Bulletin of the Geological Society of Finland, Vol. 95, 2023, pp 47–58 https://doi.org/10.17741/bgsf/95.1.004

The morphostratigraphic imprint of the Baltic Ice Lake drainage event in southern Finland

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Abstract

Digital elevation models, based on laser scanning imageries (LiDAR-DEM) and aided by ground penetrating radar (GPR) data, were used to study glaciofluvial Gilbert-type ice-contact deltas in the Younger Dryas Salpausselkä end-moraine zone in southern Finland. The geomorphological data analysed were used to reconstruct the water-level drop of the late glacial Baltic Ice Lake to the early Holocene Yoldia Sea and tie these changes to a wider stratigraphic context. The results indicate that the sudden drainage event at around 11 650 cal. yrs BP left its imprint not only on the varved sediments but also on ice-contact glaciofluvial deltas in the Second Salpausselkä zone throughout southern Finland. This morphostratigraphic boundary can be placed at locations where the ice-contact deltas occur at two different levels; the higher-level deltas formed during the Baltic Ice Lake B III water-level stage and the lower-level deltas during the Yoldia Sea Y I water-level stage. This morphostratigraphically defined boundary in southern Finland marks the Pleistocene/Holocene chronostratigraphic boundary in southern Finland and shows the corresponding positions of the Scandinavian Ice Sheet's Finnish Lake District Ice Lobe and the Baltic Sea Ice Lobe.

Keywords: Stratigraphy, Pleistocene/Holocene boundary, glaciofluvial ice-contact delta, LiDAR DEM, Salpausselkä, Baltic Ice Lake, Yoldia Sea

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Editorial handling: Pertti Sarala (e-mail: pertti.sarala@oulu.fi)

1. Introduction

During the last deglaciation extensive ice lakes were formed next to the ice sheet margins in North America and Fennoscandia. The most extensive ice lakes, such as the Lake Agassiz – Lake Ojibway ice lake complex existed in North America, while in northern Europe the Baltic Ice Lake and the White Sea Ice Lake were the most extensive ice lakes during the last deglaciation (Fig. 1). In southern Finland the Scandinavian Ice Sheet (SIS) terminated into the Baltic Ice Lake into which ice-contact deltas and subaquatic fans were deposited. These ice-contact deltas and subaquatic fans constitute the First and Second Salpausselkä end moraines, both of which are a part of the end-moraine chain that can be followed throughout Fennoscandia marking the former extent of the Younger Dryas ice margin of the SIS (Mangerud et al. 2022).

Perhaps the most significant event in the Late Pleistocene and Holocene history of the Baltic Basin area took place during the last deglaciation when the water-level of the Baltic Ice Lake suddenly dropped as a new outflow route to the Atlantic Ocean opened in the Billingen area, south central Sweden and the Yoldia Sea phase started in the Baltic Basin (e.g. Donner 1995). It has been estimated that 7800 km^3 of freshwater catastrophically drained into the North Atlantic and the water-level of the Baltic Basin dropped between 25 to 28 m within a couple of years (e.g. Jakobsson et al., 2007). The overlapping age estimates of the drainage event, 11 590±100 cal. yr BP (Saarnisto & Saarinen 2001), 11 560 calendar years BP (Andrén et al. 2002), and 11 620±100 cal. yr BP (Stroeven et al. 2015) suggest that the catastrophic outburst took place at, or very close to the formally defined Pleistocene/Holocene boundary 11 700±99 yrs b2k (i.e., before year 2000) which corresponds practically to 11 650±100 cal. yr BP. This event left clear erosional and depositional marks on the geological record in the Billingen area, south central Sweden (e.g., Johnson et al. 2022) and also in Finland (e.g. Sauramo 1923; Donner 1995; Hyttinen 2012). For example, the laminated clays in southern Finland and Sweden which are thought to have been deposited in the Baltic Ice Lake prior to the water-level drop display reddish-hued rhythmites, above which the thick so-called "zero varve" exists. At two reference sites, Jokela and Koria in southern Finland, the "zero varve" defined by Hyttinen et al. (2011a) is 0.2 m to 0.4 m thick, massive and/or syndepositionally deformed silt and sand above which thin laminated varve sequence occur. It is generally thought that the water-level drop increased erosion which led to an increased suspended sediment input into the Baltic Basin and the deposition of the "zero varve".

