



Article

When the River Began—The Formation of River Motala Ström and Human Presence in the Early Holocene, Sweden

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Received: 3 July 2020; Accepted: 21 August 2020; Published: 29 August 2020



Abstract: In conjunction with the extensive archaeological projects conducted at the current outlet of Sweden's second largest lake, Lake Vättern, macrofossil, pollen and diatom records have been studied from ¹⁴C-dated lake and river sediments from River Motala Ström in Motala and Lake Boren. These investigations have revealed sedimentary evidence of the Yoldia Sea regression, the Ancient Lake Vättern transgression, and the following stepwise river formation process. Around 9000 cal BC, two small kettlehole basins at Strandvägen and Kanaljorden became isolated from the Baltic basin. As the ice sheet retreated further north, the isostatic uplift isolated the Vättern basin from the Baltic basin. Due to the uneven isostatic uplift, the basin tilted toward the south, and the Ancient Lake Vättern transgression started in Motala. The threshold in Motala at 92.5 m a.s.l. was reached around 7200 cal BC, and River Motala Ström was formed. ¹⁴C-dated diatom records from Lake Boren, and shoreline deposits in Motala, confirm this event. The water level in Lake Vättern initially fell around 1.5 m, and around 5800 cal BC, a second erosional event cut down the threshold to modern day level. At this time, the Late Mesolithic settlements in Motala were established and expanded.

Keywords: River Motala Ström; Lake Vättern; river formation process; shoreline displacement; Mesolithic; Strandvägen; Kanaljorden

1. Introduction

River formation in formerly glaciated areas, where isostatic uplift and shore displacement is a dominating component of the postglacial landscape development, is a relatively poorly researched area cf [1,2]. This is not surprising, since most fluvial environments are erosional in character, continuously eroding, transporting, and redepositing its geological record, often making the stratigraphy very complex, and the absolute dating of events difficult [3,4]. The landscape below the highest coastline of southern Sweden is largely shaped by glaciations, subsequent isostatic uplift and eustatic changes. The river valleys in the province of Östergötland were roughly shaped during the last glacial, and early Holocene, by retreating ice sheets and covered by glaciolacustrine and marine clays during the Baltic Ice Lake and Yoldia Sea stages [5]. In the case of the Lake Vättern basin, which extends over 120 km from north to south (Figure 1), the differential isostatic uplift had a direct effect on the drainage, and a new river was formed during the early Holocene. Few river valleys in southern Scandinavia have been the stage for such intense Mesolithic activity as the river sites in Motala (Figure 1). To understand why this place has been such a focal point, the landscape and river development needs to be understood. In this

multi-disciplinary paper, we report and discuss the relevant sediment stratigraphy, chronology and river formation processes that took place in Motala. The environmental data from the archaeological sites are discussed and corroborated by data from sediment cores retrieved from Lake Boren, downstream from Motala. We pay special attention to the chronology of the River Motala Ström formation process, and the local shoreline displacement in the Vättern basin.

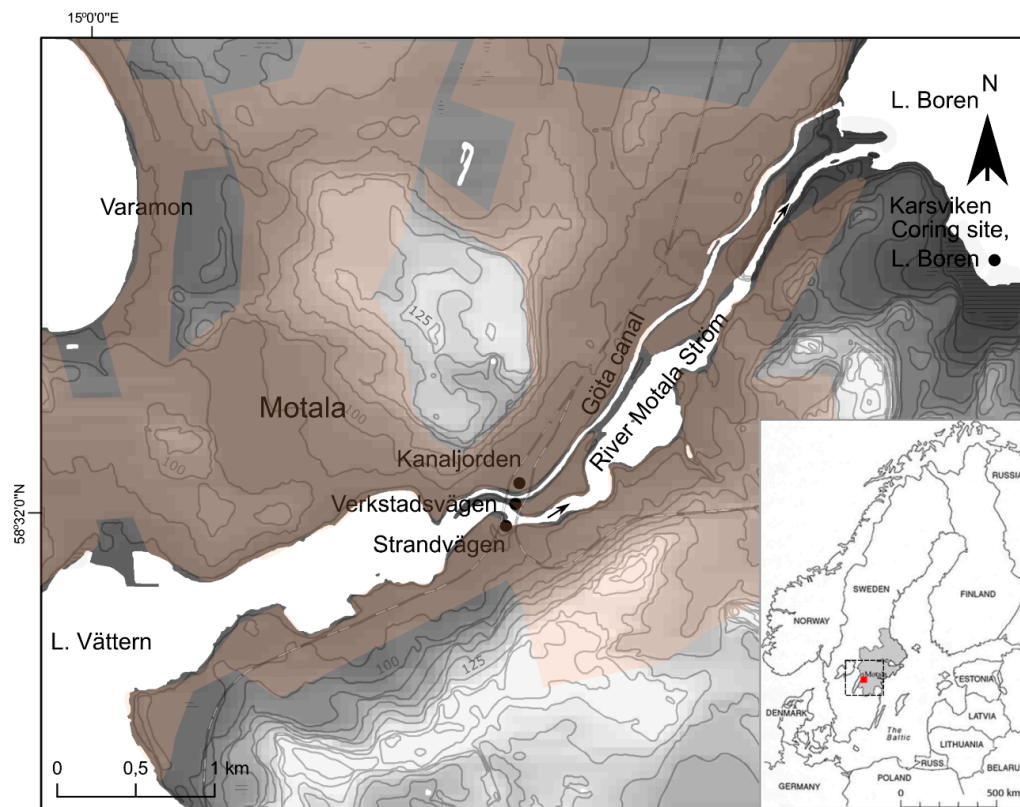


Figure 1. Elevation map with present-day River Motala Ström, the Strandvägen and Kanaljorden Mesolithic sites, and the coring site in Lake Boren. Lake Vättern had, during the early 20th century, a mean water level of 88.5 m a.s.l., and Lake Boren ca. 72 m a.s.l. Urban areas are marked in reddish color. Encapsulated: The town of Motala in east-central Sweden in red and the province of Östergötland highlighted in grey. The dashed box indicates Figure 2.

2. Site Description

The modern River Motala Ström in Motala is a form of entrenched meandering channel stream. It has during modern times been regulated, especially since the construction of a hydroelectric power plant in the 1920s, but earlier historical maps show that it has been relatively fixed, with limited stream bed erosion and very low sediment transport. The distance between Lake Vättern and Lake Boren is ca. 4 km. Lake Vättern had, during the early half of 20th century, a mean water level of 88.5 m a.s.l. (between 87.97–89.08 m a.s.l.), a residence time of ca. 70 years and a mean run-off of 42 m³/s (data from Swedish Meteorological and Hydrological Institute).

Motala has been interpreted as a central place in the Mesolithic society of eastern central Sweden [6]. Three partly contemporary sites, dating between ca. 9000–4500 cal BC have been excavated by River Motala Ström, the outflow of Lake Vättern (Figure 1).

The sites Kanaljorden and Verkstadsvägen are situated on the northern side of the river, whereas the site Strandvägen is located on the opposite southern side. Together, they comprise the largest and most complex Mesolithic settlement area known and excavated in this region. The areas at Verkstadsvägen and Strandvägen consist of central parts of the settlement, with several documented post-built

dwellings, and the first excavated Mesolithic cemetery in central Sweden [7–10]. The Verkstadsvägen site contains no fluvial or aquatic sediment deposits.

Strandvägen is centered around 89 m a.s.l. on a low sandy hill, comprised of wave-washed till, forming a promontory out in the river, adjacent to both the inner bay of Lake Vättern and a shallow backwater downstream of the first rapids of the river (Figure 1). The backwater is well protected from waves by the hill directly to the west, and contains significant gyttja deposits. The site has been the subject of large-scale excavations, and contains, beside dwellings and funeral remains, thick occupation layers along the shore, and refuse layers in the gyttja of the riverbed. The earliest remains date to ca. 7000 cal BC [9,11].

Kanaljorden contains Early Mesolithic remains, as well as a Late Mesolithic ceremonial context, with human remains placed onto a stone-packing on the bottom of a shallow wetland. The site is situated about 100 m north of the current course of the river, and ca. 250 m east of Lake Vättern [12,13]. The local topography is dominated by a low ridge with postglacial sand in the east, and a wetland in the west. The wetland has two shallow basins, one to the north and one in the south. The wetland is today a bog, but had open water during the early Holocene. The wetland, and to some extent the western slope of the ridge, displays a chrono-stratigraphical sequence of layers from the Mesolithic, i.e., the period ca. 9500–4000 cal BC. The situation is different on the top of the ridge, where finds from different periods of the Holocene occur in the same strata.

