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Tilting of Lake Pielinen, eastern Finland – an example of extreme transgressions and regressions caused by differential post-glacial isostatic uplift

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Abstract. Tilting of large lakes due to differential isostatic uplift in the glaciated regions of the Northern Hemisphere is a well-documented process. With the help of accurate digital elevation models and spatial GIS analysis techniques, the resulting hydrological changes, including shifts in the outlets and changes in the size and configuration of lakes, can now be mapped and calculated more precisely than before. As a case study to highlight the magnitude of such changes in Fennoscandia, we investigated and reinterpreted the Holocene palaeogeography and palaeohydrology of Lake Pielinen in eastern Finland. This lake is currently 99 km long and located parallel to the direction of land uplift, being thus particularly sensitive to the impacts of tilting. Our results show that the lake was formed at the end of the regional deglaciation, following drainage of a local ice-dammed lake. In its initial stage until 10 200 cal yr BP, the outlet of the newly-formed lake was located in its northwestern end, but the tilting led to a major water level transgression in the basin, eventually causing formation of a new outlet over the southeastern threshold. The lake area was 143 km long and its area was 1998 km^2 at the time of formation of the southeastern outlet at 10 200 cal yr BP. The lake level has been regressive throughout the basin during the last 10 200 years. This regression will continue for approximately another 10 000 years until all the glacial isostatic adjustment has occurred, after which Lake Pielinen will be only 89 km long and 565 km^2 in area.

Key words: glacial isostasy, post-glacial uplift, lake tilting, future projection, GIS modelling.

INTRODUCTION

The differential post-glacial land uplift in the glaciated regions of the Northern Hemisphere, mainly in Fennoscandia and North America, results from geophysical processes associated with differential surface loads caused by large ice sheets during the last glaciation (Lambeck 1999). In Fennoscandia, the ice sheet was thickest (over 2.5 km) in northern Sweden (Ehlers 1990) and the post-glacial uplift follows the thickness pattern of the ice sheet, with the most rapid (at present 11 mm yr^{-1}) absolute uplift in the Gulf of Bothnia (Milne et al. 2001). The uplift is, relative to the sea level, ~9 mm yr^{-1} (Ekman 1996), becoming radially slower towards the perimeters and decreasing to 0 mm yr^{-1} in the southeastern and southern Baltic Sea and western Russia (Fig. 1). The only area in the world with a higher current land uplift rate is located in the Hudson Bay area, where even relative uplift exceeds 10 mm yr^{-1} (Lambert et al. 1998).

During the post-glacial period the differential uplift has had a major impact on the development and configuration of seas, lakes and rivers in the glaciated areas. Both in Fennoscandia and North America, the differential uplift continues to influence hydrology of the rivers crossing the regional isobases, with the river valley gradient either increasing or decreasing, depending on whether the rivers run against or along the direction of the tilting. Even more conspicuous are the hydrological changes in large lakes located parallel to the direction of the tilting. The tilting is causing the southward expansion of Lake Winnipeg (Lewis et al. 2001), while Lake Vättern, the second largest lake in Sweden, has tilted so that the water level at its southern end has risen 25 m during the last 8000 years (Norrman 1964; Nilsson 1968). Trangressions of such magnitude can often cause the formation of new outlets, as has occurred in Lake Saimaa, the largest lake in Finland, which originally drained into the Baltic Sea basin from its northwestern end, but whose outlet since 5700 calibrated years before present (cal yr BP) has been located in its southeasternmost end (Saarnisto 1970).

In Finland, lake transgressions and shifts in outlets have been particularly common and conspicuous, due to evenness of the landscape and lack of major topographical barriers. The oldest lakes are located in eastern Finland, where a number of lakes were isolated from the Baltic Sea when the Baltic Ice Lake drained to the global sea level and large areas of dry land emerged (Hyvärinen 1966; Tikkanen & Oksanen 2002; Miettinen 2004; Rainio & Johansson 2004; Tikkanen 2006; Miettinen et al. 2007). However, most lakes in Finland have became isolated