The Quaternary chronostratigraphy is traditionally based on climatostratigraphy where Pleistocene and Holocene Epochs and Stages are defined based on climate changes (Gibbard 2013). This implies for example, that the proposed chronostratigraphic boundaries in terrestrial sequences are typically, in fact, diachronous depositional surfaces. In this respect, the rhythmite sequences at Jokela and Koria in southern Finland are stratigraphically important key sections which show isochronous marker horizon i.e., the "zero varve", not directly related to climate. The "zero-varve" horizon represents the reference datum point for the Finnish varve clay chronology which is still the base for the deglaciation chronology of southern and central western Finland (e.g., Lunkka et al. 2004). However, at Jokela and Koria there are in fact two massive and/or syndepositionally deformed silt and sand layers approximately two metres apart in vertical sections (Hyttinen et al. 2011a) that might indicate the water-level drop from the Baltic Ice Lake B III water-level to Yoldia Sea water-level YI. Therefore, the question is which one of these zero varves represents the final water-level drop from the Baltic Ice Lake to the Yoldia Sea i.e., the horizon corresponding to the Pleistocene/Holocene chronostratigraphic boundary.

The water-level drop from the Baltic Ice Lake BIII-level to the Yoldia Sea YI-level also left an imprint on the geomorphology of the Younger Dryas (YD) Salpausselkä zone. This water-level drop is recorded in sequences of raised ice-contact glaciofluvial deltas and beach levels (e.g. Donner

1995; Lunkka et al. 2019). However, only during the past decade high-precision elevation models have made it possible to morphologically define and categorise ice-contact glaciofluvial landforms into either glaciofluvial deltas or subaquatic fans which have been subsequently modified to even surfaces by littoral processes. Therefore, the aim of this article is to 1) define the Gilbert-type glaciofluvial ice-contact delta localities in the Salpausselkä zone where the water-level drop of the Baltic Ice Lake can be detected, 2) define the magnitude of the drop using LiDAR-based observations and the recently calculated uplift gradient and its direction for the Salpausselkä zone, and 3) introduce the Pleistocene/Holocene morphostratigraphic boundary in southern Finland.

Figure 1. The location of two largest ice lakes in Europe that existed in the Baltic and the White Sea basins at the end of the Younger Dryas modified after Mangerud et al. (2022). The Younger Dryas end moraines (red lines) deposited next to the Scandinavian Ice Sheet (SIS, white shading) are also indicated. The Younger Dryas end moraines in the eastern part of the SIS are as follows: Ss I-II = First Salpausselkä (southern) and Second Salpausselkä (northern) end moraines; R = Rukajärvi end moraine; K = Kalevala end moraine; P = Pääjärvi end moraine; Ke = Keiva end moraines. The Finnish Lake District Ice Lobe (FLDIL) and the Baltic Sea Ice Lobe (BSIL) of the SIS are also indicated. The study area in the Salpausselkä zone is indicated with a rectangle.

2. Study area, material, and methods

The study area is located in southern Finland (Fig. 1). The area has been glaciated several times during the Weichselian glaciation and encompasses the Salpausselkä end moraine zone which is the most extensive and continuous ice-marginal zone in Fennoscandia. Glaciofluvial deltas, subaquatic fans and sandurs as well as marginal moraines in the Salpausselkä zone were deposited at the ice margin of the Baltic Sea Ice Lobe and the Finnish Lake District Ice Lobe (Fig. 1) in the YD (e.g. Lunkka et al. 2021; Mangerud et al. 2022).

The methods used in this work include mapping of geomorphological features in the study area, where all the glaciofluvial deltas and subaquatic fans in the Second Salpausselkä zone were mapped over the past five years. Digital elevation models (DEMs) were used to differentiate the deltaic- and fan-type glaciofluvial deposits (Fig. 2). The DEMs covering southern Finland are based on LiDAR (Light Detection and Ranging) data collected by the National Land Survey of Finland. The density of the LiDAR points is at least 0.5 points per square metre and the vertical precision is between 0.3 and 1.0 metre, which offers detailed imaging of landforms and their altitude. Ground Penetrating Radar (GPR) soundings have also been performed from different glaciofluvial deltas and subaquatic fans in the Second Salpausselkä zone over the past 10 years by the author (e.g., Lunkka & Erikkilä 2012) but the internal structures of individual deltas or fans are not presented or discussed here. However, based on GPR-soundings with a RAMAC-GPR apparatus using 100 MHz and 50 MHz antennae, all of the glaciofluvial deltas discussed here are Gilbert-type deltas with clear foreset and topset facies.

The methodological approach adopted to define the water-levels in the Salpausselkä zone was based on the identification of glaciofluvial ice-contact deltas in the Salpausselkä zone from LiDAR-DEMs. In order to categorise glaciofluvial formation as a glaciofluvial ice-contact delta most and preferably all of the following features should have been recognised on the surface of a formation (e.g. Lunkka et al. 2019):

1) Feeding esker(s) with an apex area in the proximal part of a formation.

