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University of Turku

Faculty of Science and Engineering
Department of Geography and Geology
Geography Division
Doctoral programme

Supervised by

Dr. Joni Mäkinen
Department of Geography and Geology
University of Turku
Turku, Finland

D. Sci. (Tech) Heikki Vanhala
Geological Survey of Finland
Betonimiehenkuja 5
Espoo, Finland

Reviewed by

Dr. Hazen Russell
Sedimentology
Geological Survey of Canada
Ottawa, Canada

Dr. Jörg Lang
Institut für Geologie
Leipniz Universität Hannover
Hannover, Germany

Opponent

Professor Tracy Brennand
Department of Geography
Simon Fraser University
Burnaby, Canada

Cover Image: Elina Ahokangas

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Abstract

Interlobate eskers are the largest esker landforms in Finland. They formed in complex depositional conditions during the deglaciation of the Scandinavian ice sheet ca. 10 000 years ago. Their deposits can be 100 m thick, and they consist of high variety of sedimentary structures in large-scale depositional units. The significance of these large landforms to society is great as they host significant groundwater resources and sand and gravel deposits. In addition to protective legal procedures, thorough research and understanding of esker characteristics and groundwater conditions is vital for the sustainable use of eskers. The key to esker characterization is the use of a sedimentological approach for the recognition of the sedimentary structures and for the interpretation of the depositional conditions which formed the esker, as well as geophysical methods with adequate depth penetration. The combination of these two methods allows the characterization of large-scale architectural esker elements such as the coarse-grained esker core, overlapping esker fans and deformation structures (MUKHs) which form the basic hydrogeological units of the eskers. The reliable locating of these elements influencing the groundwater flow is essential in terms of groundwater utilization. In addition, knowledge on bedrock level and the variations in bedrock topography are needed to obtain the correct thickness of the esker deposits.

The detailed sedimentological characterization of the Lohtaja-Kivijärvi esker revealed a new type of esker formed between two ice lobes, an ice-lobe margin esker. In the case of this esker, the interlobate environment was altered by the readvance of the neighboring ice lobe, and therefore this esker is not purely an interlobate esker. This esker challenges the assumption of thick and extensive eskers being formed between two ice lobes due to its modest extent and thickness. In addition, its depositional characteristics revealed changes in the ice dynamics as well as in the meltwater flow patterns. Researching thick interlobate esker deposits down to the bedrock level has not succeeded so far because the depth penetration of the available geophysical methods in Finland has not been adequate. The results of the first landstreamer-based high resolution seismic reflection pilot surveys in Finland on complex and thick interlobate esker deposits are represented. The results show the applicability of the landstreamer-based high-resolution seismic reflection method in the characterization of the interlobate esker architectural elements and bedrock level and topography variation. The combined use of the sedimentological approach and geophysical methods (ground penetrating radar and high-resolution seismic reflection) is recommended for the comprehensive understanding of thick and complex interlobate esker deposits and in the future potentially for large ice-marginal landforms like the Salpausselkäs.

Keywords: Interlobate eskers, ice-lobe margin eskers, architectural elements, high-resolution seismic reflection method, landstreamer

Tiivistelmä

Saumaharjut ovat Suomen suurimpia harjumuodostumia. Ne syntyivät monimutkaisissa kerrostumisoloissa Skandinavian jäätikön sulamisvaiheen aikana noin 10 000 vuotta sitten. Niiden kerrostumat voivat olla 100 m paksuja, ja ne muodostuvat suuren mittakaavan kerrostumisyksiköistä ja niiden lukuisista erilaisista kerrostumisrakenteista. Näiden maaperämuodostumien merkitys yhteiskunnalle on huomattava niiden sisältämien pohjavesiresurssien sekä hiekka- ja soravarojen vuoksi. Lisäksi niillä on geologista ja maisemallista arvoa. Lainsäädännöllisten toimien lisäksi harjujen ominaisuuksien ja pohjavesiolosuhteiden perusteellinen tutkimus ja ymmärrys ovat elintärkeitä harjujen kestävälle käytölle. Tämä voidaan saavuttaa harjujen suurten mittakaavan arkkitehtuuristen elementtien, kuten karkean harjuytimen, päällekkäisten harjuviuhkojen ja deformaatiorakenteiden (piilosupparakenteet), luonnehtimisella. Näiden pohjaveden virtauksen kannalta keskeisten rakenteiden luotettava paikantaminen on keskeistä pohjaveden hyödyntämisen kannalta. Lisäksi tarvitaan tietoa kalliopinnan tasosta ja vaihteluista kallionpinnan topografiassa, jotta harjukerrostumille saadaan oikea paksuus.

Lohtaja-Kivijärvi-harjun yksityiskohtainen sedimentologinen luonnehdinta paljasti uuden tyyppisen, kahden jääkielekkeen välissä syntyneen harjun, jääloobin reunan harjun. Jääkielekkeiden välinen saumaympäristö oli muuttunut toisen jääkielekkeen uudelleenetenemisen myötä, ja siksi tämä harju ei ole puhtaasti saumaharju. Tämä harju haastaa pienen laajuutensa ja paksuutensa takia oletuksen siitä, että kahden jääkielekkeen väliin syntyvät harjut ovat paksuja ja laajoja. Lisäksi sen kerrostumisominaisuudet paljastivat muutoksia jäätikködynamiikassa sekä sulamisvesien virtauskuvioissa. Saumaharjujen jopa 100 metriä paksujen kerrostumien sisäisten rakenteiden tutkiminen kalliopintaan saakka ei ole onnistunut tähän mennessä, koska Suomessa saatavilla olevien soveltuvien geofysikaalisten menetelmien (maatutkan) syvyysulottuvuus ei ole siihen riittänyt. Tämä väitöskirjatyö esittelee Suomen ensimmäisen landstreamer-perusteisen tarkan resoluution heijastusseismisen pilottiluotauksen tulokset monimutkaisilta ja paksuilta saumaharjukerrostumilta. Tulokset osoittavat landstreameriin perustuvan tarkan resoluution heijastusseismisen menetelmän soveltuvuuden saumaharjujen arkkitehtuuristen elementtien sekä kallioperän tason ja topografian vaihtelun tarkasteluun. Sedimentologisen lähestymistavan ja geofysikaalisten menetelmien (maatutka ja tarkan resoluution heijastusseismiikka) yhteiskäyttöä suositellaan, jotta saavutetaan kokonaisvaltainen ymmärrys monimutkaisista saumaharjukerrostumista ja mahdollisesti tulevaisuudessa suurista reunamuodostumista, kuten Salpausselistä.

Avainsanat: Saumaharjut, jääkielekkeen reunan harjut, arkkitehtuuriset elementit, tarkan resoluution heijastusseisminen luotaus, landstreamer

Acknowledgements

Eskers have been part of my life from early age. I spent my childhood in a village called Harjuseppä (esker smith), named after Sepänharju esker in its vicinity. My interest to eskers in the university level awoke during the geomorphological mapping practical in 1999. My map sheet was from Lohtaja where the littorally reworked esker sediments form one of the most extensive littoral and aeolian deposit areas in western Finland. The final nail in my esker research coffin was hit in autumn 2000 when I was a student on physical geography methology field course in Virttaankangas. That epic weekend with sedimentological logging, northern lights and a night swim in an ice-cold spring with my fellow students has remained in my mind ever since. I later happened to notice that the esker at Lohtaja was part of the same esker chain with Sepänharju esker. I took a closer look at that particular esker chain and ended up making my master's thesis about it. Summer-autumn 2004 was my biggest field campaign so far and during it I collected the sedimentological data for my thesis work.

Firstly I'd like to thank my supervisors Joni Mäkinen and Heikki Vanhala. Joni, my first encounter with you related to eskers was that epic Virttaankangas field course in autumn 2000. I probably asked you a dozen times how to measure foreset dip and azimuth and you patiently explained and showed it to me probably another dozen times more before I finally got it. Later on you first became my master's thesis supervisor and then my PhD thesis supervisor as well. Thank you for your enthusiasm, positivity, realism and reliability throughout all these years. It has been a privilege to have you as my supervisor. Heikki, thank you for your support and guidance in geophysics and showing me the many possibilities it can offer. Thank you also for the unofficial field photo viewing sessions. Thank you also to my research director Risto Kalliola for a comprehensive view on my work and proving me new insights into it.

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List of original publications

This thesis consists of an abstract, summary and the following four papers which are referred to in the text with Roman numerals.

I Ahokangas, E., Mäkinen, J. 2014. Sedimentology of an ice lobe margin esker with implications for the deglacial dynamics of the Finnish Lake District lobe trunk. *Boreas 43:1*, 90–106.

II Maries, G., Ahokangas, E., Mäkinen, J., Pasanen, A. & Malehmir, A. 2017. Interlobate esker architecture and related hydrogeological features derived from a combination of high- resolution reflection seismics and refraction tomography, Virttaankangas, SW-Finland. *Hydrogeology Journal 25:3*, 829–845.

III Ahokangas, E., Mäkinen, J., Artimo, A., Pasanen, A., & Vanhala, H. 2018. Esker Aquifer Characterization by High Resolution Seismic Reflection Method with Landstreamer in SW Finland. (Submitted to Journal of Applied Geophysics)

IV Ahokangas, E., Maries, G., Mäkinen, J., Pasanen, A., Malehmir, A., Heinonen, S., & Pajunen, M. 2018. The characterization of esker aquifer and glacial stratigraphy by a high-resolution seismic reflection survey in the Satakunta Sandstone area, Köyliö, SW Finland. (Manuscript)

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Abbreviations

AMS	Accelerator mass spectrometry
CFEM	Central Finland End Moraine
ERT	Electrical resistivity tomography
GLOF	Glacial lake outburst flood
GPR	Ground penetrating radar
HRSR	High-resolution seismic reflection method
HTEM	Helicopter-borne time-domain electromagnetic
Hz	Hertz
LO-KI	Lohtaja-Kivijärvi esker
MAR	Managed aquifer recharge
MEMS	Micro-electro-mechanical system
Mhz	Megahertz
MUKH	Morphologically undetectable kettle hole
RMT	Radio magnetotelluric method

1 Introduction

Interlobate eskers are among the largest glaciofluvial landforms in the world. They host major groundwater resources and have high importance for the society, which calls for careful research to understand their depositional and hydrogeological characteristics (cf. Warren & Ashley 1994; Brennand & Shaw 1996; Thomas & Montaque 1997; Paterson & Cheel 1997; Russell et. al. 2003; Mäkinen 2004; Sharpe et. al. 2007). Finnish interlobate eskers, like the Säkylänharju-Virttaankangas glaciofluvial complex, were formed between two differently behaving ice lobes (Punkari 1980, 1997; Lundqvist 1989; Kujansuu et. al. 1995) during the deglaciation of the Scandinavian Ice Sheet about 10 000 years ago. Interlobate eskers have sediment thicknesses from 50 up to 100 m and complex internal structures due to variable sedimentation patterns and rapidly changed depositional processes and environments (Mäkinen 2004). However, some smaller-scale esker chains have been interpreted and shown to be interlobate, including the Lohtaja-Kivijärvi esker (LO-KI) (Punkari 1980; Ahokangas 2008; Ahokangas & Mäkinen 2014a). For their high complexity, their characterization is best conducted as architectural elements including the esker core, subaqueous fans, esker fan lobes, morphologically undetectable kettle holes (MUKHs) and littoral deposits.