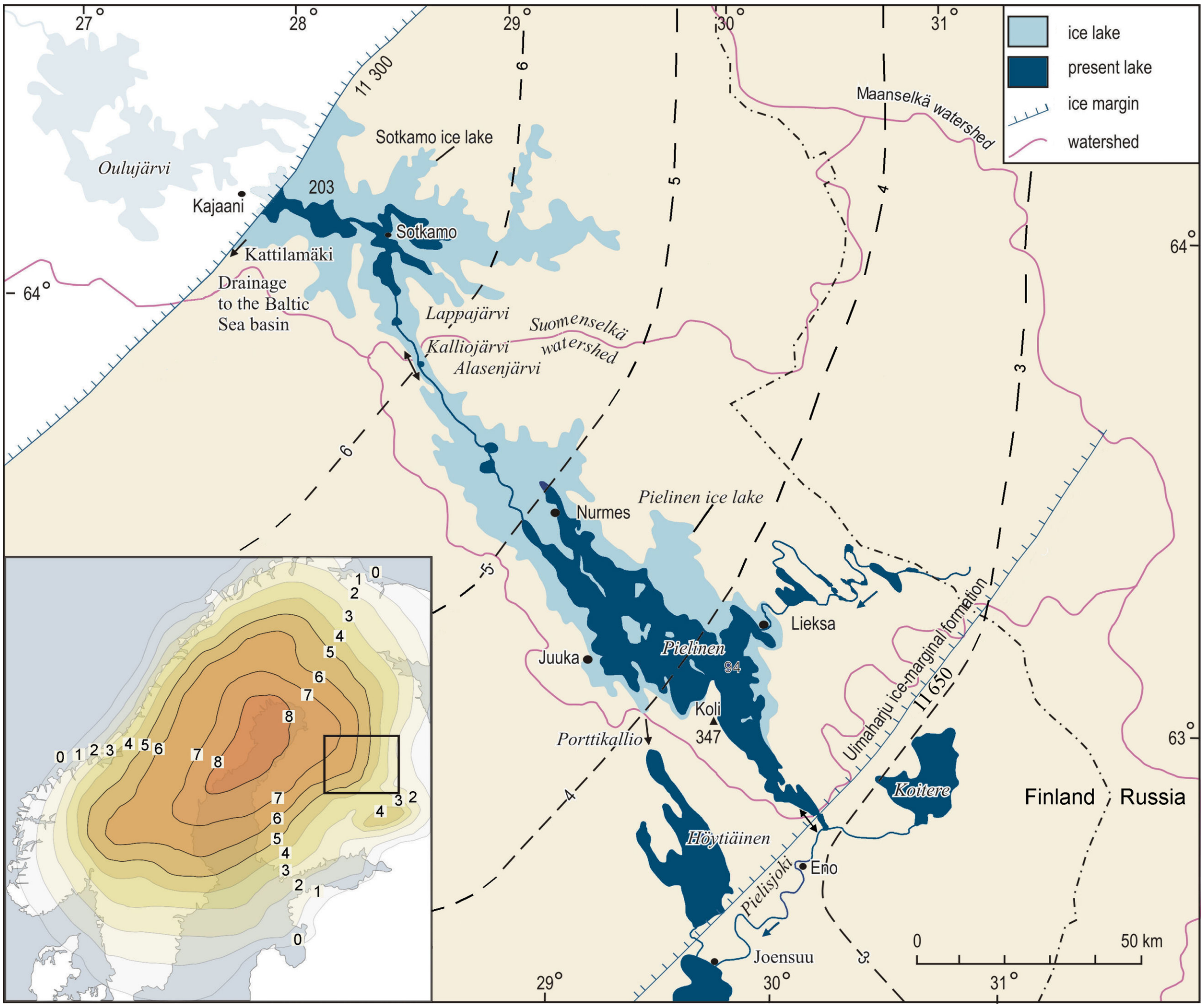


Fig. 1. Study area and its location in the eastern part of the Fennoscandian uplift area and the extent of the Pielinen–Sotkamo ice-dammed lake. The modern land uplift isobases mm yr^{-1} (Kakkuri & Virkki 2004) are indicated by the stippled line and the positions of the ice sheet margin at 11 650 cal yr BP and 11 300 cal yr BP by the solid line.

during the later Holocene stages of the Baltic Sea (Saarnisto 1971, 2000; Seppä et al. 2000; Tikkanen 2002, 2006; Seppä & Tikkanen 2006). After their formation, the large lakes and lake systems in Finland experienced significant changes, due to the differential land uplift that has caused shifts in the outlets and water level transgressions and regressions, depending on in which part of the lakes the outlets have been located. Of the largest lakes in Finland, nine have shifted their outlets at least once, and some even twice or three times. The large lake systems and the lakes in eastern and central Finland drained first into the northwest to the northern Baltic Sea, until the differential land uplift led to the formation of the present outlets (Saarnisto 1971; Tikkanen 1990, 2002). The outlet shifts 10 000–5000 years ago caused the main watershed to be relocated over 300 km southwards (Tikkanen 2002, 2006). Moreover, there have been many smaller watershed re-locations and shifts in lakes from one lake system to another (Heikkinen & Kurimo 1977; Tikkanen & Seppä 2001; Seppä & Tikkanen 2006).

Studies of lake development have traditionally been based on observations of ancient shorelines. Recently, the use of geographical information techniques (GIS) has made it possible to map and model past hydrological changes, including shifts in outlets and lake sizes, more precisely than before (Mann et al. 1999; Tikkanen & Oksanen 2002; Meyer 2003; Rosentau et al. 2004; Yang & Teller 2005; Pajunen 2006). Moreover, timing of the major transgressions and regressions, and possible associated shifts in the outlets, can now be more precisely dated, using AMS radiocarbon datings. To demonstrate the opportunities provided by the new technical approaches and to highlight the magnitude of impact of differential tilting on lake development, Lake Pielinen in eastern Finland was selected for this study, because it has several characteristics that make it ideal for exploring the impact of post-glacial tilting on lake development. The lake is elongated, with a maximum length of 99 km, and its longest axis is located parallel to the direction of tilting. Previous investigations in the region have indicated that the lake once had an older outlet at the northwestern end of the basin and that the new outlet at the southeastern end was formed due to tilting and associated water transgression. Prior investigations of changes in the direction of drainage and their chronology were based on ancient shorelines, varve clay counts and radiocarbon datings (Kilpi 1937; Hyvärinen 1966; Miettinen 1996; Saarelainen & Vanne 1997). The aim of this study is to re-assess the main events in the outlet shifts and development of Lake Pielinen in the light of current understanding. Furthermore, the goal is to illustrate and analyse the large spatial and volumetric changes associated with the large transgressive and regressive phases in lake history, using the GIS-based spatial models, palaeogeographic maps and the new AMS datings.

STUDY AREA AND THE ICE-DAMMED LAKE

Modern lake

Lake Pielinen (894.21 km^2, 93.7 m above sea level (a.s.l.) (Ymparisto.fi 2010) is located in eastern Finland and drains into Lake Saimaa and eventually into the Gulf of Finland (Fig. 1). Unlike other large lakes of the Vuoksi drainage area, Lake Pielinen has never been part of the ancient Suur-Saimaa lake complex that evolved due to tilting during the Holocene (Saarnisto 1970). The Pielinen watercourse is bordered in the northeast by the Suomenselkä watershed and in the east by the Maanselkä watershed, which is also the main watershed between the Baltic Sea and the White Sea in the east. The lake drains in the southeast through the Uimaharju ice-marginal formation, where the outflow channel crosses the modern road- and railway embankment, into the small Lake Rahkeenvesi, whose regulated surface is only 10 cm lower than the level of Lake Pielinen. The outflow river of Lake Pielinen, the Pielisjoki River, begins from Lake Rahkeenvesi and flows into Pyhäselkä (75.9 m a.s.l.), which is part of Lake Saimaa (Fig. 1).

The length of Lake Pielinen is 99 km, maximum width 28 km, and it has 1259 islands, each over 10 m^2 in area. The highest point of the shoreline is the quartzite mountain of Koli (347.2 m a.s.l.), whose peak rises 253.5 m above the level of the lake. The towns of Lieksa and Nurmes are located on the shore of the lake. The area of Lake Pielinen used in this study is 927 km^2, which is 3.6% larger than the official area of 894 km^2 (Ymparisto.fi 2010). The difference is caused by the fact that the method used here for spatial analysis is based on 100 × 100 m grids, covering numerous small islands whose total area is excluded from the data (see Mäkiaho 2007). This same methodological error concerns all values given in Table 1, which are thus slightly too high.