3. Shoreline History of the Vättern Area

When southern Lake Vättern was deglaciated ca. 11,000 cal BC, the Baltic basin was occupied by the Baltic Ice Lake, which was dammed by the retreating ice sheet to at least 25 m above the global sea level [14]. About 9800 cal BC, the lowlands east and west of central Lake Vättern were deglaciated [5,15] and as the ice sheet retreated north of Mt Billingen (Figure 2) at ca. 9600 cal BC the Baltic Ice Lake was drained down to sea level, marking the onset of the Yoldia Sea (9600–8750 cal BC). During that time, the Baltic basin was in contact with the sea through open straits across southern central Sweden [16–18]. Shore lines at 120 m a.s.l. mark the maximum level of the Yoldia Sea near Motala [5]. The shore displacement was rapid, and by 9150 cal BC, sites down to 105 m a.s.l. south of Motala had been lifted above sea level [19,20]. At that time, the Vättern basin formed a bay with a northern connection to the Yoldia Sea (Figure 2).

As the Göta River and Otteid/Steinselva straits that connected the Yoldia sea with the North Sea were lifted above sea level, the next freshwater stage of the Baltic basin, the Ancylus Lake (8750–7750 cal BC), was initiated [16,18]. The differential isostatic uplift led to the northern part of the basin rising faster, and this N-S tilting of the Ancylus Lake initiated a transgression of the southern shores of the Baltic basin, which would last approximately 500 years, until ca. 8250 cal BC [14,16,18,21]. The transgression was most marked in the southern Baltic region, but can also be traced in southern central Sweden, e.g., east of Motala near Lake Boren and Linköping, where it is registered at 82 m and 76 m a.s.l. respectively [22,23]. The transgression was followed by a regressive phase as the new southern outlet across the Danish straits opened [14,16]. During this regression, the Närke strait at 105 m a.s.l. north of Lake Vättern (Figure 2) was exposed, and a land-bridge connected to northern Sweden was formed [24,25]. The Ancylus Lake stage was followed by the transitional Initial Littorina Sea (ca. 7750–6250 cal BC) and the brackish Littorina Sea as the sea level rose above the southern threshold, around 6450–5950 cal BC [14,26].

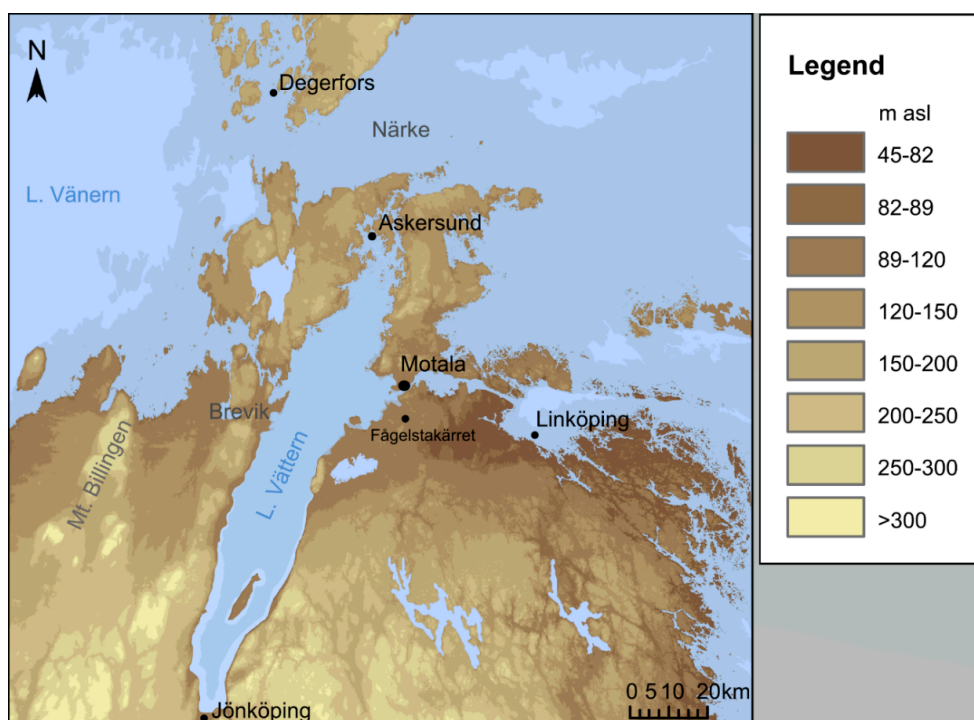


Figure 2. Map of central middle Sweden with the approximate extent of the Yoldia Sea at ca. 9000 cal BC (following online maps at www.sgu.se). The investigated area is located at the eastern shore of Lake Vättern in Motala. Notably: 150 m a.s.l. = the highest shoreline of the Baltic Ice Lake near Motala [5], 120 m a.s.l. = the highest shoreline of the Yoldia Sea near Motala [5]. The elevation of the northern threshold of the Lake Vättern basin, close to Askersund, is 105 m a.s.l., and the elevation of the Kanaljorden and Strandvägen sites at Motala is around 89 m a.s.l. The highest shorelines of the Ancylus Lake east of Motala (Lake Boren), is 82 m a.s.l. [22].

The shoreline development of Lake Vättern is complex and was subject to intensive geological studies in the first half of the 20th century [22,27–30]. The more pronounced uplift towards the north, in combination with the elongated N–S extent of the lake, has led to a tilting of the lake surface towards the south. The southern shore of Lake Vättern is presently being submerged, and records from the formerly exposed ground show that it was 11 m below the present lake surface in the vicinity of Jönköping (Figure 2) [31], but the former shoreline can be traced down to at least 31 m below the present lake surface, near the southern end [32]. Near Motala, the water level is estimated to have been as low as about 80 m a.s.l., i.e., 8 m below the present-day shoreline, before the transgression started [27]. The tilting supposedly led to a shift in outlets, from a northern outlet located near Askersund at 105 m a.s.l. (Figure 2), to the present-day outlet at Motala, at 88.5 m a.s.l. [22]. It is likely that an initial drainage in the north existed [22], but eventually, the tilting made it impossible for any riverine outlets to be sustained northwards. The tilting also caused the lake level to rise in the whole basin, until the new outlet formed. The erosion of the glaciofluvial material at the Motala threshold led to a sudden lowering of the lake level and the preservation of marked shorelines—the Ancient Lake Vättern (ALV) limit, that can be followed around the northern shores of the lake. In Motala, the ALV shoreline is measured to be approximately 92.5 m a.s.l. [27].

Shoreline and lake isolation studies indicating that the Ancylus Lake did not reach above 85 m a.s.l. in the Motala-Linköping area [23,27] suggested that Lake Vättern could not have been in contact with the Ancylus Lake at the Motala threshold. It was long assumed that Lake Vättern was isolated from the Yoldia Sea as the northern threshold was uplifted above the sea surface e.g., [22,27,30]. Recently, however, the isolation of Lake Vättern was dated to 7580 cal BC [33], which would indicate that the

northern connection remained open throughout the Ancylus Lake phase and into the Initial Litorina Sea. At that time, the Ancylus Lake east of Motala was below 76 m a.s.l. [23].

Regardless of varying geological estimates and interpretations, two basic facts can be considered as established, and form the basis of our discussion:

- (1) The River Motala Ström did not form immediately after deglaciation.
- (2) There was a transgression in the Vättern basin during the early Holocene, resulting in the formation of River Motala Ström.

4. Methods

Sediment samples were collected from several sections with fluvial sand, peat and gyttja layers. The sampling was performed on 12 sections at Strandvägen [34] and 8 sections at Kanaljorden [35], using monolith boxes. The 1-m segments of the sediment profiles were carefully wrapped in plastic and transported to the laboratory at Stockholm University, for cold storage and subsequent sub-sampling. Sediment units/layers were correlated based on sediment properties and pollen/macrofossil assemblages.

4.1. Macrofossil Analysis

Samples for macrofossil analysis were taken in vertical sections; samples measuring ca. 0.5–1 L. Samples were prepared by wet-sieving (mesh size 0.25 mm), and in some cases, when sand and gravel occurred, by flotation, according to [36]. The identifications of seeds were carried out by consulting reference collections and identification keys, especially [37–39] and [40]. Sand content was estimated by sieving (80 µm), and the silt/clay fractions were estimated macroscopically.

4.2. Pollen Analysis

Pollen samples (2 cm³) were prepared according to method A, as described by [41]. The taxonomy and identification of pollen and spore taxa follow [42], and identifications were confirmed by comparison with pollen reference collections. A Nikon microscope was used at ×400 and ×1000 magnification. At least 400 tree pollen grains were counted in each sample.