Until the 1990s, available pit excavations allowed the detailed sedimentological description and interpretation of the depositional conditions of eskers (Banerjee & McDonald 1975; Fyfe 1990; Brennand & Shaw 1996; Lunkka & Gibbard 1996; Palmu 1999). However, following the strengthening environmental regulations which have decreased sand and gravel excavation from eskers, research emphasis has shifted from pit excavations to the use of geophysical methods. The research of interlobate deposits is further hampered in places by their thicknesses which are 50–100 m. The main problem in the study of large-scale and extensive glaciofluvial deposits (eskers) is the inability of commonly used and available geophysical methods in Finland to penetrate into the deeper parts of these deposits. Ground penetrating radar (GPR), which has been proven by numerous researches to be a highly efficient and suitable method for the study of sand and gravel-based glaciofluvial deposits, has only limited depth penetration (15–30 m). The detailed and comprehensive research of large-scale esker sediments down to the bedrock level requires the use of a new research method with adequate depth penetration as well as the ability to separate the esker elements as well as the bedrock topography with good resolution.

The high-resolution seismic reflection method (HRSR) has provided good results in the research of glacial deposits and groundwater reservoirs in North America as well as in Northern Europe (Huuse et. al. 2003; Kirsch et. al. 2006; Pugin et. al. 2009; Martinez et. al. 2010; Pugin et. al. 2013a; Pugin 2013c). The depth penetration of this method is noteworthy (100 m) compared to the ground penetrating radar, and the HRSR survey resolution has been up to 0,5–1 m at best with shear-wave data (Pugin et. al. 2009). Due to these very promising results, the interest in the applicability of the HRSR method in the research of Finnish interlobate eskers increased and resulted in the launching of co-operation between the University of Turku and Geological Survey of Finland with Geological Survey of Canada and the Uppsala University Geophysics section. The suitability of the HRSR method for Finnish conditions was tested in two surveys in 2011 and 2014 in two sites on the interlobate Pori-Koski esker in SW Finland. The datasets collected in these two HRSR surveys form the basis for this thesis work.

This thesis is the first work integrating sedimentology, ground penetrating radar (GPR) and high-resolution seismic reflection (HRSR) data in the study of extensive and thick interlobate deposits down to the bedrock level (cf. Fig.1). It includes reflection seismic data collected with two different types of landstreamer equipment from two different study areas (a total of 15 km of seismic lines).

The main research objectives are:

1. To gain understanding of the interlobate depositional environment and the dynamical behavior of ice lobes/ice dynamics (papers I–IV)
2. To characterize the architectural elements of interlobate eskers and their depositional environments in Western Finland (papers I–IV)
3. To apply the understanding of depositional environments and esker architecture to hydrogeological models and groundwater flow modeling (papers II–III)
4. To analyze the applicability of the landstreamer-based high-resolution seismic reflection method in the characterization of complex and extensive interlobate deposits in Finland (papers II–IV)

The foundation of this thesis lays in the sedimentology-based esker research as well as the changes occurring in the ice lobe dynamics partly responsible for the deposition of the esker deposits. The ice dynamics are reflected in the esker deposition and depositional characteristics. The first paper (I) deals with the sedimentology of an ice margin esker formed between Näsijärvi-Jyväskylä and the

Finnish Lake District lobes in western-central Finland. It sheds more light into the depositional environment between two ice lobes by introducing an ice-lobe margin esker. This type of depositional environment deviates from an interlobate environment due to the readvance of the Näsijärvi-Jyväskylä lobe which rearranged the interlobate joint between the two ice lobes.

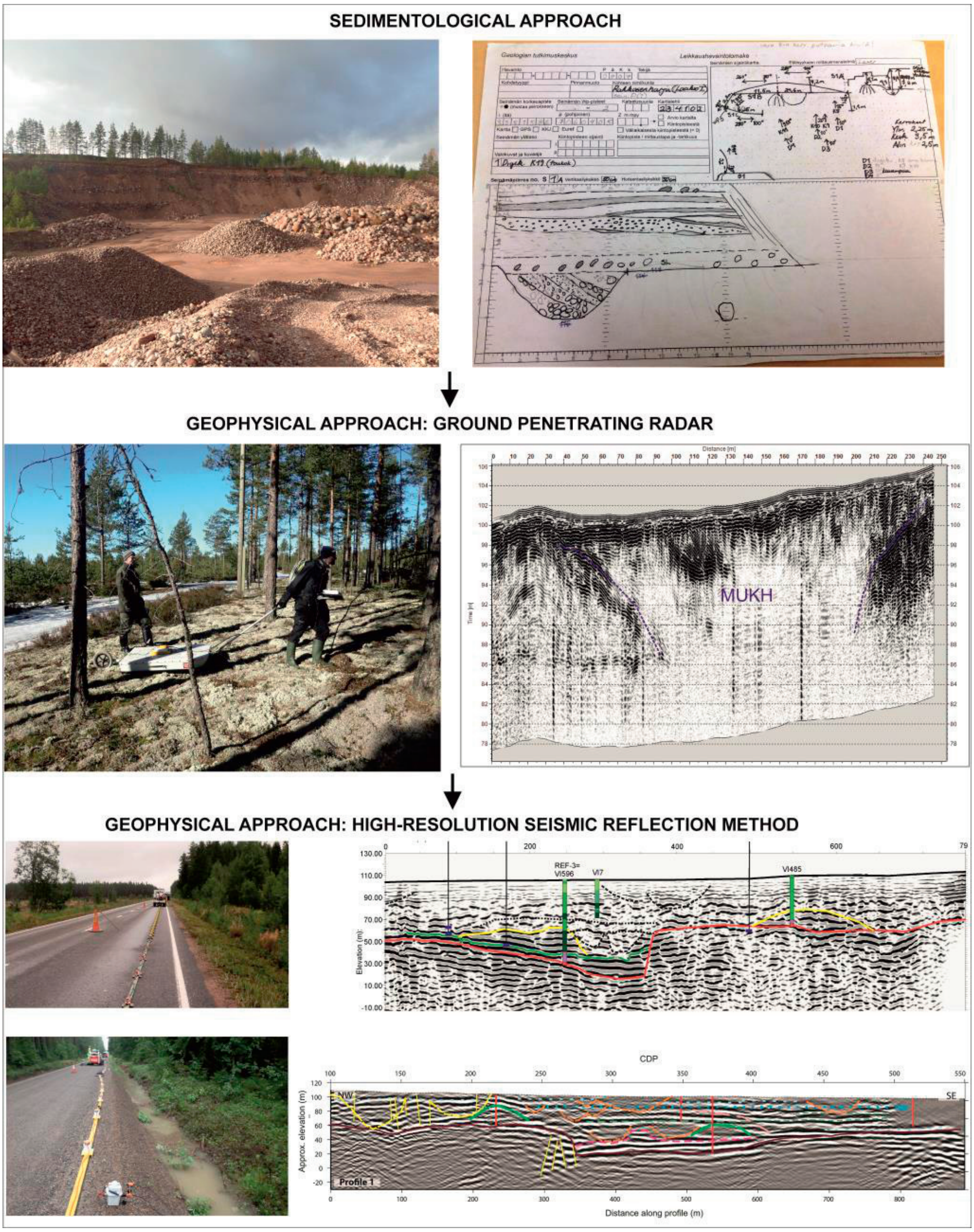

Fig. 1. Theoretical and methodological framework for this PhD thesis. The sedimentological approach (paper I) is supplemented with the two other geophysical methods (ground penetrating radar, high-resolution reflection seismic method (papers II–IV). The landstreamer-based high-resolution seismic reflection method utilized the equipment of COWI Denmark (paper III) and Uppsala University (papers II and IV). Photos by Elina Ahokangas.

The Pori-Koski esker (papers II, III and IV) was formed between the sublobes of the Baltic Sea lobe. This depositional environment was more stable than the one between the Finnish Lake District lobe and Näsijärvi-Jyväskylä where the ice-lobe margin esker was formed (paper I). The differences in the depositional conditions between pure interlobate eskers and ice-lobe margin eskers provide wider understanding of the dynamic depositional environment between two ice lobes. Paper III introduces the use of the high-resolution reflection seismic method with a landstreamer in Virttaankangas for the first time in Finland. The HRSR survey revealed previously unknown characteristics of the esker core in two different parts of the aquifer due to its better depth penetration. The survey data also helped to better explain the widening of the coarse-grained hydrogeological unit in association with the tributary cores and the secondary ice-marginal branch of the main core. Papers II and IV introduce a new advanced MEMS-based (micro-electro mechanical system) broadband seismic landstreamer (Brodic 2017) and its usability in the study of the interlobate deposits of Pori-Koski in Virttaankangas (paper II) and Köyliö (paper IV). Paper III presents the application of the advanced broadband seismic landstreamer in the delineation of the subsurface structures of a major interlobate esker system in Virttaankangas. This survey utilized the high-resolution seismic landstreamer for aquifer characterization and validation of its hydrogeological properties. Paper IV shows for the first time the dimensions and characteristics of the interlobate esker sediments within a ca. 1 km wide sandstone depression as well as the tectonic features of the deeper parts of the bedrock within the sandstone depression in Köyliö.

2 Background

2.1 Deglaciation and ice dynamics in Western Finland

The retreating margin of the Scandinavian ice sheet reached the Finnish coast at ca. 13.1. ka ago based on the combination of the results of Saarnisto & Saarinen (2001) and the correlation of the Finnish varve chronology with the Swedish one (Strömberg 1990). According to Lunkka et. al. (2004), the First Salpausselkä formed 12.3–12.1. ka and the Second Salpausselkä 11.8–11.6. ka ago based on the varved clay studies, ^{14}C AMS dates and paleomagnetic measurements by Saarnisto & Saarinen (2001). The SIS divided into ice lobes after the Salpausselkä stage (ca. 11.8 ka ago). The deglaciation of Western Finland occurred through the decay of three different ice lobes operating in the area; the Baltic Sea ice lobes in the southwest and the Näsijärvi-Jyväskylä and the Finnish Lake District lobes in the west (Punkari 1980). Three passive ice areas were formed adjacent to these lobes (cf. Fig. 2). The Salpausselkä ridges and the Central Finland End Moraine (CFEM) were formed in front of three lobes (Fig. 2). The CFEM was formed ca. 11.2-11.1 ka ago due to the advance of the Näsijärvi-Jyväskylä lobe (Saarnisto & Saarinen 2001).