2) Meltwater channels on the top of a glaciofluvial formation.

3) Kettle holes.

4) Beach/storm ridges on the distal part of a glaciofluvial delta plain.

The first three features present indicate that a glacifluvial formation can be categorised as an ice-contact glaciofluvial delta with a topset element. This together with beach/storm/lake-ice push ridges next to the delta front and a clearly defined zone where meltwater channels disappear, can be used to estimate the contemporary mean water-level with approximately ± 2 m accuracy at best (e.g., Lunkka et al., 2019). When the water-level altitude changes in restricted areas are significant and can be corrected for known spatial variations in glacioisostatic uplift rate, the amount of water-level drop can be estimated. Lunkka et al. (2019) mapped glaciofluvial ice-contact deltas and their altitudes in the Salpausselkä zone using LiDAR-based digital elevation models and GIS-tools and calculated and defined the trend of the glacio-isostatic uplift palaeo-isobases (trend 40°-220°), uplift gradients (0.6 m/km) and equidistant diagrams (distance diagrams) for the Salpausselkä zone which are utilized in this work.

It must be stressed here that if glaciofluvial formations with even surfaces do not have geomorphological elements listed above, they most likely represent glaciofluvial subaquatic fans which are post-depositionally modified by littoral processes to flat surfaces (such as spit bars) thus not indicating the water level at the time when subaquatic fans were deposited. The identification of topset element (i.e., channel fill and bar structures above the foreset element) in the glaciofluvial formation can also be done with GPR-soundings to complement the geomorphological interpretation (Fig. 2).

Once ice-contact glaciofluvial deltas have been identified and mapped, and their contemporary water-levels estimated, it is possible to map the geographical extent of glaciofluvial deltas deposited prior to the Baltic Ice Lake water-level drop, and those deposited immediately after the event, respectively.