Deglaciation and the ice-dammed lake

The post-glacial development of the Pielinen basin began when the ice sheet margin retreated to Uimaharju, at the southeastern end of the lake, where the Uimaharju marginal formation was formed in front of the momentarily stagnant ice margin. Hyvärinen & Rainio (2000) and Rainio & Johansson (2004) date this event to 11 400–11 300 cal yr BP. However, Svendsen et al. (2004) showed that the Uimaharju marginal formation was formed at the same time as the second Salpausselkä ice-marginal complex, from where the ice sheet margin started to retreat at the end of the Younger Dryas stadial, at about 11 650 cal yr BP (Rasmussen et al. 2006; Donner 2010). When the ice sheet margin retreated from Uimaharju, the current basin of Lake Pielinen started to become ice-free. The southern parts of the basin were at first connected through narrow straits to the Yoldia Sea (Kemiläinen 1982; Miettinen 1996; Tikkanen & Oksanen 2002), but rapid land uplift turned the straits into outlet channels, forming this way the Pielinen ice-dammed lake. Its first outlet flowed through Uimaharju in the southeast, but the retreat of the ice margin opened new outlet channels in the Porttikallio region in the west (Fig. 1).

Table 1. Changes in the surface area and water volume of Lake Pielinen during its post-glacial development. 10 kAP = 10 000 years after present

	Ice lake >11 300 cal yr BP	Initial lake stage ~11 300 cal yr BP	Bifurcation 10 200 cal yr BP	Pielinen at present	Post-uplift Pielinen 10 kAP
Surface area, km^2	2276	1639	1998	927	565
Volume, km^3	51.67	29.92	36.80	9.15	5.01

When the ice sheet margin retreated from the Pielinen basin to the Suomenselkä watershed, northwest of the modern lake, a connection was formed through a narrow, rocky strait between the ice-dammed lakes of Pielinen and Sotkamo. As a result, the waters of the Sotkamo ice-dammed lake started to flow southwards through the Koposenvaara outlet. These two ice-dammed lakes remained at the same level until the ice sheet margin retreated to the Kattilamäki region south of the city of Kajaani (Fig. 1). At that stage, rapid land uplift caused the outlet to shift from Koposenvaara back to Uimaharju (Hyvärinen & Rainio 2000). At its maximum stage, the Pielinen–Sotkamo ice-dammed lake formed a 200 km long twin-basin, 3975 km^2 in area, of which the area of the Pielinen ice-dammed lake was 2276 km^2 (Fig. 1, Table 1).

The main event in the early post-glacial history of the lake was the end of the ice-dammed lake stage, which occurred when a new outlet channel was opened on the northern side of the Kattilamäki hill, through which the large ice-dammed lake drained into the Baltic Sea basin. The varve chronology suggests that the drainage occurred in seven years (Kilpi 1937) and the signs of the major drainage can still be seen in the Kattilamäki region as strongly outwashed rocks and extensive gravel and sand plains (Kilpi 1937; Kemiläinen 1982). As the water level fell, the strait connection of the ice-dammed lake over Kalliojärvi dried and Lake Pielinen was isolated as a separate lake. Since the date when the ice-dammed lake drained defines the onset of Lake Pielinen, one of the aims of this study was to obtain a revised, more reliable age for the drainage that would be consistent with new information on the deglaciation chronology in eastern Fennoscandia.

MATERIAL AND METHODS

Visual observations and loss-on-ignition (LOI) analyses of the basal sediments deposited at the bottom of small lakes located in ancient outlet channels often reveal a clear boundary layer separating the underlying coarse sediments, accumulated by ancient rivers or deeply eroded basal clays, and the overlying lacustrine gyttja and mud reflecting the stagnant water after drying of the channel (Tikkanen 1995; Tikkanen & Seppä 2001; Pajunen 2006; Seppä & Tikkanen 2006). We collected sediment samples from four lakes from different parts of the ancient outlet channels of Lake Pielinen to investigate the developmental stages and periods of activity and drying of the channels. The sediment samples were taken from Lake Iso-Rokka (Fig. 2), a small lake located near the Kattilamäki region in the outlet channel of the ice-dammed lake and from Lake Lappajärvi, located at the northern end of the ancient outlet channel, northwest of the Suomenselkä watershed, and from two small ponds, Rommakkolampi and Alasenjärvi, in the ancient outlet channel near the northwestern end of the lake (Fig. 3). The sampling was carried out with a Russian peat sampler (Jowsey 1966) through the ice at Lappajärvi and Alasenjärvi, whereas Iso-Rokka and Rommakkolampi were sampled during the summer from small mires at the margins of the lakes.

To investigate the changes in organic content of the sediment, the LOI analysis at 550 °C was conducted from all sediment cores. Eight AMS radiocarbon dates were obtained from bulk sediment samples from selected levels of the cores, indicating the main changes in the outlet channels and, hence, in the history of Lake Pielinen (Table 2). The dates were calibrated with Calib 5.5 software (Stuiver et al. 2009). The various developmental stages, their spatial extents, and volumes of the lake were depicted with palaeotopographical GIS methods (Mann et al. 1999; Leverington et al. 2002; Mäkiaho 2007), using direction 305° as the maximum tilting axis. Topographic data required in these analyses were extracted and compiled from official National Land Survey digital products. Since these data do not include readily available bathymetric information, we extracted all the data including height/depth information and compiled a 25-m resolution digital elevation model (DEM) covering the entire study area, as required in spatial and volumetric analyses, using a topo-to-raster algorithm in the ArcGIS environment.

RESULTS

Drainage of the ice-dammed lake

Lake Pielinen was formed when the ice sheet margin passed the Kattilamäki hill and the ice-dammed lake drained. To obtain new information on the timing of this event, AMS datings were made from the basal organic sediments at the bottom of the drainage channel. The clearest drainage channel in the Kattilamäki region is the channel which is currently 150–200 m wide at its narrowest point, has a flat bottom and is covered by peatlands and two small lakes, Iso Ruuhijärvi (176.8 m a.s.l.) and Iso-Rokka (176.3 m a.s.l.) (Fig. 2). The bottom of this channel remains at the same level over a distance of about 5 km. The highest point of the bottom of this channel is around Lake Iso-Rokka at 178 m a.s.l. (Fig. 2). It is the lowest threshold point in the region and the waters of the ice-dammed lake thus flowed through it during the final stage of the ice-dammed lake. A sediment core was taken from the basin of Iso-Rokka.