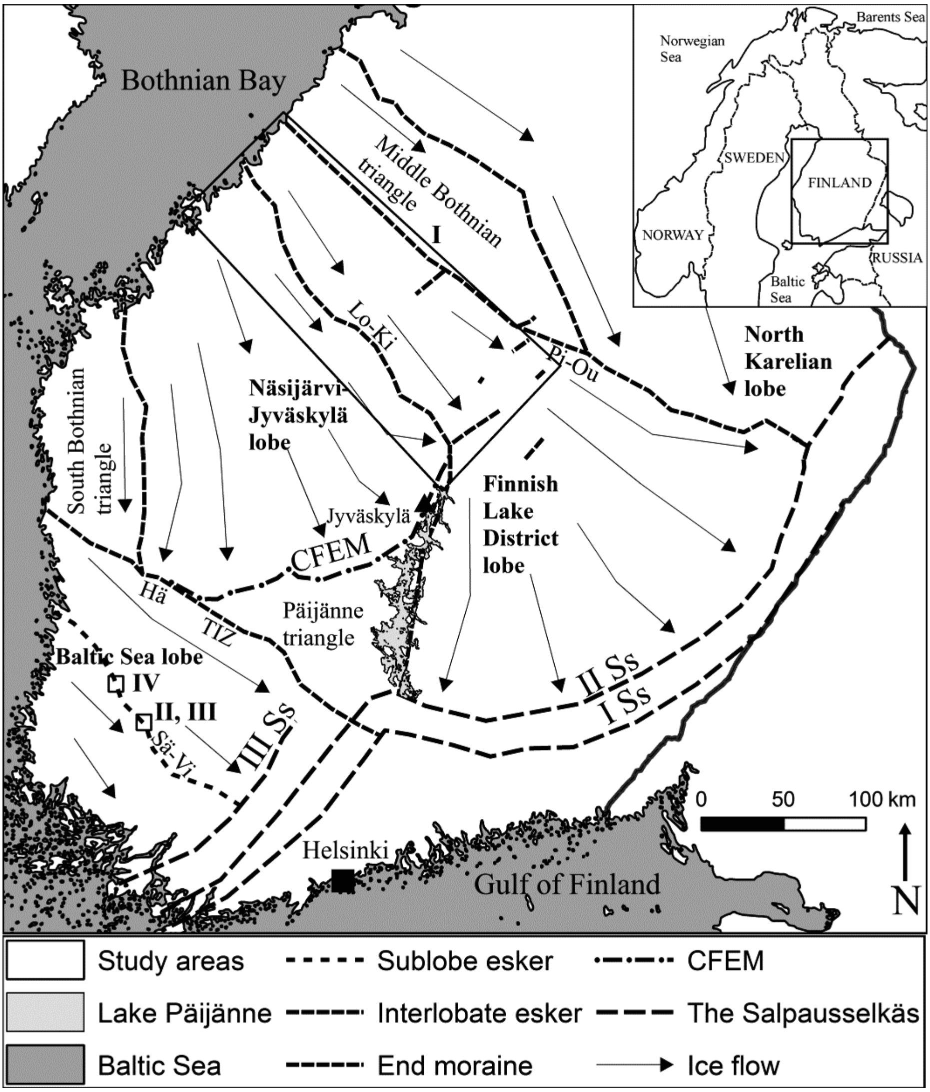

Fig. 2. The ice lobes of southern and Western Finland, main ice flow directions, ice-marginal landforms (The Salpausselkä ridges, Central Finland End Moraine (CFEM), sublobe and interlobate eskers (SÄ-VÍ: Säkylänharju-Virttaankangas, Hä: Hämeenkangas, TIZ: Tampere Interlobate Zone, LO-KI: Lohtaja-Kivijärvi esker and PI-OU: Pihtipudas-Outokumpu esker) and the study areas presented in papers I–IV. Modified from Ahokangas & Mäkinen (2014a).

This advance influenced the interlobate environment between it and the Finnish Lake District lobe. However, no evidence of the major 50 km oscillation (Rainio et. al. 1986) or ice readvance was found near the Hämeenkangas esker in the western part of the NJL (cf. Lunkka & Alhonen 1996; Lindholm 2010). No evidence of ice readvance was found in the northern end of the CFEM based on the field observations and geomorphological evidence (Ahokangas/Kajuutti /Mäkinen et. al., unpublished data) which indicates that the readvance of the NJL was very minor or occurred in individual sublobes and local oscillations (cf. Lindholm 2010).

Most of the Finnish glaciofluvial deposits were formed during the Late Weichselian deglaciation. Some older deposits of Early Weichselian or pre-Weichselian age are also found (Kujansuu et. al. 1995). The numerous esker chains were formed within the ice lobes of the SIS mainly subglacially or in ice crevasses or ice-walled channels. Some of these eskers continue from the Salpausselkä ridges to the coast of the Bothnian bay in the area of the Finnish Lake District lobes (cf. Fig. 2). In addition to the ordinary eskers, thick and extensive interlobate eskers were formed between the ice lobes or between the sublobes of the ice lobes. The interlobate zones between the ice lobes collected meltwaters and sediments which enabled the deposition of large interlobate complexes like the Säkylänharju-Virttaankangas esker, the Hämeenkangas esker and the Tampere interlobate zone (TIZ) in Southwestern Finland and the Pielavesi-Outokumpu esker in Central Finland (cf. Fig. 2).

2.2 A review of previous esker research

2.2.1 Eskers and their characteristics

An esker is a sinuous ridge composed of sand and gravel aligned parallel to the ice flow direction. The morphology of the ridges varies, ranging from elongated continuous to segmented ridges, and the shape varies as well from sharp- to broad-crested. Esker ridges can also contain tributary eskers up to the fourth order; the width of eskers varies from few tens to hundreds of meters and their height varies from few to tens of meters. The length of the ridges can be up to hundreds of kilometers (Shilts et. al. 1987; Kujansuu et. al. 1995). The ridges may contain multiple kettle holes and include deltas, sandurs or other extensions as well as multiple (parallel) ridges. The formation of eskers takes place during the deglaciation of an ice sheet and is linked to the sub- and supraglacial hydrology of an ice sheet (Shreve 1985, Hooke 1998; Greenwood et.al. 2016). It is attributed to the areas of hard bed lithologies while channels incise into the subsurface in the areas of less resistant bedrock or to thick sedimentary sequences (Clark & Walder 1994; Boulton et. al. 2009). Distributed drainage through a network of shallow canals is claimed to favor soft deformable beds. However, some well-developed esker networks are also found on thick sediments and sedimentary bedrock (Greenwood 2008; Storrar et. al. 2014; Burke et. al. 2015).

Esker formation is mostly attributed to subglacial tunnels (Brennand 1994; Menzies 2002) but also to tunnel mouths (Brodzikowski & van Loon 1991) or the deposition of subaqueous fans, deltas or esker beads at the ice-front (Rust & Romanelli 1975; Powell 1990). Eskers can also develop in inter-lobate positions or ice lobe confluences on glaciers and ice sheets (Huddart et. al. 1999; Russell et. al. 2001; 2006). The role of a stable conduit environment (up to hundreds of years) for esker deposition has been emphasized (Kleman et. al. 1997; Boulton et. al. 2009; Clark et al. 2012), but rapid or even single formation of eskers during jökuhlaups or glacial lake outburst floods (GLOFs) has also been observed (cf. Russell et. al. 2001; Fiore et. al. 2002; Burke et. al. 2010; Burke et. al. 2012: Burke et. al. 2015). Various genetic classifications of eskers have been made. The classification of Warren & Ashley (1994) divides eskers into tunnel fills, ice-channel fills, segmented tunnel fills and beaded eskers. The morphology of tunnel-fill eskers and their relation to hydraulic conditions beneath the glacier, especially the rates of the melting and freezing of the tunnel walls, lead to a division into multiple-crested, broad-crested and sharp-crested eskers (Shreve 1985). There is no single and comprehensive genesis for eskers. The variations in ice dynamics, meltwater supply and flow, sediment supply, sedimentary structures etc. create unique depositional conditions for each esker ridge. The importance of researching individual eskers is highlighted as well as the use of the term ‘esker’ rather in a morphological sense instead of as an indication of genesis (cf. Huddart et. al. 1999).

Eskers are also known to occur on the floors of tunnel valleys (Brennand & Shaw 1994; Ó Cofaigh 1996) and in the downglacier ends of meltwater corridors (Burke et. al. 2010). Tunnel valleys and meltwater corridors are also the products of subglacial channelized meltwater flows (Greenwood et. al. 2016). Recently, new landforms (murtoos) indicating the meltwater networks preceding esker formation have been found in SW Finland (Mäkinen et. al. 2017) and Sweden (Peterson et. al. 2017; 2018). These murtoo landforms appear to be a combination of both till and glaciofluvial material (Mäkinen et. al. 2018; Peterson et. al. 2018), and they appear in wide-spread routes found especially in the area of the Baltic Sea and Finnish Lake District lobes as well as in Sweden (Peterson et. al. 2017; Ojala et. al. 2018 subm.). Murtoo landforms often form distinct routes that are either connected to bedrock valleys or eskers (Mäkinen et. al. 2017).

2.2.2 Previous research on interlobate complexes

Research on interlobate eskers has had its emphasis on the end of 1990s and early 2000s. The formation of eskers has been attributed to interlobate joints between differently behaving ice streams (Punkari 1980; Lundqvist 1989; Kujansuu et. al.

1995). Lunkka & Gibbard (1996) question the interlobate origin of Hämeenkangas-Pohjankangas. The time-transgressive and interlobate origin of the Säkylänharju-Virttaankangas glaciofluvial complex in SW Finland was described by Mäkinen (2004) based on sedimentological evidence. A few master's theses have addressed interlobate (Lindholm 2010) or ice-margin eskers formed between two ice lobes (Ahokangas 2008) due to the disturbance of the interlobate environment by ice lobe advance (Ahokangas & Mäkinen 2014a). In addition to the depositional environment between two differently behaving ice streams, interlobate lake basins (Warren & Ashley 1994, Thomas & Montaque 1997) or the deposition of glaciofluvial complexes between ice-lobes in Canada (Paterson & Cheel 1997) have been previously addressed. Recently, braided-channel deposits from an interlobate area between ice lobes in Poland (Gruszka et. al. 2012) and interlobate complexes formed due to time-transgressive ice stagnation between two major ice lobes (Santos 2012) have been described. The glaciofluvial nature has been demonstrated for two large inter-lobate 'moraines' in North America, the Harricana Moraine (Brennand & Shaw 1996) and the Oak Ridges Moraine (Barnett et. al. 1998; Russell et. al. 2003; Sharpe et. al. 2007). Synchronous deposition inside a subglacial interlobate tunnel has also been proposed for the Harricana Moraine (Brennand & Shaw 1996). Geological Survey of Finland has also published reports related to some interlobate eskers in Finland, including the Hämeenkangas-Pohjankangas (Ahonen et. al. 2014), Ylöjärvi-(Tampere)-Koski (Ahonen et. al. 2015), Ulvila-Köyliö (Palmu et. al. 1994) and Kempeleenharju (Breilin et. al. 2006) interlobate esker chains.