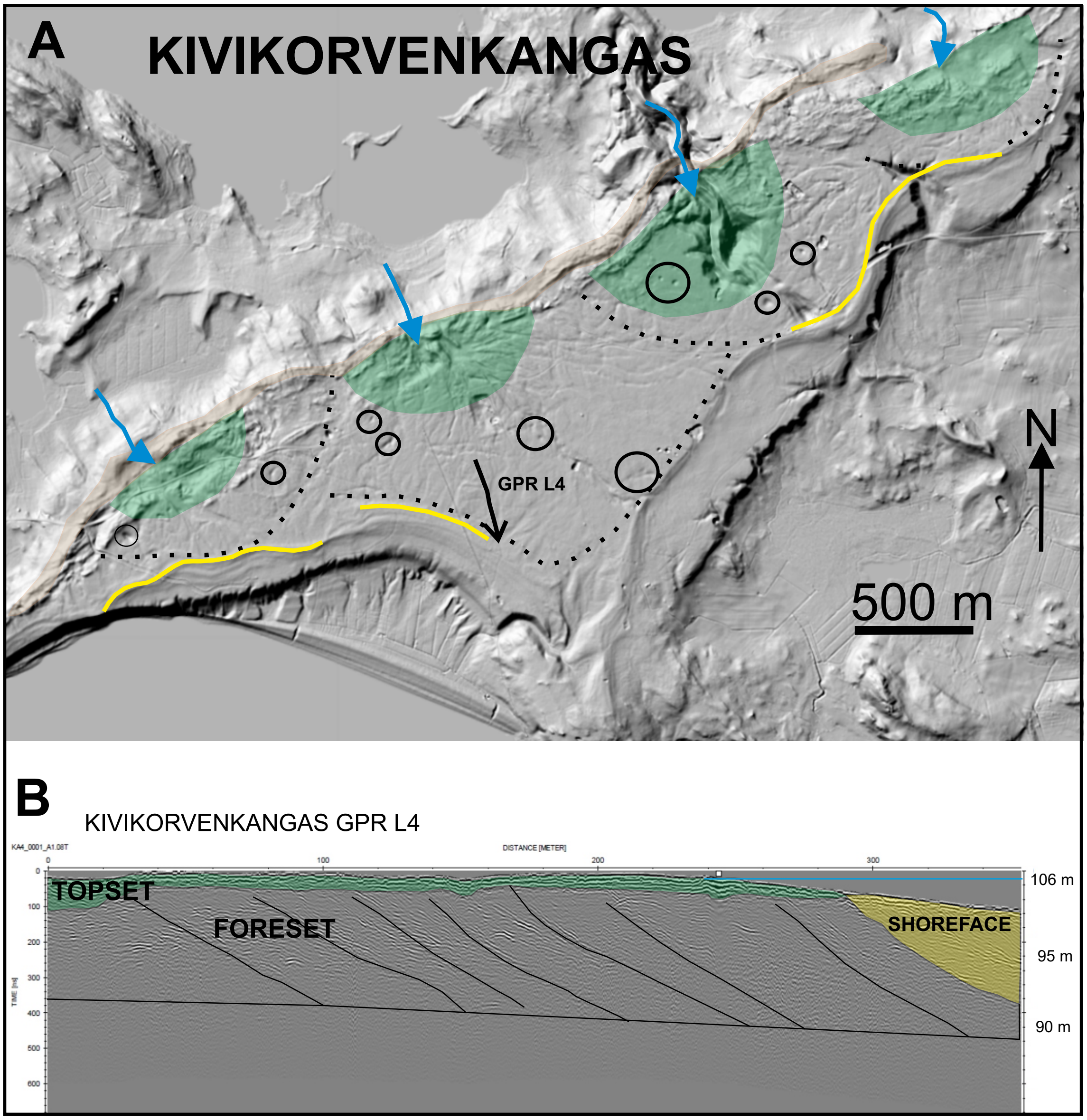

Figure 2. Criteria to recognise glaciofluvial ice-contact deltas in the Salpausselkä zone are based on distinct geomorphological features and the internal structure of glaciofluvial formations used in this study (see text). A) LiDAR-DEM of the Kivikorvenkangas glaciofluvial formation (see Fig. 4a for its location) where four Gilbert-type ice-contact deltas coalesced to form a continuous Second Salpausselkä ridge (black stippled lines). Meltwater channels and kettle holes (black circes) occur on the delta plain. The water-level estimates are based on the disappearance altitude of meltwater channels and their relationship to the storm/ice pushed beach ridges. Blue arrows = feeding eskers, light brown areas = ice marginal moraines, green areas = apex cones in the proximal part of the delta, yellow lines = beach ridges. (DEM base-map the National Land Survey of Finland). B) The internal structure of the Kivikorvenkangas delta GPR line L4 (see Fig. 2a) where the topset and foreset elements as well as the shoreface facies element can be recognised.

Table 1. The list of glaciofluvial delta pairs, location co-ordinates, estimated water-level altitude above the present sea level in metres. The higher altitude is the Baltic Ice Lake B III water-level and the lower the Yoldia Sea YI water-level (e.g., Donner, 1995). The direction of the uplift palaeoisobases and the calculated uplift gradient 0.6 m/km (the dip direction 130°; Lunkka et al. 2019) have been taken into account in water- level difference calculations (column corrected water level difference).

Delta pairs and names of glaciofluvial deltas	Co-ordinates / WGS84	Water level estimate (m a.s.l.)	Corrected water level difference/m	Baltic Basin water level phase
1. Kaljakuru	60.548°N/24.070°E	148 m		B III
Lehtimäki	60.526°N/23.991°E	121 m	28 m	Y I
2. Sauvalanmäki	60.817°N/24.492°E	155 m		B III
Tunturivuori	60.836°N/24.475°E	128 m	28 m	Y I
3. Paapelinmaa	61.020°N/24.848°E	161 m		B III
Tapulinmäki	61.026°N/24.835°E	135 m	28 m	Y I
4. Suurimäki	61.082°N/24.903°E	161 m		B III
Palomäki	61.087°N/24.891°E	136 m	25 m	Y I
5. Likojärvi	61.200°N/25.159°E	164 m		B III
Vuorenpää	61.164°N/24.956°E	138 m	28 m	Y I
6. Tuhkamäki	61.200°N/25.441°E	160 m		B III
Hassinmäki	61.270°N/25.449°E	134 m	29 m	Y I
7. Sudenhaudankangas	61.095°N/27.104°E	119 m		B III
Kotilahti	61.199°N/27.342°E	95 m	26 m	Y I
8. Sarviniemi	61.274°N/28.054°E	110 m		B III
Akonkangas	61.430°N/28.450°E	85 m	25 m	Y I

3. Results

At several sites in the Salpausselkä zone there are glaciofluvial landforms that fulfil the glaciofluvial ice-contact delta criteria described in the methods (see also Lunkka et al. 2019). At these locations ice-contact deltas are composed of sand and gravel and they all are Gilbert-type glaciofluvial deltas (e.g. Miller 1996). At present, the glaciofluvial delta levels, from which contemporary water-level altitude can be estimated, occur at different altitudes in the study area because of a variable glacioisostatic uplift. However, since the glacioisostatic uplift isobases and direction of tilting is known in the study area (uplift gradient 0.6 m/km and uplift dip direction 130°; Lunkka et al., 2019), the ancient corresponding water-levels can be calculated for the study area. Mapping of the glaciofluvial deltas in the Second Salpausselkä area and north of it revealed that the ice-contact glaciofluvial deltas at eight locations only form delta-pairs where the water-level at the ice margin (deduced from the delta surface elements) indicate that they were deposited during two distinctly different Baltic Basin water-level stages (see Table 1 and Figs. 3 and 4a).