When the drainage of the ice-dammed lake was over, the flow of water in the channel ended abruptly and the lacustrine sediment began to accumulate in the small basins in the channel. The results show that the strong

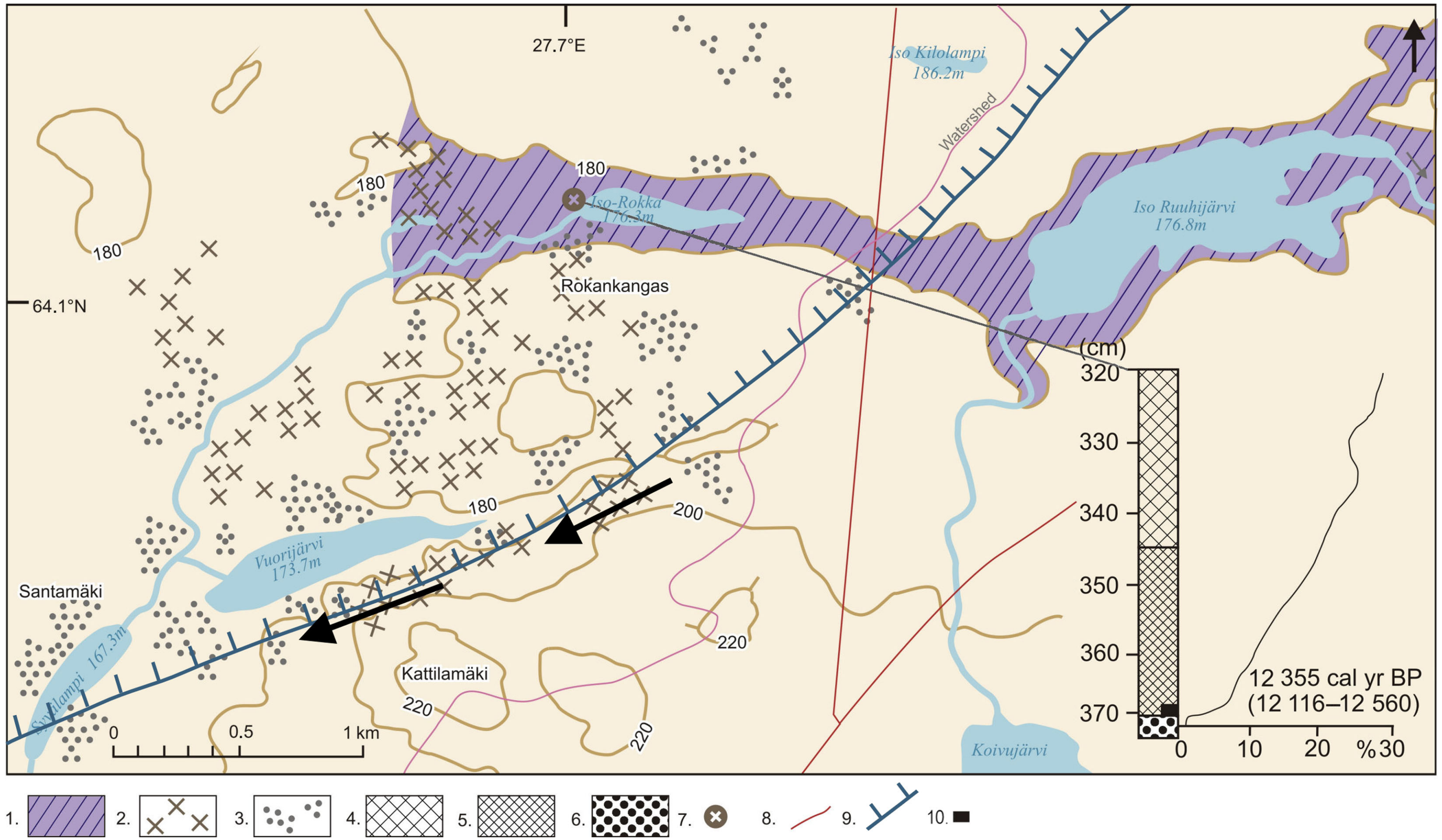


Fig. 2. The drainage channel at Kattilamäki and the lithology and LOI curve of Lake Iso-Rokka. The arrows indicate the direction of the drainage of the ice-dammed lake. 1, Drainage channel of the ice-dammed lake; 2, washed rocks; 3, boulder fields; 4, gyttja; 5, clay-gyttja; 6, stony sand and gravel; 7, sample site; 8, road; 9, ice-marginal position at the beginning of the drainage; 10, AMS datings.