4.3. Lake Boren Sediment Coring

In order to date the breakthrough of River Motala Ström into Lake Boren, a sediment coring was performed at the centre of Karsviken, close to the river outlet (Figure 1). A Russian corer was used to retrieve core sections 100 cm long and 5 cm ø. In total, 3.5 m of sediment was retrieved from five parallel cores. Then, 1-cm slices of sediment were sampled every 5 cm for diatom analysis. Where necessary, parallel cores were correlated, and several 2-cm slices from the same level were combined to find enough terrestrial macrofossil material. The sediment was deflocculated, wet sieved at 500 µm, and the macrofossils were dried overnight at 50 °C. Samples were sent to the Ångström Laboratory in Uppsala for ¹⁴C-dating and calibrated using Oxcal v. 4.2.4. [43], and the INTCAL13 calibration data set [44]. The calibrated dates were combined into an age-depth plot.

4.4. Diatom Analysis

Permanent slides for diatom analysis were prepared according to [45]. The residue was mounted in Naphrax high resolution mountant (Brunel Microscopes Ltd., Wiltshire, UK). Counting was performed under ×1000 magnification using immersion oil. Count sums ranged between 100–190 diatoms/sample. Species identification was carried out mainly with the aid from [46–49]. The species were classified after salinity preferences. Taxa typical for the Ancylus Lake were distinguished from other freshwater taxa, following e.g., [50,51].

5. Results and Interpretation

Of all studied sections at Kanaljorden and Strandvägen, the most complete sediment stratigraphy was found in section C 13059 from Strandvägen, and log 3 from Kanaljorden [35]. Here we focus on data from the Lake Boren sediment core, and section C 13059, where sediments from all interpreted geological events are preserved (i.e., with least erosion and most deposition), but make correlations and comparisons with other sections from the sites. From the Kanaljorden site, we focus on dated stratigraphical units.

5.1. Lake Boren Sediment Records

The diatom stratigraphy has been divided into four zones, which are presented in Figure 3. Zone 1 is dominated by taxa typical for the late Ancylus Lake [50–52]; *Aulacoseira islandica*, *Ellerbeckia arenaria*, *Amphora pediculus* and *Epithemia turgida*. In zone 2, indifferent and freshwater taxa increase, tentatively interpreted as a result of the isolation of Lake Boren. According to the age-depth plot (Figure 4, Table 1), the isolation is dated to 8250 cal BC. During this initial phase of Lake Boren, it is likely that pH was enhanced by surrounding limestone bedrock [5,53]. This is also reflected in the diatom flora, since *Rhoicosphaenia abbreviata* is common [54]. Beside this taxon, the indifferent *Cocconeis placentula*, *Pseudostaurosira brevistriata* and freshwater living *Aulacoseira ambigua*, *Cyclotella radiosa* and *Gomphonema* spp. appear in zone 2. The relatively high abundance of planktonic diatoms and the deposition of laminated silty gyttja clay in this zone indicate relatively deep and well-stratified waters. In zone 3, freshwater taxa decrease, and indifferent taxa increase, especially *Staurosira construens*, *Staurosirella lapponica* and *Pseudostaurosira brevistriata*. These taxa are known as opportunists, i.e., they flourish during periods of pronounced changes in the environment, e.g., in water chemistry cf [55,56]. This situation is likely to have occurred when water from Lake Vättern started to flow into the Lake Boren basin from the west, lowering the pH values in Lake Boren. Oxygenation of the bottom waters during this phase leads to increased bioturbation and a shift to non-laminated sediments. According to the age-depth plot this phase, representing the opening of the spillway over the Motala threshold and establishment of River Motala Ström, started around 7200–6900 cal BC (age from linear interpolation in Figure 4), and lasted ca. 1000 years (Figures 3 and 4). In zone 4 (beginning around 6200–5900 cal BC), the situation stabilized, causing a distinct decrease in *Staurosirella lapponica*, and common freshwater taxa were established. Several new taxa are introduced, e.g., *Cymbella falsalis diluviana*, *Neidium iridis* and *Pinnularia* spp.

Table 1. ^{14}C -dates from the Lake Boren sediment core.

Depth (cm)	Lab. Nr	$\delta^{13}\text{C}$ VPDB	^{14}C age BP	Age cal BC (2 σ)
447.5	Ua-51176	−29.3	6156 ± 38	5215–5002
542.5	Ua-51177	−26.5	8708 ± 43	7936–7597
557.5	Ua-51178	−25.5	8847 ± 46	8213–7787
566.5	Ua-51179	−27.0	9137 ± 33	8451–8279

The dating of the isolation of Lake Boren, with a threshold at approximately 76 m a.s.l., at 8250 cal BC, agrees with earlier studies of isolation basins from the area around Linköping, suggesting that lakes with threshold elevations in the interval 72 to 77.6 m a.s.l. [23] were isolated from the Ancylus Lake. The isolation is likely to have taken place following the Ancylus transgression, which ended in approximately 8250 cal BC [18].

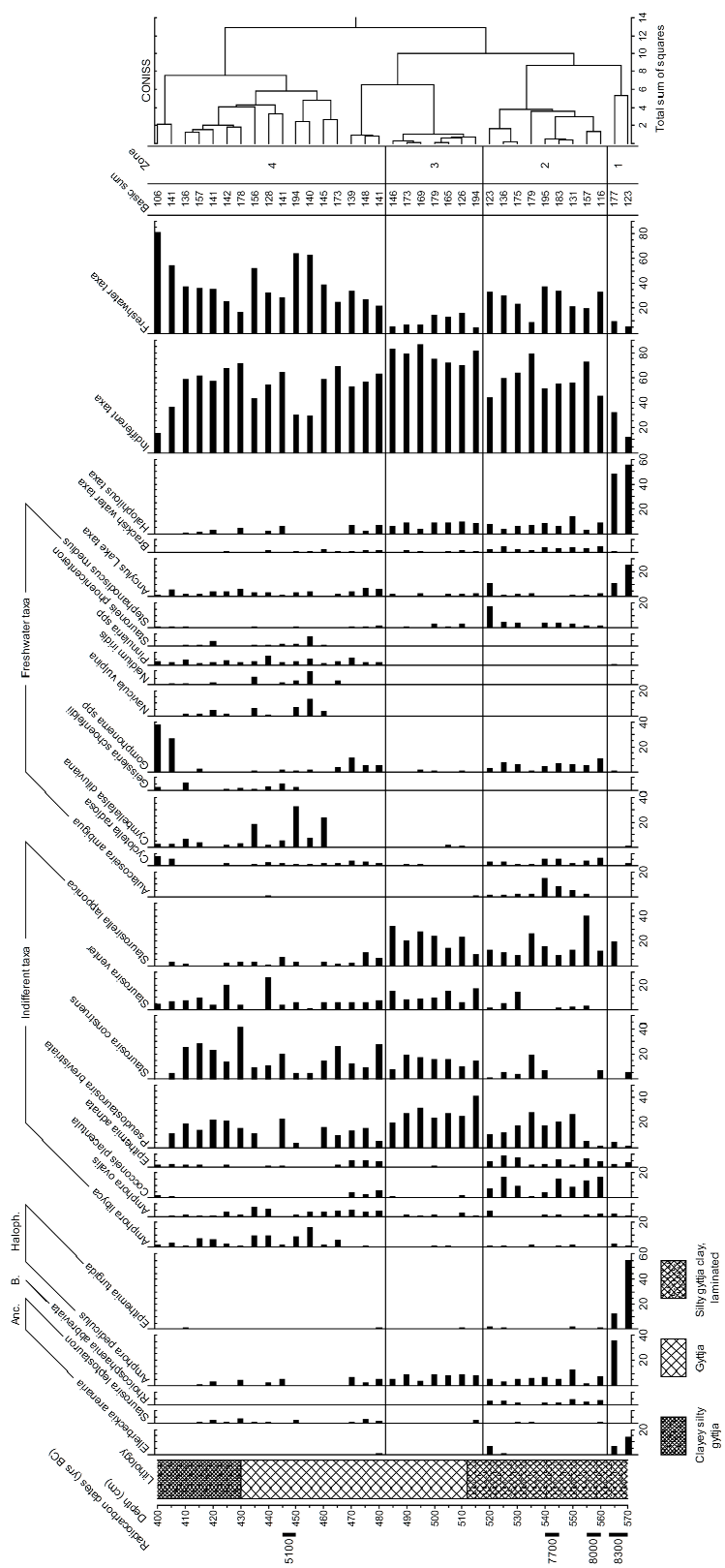


Figure 3. Diatom data from Lake Boren.

