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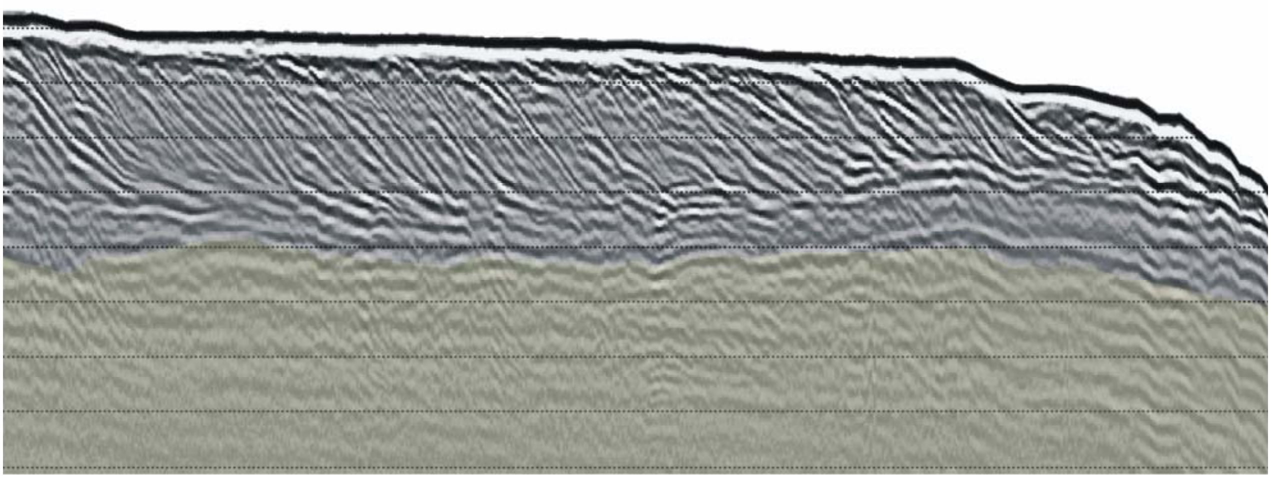

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Telephone:	08-5531430, International tel: +358-8-5531430
Telefax:	08-5531484, International fax: +358-8-5531484
E-mail:	pekka.tuisku@oulu.fi
www:	http://cc.oulu.fi/~resterr/

THE APPLICATION OF GROUND PENETRATING RADAR TO THE STUDY OF DEPOSITIONAL ENVIRONMENTS

ANTTI PASANEN

Department of Geosciences, University of Oulu, P.O. Box 3000, FI-90014 University of Oulu, Finland

ABSTRACT

This thesis comprises five original papers dealing with the internal structures of the Middle and Late Pleistocene clastic, coarse-grained sediments. The study of these structures is important for the determination of the depositional environment. The internal structures have been studied using well established sedimentological methods, including section logging, borehole records, clast lithological and clast-fabric analyses, and structural measurements from the glaciotectonic thrust faults and folds.

The sedimentological methods usually give point-form data. This was compensated for by extensive use of ground penetrating radar (GPR) on the deposits. GPR is the main method applied in this thesis. The data have been interpreted using the radar stratigraphy and radar facies analysis techniques. By using these techniques the internal structure of the deposit and the relative stratigraphic position can be determined, and the depositional environment can be interpreted. Geomorphology was also used in preliminary studies and to assist in evaluating the depositional environment.

The depositional environments studied in this thesis comprise fluvial, glacial, glaciodeltaic, glaciotectonic and littoral environments. The original papers are from three different regions, two are from East Anglia, England, two from the Oulu region, Finland and one from Russian Karelia, Northwest Russia. The implications of the interpretation of the internal structures and depositional environments includes the determination of the glacial shear-stress direction of the Late Weichselian glaciation in the Oulu region, the reconstruction of the ice-limit of the Wolstonian (Saalian) glaciation in East Anglia and

the reconstruction of the palaeotopography of the White Sea Basin in Northwest Russia during the late Younger Dryas Stadial (Late Weichselian).

The development and use of the radar stratigraphy method are outlined and discussed. It is suggested that the reflections caused by the secondary processes should be included in the radar stratigraphical interpretation and that an atlas of the radar facies from different depositional environments should be prepared.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors, Professor Juha Pekka Lunkka, from the University of Oulu and Professor Philip L. Gibbard, from the University of Cambridge, for introducing me to sedimentology and radar stratigraphy. I would like to thank them for their advice, guidance and support during this project. I would also like to thank Professor Matti Räsänen and Professor Nick Eyles who reviewed this thesis.

I owe my gratitude for the staff of the Department of Geology, University of Oulu and especially for M.Sc. Tiina Eskola for assisting in the data collection, M.Sc. Keijo Nuutinen for introducing me to the ground penetrating radar technique and assisting in the data collection, and Mrs. Kristiina Karjalainen for help with drafting of the figures. The whole Palaeoecology Group and M.Sc. Anna-Riikka Pehkonen-Ollila, M.Sc. Helena Vikstedt and B.Sc. Brita Telenvuo are thanked for interesting 'on and off topic' conversations during the coffee breaks. I would also like to thank Professor Veli-Pekka Salonen from the University of Helsinki, Finland and M.Sc. Niko Putkinen from the Geological Survey of Finland.