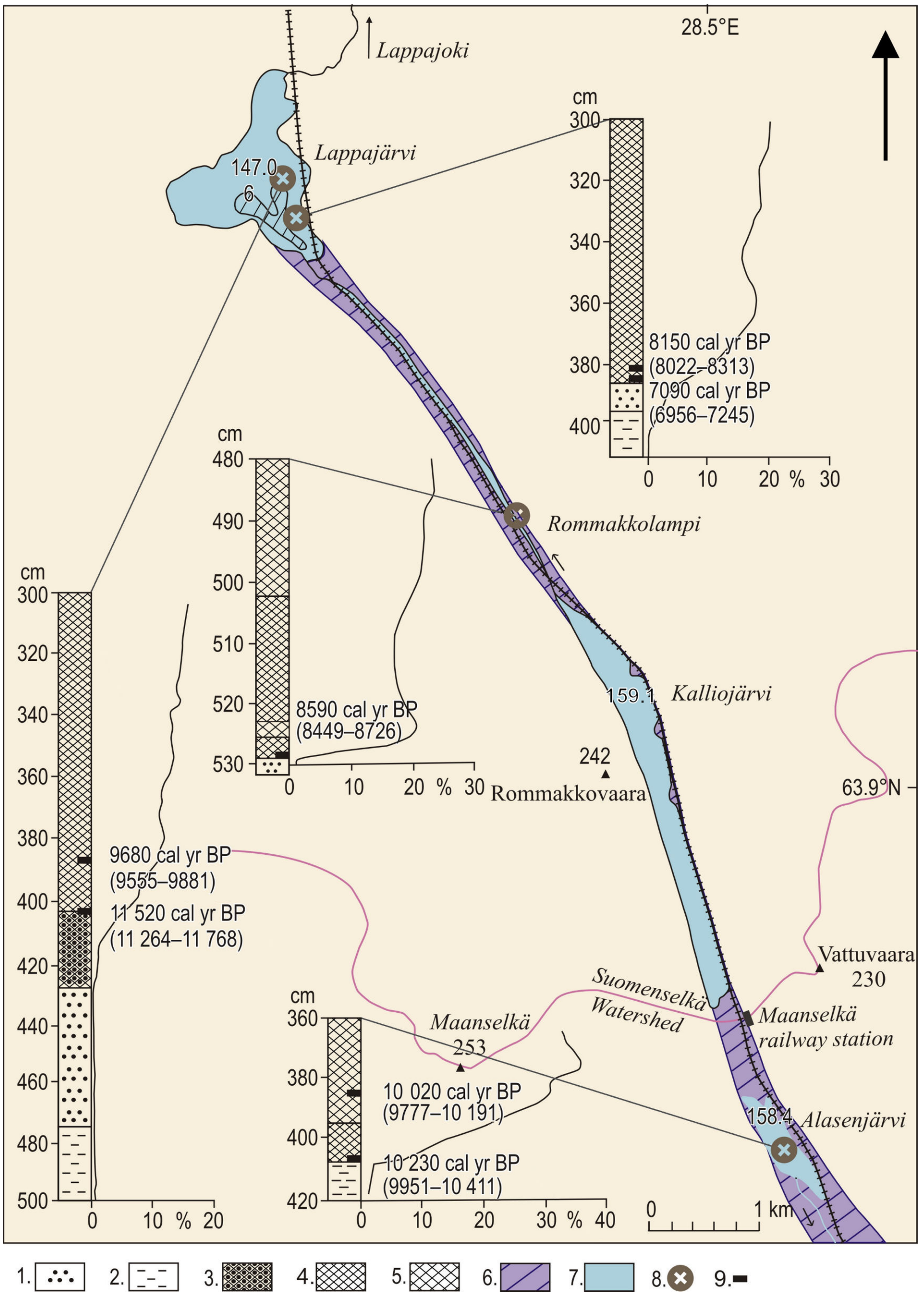


Fig. 3. The northwestern drainage channel (Kalliojärvi channel) and the lithologies of the sampling sites. 1, Sand; 2, clay of the ice-dammed lake; 3, gyttja clay; 4, clay gyttja; 5, gyttja; 6, ancient northwestern outlet; 7, present watercourses; 8, sample site; 9, AMS datings.

flow during the drainage washed out nearly all the mineral sediment and that the lacustrine sediment occurs directly over a washed, rocky surface. At the eastern end of the small lake, the sampler penetrated a thin layer of coarse gravel interspersed with small pebbles. Here a 370-cm sediment core was obtained, reaching the limit of inorganic sediment. Above this limit the sediment is clay gyttja, with an organic content of 7% and rich in mica (Fig. 2), reflecting the washing of the bedrock of the slopes and the till covering it during the drainage. Above a depth of 345 cm, the sediment is gyttja until it becomes peat near the surface of the core. The AMS date obtained from the bottom of the clay gyttja gave an age of 12 360 cal yr BP (10 450±50 ^{14}C yr BP). In comparison with the deglaciation chronology presented earlier, this age is clearly too old, dating to the time when the region was still covered by

Table 2. AMS radiocarbon dates. All dates are prepared from bulk gyttja sediment samples

Name	Depth, cm	^{14}C age	Calibrated age 2 sigma range	Calibrated age median
Lappajärvi I	382–380	7 345 ± 55	8 022–8 313	8 150
Lappajärvi I	385–383	6 190 ± 50	6 956–7 245	7 090
Lappajärvi II	388–386	8 720 ± 50	9 555–9 881	9 680
Lappajärvi II	404–402	10 020 ± 60	11 264–11 768	11 520
Alasenjärvi	388–386	8 890 ± 55	9 777–10 191	10 020
Alasenjärvi	408–406	9 065 ± 60	9 951–10 411	10 230
Kalliojärvi	529–527	7 810 ± 50	8 449–8 726	8 590
Iso-Rokka	369–367	10 450 ± 50	12 116–12 560	12 360

the ice sheet, probably due to the reworked organic material deposited in the basin after the drainage. A more realistic and probably more accurate date was therefore obtained from the revised deglaciation chronology. Since the revised chronology (Svendsen et al. 2004) suggests that the ice sheet began retreating from the Uimaharju marginal formation at the end of the Younger Dryas stadial at about 11 650 cal yr BP, we assume that it retreated to the Kattilamäki region in about 350 years, thus giving an age of 11 300 cal yr BP for the drainage of the ice-dammed lake and formation of Lake Pielinen. This age is consistent with the revised age of 10 500 cal yr BP for deglaciation of the Norrbotten coast in Sweden (Lindén et al. 2006) if we assume a constant retreat rate from the Uimaharju marginal formation to Norrbotten, but is not constrained by reliable AMS radiocarbon or varve clay chronology, and represents thus only a rough estimate for the age of the formation of Lake Pielinen.

The ancient northwestern outlet channel (Kalliojärvi channel)

On the basis of the elevation difference between the level of the ice-dammed lake, 203 m a.s.l. (Saarelainen & Vanne 1997), and the threshold of the new outlet at Kattilamäki, 178 m a.s.l., the level of the ice-dammed lake dropped by 25 m during its drainage at Kattilamäki at 11 300 cal yr BP, and in the Pielinen basin by 15–17 m until the Kalliojärvi threshold at the northwestern end of Lake Pielinen began to regulate the level. The drop also influenced the southern end of the lake, where a fall in the water level by 15–17 m exposed large areas of dry land north of the Uimaharju threshold and the direction of the water flow through Uimaharju turned northwards, as indicated by the occurrence of a 7 m deep depression on the modern lake bottom on the northern side of the threshold. The waters of newly formed Lake Pielinen began to flow northwestwards through the Kalliojärvi channel and crossed the present Suomenselkä threshold in a narrow, rocky gorge, still clearly visible in the field (Figs 1 and 3). The threshold of this ancient outlet channel, covered by a thin peat layer, is located at an altitude of 160 m, 66 m above the present level of Lake Pielinen.

To investigate the timing of the drying of the ancient northwestern outlet and the consequent formation of the present outlet at the southeastern end of the lake, a number of sediment cores were taken from small lakes located at the bottom of the northwestern outlet channel. Finding suitable sediment cores from the channel was difficult. Near the Kalliojärvi threshold region the corer frequently hit washed rocky surfaces, with no fine sediment between the overlying peat and the underlying rock. After several attempts a core was obtained from a small basin (Rommakkolampi) located on the bottom of the ancient outlet channel, where the basal sediment consisted of stony sand overlain by a thin layer of silt and thicker bed of gyttja (Fig. 3). The AMS date from the contact between the silt and gyttja gave an age of 8590 cal yr BP (7810 ± 50 C^{14} yr BP) (Table 2). As shown later, this date is inconsistent with other dates for the same event and too young to reflect the timing of the drying of the ancient outlet, probably because a small stream which remained in the channel after its drying inhibited the accumulation of organic material at the sampling point.