2.2.3 The history of Finnish esker research

The history of scientific esker research yields all the way back to the 1870s when the first detailed observations on esker structure were made (Stone 1899; Jopling 1975) and is strongly connected to the development of the glacial theory. A short review of the history of esker research is provided by Mäkinen (2004). In Finland, Aario (1972) was the first to proceed towards sedimentology-based work on glaciofluvial sediments. In addition, the inventory of sand and gravel resources as well as the nationwide esker investigations took place in the 1970s and 1980s (Niemelä 1979, Kontturi 1984). The inventory investigations included drillings, seismic soundings and test pit excavations but still lacked the sedimentological approach. The morphology and characteristics of Finnish eskers were described by Kujansuu et. al. (1995), and the combination of glacial geomorphology with sedimentology emerged in the 1990s (Fyfe 1990, Lunkka & Alhonen 1996; Lunkka & Gibbard 1996; Palmu 1999).

Overall, the sedimentological esker research in Finland has been relatively modest in the past 18 years (2000–2018). The time-transgressive and interlobate origin of the Säkylänharju-Virttaankangas glaciofluvial complex was described by Mäkinen (2004) based on sedimentological evidence. The sedimentology of the proximal part of the Pernunnummi sandur delta in the Third Salpausselkä was researched by Mäkinen & Palmu (2008), and the sedimentology of an ice margin esker and ice dynamics of the Finnish Lake District lobe trunk by Ahokangas (2008) and Ahokangas & Mäkinen (2014a). Esker researches combining sedimentology and geophysical methods have been relatively scarce (cf. Artimo et. al. 2003a; Mäkinen 2003, Pasanen 2009). Some research on the impacts of the anticipated climate change on unconfined aquifers (Okkonen et. al. 2010), groundwater-surface water interaction on esker aquifers (Rossi et. al. 2012; Ala-aho et. al. 2015; Rautio & Korkka-Niemi 2015; Rautio et. al. 2018), and the impact of bedrock structures on glaciofluvial deposits (Skyttä et. al. 2015) has been made.

2.2.4 The 3-D hydrogeological modeling and groundwater-related research on eskers

The three-dimensional approach to esker characterization in Finland was launched due to the requirements of the European Union Water Framework Directive (European Parliament and Council 2000). One of the first 3-D hydrogeological and numerical groundwater modeling works in Finland was Artimo's PhD thesis (2003). In addition, several masters' theses on the 3-D hydrogeological modeling of eskers (eg. Rautanen 2007; Tuhkanen 2008; Mäki-Torkko 2009) as well as on the geophysical research of groundwater areas mainly in the Oulu region (Rundelin 2001; Martinkauppi 2006a; Kaikkonen 2007; Knuuti 2008) have been made. Internationally, the 3-D approach in aquifer characterization has also been utilized e.g. in the research of the glaciofluvial sediments of formed braided river environments (Beres et. al. 1995, 1999). In North America, the regional 3-D hydrogeological model of a Quaternary glaciated basin was formed by Ross et. al. (2005) and a 3-D hydrostratigraphical model of a glacial sediment assemblage by Atkinson et. al. (2014). The 3-D geological model for the glaciofluvial-glaciolacustine Oak Ridges Moraine complex (cf. Barnett et. al. 1998) was constructed by Sharpe et. al. (2007). In UK, Turner et. al. (2015) developed a detailed 3-D geological framework model of complex Quaternary deposits.

Geological Survey of Finland has launched several projects related to eskers and groundwater reserves since the 1990s and has produced numerous reports. The nationwide POSKI project launched in the 1990s (cf. Britschgi 1994) aims at increasing awareness of the protection of groundwater reserves and at simultaneously securing the local supply of construction rock material. The groundwater area characterization project (HARA) utilizes various geophysical methods in the characterization of glaciofluvial deposits (e.g. Tikkanen & Mattson 1996; Eskelinen & Valjus 2007; Ahonen & Valjus 2010; Ahonen et. al. 2011, Nurminen et. al. 2015) and lately also in the creation of 3-D models on eskers and Quaternary deposits (e.g. Valpola 2017). These reports unfortunately lack a more detailed understanding of the sedimentary structures and the depositional history of the esker deposits, in addition to the more detailed characteristics of the major esker architectural elements. These reports are mostly conducted from the practical perspective for groundwater utilization, and their scientific content remains minor.

2.2.5 Ground penetrating radar (uppermost parts) and the high-resolution seismic reflection method (lowermost parts) in esker research

The ground penetrating radar has been applied in vast geological and urban environments. The applications related to hydrogeological studies and moreover to glaciofluvial deposits became more common in the late 1990s (eg. Sutinen 1992; Beres et. al. 1995; Olsen & Andreasen 1995; Beres et. al. 1999). Huggenberger & Aigner (1999) acknowledged the challenges in aquifer sedimentology regarding the role of sedimentological information (heterogeneity) in groundwater models as well as the integration of geological and geophysical information in the description of aquifer structures. The combination of sedimentology and ground penetrating radar has provided more detailed information on esker characteristics (Russell et. al. 2001; Fiore et. al. 2002; Mäkinen 2003b; Burke et. al. 2008; Burke et. al. 2012; Lejzerowicz et. al. 2012; Mäkinen et. al. 2018) and other glaciofluvial and glacigenic sediments (Neal 2004, Pasanen 2009) during past the 15 years. The 3-D approach in aquifer characterization has also been utilized in various deposits (Beres et. al. 1999; Baker et. al. 2001). Recently, the combination of GPR and other geophysical methods, like electrical resistivity tomography (ERT), has been used in the research of esker architecture (Pellicer & Gibson 2011; Burke et. al. 2012; Burke et. al. 2015; Ahokangas et. al. 2015).

The seismic reflection method originates from the oil industry and exploration in the stratified sedimentary rocks. The seismic reflection method has been mostly utilized in hydrocarbon exploration and in the research of crustal structures now reaching penetration depths of many kilometers (Reynolds 2011). During the last 30 years, the use of high-resolution seismic reflection method investigations related to engineering and environmental topics in depths below 200 m has become more common (Steeples & Miller 1988). High-resolution seismic surveys with planted geophones have been used on complex groundwater reservoirs, aquifers and structures hosting or controlling their locations (Pugin et. al. 1999; Juhlin et. al. 2002; Francese et. al. 2005; Giustiniani et. al. 2008; Ahmad et. al. 2009). In addition, a towable landstreamer has been used in the high-resolution seismic surveys. A landstreamer consists of an array of seismic receivers fixed to a baseplate or sledge and attached to a non-stretch material that allows the towing of the system along the ground by a vehicle. Kruppenbach et. al. (1975) introduced a towable land cable which is the first prototype of a towable landstreamer. The first seismic landstreamers were developed for conventional oil exploration in the arctic environment (Eiken et. al. 1989). The advantage of the towable landstreamer compared to the planted geophones is noteworthy in terms of survey time (up to 1.5–6 line km/day) and the amount of required field personnel (Pugin et. al. 2009). The near-surface applications of the high-resolution seismic reflection method with a landstreamer have mainly focused on groundwater mapping (eg. Almholt et. al. 2013), the architecture and hydrostratigraphy of Quaternary aquifer complexes (Pugin et. al. 1999), characterization of buried eskers (Pugin et. al. 2009; Cummings et. al. 2011), interlobate eskers (Maries et. al. 2017; Brodic et. al.2018) and various hydrogeological studies on tunnel valley aquifers in Europe and North America (Praeg 2003; Pugin et. al. 2004; Kehew et. al. 2012; Oldenborger et. al. 2013; Stewart et. al. 2013; Pugin et. al. 2014a). In addition, the landstreamer-based seismic surveying has been used in the mapping of contaminated sites or natural hazard studies (Hunter et. al. 2010; Martinez et. al. 2012; Krawczyk et. al. 2012) and in urban and paved areas (Huggins, 2004; Inazaki 2004, 2006 Brodic et. al., 2015; Malehmir et al. 2015; Pilecki et al. 2017).

2.3 The basic principles of ground penetrating radar and the high-resolution seismic reflection method

The ground penetrating radar and seismic reflection data are subject to the same conditions in terms of wave propagation kinematics as well as reflection and refraction responses to subsurface discontinuities. The broad assumptions supporting the processing and interpretation of seismic reflection data should also be applied to ground penetrating radar data (Neal 2004). The reflection profiles were previously subdivided into seismic sequences by surfaces of discontinuity (seismic sequence boundaries), while the current terms used in seismic stratigraphy are seismic packages, seismic surfaces and seismic facies (Mitchum et. al. 1977) and radar surfaces, radar packages and radar facies (Neal et. al. 2002). For the ground penetrating radar, the dielectrical properties of the subsurface determine the nature of the reflected signal as well as the penetration depth and the attenuation of the electromagnetic pulse. The dielectric permittivity (ε), electrical conductivity (σ) and magnetic permeability (μ) are the material properties controlling the behavior of electromagnetic energy in a medium (Neal 2004). A high-frequency electromagnetic pulse is transmitted to the subsurface in ground penetrating radar profiling. Some part of this electromagnetic energy is reflected or refracted from the electrical boundaries. The remaining part of the energy penetrates deeper into the subsurface and is reflected from deeper boundaries, scatters or attenuates.

For seismic waves, external force F is applied across an area A of a surface of a body. The forces inside the body are established in proportion to the applied external force. Stress is the ratio of the force to area (F/A). The stressed body undergoes strain (the amount of deformation expressed as the ratio of the change in length/volume to the original length/volume) (Reynolds 2011). The deformation of a material (strain, ε) results from a force per unit area (stress, σ) acting on the material. The relation between stress and strain is called Hooke's Law ($\sigma = E\varepsilon$). Stress and strain are directly and linearly related, and the body behaves elastically until the yield point is reached. The body reverts to its pre-stressed shape below the yield point. At stresses beyond this point, the body behaves in a plastic or ductile manner and permanent damage occurs. Further stress causes the body to strain until it fractures (Reynolds 2011). For a seismic wave, the elastic properties of the subsurface media influence the wave propagation and velocity. A seismic wave can be defined as a propagation of elastic disturbance through the subsurface media (Sheriff 2002). The propagating seismic wave causes stress resulting in a temporary strain (or deformation) of the media. The strain caused by a seismic pulse is usually so minor that Hooke's law holds, except very near to the seismic source.