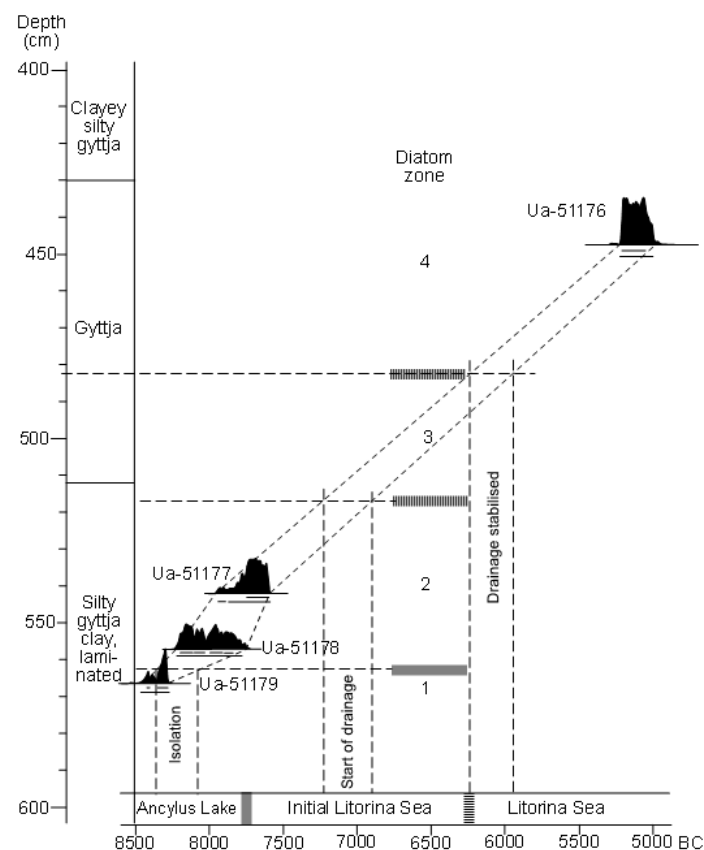


Figure 4. Chronology and sediment stratigraphy of sediment core from Karsviken in Lake Boren. Age-depth interval is based on linear interpolation of ^{14}C -dates (2σ error).

5.2. Strandvågen Sediment Records

Eleven macrofossil samples were analyzed directly from section C 13,059, but many more from adjacent sections. The text below describes results from mainly section C 13,059, but also from easily correlated sections. All terrestrial, telematic and aquatic plants were identified, as well as lithic, faunal, and archaeological macroscopic remains (Figure 5).

A total number of 29 pollen samples were analyzed from fluvial and aquatic sediments, and at least 400 tree pollen grains were counted in each sample. From section C 13,059, a total of 20 pollen samples were analyzed, and these are presented in Figure 6. To enhance the chronostratigraphical power of the pollen analysis, samples were screened at a lower magnification for pollen grains like *Alnus*, *Tilia*, *Picea* and *Cerealia*. The screening was done using 3–4 glass slides and a screening sum equivalent of ca. 2000 pollen. Pollen detected during screening is presented as 0.5 % in Figure 6.

The lowermost aquatic sediment in the stratigraphy (in several sections, from both Kanaljorden and Strandvågen) is a light brown-grey clay, identified as postglacial clay [34,35]. The uppermost part of the clay sediment contains a few macrofossils of *Empetrum nigrum* and *Potamogeton* sp. [34] These were probably deposited in a shallow near-shore environment during the last phase of the Yoldia Sea. There is little evidence of any erosion at the contact to the overlaying calcareous gyttja in section C 13,059.

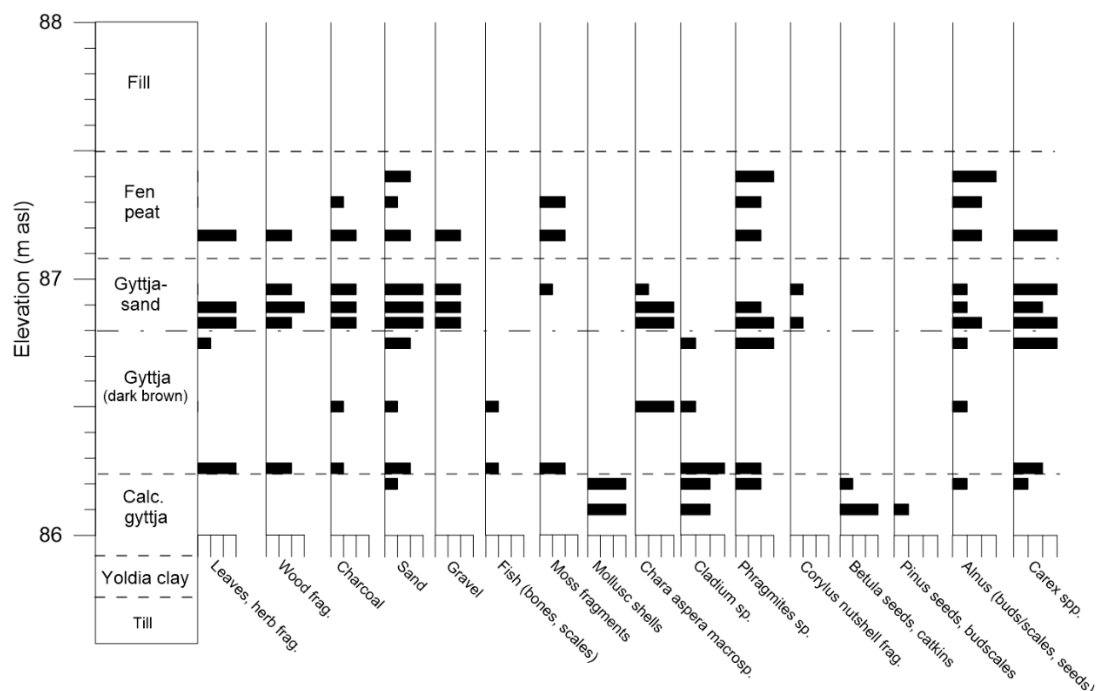


Figure 5. Macrofossil remains from section C 13,059 at Strandvägen. Mainly terrestrial and telematic/submerged organic plant material is presented, but lithic, faunal and archaeological macroscopic remains, relevant for water depth reconstruction and changes in the sedimentary environment, are also included. The material is quantified according to a three graded scale (1–3). For fragmented material, 1 represents single occurrences in the whole sample, 3 represents material dominating the sample, and 2 is the intermediate grade used when a type of macrofossil could be described as “common” within the sample. Seeds/fruits of *Cladium*, *Carex*, and all tree taxa are presented as amalgamated with tissue fragments, catkin scales, bud scales and macrospores. The scale is relative to the taxa in all samples; generally, 1 represents 1–9 diaspores, and 3 represents >50 diaspores.

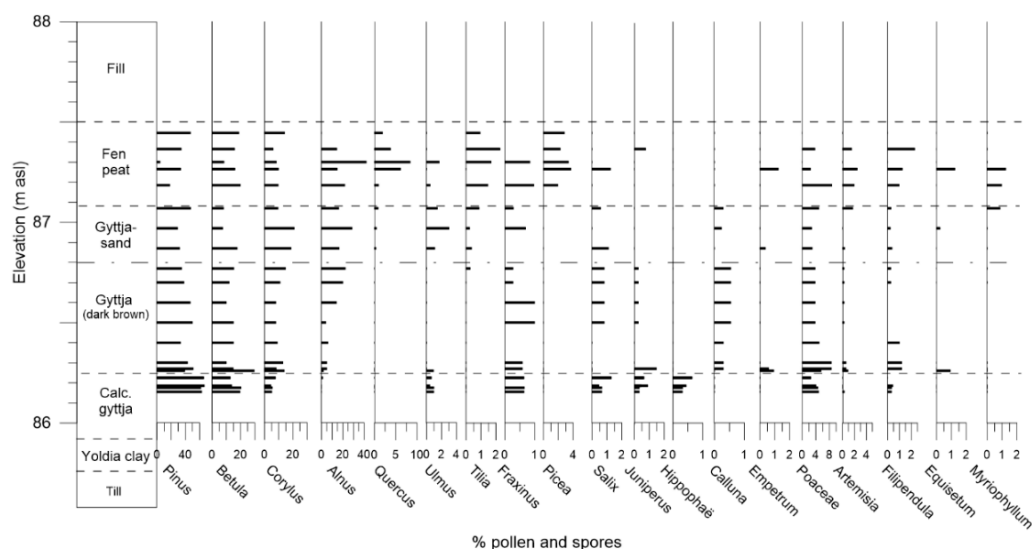


Figure 6. Pollen percentage data from section C 13,059.