My gratitude goes also to the staff and students of the Quaternary Palaeoenvironments Group in the Department of Geography, University of Cambridge, England for conversations, company and helping me during my stay in Cambridge, especially B.Sc. M.Phil. Oliver Bazely, BA M.Phil. Karolina Leszczynska, M.Sc M.Phil Deepti Bisht, PhD Maria Papanikolaou, B.Sc. PhD Steve Boreham, B.Sc. Chris Rolfe and Professor Emeritus Richard G. West. From Cambridge I would also like to thank Mrs. Ann Jennings, MA PhD Laurie Friday and MA PhD Adrian Friday for taking care of me during my stay. Keep up the good work with the rabbits!

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ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
CDP	Common depth point
CMP	Common mid point
GPR	Ground Penetrating Radar
GPS	Global Positioning System
Hz, MHz	Hertz, megahertz
LGM	Last Glacial Maximum
OSL	Optically Stimulated Luminescence
SIS	Scandinavian Ice Sheet
TWT	Two-way travel time

ε, ε_r	Dielectric permittivity, relative dielectric permittivity
μ, μ_r	Magnetic permittivity, relative magnetic permittivity
σ	Electric conductivity

LIST OF ORIGINAL PAPERS

This thesis is based on the following five papers, referred to as Papers I, II, III, IV and V.

I. Gibbard, P. L., West, R. G., Pasanen, A. H., Wymer, J. J., Boreham, S., Cohen, K. M. & Rolfe, C., 2008. Pleistocene geology of the Palaeolithic sequence at Redhill, Thetford, Norfolk, England. Proceeding of the Geologists' Association, 199(2), 175-192.

II. Pasanen, A. & Lunkka, J. P., 2008. Glaciotectonic deformation of till-covered glaciofluvial deposits in Oulu region, Finland. Bulletin of the Geological Society of Finland, 80, 89-103.

III. Gibbard, P. L., Pasanen, A., West, R. G., Lunkka, J. P., Boreham, S., Cohen, K. M. & Rolfe, C. 2009. Late Middle Pleistocene glaciation in Eastern England. Boreas 10.1111/j.1502-3885.2009.00087.x. ISSN 0300-9483. (in press)

IV. Pasanen A. 2009. Radar stratigraphy of the glaciotectonically deformed deposits in Isoniemi area, Haukipudas, Finland. Bulletin of the Geological Society of Finland, 81, 37–49.

V. Pasanen A., Lunkka J. P., Putkinen N. Reconstruction of the White Sea Basin during the late Younger Dryas. Manuscript. (in review)

CONTRIBUTIONS

The following table indicates the major contributions of the authors of the original articles.

Paper	I	II	III	IV	V
Planning	PG,RW	AP, JPL	PG,RW,AP	AP	AP,JPL
Data collection	PG,RW, AP	AP	PG,RW,AP	AP	AP,JPL,NP
Data analysis	PG,RW, AP,SB	AP	PG,RW,AP,SB	AP	AP,JPL
Interpretation of results	PG,RW, AP	AP, JPL	PG,RW,AP,SB	AP	AP,JPL
Manuscript preparations	PG,RW, AP	AP, JPL	PG,RW,AP,SB	AP	AP,JPL,NP

Table 1. Contributions. AP= Antti Pasanen, JPL= Juha Pekka Lunkka, PG= Philip L. Gibbard, RW= Richard G. West, SB= Steve Boreham, NP=Niko Putkinen

All the material in this study was collected by the authors unless otherwise stated in the original papers. AP was in charge of the ground penetrating radar (GPR) in Papers I, III, IV and V. SB conducted the clast lithological analyses in Papers I and III. The preparations and part of the sedimentological analyses for Papers I and III were started before AP started his PhD project but AP carried out the field studies performed in 2007, and took part in writing together with PG and RW. Paper II was written by AP with comments from JPL, Paper IV was written by AP and Paper V by AP and JPL.

