decrease of the thermohaline circulation in the North Atlantic. The NW European terrestrial equivalent of this cool climatic phase may have been dry and continental, i.e., the Rammelbeek Phase (van der Plicht et al., 2004). At ca. 11,250 cal BP this dry and continental phase was followed by a phase with a more humid climate, the Late Preboreal, during which a hiatus developed in the Kreekrak record (see above). The change to a cooler and wetter climate at the start of the Late Preboreal was probably triggered by a sudden decline of solar activity, which is evident from the sharp rise of the cosmogenic nuclides ^{14}C and ^{10}Be (van der Plicht et al., 2004).

The early Boreal (10,710–10,000 cal BP) was a relatively stable period, showing a densely forested landscape. Sedimentation rates were low. The botanical data — presence of pollen of *Corylus avellana* (15 °C, Hoffmann et al., 1998) and seeds of *Lycopus europaeus* and *Typha angustifolia/latifolia* — suggest a minimum mean July temperature of 15–16 °C at the start of the Boreal. Accumulation of peat in the former lake resumed due to a slowly rising groundwater level, probably influenced by slow but ongoing aggradation in the Schelde river channel, as observed further upstream (Kiden, 1991). The geochemical data indicate that little changed in the water supply during this period.

7. Conclusions

Detailed botanical (microfossil and macroremain), zoological and geochemical analyses of organic deposits recorded near Kreekrak (southwestern Netherlands) provided new insights into Early Holocene environmental change in this area of which thus far little was known. An accurate chronology of the record, which covered the Late Glacial/Holocene transition to early Boreal, was obtained by AMS ^{14}C wiggle-match dating (WMD). The Kreekrak record is the first one in The Netherlands where a WMD based chronology could be obtained that covered the Late Glacial/Holocene transition and the early Preboreal. The Kreekrak botanical record reflects the end of the Younger Dryas to early Boreal and can be well correlated with pollen records from other sites in The Netherlands and Belgium.

The palaeo-topography of the area at the beginning of the Holocene suggests that the Kreekrak lake was formed in an abandoned channel of the River Schelde. Around ca. 11,490 cal BP infilling started with predominantly organic deposits in slow running water. As a result of the warmer climate the area became forested with birch and poplar during the Friesland Phase (ca. 11,490–11,365 cal BP). Biological productivity of the lake and lake surroundings increased. In the lake, aquatic vegetation with both submerged and floating taxa developed, while willows, reed swamps and grasslands fringed the shores. Precipitation increased during this period, which caused a rise in the lake water table and an increase in the supply of oxic surface (=river) water into the Kreekrak lake. Around ca. 11,435 cal BP the lake water became stagnant, probably as result of a total cut-off of the river channel. This caused a shift in the water supply of the lake, e.g., the local surface water source was disconnected, while the supply of reduced Fe-rich groundwater (i.e., seepage) became dominant. During the Rammelbeek Phase (ca. 11,365–11,250 cal BP), the climate was more continental and the abundance of grasslands and open herbaceous vegetation increased. The supply of Fe-rich groundwater continued and biological productivity remained high. In the lake, the water level slightly decreased but aquatic vegetation remained present. At the end of the Rammelbeek Phase a sudden reduction in the supply of Fe-rich groundwater occurred, which caused a lowering of the groundwater level in the area. This may have resulted in the development of a hiatus, which covers the Late Preboreal (11,250–10,710 cal BP). During the early Boreal (10,710–10,000 cal BP) the landscape became densely forested and accumulation of peat in the former lake resumed due to a slowly rising groundwater level. The Boreal was a relatively stable period. Sedimentation rates were low.

This study confirms that seepage of groundwater in the Kreekrak area is not only occurring today but that it was also an important factor in the past. Especially during the end of the Late Glacial and the Early Holocene it has contributed to the existence of small lakes, such as the one near Kreekrak. During this period, the Kreekrak lake was fed by surface run-off, precipitation and groundwater seepage and initially also by inflowing river water. Changes in the hydrology and chemistry of the lake could be related to major climatic changes that occurred during this period. However, this climatic sensitivity changed when at the end of the Rammelbeek Phase groundwater seepage strongly decreased or ceased, resulting in a depositional hiatus in the sedimentary sequence. This was probably caused by a delayed reaction of the groundwater system to the relatively dry climate of the Rammelbeek Phase.

Due to Holocene tidal erosion and a thick (>10 m) Holocene cover only the main outlines of the Late Glacial/Early Holocene fluvial landscape in the Schelde palaeovalley are known. The Kreekrak record shows that river activity probably was still present during the latest part of the Younger Dryas and into the earliest part of the Holocene, but that it declined during the later part of the Friesland Phase.

The combination of palaeobotanical analyses and geochemical analyses of major and trace elements in the Kreekrak record shows a close interrelation between landscape development and geochemistry. It appears that the environmental development of this area during the Early Holocene was largely influenced (directly or indirectly) by major climatic changes that occurred during this period, which determined local factors such as the composition and density of the vegetation, occurrence of seepage and river activity. Further research of this type has the potential to develop the application of major- and trace element geochemistry in palaeoenvironmental reconstructions.

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