The glaciofluvial ice-contact deltas deposited at the margin of the Baltic Sea Ice Lobe form the semi-continuous Second Salpausselkä zone in southwestern Finland. In this area the water-level altitudes interpreted from individual delta surface elements range from 121 m in the SW to 164 m in the NE (Fig. 4a and Table 1). The high delta-levels of five delta-pairs from SW to NE range from 148 m to 164 m and the low delta-levels from 121 m to 138 m, respectively. The uplift-corrected (i.e., 0.6 m/km, dip direction 130°) elevation difference between the higher and lower delta-levels (i.e., water-levels) is estimated to be between 25 m and 28 m (Table 1).

The glaciofluvial ice-contact deltas and subaquatic fans deposited at the margin of the Finnish Lake District Ice Lobe form the arc-shaped Second Salpausselkä ridge which runs as a continuous formation across southeastern Finland to Russian Karelia. Altitudes of the glaciofluvial ice-contact delta surfaces range from 160 m in the west to 110 m in the east of the study area (Fig. 4a and Table 1). On the proximal areas of the Second

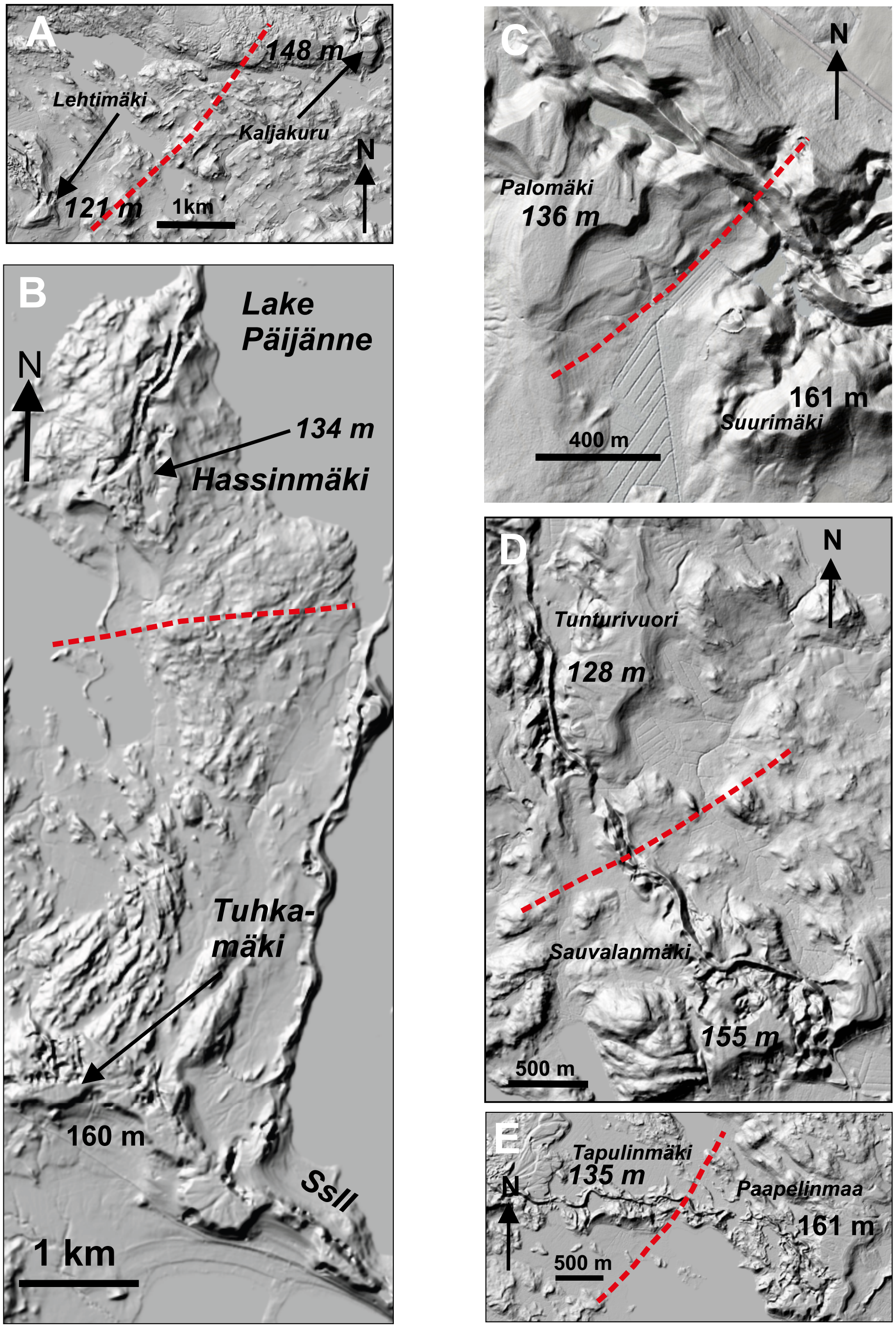

Figure 3. LiDAR-DEMs of the glaciofluvial ice-contact deltas at two distinctly different altitudes in the Second Salpausselkä zone. Ice-contact deltas were built up to the higher Baltic Ice Lake level B III as the ice front located in the Second Salpausselkä. Immediately after the formation of the Second Salpausselkä and the Baltic Ice Lake drainage event, the glaciofluvial ice-contact deltas on the proximal side of the Second Salpausselkä were deposited to the Yoldia Sea Y I water-level. Examples of closely spaced delta-pairs shown in the figure: A) Kaljakuru (148 m) – Lehtimäki (121 m), B) Tuhkamäki (160 m) – Hassinmäki (134 m), C) Suurimäki (161 m) – Palomäki (136 m), D) Sauvalanmäki (155 m) – Tunturivuori (128 m), E) Paapelinmaa (161 m) – Tapulinmäki (135 m) (see Table 1 for the co-ordinates of the delta-pairs and Fig. 4a for other delta-pair altitudes). Red dotted lines indicate the Pleistocene/Holocene boundary at these sites. (DEM base-map the National Land Survey of Finland)