The seismic waves are described by the seismic wave equation which is derived from Newton's Second Law of Motion, Hooke's Law and the absorptive properties of materials (convert seismic energy to heat and sound energy) which attenuate the amplitude of seismic waves (Styles 2012). The seismic waves are created by active seismic sources (explosive, mechanical, pressure) transmitting energy into the subsurface or by passive sources originating from earthquakes, traffic, industry etc. The waves travel away from the seismic source at a velocity determined by the elastic moduli and the densities of the media which they pass through. The two main types of seismic waves are the body waves (passing through the bulk of a medium) and the surface waves confined to the interfaces between media of contrasting elastic properties (particularly the ground surface) (Reynolds 2011). The body waves in the subsurface can be P-waves (compressional, longitudinal, push or primary) or S-waves (shear waves, secondary or transverse). P-waves have higher velocity compared to S-waves. In addition to these, two types of surface waves can travel between the boundary and the free surface (Rayleigh or Lowe waves).

3 Material and methods

3.1 The study area

The two researched esker chains are located in Western Finland (cf. Fig. 2). The Lohtaja-Kivijärvi esker (LO-KI) is located between the trunk area of the Finnish Lake District lobe and the eastern margin of the Näsijärvi-Jyväskylä lobe, and the second, Pori-Koski esker, between the sublobes of the Baltic Sea lobe. The 150 km long LO-KI extends across the supra-aquatic Suomenselkä watershed area to the subaquatic coastal area and to the bottom of the Bothnian Bay (cf. Paper I: Fig. 2). The Pori-Koski esker extends from the Third Salpausselkä end moraine across south-western Finland to the coast of Gulf of Bothnia and further on to the bottom of the sea until Härnösand on the eastern coast of Sweden (Ignatius et. al. 1980). The first HRSR research site, the Virttaankangas plain, hosts an artificial groundwater plant providing water for the entire Turku region (Artimo et. al. 2007). The thick interlobate esker deposits infill a major fracture zone in the eastern part of the Virttaankangas plain (Valjus 2006) and form a distinct ridge in the west with the bedrock on a higher level (cf. Paper II: Fig. 1). The second research site is located at the Köyliö sandstone depression which is completely filled with interlobate esker sediments and hosts a major groundwater reserve in the Köyliö area (Palmu et. al. 1994) (Paper IV: Fig. 1).

Research on the LO-KI has been quite sparse. The first references to the esker were on the explanations of maps of Quaternary deposits (Brander 1934; Okko 1949; Mölder & Salmi 1954). The LO-KI was mostly researched in relation to sand and gravel resource assessments (e.g. Iisalo 1973; Kurkinen & Tikkanen 1978; Vainiomäki 1980; Mäkelä et. al. 1990; Ristaniemi et. al. 1992) and geochemical assessments (Iisalo 1978). The sedimentology of the esker chain was researched for the first time from a total of 26 pit excavations in the master’s thesis work by Ahokangas (2008). The Säkylänharju-Virttaankangas esker has been extensively researched in relation to the establishment of the Virttaankangas MAR plant by Turku Region Water Ltd. (cf. Artimo 2003; Mäkinen 2004, Artimo et. al. 2007).

The geophysical research in Virttaankangas consisted of ground penetrating radar profiles (Hänninen & Salmi 1989; Geo-Work 2002, 2003, 2005), seismic refraction profiles, gravity measurements, as well as abundant drill hole logs (Maa ja Vesi Oy ja Suunnittelukeskus Oy 1975; Mattson 1996; Elo 1998; Geological Survey of Finland 2003, 2006). The Köyliö site has been the most comprehensively approached by Palmu et. al. (1994) who utilized several geophysical techniques (gravimetric measurements, seismic refraction profiles, magnetic data) in their research on the sandstone depression. Research related to the planned but unrealized Kolsi-Kauttua water transport tunnel included structural and hydrogeological mapping in the Köyliö area (Kurimo et. al. 2010). This research provided information on the fracturing of the bedrock in the Köyliö area. In addition, the groundwater related research with ground penetrating radar profiles and drill holes was utilized (Mäkinen & Ahokangas 2012, 2013, Ahokangas & Mäkinen 2014b).

3.2 Methods

3.2.1 Sedimentological logging (lithofacies analysis) and geomorphological map interpretation

The present thesis has its base in the use of lithofacies analysis (Miall 1985), as various sedimentary facies form the esker deposits themselves and are indications of the depositional environment and all the conditions applying to them. Along the 100 km long LO-KI esker, 5 sites out of the 15 logged sites (cf. Ahokangas 2008) were selected for Paper I. These sites ranged from the supra-aquatic Suomenselkä area to the deep water area in the coast of the Bothnian plain in order to represent the main depositional characteristics along the esker chain. The lithofacies characteristics of the eskers were documented to sketches and log profiles with field notes, photographs, paleoflow measurements and altimeter measurements of the relative altitude of the sections (1 m resolution). These were supplemented with measured clast orientations (dip and strike of the ab-planes), determined clast roundnesses on a scale of 1–5 (1: angular, 5: well-rounded) and grain sizes, determined both in the field and from sieved sediment samples. The results were modified from the Finnish Geo grain size scale (Geological Survey of Finland) to the Udden-Wentworth scale. The geomorphological mapping in the largely forest-covered trunk area of the Finnish Lake District ice lobe involved assembling 1:50 000 base maps (supplemented with selected 1:20 000 base maps) supported by the results of the earlier investigations related to the lobe (Brander 1934; Aartolahti

1972; Glückert 1973, 1974; Kujansuu & Niemelä 1987; Mäkelä 1988, 1995; Bargel *et al*. 1999b).

3.2.2 The geophysical data acquisition procedures of this thesis

The ground penetrating radar profiles were utilized in the creation of a depositional model for the esker environments in the Virttaankangas and Neittamonnummi-Köyliönjärvi sites. The uppermost 15–20 m of the subsurface were revealed in the profiles. In Virttaankangas, the GPR survey lines of 1989 (Hänninen & Salmi 1989), 2003 (Geo-Work Oy 2003) and 2009 (cf. Artimo et. al. 2010) were utilized already during the formation of the 3-D hydrogeological units for the planned artificial groundwater plant (cf. Artimo et. al. 2003a, 2003b) and the 2005 GPR lines (Geo-Work Oy 2005) in the characterization of the extent of the perched groundwater area and on the suitability of the infiltration pool areas for infiltration (Artimo et. al. 2007). In addition, the 2009 GPR lines were targeted on the glaciofluvial coarse unit of the aquifer (cf. Artimo et. al. 2010). The 1989 survey was conducted with 80 MHz antennae and the 2003 and 2005 surveys with 100 MHz antennae.

The seismic profiles of the pilot survey of 2011 extended across the entire area of the Virttaankangas artificial recharge plant (Paper III). Their location was selected based on the varying groundwater table depth and bed topography and in addition to the existing combined sedimentological and groundwater flow model. Drill holes adjacent to all the profiles provided reference data for interpretation. The seismic profiles were located in the existing road network with relatively hard-surfaced sandy and gravelly roads as well as in two public paved roads (profiles 1 and 8). Traffic control was arranged for these two profiles in order to guarantee the safety of the field personnel and road users. The profiles were mostly located on level ground with the exception of profile 9 rising up to the esker ridge at Porsaanharju. The seismic survey started with one pre-survey test followed by 5 days of data acquisition in good weather conditions. In order to avoid infrastructure damages, the acquisition was interrupted 5 m before and after cross-cutting water pipelines and groundwater wells. The movement of the 200 m landstreamer was guided on the road by 3–5 field personnel members. Seismic profile coordinates were measured with Trimble DGPS during the surveying. The altitudes for the topographic line corrections were obtained from national LiDAR data of 2 m horizontal and 0.3 m vertical resolution.

The 2011 pilot survey (Paper III) in Virttaankangas was conducted with COWI's (Denmark) Minibuggy with a Minivib II® (Industrial Vehicles International Inc.) energy source using a 5+1 second linear vibrator sweep ranging from 15 to 250 Hz (Fig. 3A). A 216-channel seismograph (Geometrics Ltd) was used in seismic trace acquisition. The 200 m long landstreamer contained 48 three-component geophones with 1 m spacing and 76 vertical component geophones with 2 m spacing (Fig. 3B). The shots by the vibrating plate took place every 4 meters and the landstreamer was pulled forward by the traffic tractor after each shot (cf. Fig. 4A). The 2011 survey produced 9 seismic profiles (total 8.2 km). Both P- and S-wave data were collected in this survey.

Fig. 3. The landstreamer equipment used in the HRSR surveys of 2011 (a, b) and 2014 (c,d). Photos by E. Ahokangas 2011 and 2014.

The two seismic profiles of the 2014 survey in Virttaankangas (ca. 1 km each) (Paper II) were acquired on sandy roads and partly on a trail in the forest with loose sandy sediments. Profile 1 was mainly on even ground while profile 2 ran along a road going uphill on the esker ridge. The two seismic profiles of the 2014 survey at the Köyliö site (Paper IV) were acquired along harder sandy roads which had crossing trafficked roads and bridges in places, creating minor data gaps in the profiles. In places, the seismic profile was too close to houses which prevented data acquisition in their vicinity due to the risk of damage to infrastructure. Due to the more frequent traffic along the roads with the seismic profiles as well as on the crossing roads, traffic control was arranged to ensure the safety of the field personnel and other road users. The length of the Köyliö site seismic profile 1 was ca. 2.3 km and profile 2 ca. 2.6 km. Profile 2 crossed a heavily trafficked road and was therefore acquired in two parts.