From the sandy calcareous gytja, a total of nine macrofossil samples were analyzed, and two from section C 13,059 (Figure 5). The calcareous gytja is characterized by shell fragment of mollusks

and some precipitated carbonates (calcareous sand), and the clay/silt content increase slightly upwards from ca. 86.20 m a.s.l. The layer represents the shallow (but with low wave-energy) freshwater environment, in the small isolated basin called Lake Strandvågen (isolated after ca. 8800 cal BC). Remains of subaquatic mosses (Figure 5), and charales, e.g., *Drepanocladus* spp., *Chara* cf. *aspera* and *Nitella* cf. *opaca*, reflect the bottom flora in the shallower parts of Lake Strandvågen and Kanaljorden, but are absent in section C 13,059; probably because the section is from a deeper part of the basin, i.e., >2 m water depth [57]. Regular occurrence of terrestrial plant macrofossils, such as birch (*Betula* spp.), pine (*Pinus sylvestris* L.), lesser spearwort (*Ranunculus flamula* L.) and sedge (*Carex* spp.) indicate relative closeness to the shore, and possibly a rising water table leading to a successive inundation of the shore flora. The pollen data from the lower parts of the calcareous gyttja (Figure 6) show that alder (*Alnus glutinosa* L.) has not yet spread on the local shores, until the uppermost part of the calcareous gyttja, where alder pollen occur. This implies that the lower part of the calcareous gyttja is older than at least 7500 cal BC, when alder pollen increases in the Motala area [19]. However, in the uppermost part of the calcareous gyttja, alder pollen appears (Figure 6), and fruits of alder occur. On the dry land, around the small kettlehole lakes in Motala, pine, birch, hazel and grasses dominated the vegetation, with some elm (*Ulmus*) and ash (*Fraxinus*). There is no charcoal indicating human occupation in the calcareous gyttja, but a couple of edible weeds occur, such as shepherds-purse (*Capsella bursa-pastoris* L.), fat hen (*Chenopodium album* L.), and a seed of rowan berry (*Sorbus aucuparia* L.) The presence of those plants is notable, and possibly an indication of human presence, as implied by finds from Kanaljorden [13,35]. The uppermost part of the calcareous gyttja is dated to 8200–7600 cal BC (Figure 7, Table 2).

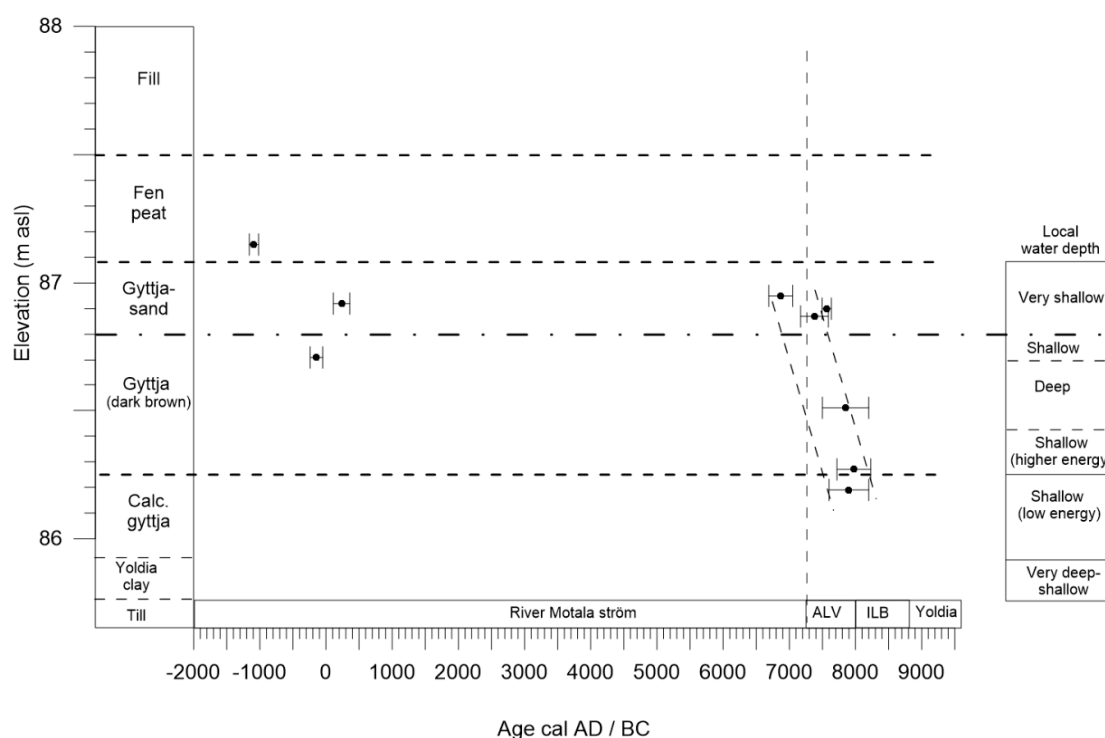


Figure 7. Stratigraphy and ^{14}C -dates (2σ error) of section C 13,059. The section contains sediment from the deepest part of the investigated basins in Motala. ALV = Ancient Lake Vättern transgression. ILB = Isolated Lake Basin (Lake Strandvågen). Diagonal dashed lines are suggested age-depth interval for the uppermost calcareous gyttja (ILB gyttja), dark brown gyttja (ALV gyttja) and lowermost gyttja-sand (River sediment). The boundary between the dark brown gyttja and the gyttja-sand is gradual and mainly based on sampling levels of macrofossils. The local water depth reconstruction is based on macrofossils and sediment properties, such as sand and silt/clay content.

Table 2. ^{14}C dates from Holocene stratigraphical sequences in Motala (Strandvägen and Kanaljorden). The ^{14}C ages were calibrated using the OxCal 4.2.4 software [43], and the INTCAL 13 calibration data set [44]. All dates relevant for stratigraphical interpretation are included. Several archaeological radiocarbon dates (over 200) are not included [58,59], and younger dates (*Corylus*) from section C 13059 are omitted but shown in plots.

Site	Locality	Section, Archaeological Context	Sediment Layer	m a.s.l.	Sample No	Dated Material	C^{14} -Age BP	Age cal a BC (2 σ)
Strandvägen	Cemetery	Mesolithic burial 02	Sandy filling	91.1	Ua-30873	Charred <i>Corylus</i>	7963 \pm 45	7050–6690
		Mesolithic burial 10	Sandy filling	90.85	Ua-31398	<i>Quercus</i> charcoal	8099 \pm 53	7310–6820
		Mesolithic burial 09	Sandy filling	90.32	Ua-31397	<i>Pinus</i> charcoal	8035 \pm 52	7140–6750
	Backwater	C 5257	River sediment (gyttja/sand)	87.78	Ua-31810	Nutshell <i>Corylus</i>	7187 \pm 122	6400–5800
	Western part of backwater	C 4248	River sediment (gyttja/sand)	87.76	Ua-29700	Seeds (<i>Betula</i>)	1566 \pm 65	–350––640
		C 4248	River sediment (gyttja/sand)	87.74	Ua-31811	Nutshell <i>Corylus</i>	7301 \pm 217	6600–5700
		C 4248	River sediment (gyttja/sand)	87.7	Ua-31812	Nutshell <i>Corylus</i>	6522 \pm 51	5610–5370
		C 4248	River sediment (gyttja/sand)	87.67	Ua-29701	Nutshell <i>Corylus</i>	6749 \pm 38	5730–5610
		C 4248	River sediment (gyttja/sand)	87.65	Ua-29702	Seeds (<i>Betula</i> , <i>Pinus</i> , <i>Scirpus/Carex</i>)	9119 \pm 85	8650–8200
		C 4248	River sediment (gyttja/sand)	87.58	Ua-31813	Nutshell <i>Corylus</i>	6684 \pm 40	5670–5520
		C 4248	River sediment (gyttja/sand)	87.52	Ua-31622	Seeds (fen plants)	9038 \pm 75	8450–7960
		C 4248	River sediment (gyttja/sand)	87.49	Ua-31621	Seeds (fen plants)	9419 \pm 72	9150–8450
		C 4248	River sediment (sandy gyttja)	87.48	Ua-31249	Wood (<i>Pinus</i>)	9045 \pm 58	8430–7980
		C 4248	River sediment (sandy gyttja)	87.41	Ua-29984	Seed (<i>Menyanthes</i>)	9356 \pm 78	8820–8330
	Eastern part of backwater	C 13059	River sediment (gyttja/sand)	86.9	Ua-54534	Wood (<i>Pinus</i>)	8532 \pm 38	7600–7530
		C 13059	River sediment (gyttja/sand)	86.9	Ua-31815	Wood (<i>Pinus</i>)	7961 \pm 46	7050–6690
		C 13059	River sediment	86.8	Ua-31816	Wood (<i>Salix</i>)	8354 \pm 95	7590–7170
		C 13059	Dark brown gyttja	86.5	Ua-31818	Wood (<i>Salix</i>)	8673 \pm 100	8200–7500

Table 2. Cont.