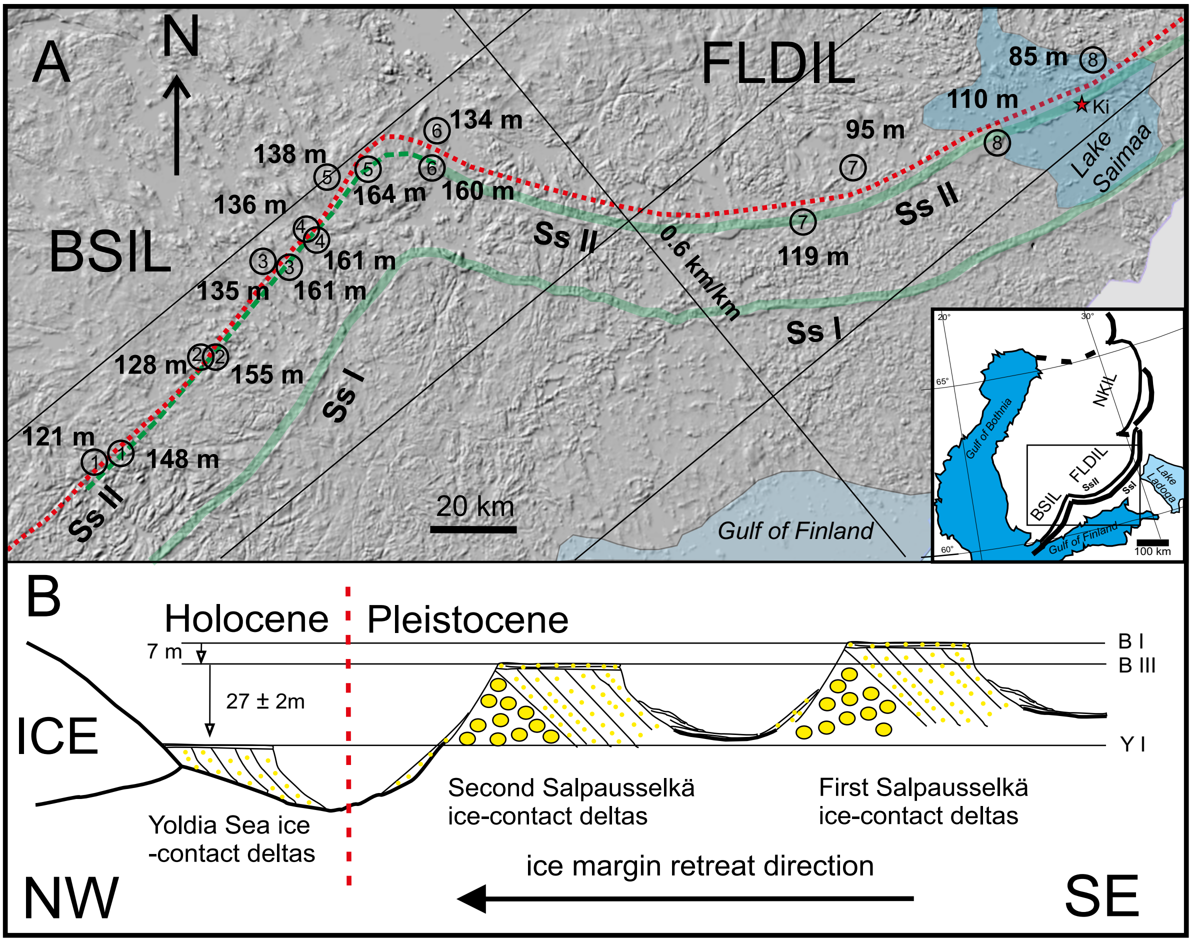

Figure 4. A) A map showing the location of the glaciofluvial delta-pairs (circles numbered 1-8) in the Second Salpausselkä zone and their estimated water-level altitudes (see also Table 1 for corresponding 1-8 delta pairs for their co-ordinates). Palaeoisobases (SW-NE oriented thin black lines,) and the uplift gradient (0.6m/km, dip towards SE) from Lunkka et al. (2019). The Kivikorvenkangas delta complex (Baltic Ice Lake BIII water-level 106 m) shown in Fig. 2 is marked with a star and its uplift corrected water-level difference to the Yoldia Sea YI water-level at Akonkangas (number 8) is 25 m. The Pleistocene/Holocene morphostratigraphic boundary (red lines in Fig. 4a and 4b) across southern Finland is also shown. First and Second Salpausselkäs are marked in green. The former SIS's ice lobes are: BSIL = Baltic Sea Ice Lobe and FLDIL = Finish Lake District Ice Lobe. B) A schematic presentation of the Baltic Basin water-level changes during the Baltic Ice Lake phase (B I and B III) and the 27±2 m water-level drop to the Yoldia Sea Y I water-level. The First Salpausselkä glaciofluvial ice-contact deltas were deposited at the Baltic Ice Lake water-level B I, and the Second Salpausselkä glaciofluvial ice-contact deltas at the Baltic Ice Lake water-level B III, 7 m below B I water-level (Lunkka et al. 2019). (DEM base-map the National Land Survey of Finland).

Salpausselkä deltas, altitudes of delta surfaces indicating contemporary water-level range from 134 m in the west to 85 m in the east (Fig. 4a). The difference between higher and lower delta surface levels in the southeastern Salpausselkä zone is between 25 m and 29 m, when taking into account the glacioisostatic uplift gradient and its dip-direction.

In addition to a clear delta-pairs, there are also many individual glaciofluvial deltas in the Second Salpausselkä and its proximal area which show a similar trend in the height difference of delta levels as listed in Table 1. In the context of the Baltic Basin water-level change, the results show that slightly after the deposition of the Second Salpausselkä glaciofluvial ice-contact deltas the water-level dropped 27 metres on average in front of both FLDL and BSIL (Fig. 4b). The drainage event is morphostarigraphically mappable and can geographically be placed in the middle of the higher and the lower delta generations (Figs. 3 and 4).

4. Discussion