The next sediment cores were taken from Lake Lappajärvi (147 m a.s.l.), another lake located at the northern end of the ancient outlet channel (Fig. 3). The altitude of this lake suggests that it had at first been a bay of the Yoldia Sea but had quickly become isolated from it due to rapid land uplift. The ancient outlet flowed into the lake at high speed through a narrow, steep gorge and eroded the sandy deposits of an esker located on the southern coast of the lake, carving a narrow, over 10 m deep depression on the bottom of the lake. Apart from the depression, the depth of the lake is 2–6 m. The first core (Lappajärvi I) was taken from the eastern part of the lake, about 70 m from the shore and 400 m from the delta of the ancient outlet channel. A number of corings showed that the sediment stratigraphy begins with fluvio-glacial sand at the bottom, followed by clay accumulated in the ice-dammed lake, sand and gravel deposited during the drainage of the ice-dammed lake, and finally by clay gyttja, which was interpreted to have been deposited after drying of the ancient northwestern outlet channel (Fig. 3). Two AMS dates were obtained from the contact of the sand and gravel layer and the clay gyttja layer. The resulting ages were 7090 cal yr BP (6190±55 ^{14}C yr BP) from depths of 385–383 cm and 8150 cal yr BP (7345±55 ^{14}C yr BP) from depths of 382–380 cm, thus showing an inversion of the dates (Table 2).

Since the dates are in inverse order and are clearly too young, a new sediment core (Lappajärvi II) was taken from the northern part of the lake, farther away from the delta of the ancient outlet channel. A sediment sequence was sampled from depths of 500–300 cm. Two AMS dates were made from the new core. An age of 11 520 cal yr BP (10 020 ± 60 ^{14}C yr BP) was obtained from depths of 404–402 cm, from the contact of the underlying gyttja clay and overlying clay gyttja and an age of 9680 cal yr BP (8720 ± 50 ^{14}C yr BP), from depths of 388–386 cm, from the point where the rise in the organic content of the sediment ends (Fig. 3).

When the flow of water, caused by drainage of the ice-dammed lake and the subsequent water level drop, ended, the sediment brought in by the outlet of Lake Pielinen began to accumulate at Lake Lappajärvi and formed silty, banded sediment on top of the sands formed during drainage of the ice-dammed lake. This sediment is rich in mica and the radiocarbon age from the mica-rich layer, 11 520 cal yr BP (10 020 ± 60 ^{14}C yr BP) is clearly too old, due to the older organic material washed in from the surroundings of the lake. The washing was at first active in the surrounding catchment, because the fall in the water table by 25 m abruptly exposed unvegetated terrain to erosion. The proportion of organic material begins to increase in the silty, mica-rich sediment until it reaches a point where the steep rise turns to a gentle, steady increase. This point probably reflects the time moment when the water flow in the Kalliojärvi channel ended and the outlet of Lake Pielinen shifted to the southeastern end of the lake. The radiocarbon date from this point thus suggests that the northwestern outlet had dried at least by 9680 cal yr BP (8720 ± 50 ^{14}C yr BP).

Sediment cores were also taken from a small lake (Alasenjärvi, 158.4 m a.s.l.) near the northwestern threshold of Lake Pielinen (Fig. 3). The modern threshold is about 1 m higher than the level of the lake and is located about 500 m northwest of the lake. The lake was cored because its basin was under the surface of the ancient northwestern outlet and a major change in the sedimentary conditions in the lake probably occurred when the new outlet in the southeastern part of Lake Pielinen opened. A number of corings in different parts of the lake showed that there is a 10–50 cm thick layer of clay deposited during the ice-dammed lake in the centre of the basin, in contact with the overlying lacustrine clay gyttja and gyttja. Unlike at the other sites, this stratigraphic contact is very sharp and clear and likely represents sedimentary changes due to the drying of the ancient northwestern outlet. An AMS dating from depths of 408–406 cm, right above the contact, gave an age of 10 230 cal yr BP (9065±60 ^{14}C yr BP), which is thus assumed to reflect the timing of the southeastern outlet. Another dating from depths of 388–386 cm, where the organic content of the sediment rises, gave an age of 10 020 cal yr BP (8890±55 ^{14}C yr BP), reflecting stable lacustrine conditions in the basin (Table 2).

Transgressions and regressions of Lake Pielinen

The largest extent of the Pielinen basin is associated with the stage at which the ice-dammed lake of Pielinen was connected with that of Sotkamo (Fig. 1, Table 1). At that time the water level at the modern northern threshold at Kalliojärvi was at an altitude of 177 m a.s.l., i.e. 17 m above the altitude of the present threshold (Miettinen 1996; Saarelainen & Vanne 1997). The ancient shoreline reflecting this ice-dammed lake stage (>11 300 cal yr BP) is strongly tilted due to differential land uplift, with a gradient of 59 cm/km (Fig. 4). Large areas were submerged, especially at the northwestern end of the lake (Fig. 5A). After abrupt drainage of the vast Sotkamo-Pielinen ice-dammed lake and drop in the water level of the Pielinen basin, the outlet of newly formed Lake Pielinen was located at its northwestern end and rapid transgression started in the entire lake basin. As a result the water level rose in the southeastern areas of the basin by 15–17 m in 1100 years, assuming that the estimated age of 11 300 cal yr BP for the formation of the lake is correct, finally causing the formation of a new channel over the Uimaharju threshold (Fig. 5B). It seems that no abrupt erosion was associated with this process, because the outlet over the Uimaharju marginal formation had already existed during the ice-dammed lake and the water started to flow in an existing channel.

Since the shift in the outlet from Kalliojärvi to Uimaharju was gradual rather than abrupt, a bifurcation developed in Lake Pielinen, during which the ancient northwestern outlet gradually dried and the entire outflow shifted to the Uimaharju threshold (Fig. 5C). During the bifurcation, Lake Pielinen reached its maximum extent. It was 143 km long and its area was 1998 km^2, 22% larger than during its formation. The gradient of the corresponding ancient shoreline is 46 cm/km. Since the outlet was now shifted to the southeastern end of the lake, a regressive stage began in the entire basin, affecting most strongly the northernmost areas, and has since continued to this day. Consequently, to this day, the lake has become