Site	Locality	Section, Archaeological Context	Sediment Layer	m a.s.l.	Sample No	Dated Material	C ¹⁴ -Age BP	Age cal a BC (2σ)
Kanaljorden	Southern basin	C 13059	Dark brown gyttja	86.3	Ua-31819	Seeds (<i>Scirpus/Carex</i>)	8834 ± 66	8230–7720
		C 243837	Calcareous gyttja	86.2	Ua-31820	Seeds (<i>Scirpus/Carex</i>)	8783 ± 48	8200–7600
		Log 3	Peaty gyttja	89.59	Ua-41617	Seeds (<i>Betula</i>), charcoal	6836 ± 43	5808–5638
		Log 3	Cobelly gravelly sand	89.46	Ua-41616	Seeds, catkin-bracts (<i>Betula</i>)	9016 ± 95	8468–7835
		Log 3	Calcareous gyttja	89.36	Ua-41615	Budscale, seed, bud (<i>Betula</i>)	9876 ± 186	10072–8806
		Log 3	Calcareous gyttja	89.23	Ua-41614	Seeds (<i>Scirpus/Carex</i>)	9699 ± 62	9288–8840
		P2861	Sandy gyttja	89.56	Ua-39277	Charcoal	8201 ± 43	7340–7070
		P2861	Sandy gyttja	89.46	Ua-41616	Seeds (<i>Betula</i>)	9016 ± 95	8468–7935
		P2861	Cobelly gravelly sand	90.88	Ua-51087	Charcoal, seeds (<i>Corylus</i>)	6903 ± 51	5899–5674
		P2861	Cobelly gravelly sand	90.47	Ua-51085	Charcoal, seeds (<i>Alnus</i>)	7223 ± 51	6215–6011
		P2861	Cobelly gravelly sand	90.45	Ua-51086	Charcoal, seeds (<i>Alnus</i>)	7192 ± 50	6210–5987
		P2861	Cobelly gravelly sand	90.42	Ua-54350	Nutshell <i>Corylus</i>	7302 ± 37	6231–6074
	Northern basin	wooden fish trap F362 in L187	Shell/Calcareous gyttja	88.95	Ua-41897	<i>Salix</i> twigs	6878 ± 40	5846–5670
		Log 5	Peat below calcareous gyttja	89.6	Ua-41951	Catkin-bracts, seeds (<i>Betula</i>)	9652 ± 82	9265–8801

The sharp contact between the calcareous gyttja and the overlaying dark brown silty/sandy gyttja could indicate erosion. However, the difference in macroscopic content of the two layers, together with the ^{14}C -dates, suggests only a limited hiatus and minor reworking of the calcareous gyttja (Table 2, Figure 7). Three macrofossil samples were collected from this dark brown gyttja, and it is possibly contemporary with the earliest traces of occupation in the area. The sand content is higher in the dark brown gyttja than in the calcareous gyttja, with the highest concentrations in the lowermost and uppermost part (86.25 and 86.75 m a.s.l.), indicating higher energy in the water (Figure 5). Plant macrofossils in the lower part of this layer are dated to 8200–7700 cal BC (Figure 7), and it is likely that the material was accumulated in Ancient Lake Vättern (ALV), after its transgression over Lake Strandvägen, probably shortly after ca. 8000 cal BC. This interpretation of ALV incursion is chronologically supported by the complete absence of *Tilia* pollen, as the ALV brings high concentrations of e.g., *Betula*-, *Corylus*- and *Juniperus* pollen into the small basin, and drown local shoreline shrubs such as *Hippophäe* and *Salix* (Figure 6). The plant macrofossils in the dark brown gyttja are dominated by species which commonly occur in the Mesolithic contexts at the site [9,34], and lack traces of the younger flora with meadow and weed vegetation, which characterize the medieval- and Iron age material at adjacent sites. The occurrence of elderberry (*Sambucus nigra* L.) and raspberry (*Rubus idaeus* L.) in the lower part of the gyttja may reflect Mesolithic gathering or the local flora. This interpretation is strengthened by the pollen flora, which contains early Holocene elderberry [35]. In e.g., the Czech Republic, elderberry has been found in Mesolithic archaeological contexts [60], but in Scandinavia, the earliest finds of seeds so far seem to be from the Middle Neolithic in Denmark [61]. Small amounts of charcoal occur in the middle and lower parts of the dark brown gyttja, possibly deriving from a contemporary occupation. The lowermost part of the unit is a coarse-detrital gyttja which is fining upwards from ca. 86.4 m a.s.l. This combination of changes in sand content, macrofossils and pollen are interpreted as a successive rise in the water level, leading to greater distance to the shore (Figures 5–7). Alternatively, the sediment could also be explained by reworking caused by a younger fluvial event, but the lack of plant macrofossils and pollen typical for the younger periods (e.g., *Picea* and *Tilia* pollen) make this unlikely. At 86.5 m a.s.l., the sediment is a fine-detrital gyttja with low sand content and high amounts of *Chara* sp. macrospores (oospores), indicating deeper water conditions (Figure 5). We interpret this sediment as deposited during the highest stand of ALV, reported to be 92.5 m a.s.l. by [27]. This would indicate that the local water depth at this time was at most six meters, which is very plausible, considering the micro- and macroscopic content. At 86.69 m a.s.l., a two cm sandy layer contains the lowermost distinct charcoal horizon (>20 frag.), and the charcoal is, because of the high concentration, most likely of anthropogenic origin. This level can be interpolated to be 7500–7000 cal BC (Figure 7), and probably reflect the first fall in water level in the Vättern basin, as River Motala Ström is formed, causing a sudden regression. It is unclear if the gyttja only contains material deposited in ALV, or if some of the organic material may be reworked from the substratum of calcareous gyttja. It is noteworthy that a part of the organic material seems to originate from occupational waste, not only elderberries and a high amount of charcoal, but also fish scales and fruits of floating sweet grass (*Glyceria flutans* L.) In Scandinavia, this tasty water grass is recorded as collected food during the Middle Neolithic and later, e.g., in Alvastra Pile dwelling [62]. In the uppermost part (ca. 86.7–86.8 m a.s.l.), the unit is again a sandy coarse-detrital gyttja, which may reflect a lowering of the water level, causing the shore to move closer with its vegetation of reeds (*Phragmites australis* L.) and rush (*Schoenoplectus lacustris* Palla). The lowering of the water table is connected to the channel erosion and successive down-cutting of River Motala Ström, during the first regression event in Lake Vättern. The first *Tilia*-pollen appears in the uppermost part of the dark brown gyttja (coarse-detrital gyttja at 86.77 m a.s.l.), which dates it to ca. 6200 cal BC or later [19], although the pollen grains appear to be corroded, which might indicate some redeposition.

Above the dark brown gyttja is a grey-brown sandier unit, with variable gyttja content, rich in e.g., gravel, charcoal, wood fragments and hazel nutshells (*Corylus avellana* L.) This sediment is interpreted as near-shore river sediment, deposited in the backwater adjacent to the Late Mesolithic

settlement, but probably exposed to, e.g., channel erosion and flooding events. The contact between the two stratigraphical units is gradual, and the boundary is set to 86.8 m a.s.l., mainly based on macroscopic content (Figure 5). The macrofossil content is similar to the near-shore material in other sections [34], but also contains some species indicating shallow and stagnant water e.g., mare's tail (*Hippuris vulgaris* L.), sedges (*Carex* sp.) and alder. This unit is the most well-dated of all at Strandvägen, with numerous dates of charred (and uncharred) hazelnuts, telmatic macrofossils and numerous archaeological finds [9,58] (Table 2). The age of the material is Late Mesolithic (mainly 6000–5000 cal BC), mixed with reworked older macrofossils, mainly originating from the calcareous gyttja. High concentrations of charales (*Chara* spp. and *Nitella* spp.) and mollusk shell fragments also corroborate this redeposition. The sediment texture of the layer seems to be composed of aggregated lumps of calcareous gyttja, a phenomenon characteristic for fine-grained sediments in fluvial regimes where the riverbed is eroded and redeposited. The pollen from the unit also indicates redeposition with slightly higher amounts of corroded pollen grains of mainly *Pinus*, *Betula* and *Ulmus*. However, the presence of uncorroded *Tilia*, and total absence of *Picea*-pollen (Figure 6), indicate that material younger or older than Late Mesolithic is unlikely to be present in the river sediment of section C 13,059. Younger dates occur in the upper parts of the unit, but these are from intrusive charred wooden stakes associated with a ritual context from early Iron age, belonging to the overlaying fen peat (Table 2).