The Baltic Ice Lake drainage event at the end of the last deglaciation has been widely studied during the past hundred years. According to the dating results based on the combination of methods including varve counting, paleomagnetic measurements and ^{14}C-AMS age determinations (Saarnisto & Saarinen 2001; Andrén et al. 2002; Stroeven et al. 2015), the drainage event and the water-level drop of the Baltic Ice Lake B III-level to the Yoldia Sea Y I-level took place between 11 600 and 11 700 cal. yr BP and lasted less than ten years (e.g., Jakobsson et al. 2007). The age of the drainage event is virtually the same as the Pleistocene/Holocene boundary, formally placed at 11 700±99 yrs b2k (i.e., 11650±99 cal. yr BP) (Walker et al. 2008).

Since the Baltic Ice Lake water-level drop was a sudden, catastrophic event (e.g. Jacobsson et al. 2007; Hyttinen 2012), it left its mark in the sedimentary record, and can potentially be used as a chronostratigraphic horizon to separate between the Pleistocene and Holocene Epochs if the horizon itself is mappable and the local stratotype section and type area can be adequately recognised and bed contacts defined. It has been generally assumed that as the Baltic Ice Lake level dropped vast amount of former ice lake-bed emerged above the water level, was eroded, reworked and derived into the Yoldia Sea. The increased sediment load deposited in a shallow water facies (shoreface zone) as massive homogenous silt/clay and deformed sand/gravel and in the off-shore areas as debris-flow and deformed fine-grained sediments (e.g., Sauramo 1923; Niemelä 1971; Hyttinen 2012). Two of this type "zero-varve" horizons upon and interbedded with the so-called reddish-hued rhythmites is found at the Jokela and Koria sites onshore southern Finland where the upper one is claimed to represent a water-level drop horizon (Hyttinen et al. 2011a) i.e., the chronostratigraphic Pleistocene/Holocene boundary in Finland. On the other hand, offshore evidence from acoustic investigations of the sediment record in the northeastern Baltic Sea and the Gulf of Finland, suggest that the lower of the two acoustic facies interpreted as showing deformation, might represent sediments disturbed as a result of the Baltic Ice Lake level drop (Hyttinen et al., 2011b). If the interpretation of the acoustic facies is correct and the debrite-unit is traceable across the Baltic Basin, it could be used as an indicator of the Pleistocene/Holocene boundary.