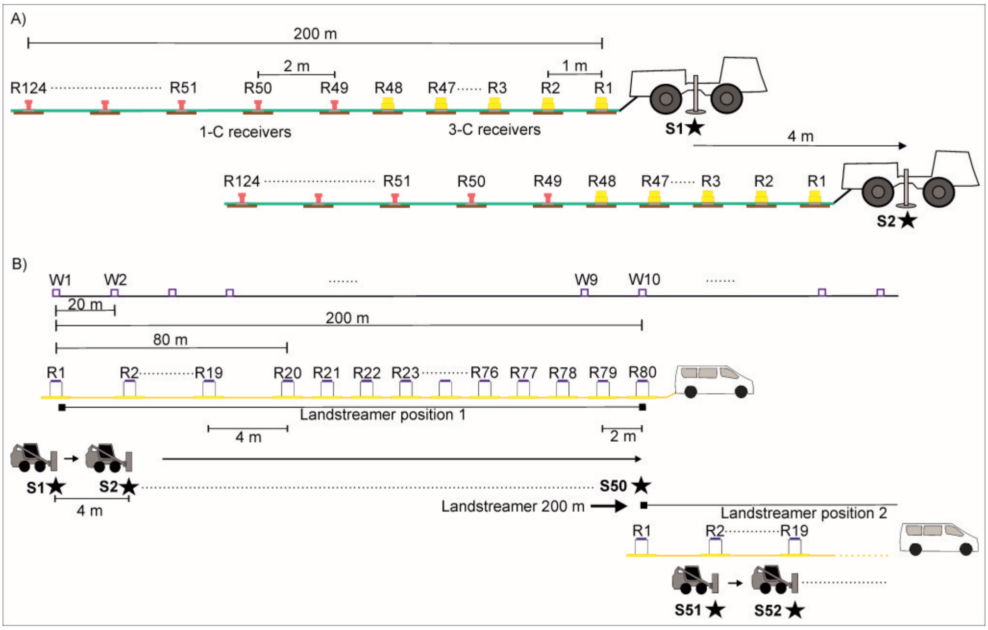

Fig. 4. A diagram showing the seismic data acquisition procedures in the 2011 survey by the equipment of Cowi Denmark and in the 2014 survey with the University of Uppsala landstreamer and wireless sensors (modified from Brodic et. al. 2018). A) The landstreamer of the 2011 survey consisted of 3-C receivers spaced 1 m apart and 1-C receivers spaced 2 m apart. The shots by the vibrating plate took place every 4 m, and then the landstreamer was towed with the traffic tractor for 4 m to the next position until the whole length of the seismic line was covered. B) The landstreamer of the 2014 survey was supplemented by wireless sensors (W1, W2 …) placed 20 m apart next to the landstreamer. The shots by the drop weight took place every 4 m along the entire 200 m length of the landstreamer. Then the landstreamer was moved forward 200 m by the towing and recording vehicle and the shots were repeated. This procedure was repeated until the whole length of the seismic line was covered. The wireless sensors were moved 2–3 times to new positions when the seismic profiles were over a 1000 m long.

The 2014 surveys (Papers II and IV) were conducted with a Sercel Lite 428 data acquisition system and a 200 m long landstreamer comprising of 80 3C (three-component) MEMs sensors (Brodic et al. 2015). The seismic source consists of a 500 kg drop weight mounted on a Bobcat (Fig. 3C). This landstreamer utilizes new accelerometer technology (digital DSU3 3C) allowing better receiving of the seismic signal from the subsurface compared to the traditional geophones. In addition to the landstreamer, 50–51 single-component wireless sensors connected to 10 Hz geophones (Fig. 3D) were placed about every 20 m along the profiles to account for the low fold at the end points of each segment (Fig. 4B). The landstreamer consisted of four segments with each containing 20 sensors. One segment had its sensors 4 m apart while in the other three they were spaced 2 m apart. The drop weight shots given by the Bobcat were repeated 3 times on one shot point, after which the Bobcat was moved to a new shot position (shot interval 4 m). After the data had been collected for the whole length of the 200 m landstreamer, it was towed another 200 m to a new position (cf. Fig. 4B). This procedure was repeated until the data along whole length of the seismic profile was acquired. The wireless sensors were moved 2–3 times in case the length of the seismic profile exceeded 1000 m. The presence of wireless sensors along the entire length of the seismic profiles was used to compensate the low fold at the end points of each segment and allowed the exclusion of overlap between the previous and the following landstreamer position (cf. Brodic et. al. 2018). Only P-wave data was utilized in Papers II and IV.

The 3-D hydrogeological reference model forms the basis for the understanding of the groundwater environment and flow model. The three basic large-scale esker elements of the reference model are the esker core (glaciofluvial coarse-grained unit), MUKH structures (separated unit) and large-scale cross-bedded fan lobe channels extending towards the esker margins (glaciofluvial fine-grained unit) (cf. Artimo et. al. 2003b; Artimo et. al. 2010). The interpretation of the seismic profiles of the 2011 HRSR survey focused on the detection of the position and dimensions of the main architectural elements: esker core, MUKH structures and fan lobes in case they were identifiable in the profiles. The 2014 HRSR survey was guided by the defined hydrogeological units and the reference depositional model for the coarse-grained unit (Article II).

4 Results and discussion

4.1 Ice lobe margin esker was revealed from the trunk of the dynamic Finnish Lake District lobe

The arched architecture of the esker core deposits was exposed at three sites of the Lohtaja-Kivijärvi esker (Ahokangas & Mäkinen 2014a). The arched architecture of the core deposits in the Säkylänharju-Virttaankangas esker was exposed only at the Kiviharju pit (Mäkinen 2003a). These deposits represent a deposition within a pressurized subglacial tunnel with powerful water flow. The core deposits are mantled by sandy to gravelly deposits which represent the deposition of esker beads (short beads, cf. Warren & Ashley 1994), re-entrant or esker fan sediments. In places the mantling deposits are deformed and contain MUKH structures, indicating the removal of ice support from the esker flanks as well as the burial and melting of ice blocks. In addition, the measured palaeoflow directions in the mantling deposits indicate the confinement of the water flow between ice walls. Two study sites of the LO-KI show features of seasonal to annual esker deposition (Ahokangas 2008), which was also observed in the extensive Säkylänharju-Virttaankangas esker in SW Finland (cf. Mäkinen 2003). The observed different esker types of the LO-KI correspond with the water depth at the ice margin (Paper I: Fig. 7). Short beads and esker fans are found in the shallow water area east of the Suomenselkä watershed. The watershed area is dominated by sandurs and their feeding eskers. The shallow water area and deep water area west of the watershed exhibit the largest variation in esker types. Esker fans, beads and re-entrant deposits are present in these areas. Only an esker fan was reliably identified in the very deep water area due to the heavy littoral reworking of the esker deposits and a lack of suitable pit excavations (low groundwater table). The position of the esker ridges showed shifts in its position especially in the deep water area (water depth ≥100 m). The esker pattern started to resemble a segmented tunnel fill (Warren & Ashley 1994) in the deep water area, indicating instability of the meltwater network with increasing water depth (Fyfe 1990).

The changes in the ice dynamics of the Finnish Lake District lobe trunk were reflected in the sedimentology and depositional conditions of the LO-KI. The readvance of the eastern corner of the Näsijärvi-Jyväskylä lobe was resisted by the neighboring lobe. The interlobate area between the lobes originating from the Salpausselkä stage was disturbed by this readvance. Therefore the LO-KI cannot be considered a true interlobate esker but rather an ice-lobe margin esker. The geomorphological and sedimentological changes of the LO-KI indicate the adjustment of the deglacial dynamics of the FLDL trunk to new flow conditions, changes in bed topography and finally the increase in water depth from the partly supra-aquatic Suomenselkä watershed towards the present coast of the Bothnian bay (Ahokangas & Mäkinen 2014a).

The higher Suomenselkä watershed area enhanced the meltwater production, leading to the formation of four parallel esker chains (cf. Paper I: Fig. 8). The deposition of the LO-KI decreased significantly after the supra-aquatic area at the Mustalammit break. The breaks and varying depositional patterns of the LO-KI and its tributary the Kanala esker are related to the appearance and disappearance of the neighboring Lestijärvi-Kinnula esker with the highest sediment volume in the central trunk area. Another major division point occurs at Rahkosenharju which in turn has the highest sediment volume in the deep water area. This ridge was deposited after the disappearance of the Lestijärvi-Kinnula and Kanala tributary eskers. The alteration of emerging and disappearing esker deposits indicates the switching of meltwaters between the two parallel tunnels and implicates water piracy (Joughin et. al. 2004; Vaughan et. al. 2008) between the LO-KI and LE-KI eskers. However, the continuation of the esker deposits could not be reliably confirmed due to a lack of sedimentological data in these gap areas covered by extensive peat bogs. At least no marked esker ridges were observed within the peat bogs. It is plausible that minor (1–3 m high) esker ridges are masked beneath the peat bogs which could be further researched in the future.

The LO-KI exhibits high variability in the meltwater system and discontinuity in the esker deposits. In contrast to Punkari’s (1997) statement on how an interlobate environment was favorable for the deposition of substantial glaciofluvial landforms, the research on this esker revealed that esker deposition between two ice lobes is a not prerequisite to the deposition of substantial landforms. Despite its modest size compared to other interlobate eskers in Finland, this esker highlights the importance of detailed research on sedimentology and depositional conditions of eskers despite their size or extent. The depositional history of this esker proved out to be far more complex and dynamic than its appearance suggested. The results of Paper I highlight the importance of researching each esker individually (cf. Huddart et. al. 1999).

Paper I highlights the advantage of an extensive sedimentological dataset in the description of the depositional history of a 150 km long esker chain. However, the need for the use of ground penetrating radar became also apparent, especially in the coastal area of the Bothnian bay where the heavy littoral reworking of esker sediments prevented the accurate outlining of the esker core position. The available pit excavations were mostly water-filled due to the low ground water table (only 2–3 m in depth). The detailed sedimentological characterization of eskers enables the construction of accurate and reliable hydrogeological models and groundwater flow models. Where available, all the sedimentological data should be utilized for a construction of a sedimentological model representing the depositional conditions and stages of the esker. This sedimentological model should be used as the basis for further research and be implemented with geophysical data for more reliable esker characterization.

4.2 Landstreamer-based HRSR method detects the bedrock surface and its characteristics

The combined use of seismic tomography and seismic reflection profiles provides accurate information on the bedrock level and bedrock topography variations (Papers II & IV). The distinction of the bedrock surface was improved with the seismic reflection profiles and the available reference drill holes extending down to the bedrock. The seismic velocities of the bedrock allow the estimation of the amount of fracturing and weathering and occasionally the estimation of rock types. The seismic tomography provided ca. 5000 m/s velocities for the bedrock in the Virttaankangas study area (Paper II). The bedrock velocities were markedly lower in the Köyliö study area (3000–4000 m/s) due to the presence of sandstone and weathered/fractured Svecofennian basement rocks (Paper IV). In addition, the seismic tomography profiles enabled the estimation of the dimensions of the sandstone depression and the position of the sandstone contact in the Köyliö study area. This was due to the velocity contrast between the infilling glaciofluvial sediments with velocities of 1000–2000 m/s and the underlying bedrock surface with a 3000–4000 m/s velocity.

MEMS-based landstreamer surveying (2014) (Papers II and IV) enabled the precise distinction of the bedrock surface with strong and high amplitude reflections. These reflections were mainly continuous and undulating in places. The distinction of bedrock was the most uncertain in the SW end of profile 2 in Virttaankangas where it did not provide any distinct reflections (Paper II). Therefore the bedrock level interpretation was based on reference drill hole VI282 located ca. 20 m off the profile. It is plausible that there is a rapid rise in the bedrock level from the drill hole towards profile 2 and that the actual bedrock surface is higher in the profile. The bedrock surface distinction in the Köyliö study area was more challenging due to the thickness of the overlying glaciofluvial deposits within the sandstone depression (Paper IV). The reflections originating from the bedrock surface were well recognizable elsewhere except in the deepest part of the depression. In addition, the strong and high amplitude signal on the SW flank of the sandstone depression was confirmed to originate from the bedrock by reference drilling REF-2017.