Overlaying the river sediment is sandy fen peat (peat with coarse-detrital gyttja), rich in fragments of mosses, reed, and alder (Figure 5). The peat contains *Picea* pollen (Figure 6), which expanded in the Motala area during the early Iron age [19], and the unit is ^{14}C -dated to the same age (Figure 7), although rich in Mesolithic macrofossil material in other sections. The unit is most likely deposited during the Iron Age, a period with a slightly higher water level than the Mesolithic.

5.3. Kanaljorden Stratigraphy

The small Kanaljorden basin is situated in a more elevated location, and more exposed to wave erosion than Strandvägen, as indicated by more sandy, well-sorted sediments. However, the higher and more northerly location has most likely protected the site from river erosion. The ^{14}C -dated stratigraphy in Log 3 (Tables 2 and 3) corresponds to the different stages of the basin—the lowermost two (postglacial clay and calcareous gyttja) mirroring the sedimentary units in section C 13,059. However, unlike Strandvägen, in log 3 (Table 3), the postglacial clay is coarsening upwards into silt and sand, interpreted as reflecting the isolation of the small lake basin (Lake Kanaljorden) from the Yoldia Sea. The Kanaljorden calcareous gyttja is very similar to the calcareous gyttja of Strandvägen, both in organogenic and minerogenic material [35]. The lowermost gyttja is ^{14}C -dated on terrestrial macrofossils to an age around 9200–8800 cal BC, and the uppermost interpreted age of the unit is ca. 8400–7900 cal BC, based on a ^{14}C -sample of birch seeds and catkin scales from Log 3 (Table 2, Figure 8). The sample was taken at the bottom of the layer of sand at 89.46 m a.s.l., slightly above the calcareous gyttja. It is likely redeposited material from a reworked part of the uppermost calcareous gyttja. As the macrofossils are fragile and prone to destruction, it is likely a single short redeposition event. The sandy gravel unit above the calcareous gyttja (Table 3 and adjacent sections) represent a significant hiatus, most likely caused by the erosional ALV transgression. The following period, approximately 8000–6200 cal BC, few terrestrial macrofossils accumulate in the basin, apart from charcoal dated to ca. 7340–7070 cal BC (Table 2). A wicker fish trap was encountered in the Kanaljorden basin at ca. 88.95 m a.s.l. [59] (Table 2), corresponding to the top layer of the unit of sandy peaty gyttja in Log 3 (Table 3). This is interpreted as shallow lake sediments, or beach zone strata, deposited during a period when the Kanaljorden basin was in contact with Lake Vättern. This layer was later covered by sediment that formed in the small isolated lake sometime after 6200 cal BC, and by the man-made stone foundation that was built there shortly afterwards. The trap is dated to 5850–5650 cal BC, and ^{14}C -dates of archaeological material deposited on top of the covering stone-packing are only marginally younger [12], indicating that the fish trap was built shortly before the end of the beach zone phase. A series of four ^{14}C -samples that span the end of the phase is found in a 65 cm thick stratified

sequence of redeposited silt, sand and peat, at 91.2 m a.s.l. (Table 2). These samples cover the time period 6220–5730 cal BC, and suggest a similar terminus as the date of the fish trap. The overlaying peaty gyttja, deposited after 6220–5730 cal BC, indicates shallow water and low-energy conditions and is interpreted as representing an isolated lake/fen environment (Table 3).

Table 3. Lithology and sediment stratigraphy of Log 3 at Kanaljorden.

Lithology Log 3	m a.s.l.	¹⁴ C-Samples (m a.s.l.)	Interpreted Environment
Peat	>89.62		Fen/bog
Peaty gyttja	89.56–89.62	89.58–89.60	Fen
Sandy peaty gyttja	89.50–89.56		Beach deposit
Sandy gyttja	89.44–89.50	89.45–89.47	ALV transgression layer (erosional)
Gravelly sandy gyttja (w. cobbles)	89.44–89.50	89.355–89.375	
Calcareous gyttja	89.18–89.44	89.22–89.24	Isolated lake basin (ILB)
Blue-grey clay	89.14–89.18		Yoldia Sea clay
Boulders	89.08–89.14		Glacial till

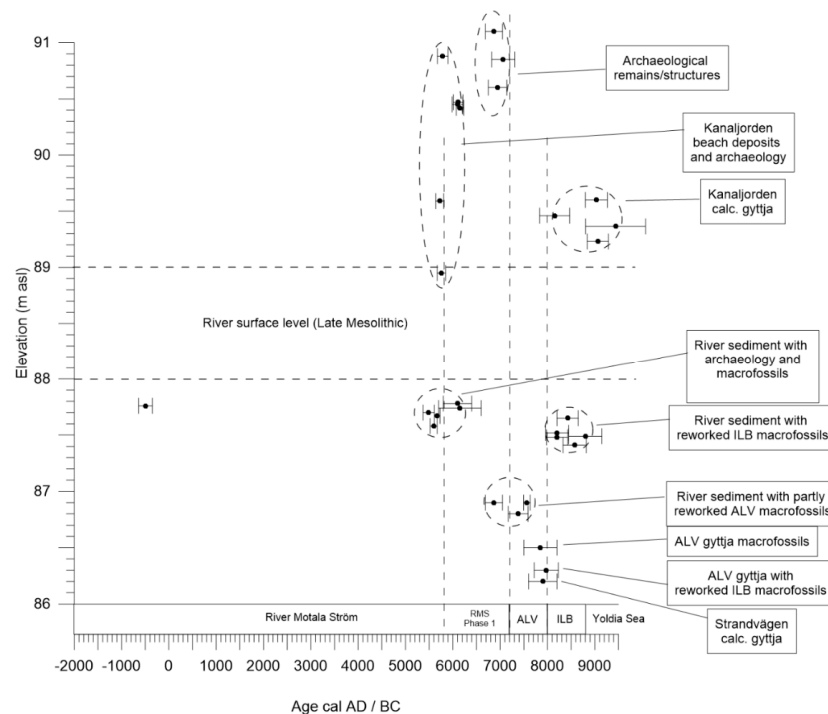


Figure 8. ¹⁴C-dates (2σ error) from the isolated lake basins (ILB) calcareous gyttja (Lake Strandvägen and Lake Kanaljorden), Ancient Lake Vättern (ALV) transgression sandy units (Kanaljorden), ALV gyttja (Strandvägen), and river sediment (Strandvägen). Dates from sediment units in several sections, and at slightly varying elevation, are included in the figure. The ILB stage begins around 9000–8800 cal BC, with the accumulation of calcareous gyttja. The ILB stage ends sometime after 8000 cal BC—a short hiatus (less than 400 years) is likely as the calcareous gyttja is eroded by the ALV transgression. The ALV transgression reaches 92.5 m a.s.l. around 7500–7000 cal BC, according to dates from ALV gyttja, and dates from cultural structures/deposits indicate the regression to begin around 7200 cal BC. After the rapid regression, during River Motala Ström (RMS) phase 1, Lake Vättern is likely at a still-stand between 90.5–91.5 m a.s.l., and in contact with the Kanaljorden basin, where sandy layers are deposited. During this period, few terrestrial macrofossils accumulate in the basins. At ca. 5800 cal BC, archaeological material accumulates en masse around both archaeological settlements, as Lake Vättern falls to around 88.5 m a.s.l., completely isolating the Kanaljorden basin. The Strandvägen basin came in contact with the river, with partial erosion and redeposition of older sediments. Mainly the shallow, marginal parts of the Lake Strandvägen calcareous gyttja are reworked, and macrofossils are redeposited in the river sediment. Mesolithic ¹⁴C-dates are presented in Table 2.

6. Discussion

6.1. The Tilting of Lake Vättern and the Northern Outlet

The N-S tilting of the Lake Vättern basin after the isolation in the north would have created an increasing available basin volume. Possibly, a large portion of the ALV water surplus (net runoff) would instead be swallowed by the continuously increasing available volume, negating or at least minimizing the northern outlet discharge. The pivot point for the tilting process was located at the northern threshold, meaning the whole basin experienced the ALV transgression, whereas as soon as River Motala Ström formed, the pivot point moved to Motala, and a regression began in the northern part of the basin. It is possible that this meant that no northern outlet existed during the ALV-stage in the early Holocene [22], depending on the rate of tilting.