The water-level drop event, however, can be best seen in the major drop in glaciofluvial ice-contact delta altitudes in the Salpausselkä zone. In this area the change between the ice-contact delta water level in the Second Salpausselkä representing the Baltic Ice Lake level B III is on average 27 m higher than the glaciofluvial ice-contact delta water-level north of the Second Salpausselkä, which represents the Yoldia Sea level Y I when the uplift gradient and its dip direction have been taken into account (Fig. 4b). In the western Salpausselkä arc, the Second Salpausselkä glaciofluvial ice-contact deltas and subaquatic fans do not form a continuous geomorphological ridge, while the eastern arc of the Second Salpausselkä is a continuous ridge composed glaciofluvial ice-contact deltas and subaquatic fans. The glaciofluvial ice contact delta-pairs (Table 1) in the western and eastern arcs indicating two different water-levels B III and Y I are only the distance of 1 km to 5km apart when the distance is measured perpendicular to the palaeoisobases (Figs. 3 and 4a). The water-level drop of 25 – 28 m deduced from delta-level differences in front of the former Baltic Ice Lobe has already been known for decades (e.g. Donner 1995). However, this study shows for the first time that a similar 27 m ± 2 m water-level drop also occurred in front of the Finnish Lake District Lobe to the eastern part of the present Saimaa Lake basin. This suggests that the water-level drop was more or less synchronous (within the dating resolution) in front of both ice lobes. The synchronous morphostratigraphic boundary line on the map can be placed to the middle in between the glaciofluvial deltas showing two distinctly different water-levels (Fig. 4).

The De Geer moraine ridges (i.e., ice grounding line positions during the ice retreat) in the study area might have been formed annually or they formation can be related to various non-annual processes at the grounding line (e.g., Dowdeswell et al. 2020). If the De Geer moraine ridges (i.e., ice grounding lines ridges) in the Salpausselkä zone formed annually, the ice-front retreat rate during the last deglaciation can be calculated based on the internal distance between the ridges (e.g. Ojala 2016). Furthermore, the number of De Geer-moraines located between the two ice-contact glaciofluvial deltas deposited at B III and Y I water-levels, indicates the maximum duration of the water-level drop event in southern Finland. Using this assumption, the drainage event lasted 10 years in the western arc of the Salpausselkä whilst in the eastern arc 50 years. This also represents the chronological uncertainty of the Pleistocene/Holocene morphostratigraphic boundary in southern Finland.

5. Conclusions

Based on the results presented here and combined with the former results on the effects of the Baltic Ice Lake water-level drop in the Salpausselkä zone, southern Finland the following conclusion can be made:

1) The geomorphological criteria (feeding esker(s) with an apex area in the proximal part of a formation, meltwater channels on the top of a glaciofluvial formation, kettle holes on the glaciofluvial delta surface and beach ridges on the distal part of a glaciofluvial delta), supported with GPR structural data are fundamental in order to identify true ice-contact deltas and make correct interpretations of the past water-level estimates.
2) The water-level estimates using the ice-contact glaciofluvial deltas in front of the Baltic Sea Ice Lobe and the Finnish Lake District Lobe indicate a synchronous ice marginal position across southern Finland where the drop of the water level was 27±2 metres in front of both ice lobe margins.
3) Dated by a correlation to other sedimentary archives, the Baltic Ice Lake level drop took place at c. 11 700 years ago. Therefore, the morphostratigraphic boundary defined here can be traced across southern Finland, and as such it represents a morphological expression of the Pleistocene/Holocene boundary in southern Finland (Fig. 4a).
4) The morphostratigraphically defined stratotype area for the Pleistocene/Holocene boundary in Finland is suggested to locate in the Second Salpusselkä zone, southern Finland and its type localities indicated in Table 1.

Acknowledgements

The author thanks Dr. Anders Romundset and one anonymous reviewer for constructive suggestions and valuable comments that helped to improve the manuscript.

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