In addition to the accurate detection of the bedrock surface, the 2014 HRSR survey revealed new unknown features in the bedrock both in the Virttaankangas and Köyliö study sites. In Virttaankangas, the margin of the bedrock fracture showed distinct faults in profile 1 (Paper II, Fig. 10c). The faulted bedrock fracture margin may indicate the presence of a remnant of Jothnian sandstone within the valley and support the assumption of a sandstone satellite beneath the Virttaankangas plain (Kaitanen & Ström 1978). Interestingly, horizontal reflections in a concave geometry were found within the bedrock beneath the esker core in profile 2 (Paper II: Fig. 11c). These indicate the intense fracturing of the bedrock due to the pressurized meltwater flow in the subglacial tunnel above the bedrock. This implies that the aquifer is extending down to the bedrock. The thick till beds present on top of the fractured bedrock surface in the bedrock fracture inhibit the extension of the aquifer down to the bedrock. The steeply dipping bedrock surface observed in the seismic tomography and reflection profiles was interpreted as the sandstone contact in the Köyliö study site (Paper IV). Our results indicate that the sandstone contact is not stepwise but rather a steeply dipping bedrock surface. The position of the sandstone contact was shown to be 500 m further east in profile 1 and 350–400 m west than previously interpreted. Some horizontal, slightly undulating reflections were detected within the bedrock in the SW part of profile 1. These were interpreted as horizontal diabase laccoliths that had intruded into the sandstone. A further tectonostratigraphic interpretation of the bedrock in profile 2 revealed reflections cut by a systematic array of breaks forming a structure corresponding to the one on the sandstone outcrops nearby in Kiparoja, Eura (Pajunen & Wennerström 2010). These breaks are interpreted to represent brittle faults, fracture zones and intense jointing. The open bending of the reflection lines is interpreted as an open fold structure which has been described as an outcrop on the eastern end of Leistilänjärvi, Nakkila. The interpretation is in agreement with the idea of the sandstone basin formed by oblique transtension represented by Pajunen & Wennerström (2010).

The 2011 landstreamer survey revealed thicker reflection packages originating from the bedrock surface (Paper III) compared to the 2014 surveys (Papers II, IV). The uppermost surface of these packages could be interpreted as the bedrock surface, and this interpretation was confirmed by existing and new reference drill holes (REF1–3) in the Virttaankangas bedrock fracture zone (Paper III, Fig. 4 and 5). The interpretation of the bedrock surface was complicated by thick till beds overlying the bedrock in the fracture zone. These compact till beds produced their own strong and high amplitude reflections similar to the ones originating from the bedrock surface (Paper III). In addition, the bedrock was heavily fractured and/or weathered in the bedrock fracture zone (Paper III: Fig. 6). The gravimetric profiles and drill holes were used in the separation of the till bed seismic signature from the bedrock surface signature. In addition, the more accurate results of Paper II were utilized in the interpretations.

The 2011 and 2014 landstreamer-based HRSR surveys both provided accurate data on the bedrock surface as well as the features present within the bedrock. The surveys provided the bedrock surface with 5 m (2011 survey) and 1–3 m accuracy (2014 survey) as well as new features within the bedrock. The structural geology of the Satakunta sandstone basin was revealed for the first time by the HRSR survey, and its interpretation is in agreement with the idea of the basin formation by oblique transtension (Pajunen & Wennerström 2010). The fracturing of the bedrock within the bedrock fracture and beneath the esker core expands the aquifer into the bedrock, providing new potential hydraulic connections. The new and more accurate positioning of the sandstone contact yields enables more accurate estimations of the sandstone depression dimensions as well as the confinement of the aquifer in the Köyliö study site. The bedrock topography and deformation zones have major influence on esker geometry and deposition (cf. Skyttä et. al. 2015). The bedrock forms the base on which the esker deposition takes place. Eskers follow the flanks of major valleys and can climb over topographic obstacles due to the high pressure in subglacial tunnels (cf. Shreve 1985). They can also follow and infill bedrock fracture zones and depressions. Esker alignment, the direction of the fan lobes and the position of the largest MUKH structures (Mäkinen 2003b) are all influenced by the underlying bedrock topography. In addition, bedrock thresholds can influence the groundwater patterns and act as barriers for groundwater flow in aquifers. Therefore their reliable recognition and characterization are vital for esker characterization and the constructed hydrogeological and groundwater flow models.

4.3 The main esker architectural elements and seismic facies of interlobate esker deposits are revealed

A feature with arched geometry and convex reflections (cf. Pugin et. al. 2009) was detected in both landstreamer-based HRSR surveys on all survey lines (Papers II–

IV). The dimensions of the arched feature were in agreement with the known esker core dimensions, and therefore it was interpreted as the coarse-grained esker core with high hydraulic conductivity. The esker core consisted of two parts in the Köyliö study area. It followed the flanks of the Virttaankangas bedrock fracture (Papers II, III) and the flank of the sandstone depression in Köyliö (Paper IV). However, we found no indication of the esker core leaning to the sandstone contact as previously suggested by Lindroos (1983) or following it (Palmu et. al. 1994). The esker core was mostly found on top of the bedrock surface but was underlain by till beds in the Virttaankangas bedrock fracture (Papers II, III). These beds were eroded during the esker deposition in the bedrock fracture, increasing the possibility of a hydraulic connection between the esker aquifer and the underlying fractured bedrock. Two new features were found in the 2011 HRSR survey: the joining point of the Löytäne tributary esker to the main esker and a loop in the esker core in the bedrock fracture (Paper III). The locating of the joining point of the tributary esker with the main esker explained the short residence times in one of the MAR plant well areas as well as the origin of the extensive coarse-grained fan lobe system in the central part of the Virttaankangas plain. The detected loop explains the presence of extensive coarse-grained deposits in the bedrock fracture as well as the enormous yield of one of the wells (VI588). In the Köyliö site, the top part of the coarse-grained esker sediments was found to be in the depth of 50–60 m which is too deep for groundwater intake in the area (Paper IV).

Several large-scale trough-shaped features with horizontal reflections (200–300 m wide, 10–40 m high) were detected lateral to and on top of the esker core (Paper II & IV). Only one trough-shaped feature of this type was recognized from the 2011 HRSR data (Paper III, Fig. 6). These features were interpreted as subaqueous esker fans. The fans found on top of the esker core are proximal channelized fans with coarse-grained sediments and high hydraulic conductivities which can add up to the thickness of the esker (Maries et. al. 2017). In addition to trough-shaped subaqueous fans, large structures with concave geometry were found both in the Virttaankangas and Köyliö sites (Papers II–IV). These features are deeper than the interpreted fans and the amplitudes of their internal reflections vary and can be discontinuous. In places the internal reflections of these features were weaker than in the surrounding sediments which were one of the qualities used in their distinction (Paper III). The largest concave structure (width 200 m, depth 50–60 m) extending down to the bedrock was found in profile 2 in Virttaankangas (Paper II). This feature also showed distinct deformation and discontinuation of beds. These deep concave structures with faults are interpreted as MUKH structures (Mäkinen 2003b) formed due to the melting of buried ice within esker sediments. The discontinuity of reflections and internal beds is due to the deformation of sediments.

The recognition of the fan lobes extending from the esker core towards the esker flanks as well as MUKH structures adjacent to the esker core is of high importance to the hydrogeological conditions. The proximal fan apex with its coarse-grained sediments on top of the esker core increases the hydraulic potential of the core. The proximal-distal fining of the fan lobes influences the groundwater flow patterns and directs groundwater flow towards the distal part of the fan lobes. The MUKH structures are known to have a major influence on groundwater flow and residence times (Artimo et. al. 2010) due to their deformed and slumped sediments. This highlights the need to identify these features either from pit exposures (Paper I) or from geophysical data (Papers II–IV). The landstreamer-based HRSR method is a valuable tool in the recognition of main architectural esker elements within thick interlobate esker deposits. It should be combined with a sedimentological model as well as ground penetrating radar data in order to achieve the best results for both the near surface parts and the deeper parts of esker deposits.

The distal deposits with fans and fan lobes were found outside the bedrock fracture and on the SW flank of the Virttaankangas plain in profile 2 (Paper II). Only seismic line L5 completely on the northeastern flank of the Virttaankangas plain and the NE end of seismic line L8 revealed details on the fine-grained distal and littoral deposits (Paper III). The S-wave seismic line L5 revealed the most interpretable reflections of all the S-wave lines. The deposits on the esker flank were mostly silty and sandy which allowed better depth penetration for the S-waves, resulting in the detection of a diamicton on top of the bedrock on seismic line L5. In addition, the fine-grained bed and adjacent perched groundwater table as well as trough-shaped features related to the spit-platform foresets (cf. Mäkinen & Räsänen 2003) were detected. The silt and sand-dominated distal esker deposits were mainly deposited on top of the coarse-grained esker deposits in the sandstone depression at the Köyliö site (Paper IV). Their presence influenced the weakness or complete lack of reflections in the uppermost 20–30 m of the seismic profiles. This was compensated by the existing 100 MHz GPR profiles showing the sedimentary structures in more detail.

The main reflection patterns in the 2014 HRSR data could be interpreted as large-scale seismic facies (Paper II: Fig. 8). The resolution of the seismic data and the small-scale complexity of the sediments inhibited a more detailed interpretation of the esker fan sediments (Maries et. al. 2017). Nevertheless, the MEMS-based HRSR data provided abundant detail on the architectural esker elements, including the dual esker core, faulting present in MUKH structures and details in the subaqueous fan lobes and their cut and fill channels. The main esker architectural elements (esker core, MUKH structures and fan lobes) were also revealed in adequate detail in the 2011 HRSR survey. The dimensions and the position of the main and tributary esker cores were revealed throughout the MAR plant area in Virttaankangas. The survey resolution inhibited a more detailed interpretation of the fan lobes and in places their overall separation from the 2011 profiles. However, the S-wave data provided details on the distal esker sediments and littoral deposits. The detailed knowledge on the characteristics of these esker architectural elements will serve as a valuable tool for the future characterization of esker deposits. In addition to the bedrock surface level and topography, the reliable recognition of these architectural elements is of high importance since they form the basis for the hydrogeological models of eskers. Both landstreamer-based HRSR surveys proved to be excellent in the distinction of the key architectural elements of eskers.