6.2. The Ancylus Lake in the Vättern Basin?

The Ancylus transgression maximum around 8300–8200 cal BC has been recorded in the southern Baltic area but is not well documented further north [63]. According to [33], the Ancylus Lake and the Initial Littorina Sea reached into the Vättern basin before it was completely isolated from the Baltic basin. However, this interpretation seems to hinge on a few radiocarbon dates of unknown organic material. In our reconstruction, we have assumed that the minimum level of the ALV was 83 m a.s.l. (Figure 9; 80–86 m a.s.l. has been suggested as the ALV minimum [27,30]). This level is similar to the level of the Ancylus transgression shoreline found near Lake Boren, well below the threshold at Motala. According to [27], pronounced beach deposits are situated in the Askersund area at 104 m a.s.l., and these are interpreted as remnants of the Ancylus transgression maximum, inferring that the Ancylus transgression never entered the Vättern basin. Furthermore, in Närke, studies of small lake basins at 61.5–62.5 m a.s.l. showed they were isolated from the Initial Littorina Sea [52,64], making the presence of the Ancylus Lake, or the Initial Littorina Sea, in the Vättern basin improbable.

However, judging solely from the data presented in this paper, it is still possible that the early part of the ALV phase might have been in contact with the Ancylus Lake through a northern connection. Future studies of the isolation sequence from small lake basins in the Askersund area might help clarify this problem.

6.3. Dating River Motala Ström and the River Formation Process

The small kettlehole basins, Lake Strandvägen and Lake Kanaljorden, emerged from the Yoldia Sea around 9000–8800 cal BC, and in the isolated lake basins (ILB), the accumulation of calcareous gyttja started. The ILB stage ended sometime after 8000 cal BC (probably 8000–7600 cal BC), as the calcareous gyttja was eroded by the ALV transgression (Figures 8 and 9).

As the local transgression continued, the threshold at 92.5 m a.s.l. was reached around 7200 cal BC, and River Motala Ström was formed. The age is based on all available dated events: the interpolated Lake Boren diatom signal (7200–6900 cal BC), the archaeological structures and deposits at 90.5–91 m a.s.l. (7200–7000 cal BC), and the interpolated water depth decrease in section C 13,059 (7500–7000 cal BC). The ALV transgression left distinct beach ridges at Motala at a level of ca. 92.5 m a.s.l. [22,27]. It is possible that the rising shoreline in Motala caused massive groundwater infiltration into the glaciofluvial deposits, effectively slowing the transgression as it reached above ca. 90 m a.s.l. The groundwater aquifer in the sand and gravel material would then have been drained by springs on the eastern slope of the esker. These would, in turn, have created a small stream which drained into the Lake Boren basin. The rising ground water table of the glaciofluvial deposit would also have affected the water level of the two small isolated lake basins, making it rise as the ALV transgression progressed. In log 6 and 3 at Kanaljorden, and section C 13,059 at Strandvägen, the fining-upwards of the calcareous gyttja, and the macrofossil record indicate a water depth increase prior to the ALV transgression.

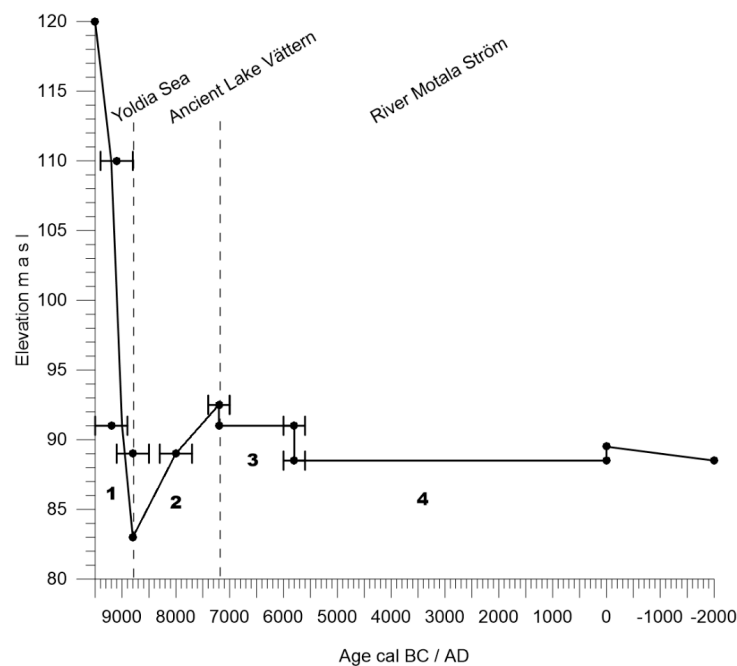


Figure 9. Shore displacement history in Motala. (1) The Yoldia Sea shoreline fall from ca. 120 m a.s.l., and Fågelstakärret fen (110 m a.s.l.) [19], Lake Kanaljorden (estimated threshold 91 m a.s.l.), and Lake Strandvägen (estimated threshold 89 m a.s.l.) become isolated around 8800 cal BC. Ancient Lake Vättern (ALV) is isolated from the sea and drops to ca. 83 m a.s.l. (80–86; [27,30]). (2) ALV transgression starts as the northern connection is closed or possibly begin as part of the Ancylus Lake transgression. The Strandvägen and Kanaljorden basins become inundated shortly after 8000 cal BC. (3) River Motala Ström is first formed between 7500–6900 cal BC, and this first channel head (at the first rapid) was located east of Strandvägen. As it quickly erodes through glaciofluvial deposits, the Lake Vättern water level drops to ca. 91 m a.s.l. The Strandvägen site becomes an island, with early settlement remains, and the Kanaljorden basin most likely becomes part of the Lake Vättern beach zone during the Lake Vättern stillstand. (4) At 5800 cal BC, the headward erosion has moved the channel head west to Strandvägen, and the Lake Vättern shoreline falls to ca. 88.5 m a.s.l., or slightly higher. The main Mesolithic settlements are founded at the first rapids. During the Early Iron Age (ca. 200 cal BC–100 cal AD), the mean water level rises slightly, accommodating for accumulation of fen- and river peat in the backwater at Strandvägen. Events are based on one or several ^{14}C -dated (2σ error) units or records.

During this first phase of River Motala Ström (Figure 9), the channel head (the first rapids) would have been located further east, gradually eroding the glaciofluvial deposits of the Lake Vättern threshold. It is a very likely scenario, even though this glaciofluvial threshold today is completely gone. Through headward erosion, the channel head then migrated upstream, to the west. It is uncertain if the threshold erosion and channel cut-down process was slow or sudden, but the dated archaeological shoreline deposits at 90.5–91 m a.s.l. favor the explanation with two threshold erosion events at ca. 7200 and 5800 cal BC (Figures 8 and 9). Moreover, the well-preserved raised beaches located 90–91 m a.s.l. at Varamon in Motala [5], and at Brevik on the western side of Lake Vättern [22], suggest an extended period of still-stand at 91 m level. The still-stand came to an end around 5800 cal BC, and the wetland basin at Kanaljorden became once more a small isolated lake, without any connection to Lake Vättern nor the river (Figure 9). This small lake became a place of ritual deposition of the selected parts of disarticulated humans and animals, as well as artefacts and tools of bone, antler and stone [12,65]. The ritual depositions date to a time span of perhaps 200 years and then ceased. Around the same time, the lake was gradually overgrown by reeds and turned into a fen.

It is possible that the Holocene climatic evolution has played a role in the threshold, and channel, erosion process. Beginning around 6200 cal BC, the so-called 8200-event marked the onset of the

Northgrippian period [66], which may have brought increased effective moisture, as lower evaporation compensated for reduced precipitation [67]. The event itself may, however, not have brought wetter climate in Scandinavia, but a shift to higher precipitation amounts, or increased effective moisture, might have begun after the event itself, around 6000 cal BC (e.g., [68]). Such a climate change might have raised the regional lake water levels, and eventually, triggered an erosion event as the river discharge increased.

As the river course stabilized, it gave the hunter-gatherers in Motala excellent regional contact routes, and the basis for a more sedentary lifestyle. The archaeological record suggests a year-round presence during the Late Mesolithic, mostly relying on stationary fishing [9]. And perhaps, the people who lived by the river shared tales around the hearth of the day when the river began.

Author Contributions: Conceptualization, J.B.; Investigation, J.B., A.P., L.H., F.H., J.R., and F.M.; Writing—original draft presentation, J.B., A.P., J.H., L.H., F.H., J.R. and F.M.; Writing—review and editing, J.B., A.P., F.H. and F.M.; Methodology, J.B., A.P., J.H. and J.R.; project administration, F.H. and F.M.; Funding acquisition, F.H. and F.M. All authors have read and agreed to the published version of the manuscript.

Funding: The archaeological excavations in Motala have been conducted within the Swedish contract archaeology system and have been funded by the Swedish Transport Administration after the decision from the local authorities of the cultural heritage sector, the County Administration of Östergötland.

Acknowledgments: We would like to thank the three anonymous reviewers for their valuable comments on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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