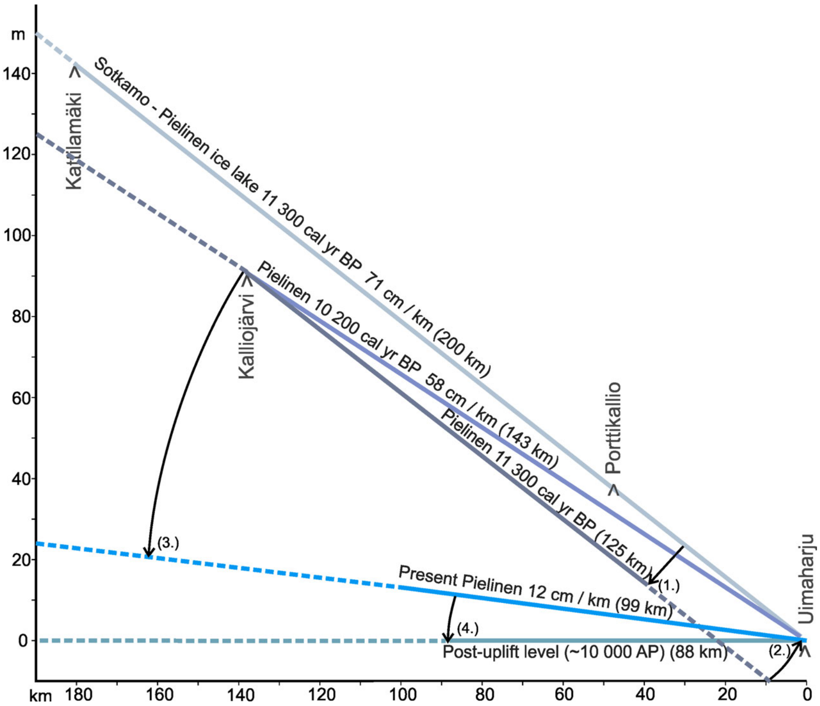


Fig. 4. Tilting of the shorelines corresponding to the main developmental stages of Lake Pielinen. The gradients are given in relation to the post-uplift shoreline, roughly at 10 000 years after present. The numbering indicates the chronological order of the shoreline shifts.

shortened by 40 km at its northwestern end, its level has decreased by 50 m in its northern part, over 1000 km^2 of the former lake bottom has become dry land and the area of the lake has diminished by 54%. The total volume of water decreased by 75%, from 36.8 km^3 to 9.15 km^3 (Table 1).

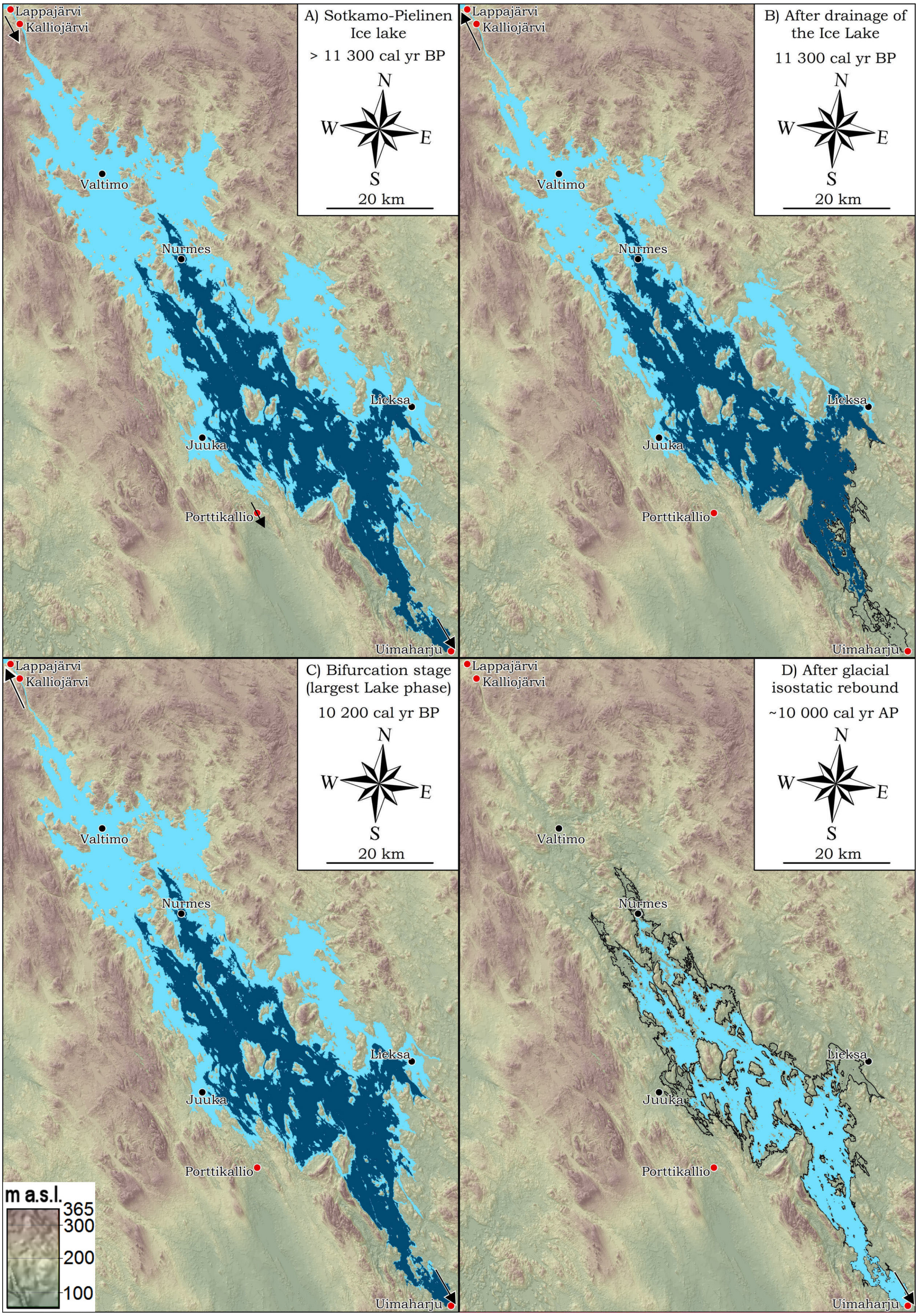
The tilting of the basin and the regressive phase of Lake Pielinen have not yet ended, but will continue as long as the isostatic land uplift occurs. Estimations of the remaining uplift time vary, usually between 7000 and 12 000 years (e.g. Salonen et al. 2002). In our projection we used an estimate of 10 000 years. According to Ekman & Mäkinen (1996), the remaining uplift is 90 m at the northern end of the Bothnian Bay, where land uplift is most rapid, and this was the value we used in the projection shown in Fig. 5D. This figure shows that the lake basin will tilt about 12 cm/km more and Lake Pielinen will continue to diminish until it will be only 89 km long, 565 km^2 in area and 5.01 km^3 in volume (Fig. 5D, Table 1).

DISCUSSION AND CONCLUSIONS

Dating the outlet channel changes

The clearest evidence for the drying of the ancient north-western channel is provided by the basal sediment of Lake Alasenjärvi, located at the threshold of the northwestern outlet. After drainage of the ice-dammed lake, Lake Alasenjärvi was located slightly south of the threshold, so that the water flow was relatively sluggish, and no strong erosion occurred, but still was strong enough to prevent deposition of lake sediment on top of the underlying clay as long as the river existed. The clay began to be overlain by fine-grained lake sediment only after the flow in the northwestern outlet ended and Lake Alasenjärvi was isolated as a separate small lake. Radiocarbon dating from the lake-sediment layer on the top of the clay showed that this shift occurred at 10 230 cal yr BP (9065±60 ^{14}C yr BP).