4.4 Landstreamer-based HRSR method offers new possibilities for future geological studies

The two landstreamer-based HRSR surveys provided reliable data on the bedrock surface and topography, main architectural elements of eskers and even the groundwater table (Paper II) in the Finnish geological conditions (Papers II–IV). This method has proven to be suitable for the characterization of eskers and their hydrogeological properties based on research conducted directly on glaciofluvial deposits in both a bedrock fracture environment and on an esker ridge with relatively steep flanks. In Finland, eskers are found on top of crystalline bedrock or filling in bedrock fractures and sandstone depressions like in Köyliö and in the Muhos formation in the Oulu region. International landstreamer-based HRSR surveys have been mostly used in the characterization of buried eskers within tunnel valleys carved into sedimentary rocks (Pugin et. al. 2009, Oldenborger et. al. 2011) and tunnel valleys infilled with various types of glacial deposits, often having interbeds of tills and overlying fine-grained sediments (Praeg 2003; Kehew et. al. 2012; Stewart et. al. 2013).

The P-wave data produced with the geophone-based landstreamer was still adequate in the determination of the bedrock surface and topography, esker core location as well as MUKH structures, which all have major importance for the groundwater flow within the esker. The use of the MEMS-based landstreamer HRSR surveying is highlighted in cases where high-accuracy data is needed in the esker aquifer characterization. Landstreamer-based HRSR surveying should be conducted in other extensive glaciofluvial deposits (interlobate eskers) and ice-marginal landforms with varying depositional conditions and groundwater table level in order to get a comprehensive understanding of the potential of this method in Finnish conditions. The use of the geophone-based landstreamer should not be discouraged despite the lower resolution of the obtained data. Instead, this type of landstreamer should be tested with a more efficient source (e.g. drop weight) to see its influence on the survey resolution. The best conditions for the application of the landstreamer-based HRSR method are where the groundwater table is close to the land surface and where the water-saturated sediments are overlain by fine-grained deposits. The latter condition could be met only on the northeastern flank of the Virttaankangas plain. The use of S-wave surveying should be further encouraged especially on the research on distal esker deposits and clay-covered eskers. The S-wave penetration to distal esker deposits was better outside the coarse-grained unit in Virttaankangas. This PhD thesis has utilized only seismic profiles as cross-sections across the aquifer. In future surveys, the seismic lines should be designed to cross-cut each other to also enable the 3-D characterization of the aquifer.

The use of the landstreamer-based HRSR method on the complex interlobate eskers in Finland faces some challenges and restrictions. Firstly, the complex and highly varying depositional conditions introduce a large variation of sedimentary structures in interlobate esker deposits. This in turn leads to major variations in the grainsize of the deposits both above and below the groundwater table, providing challenges for the construction of a reliable velocity model. The large internal variation of depositional characteristics, especially if numerous MUKH structures are present or if in the proximal part of ice marginal landforms deformation, till interbeds and or covering till beds are present. All these heterogeneities lead to significant seismic velocity changes (from 0 to up to 6000 m/s) occurring within only a few tens of meters from the land surface down to the bedrock level. Secondly, the thick dry core is a major problem in the interlobate esker deposits. The deeper the groundwater table is, the harder it is for the seismic signal to penetrate deep enough without major signal deterioration. One of the most challenging situations was when the deep groundwater table occurred simultaneously with the most coarse-grained esker sediments (esker core and proximal fan apex) in the Virttaankangas 2014 survey profile 2 (Paper II: Fig. 11c, Zone 3). In addition, marked variation in the thickness of the dry core (10–40 m) occurred along this profile. Third, the separation of the seismic signal originating from (fractured) bedrock and overlying till beds and esker core was challenging with the geophone-based landstreamer as their reflection patterns were similar and seismic velocities are within a close range (Paper III). The resolution of the geophone-based landstreamer was only ca. 5 m which sets limitations to the detection of eg. fan lobes and the separation of bedrock, till beds and esker cores from each other.

Due to the need to move the landstreamer by towing, the HRSR surveys are still dependent on the existing road networks. The single component wireless sensors connected to 10 Hz geophones can compensate the lack of a road network to some extend but cannot replace the actual landstreamer. The sensitivity of the landstreamer equipment to the noise caused by rain is the main restraint caused by weather conditions. One or two extra days in the survey timetable should be included in order to compensate for the possibility of rainy days. In addition, the availability of landsteamer equipment restricts the use of the HRSR method in Finland. Currently there is no landstreamer equipment available in Finland. The nearest available landstreamers used to collect the seismic data for this PhD thesis are found from COWI Ltd (Denmark) and from Uppsala University (Sweden). These HRSR surveys were made as part of commercial and research-based co-operations. The landstreamer of COWI Denmark is available at commercial prices while the MEMS-based broadband landstreamer of Uppsala University is actively being used in research purposes.

4.5 Finnish esker and groundwater research can be forwarded by combining sedimentological, ground penetrating radar and high-resolution reflection seismic methods

This PhD thesis has provided the first combined use of sedimentological approach with ground penetrating radar and the HRSR method in esker characterization. The combined use of sedimentological models, GPR profiles and landstreamer-based HRSR method provides comprehensive understanding of both the upper and lower parts of the interlobate esker deposits. This level of information provides excellent possibilities for detailed (3-D) aquifer characterization and further for more reliable groundwater flow modeling. This method package provides a comprehensive tool for groundwater aquifer characterization and further groundwater-related applications. Internationally, the ground penetrating radar and high-resolution seismic reflection method (cf. Carpentier et. al. 2012) are often used in combination with other geophysical methods like electric resistivity profiling (Ahmad et. al. 200), the airborne time-domain electromagnetic method (Oldenborger et. al. 2013) and the high-resolution airborne electromagnetic method (Pugin et. al. 2014). The power of this approach is the synthesis of all the produced data. In addition, some methods may not work in field conditions and therefore must be supplemented with another method (e.g. ground penetrating radar signal cannot penetrate clay-rich sediments but the HRSR and electric resistivity methods can).

The Köyliö seismic profiles lacked significant signals in the uppermost 20 m due to the presence of weakly reflective distal esker deposits on top of the sandstone depression (Paper IV). Nevertheless, the role of GPR in the characterization of the uppermost part of the subsurface is crucial. It can be used as a first tool in the construction of a sedimentological model for a particular area, especially if there are no pit exposures available. The use of the GPR is also very cost-effective, and a survey can produce up to 5–10 km of lines a day. The use and capabilities of the 40 MHz antenna GPR data on eskers should be further assessed. In places, the use of this antenna could provide better depth penetration (up to 30–40 m).

In addition to GPR, the electromagnetic method was recently tested in Virttaankangas in the delineation of the MUKH structures (morphologically undetectable kettle hole) and their influence on groundwater flow patterns (Ahokangas et. al. 2015). The results of this survey were also promising and support further testing of the method on glaciofluvial deposits. The possibilities of the radio magnetotelluric method (RMT) (cf. Bastani et. al. 2015) on glaciofluvial deposits should be further assessed. These two methods can provide direct information on the (hydraulic) conductivity of esker deposits, which is an important addition to groundwater research.

5 Conclusions and directions for future research

This PhD thesis provides a comprehensive understanding of a new landstreamer-based high-resolution seismic reflection method and its applicability in Finnish conditions. This new method has outstanding potential in the detailed characterization of complex interlobate esker deposits as well as the ice marginal deposits of Finland in the future. For the comprehensive understanding of our groundwater aquifers, the combined use of GPR and the landstreamer-based HRSR method is highly encouraged in addition to the sedimentological approach.

The main conclusions of this PhD thesis are as follows:

1. The detailed sedimentological characterization revealed a new type of interlobate esker, ice-lobe margin esker. This esker was formed due to the shift of the interlobate position between the two neighboring lobes and cannot be considered a true interlobate esker, in contrast to the Pori-Koski esker formed between the sublobes of the Baltic Sea lobe. The depositional characteristics of the ice-lobe margin esker revealed the changes in the ice dynamics of the trunk of the Finnish Lake District lobe as well as variation and reorganization of the meltwater flow. The ice-lobe margin esker highlights the fact that eskers deposited between two ice lobes do not always represent pure interlobate eskers and that they can be modest in their extent and thickness. The major interlobate Pori-Koski esker had a more stable depositional environment compared to the ice-lobe margin esker. The differences in the ice dynamics and depositional conditions between interlobate and ice-lobe margin eskers provided wider understanding of the dynamic depositional environment between two ice lobes.

2. The landstreamer-based HRSR method was utilized for the first time in the research of interlobate eskers in Finland as well as for the first time directly on the esker deposits resting on crystalline bedrock. These two pioneering surveys revealed previously unknown characteristics from both the Virttaankangas and

Köyliö study sites, increasing the understanding of the depositional characteristics and processes of large interlobate esker complexes down to the bedrock level. In addition, these new findings helped to confirm the reliability of the 3-D hydrogeological model forming the basis for the operation of the Virttaankangas MAR plant providing potable water for the Turku region.

3. The rapid technical development in the landstreamer-based high-resolution seismic reflection method enabled the use of these two techniques in the research of interlobate complexes and their comparison. The data collected by a landstreamer with 1C and 3C geophones provided the esker architectural elements and the position of the esker core. A multicomponent broadband digital-based seismic landstreamer provides detailed data on the seismic facies level from interlobate esker deposits, allowing the detailed characterization of the depositional conditions and hydrogeological characteristics of these complex and extensive esker deposits.

4. The HRSR method provides for the first time detailed understanding of the characteristics of the bedrock and its topography underlying a major interlobate esker. The fracturing of the bedrock can play a major role in the hydrogeological conditions of the esker, especially when the esker core is underlain by major fracturing like in Virttaankangas. In addition, the first details of the tectonic structures of the Satakunta sandstone were revealed in the survey. The reliable determination of the bedrock surface level and topography variation forms the basis for the construction of sedimentological, 3-D hydrogeological and groundwater flow models.

5. The combined use of sedimentology, ground penetrating radar and the landstreamer-based high-resolution seismic reflection method forms the future basis for the research of Finnish glaciofluvial aquifers in eskers and ice-marginal formations. The value of the GPR data lays in its higher resolution and in the detailed characterization of the upper subsurface sedimentary structures. The HRSR method in turn provides detailed (<5 m vertical resolution) data on the deeper subsurface parts of aquifers down to the bedrock level as well as on the characteristics of the underlying bedrock. The joined use of these two geophysical methods with different resolution and depth penetration can be used to provide detailed characterization of complex interlobate esker deposits.

The long-term goal for the research on our extensive glacial and glaciofluvial deposits would be the purchase or build-up of an own landstreamer equipment in Finland. At first, the commercial use of the available landstreamers in the Nordic countries and research co-operation with Uppsala University should be utilized to become familiar with the principles, use and processing of landstreamer-based seismic data. Once the basis for the understanding of the landstreamer seismic reflection method is achieved, the build-up or purchase of an own landstreamer in Finland should be considered. The method will have profound benefits for Finnish groundwater aquifer characterization as well as various bedrock-related characterizations in the future.

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