Hyvärinen (1966) found a similar contact between the clay and lake sediment from a peatland at the margin of Lake Alanenjärvi. He obtained a radiocarbon age of 10 005 cal yr BP (8930±220 ^{14}C yr BP), which is by and large consistent with the age obtained by us, except that the sample dated by Hyvärinen (1966) was 10 cm thick in contrast to the 2 cm thick sample dated by us. However, Hyvärinen (1966) inferred that the contact of the clay and lake sediment reflects the isolation of the peatland basin and, hence, shows the origin of Lake Pielinen, mainly because the peatland is located at an altitude of 160.2 m and thus about 1 m above the threshold altitude (159 m). However, the revised threshold altitude


A) Sotkamo-Pielinen Ice lake
> 11 300 cal yr BP
B) After drainage of the Ice Lake
11 300 cal yr BP
C) Bifurcation stage (largest Lake phase)
10 200 cal yr BP
D) After glacial isostatic rebound
~10 000 cal yr AP
N
W
E
S
20 km
Lappajärvi
Kalliojärvi
Valtimo
Nurmes
Lieksa
Juuka
Porttikallio
Uimaharju
m a.s.l.
365
300
200
100

is 160 m. In addition, when we bear in mind that the water depth in the river flowing over the threshold must have been at least 1–2 m and that the peatland's surface has risen several metres due to peat accumulation during the Holocene, it is clear that the peatland basin was under the surface of the northwestern outlet, as was Lake Alasenjärvi. Hence, our interpretation is that the accumulation of lake sediment in the basin reflects the period after the shift of the outlet to the southeastern part of the lake and the associated regression in the northwestern part.

According to Hyvärinen (1966), the opening of the new outlet in the southeast occurred at 9600 cal yr BP (8440 ± 120 ^{14}C yr BP), which implies that the Kalliojärvi channel would have been active for about 500 years, during which there should have been a transgression of at least 15 m at the southern end of the lake, corresponding to an annual water level rise of 30 mm. However, our results suggest that the transgressional stage was longer. We therefore end up with a revised chronology in which the drainage of the ice-dammed lake roughly at 11 300 cal yr BP marks the beginning of Lake Pielinen and the date 10 230 cal yr BP shows the isolation of Lake Alasenjärvi, indicating the point in time when the outlet of Lake Pielinen shifted from the Kalliojärvi channel to Uimaharju at the southeastern end of the lake and the northwestern outlet dried. Consequently, the ancient northwestern channel was active for about 1100 years during the earliest stage of the independent Lake Pielinen.

The reconstructed and mapped stages of Lake Pielinen show how the transgressions and regressions followed each other and that the resulting areal and volumetric changes in the lake are among the largest in Finland and, when related to the size of the basin, perhaps in the entire world. This is due to the fact that the longitudinal axis of the lake is parallel to the tilting axis. Other examples of transgressive lakes in Finland include Lake Oulujärvi and Lake Vanajavesi. Both have been transgressive throughout their histories and have experienced transgressions of over 10 m (Auer 1924; Koutaniemi & Keränen 1983). In the southeastern part of Lake Saimaa the magnitude of the transgression is demonstrated by the presence of submerged peat, originally formed on dry land, found at depths of over 20 m below the surface of the modern lake (Pajunen 2005). As the outlet of Lake Saimaa shifted from the northwest to the southeast, a chain of separate lakes was formed in the northern part of the lake due to the regression, while the lake shore shifted 180 km from the northwest towards the southeast (Saarnisto 1970; Tikkanen 2002). The first outlet of the largest lake in Europe, Lake Ladoga, was also located roughly in the middle of the basin and was thus transgressive in the southern part and regressive in the northern part, until the transgression caused a new outlet, the Neva River, to be formed in the southern corner of the lake at 3300 cal yr BP (Saarnisto & Grönlund 1996). After the formation of the Neva River, the surface of Lake Ladoga fell 12 m over several hundred years (Saarnisto & Grönlund 1996).

Since the last opening of the present Uimaharju outlet in the southeastern corner of the lake 10 200 cal yr BP, Lake Pielinen has been regressive. This has caused the lake area to decrease more than 50% and the lake water volume up to 75%. At the same time the shoreline formed during the largest phase of the lake has tilted, so that its gradient currently is 46 cm/km, meaning that the water level at the northern end of the lake has fallen about 50 m. If the land uplift in the Lake Pielinen area will continue at a steadily decreasing rate, the lake will tilt yet another 12 cm/km and further diminish, especially at its northern end (Fig. 5D). Many of the largest islands will be connected to the continent with isthmuses and the current towns of Nurmes, Lieksa and Juuka will lose their connection to the lake shore.

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Fig. 5. Changes in the extent of Lake Pielinen. **A**, the maximum post-glacial extent of the Sotkamo–Pielinen ice-dammed lake in the Pielinen basin before the drainage of the ice-dammed lake roughly at 11 300 cal yr BP. The present extent of the lake is shown with dark blue. The outlet channel of the ice-dammed lake in its southeastern part in Uimaharju and an older outlet channel in Porttikallio are shown with an arrow. **B**, Lake Pielinen after 11 300 cal yr BP after the drainage of the ice-dammed lake. The present shoreline is marked at the southern part of the lake. The outlet channel was in Kalliojärvi in the northwestern part of the lake. **C**, the maximum extent of the early Holocene Lake Pielinen at 10 200 cal yr BP. The lake is bifurcative with an outlet channel in the northwest and in the southeast. The present extent of the lake is shown. **D**, Lake Pielinen after all glacial isostatic adjustment has taken place, estimated to happen by 10 000 years after present. The present shoreline is shown with a black line.

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Erinevused jääajajärgses isostaatilises maakerkes põhjustavad Ida-Soome Pielineni järve arengus ekstreemseid transgressioone ja regressioone

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On antud Pielineni järve hüdroloogilise režiimi, väljavoolude, järve suuruse ja konfiguratsiooni muutuse kulg pärast jääaega, tuginedes täpsetele digitaalsetele kõrgusmudelitele ning ruumilisele GIS-analüüsile. Pielineni järv tekkis kohaliku jääpaisjärve mahajooksul. Järve varases arengus oli Pielinenil loodesuunaline väljavool. Erinevused maakerkes tekitasid umbes 10 200 aastat tagasi järvele aga uue, kagusuunalise väljavoolu. Sellest ajast on järve veetase olnud regresseeruv.