CONTENTS

1 Introduction

The internal structures of sediments (bed assemblages, contacts between units, three-dimensional form of the units and lateral variability) are the most important indicators of the depositional environment. By studying them, different depositional environments can be separated, even within a single sedimentological formation. Traditionally internal structures have been studied with section and borehole logging using lithofacies analysis (Miall, 1977; Eyles et al., 1983) for example. The sections and land cuttings are hardly ever laterally continuous or their direction does not conform to the alignment of geological formations. This demonstrates one of the fundamental problems with the traditional method of geological investigation; the data obtained usually provide point-form vertical profiles which must be correlated with other profiles. The correlation can be difficult or impossible, especially in areas with high lateral diversity of the sedimentary facies. Therefore, a continuous profiling method is needed. Geophysical methods can assist in correlation between sections and boreholes but they can be also used separately for the interpretation of the depositional environment and relative stratigraphical position. High-resolution reflection seismics offer sufficient vertical resolution for the recognition of the macro-scale sedimentary structures. From the 1980's onwards, ground penetrating radar (GPR) has been used as a high-resolution geophysical profiling technique for application to electrically low conductivity subsurfaces [cf. Daniels et al. (1988) for a review of the early history of GPR]. The conductivity of unsaturated, coarse-grained sediments (sands and gravels) is usually low (<1 mS/m; Jol, 1995) which allows good penetration depth for the GPR method. GPR has proven to be more effective in the first few tens of metres compared to high-resolution reflection seismics. In land-based studies, GPR offers higher vertical resolution (in decimetres for a 100 MHz antenna; Jol, 1995) and faster data collection speed (several line kilometres per day) compared to land-based high-resolution reflection seismics (McCann et al., 1988; Roberts et al., 1992; Cardimona et al., 1998). Unsaturated, coarse-grained sediments are effective attenuators of the high frequency (>100 Hz) acoustic pulses (Roberts et al., 1992). The received wavelength can exceed 15 m giving a vertical resolution of several metres in these sediments (Roberts et al., 1992). Also in shallow seismic studies the first metres or tens of metres may be unresolvable. High-resolution reflection seismics have proved its usability in off-shore investigations and on-land in studies where deep penetration depths are needed. McCann et al. (1988), Cardimona et al. (1998), Baker et al. (2001) and Nitsche et al. (2004) have compared the land-based reflection seismics and GPR in engineering and geological applications.

In the late 1970's, seismic stratigraphy was developed to aid hydrocarbon investigations (Mitchum et al., 1977; Roksandic, 1978; Sangree & Widmier, 1979). Because the propagation and reflection of the electromagnetic wave is analogous to the acoustic wave, Beres & Haeni (1991), Baker (1991) and Jol & Smith (1991) suggested that the principles of the seismic stratigraphy could be used in the interpretation of the GPR data.

1.1 Earlier studies

Seismic stratigraphy has been tested on worldwide datasets, whereas for GPR such datasets have not been available. Nevertheless, a substantial number of publications in the application of GPR from different depositional environments have been published since the early 1990's providing a good basis for today's interpretations. Gawthorpe et al. (1993) fully defined the concept of radar stratigraphy and its relationship to seismic stratigraphy. The earlier studies mentioned above and some studies after Gawthorpe et al. (1993) publication e.g. Beres et al. (1995; 1999) and Smith & Jol (1997), have used radar facies approach to differentiate between sedimentological units from GPR data. In the radar facies approach the radar surfaces and radar packages are not defined.

Van Overmeeren (1998) gathered radar facies of the unconsolidated sediments in the Netherlands. His work consists of examples of push-moraines, glaciofluvial, glaciolacustrine, aeolian, fluvial, lacustrine, marine and coastal depositional environments for hydrogeological applications. In addition to the examples of the studies mentioned below, many studies in other depositional environments, including particularly coastal and aeolian settings, have been performed in recent years. Neal (2004) compiled a more complete list of such studies, where GPR have been used in sedimentological applications.

1.1.1 Fluvial depositional environment

Fluvial deposits are important groundwater reservoirs in many places in densely populated areas, such as central Europe. It is important to understand the internal structure and heterogeneities of these sediments in order to prevent the pollution of the groundwater reservoirs, for example. The fluvial depositional environment has been studied using GPR by Gawthorpe et al. (1993), Roberts et al. (1997), Bridge et al. (1998), Vandenberghe & van Overmeeren (1999) and Best et al. (2003), among others. As mentioned above, Gawthorpe et al. (1993) were the first to exploit the full potential of radar stratigraphy. They used 2D GPR profiles to study a modern point bar on the Madison River in Montana, USA. Gawthorpe et al. (1993) noticed that the radar sequence boundaries represent erosional episodes whereas radar sequences and radar facies represent accretion of point bars. With the advent of sequence stratigraphy, the term 'sequence' is no longer used in radar stratigraphy, instead radar sequences are called 'radar packages' and radar sequence boundaries 'radar surfaces' (Neal et al., 2002; Neal, 2004). Roberts et al. (1997) used the radar facies approach to study structures of an avulsed channel in the River Rhône, Aoste, France. They used a grid of GPR transects to obtain a pseudo-3D image of the subsurface. They noticed that in the profile along the channel the reflections are continuous with low angle dips. They also noticed packages of dipping reflections which they thought were produced by the downstream growth of gravel bars. The cross-valley profiles showed continuous dipping reflections. They concluded that the radar facies assemblage represents complete or partial channel fill of the avulsed channels. Bridge et al. (1998) noticed the similar low-angle dips in the downstream direction in their study of the large-scale structures of the deposit on Calamus River in Nebraska, USA. They also noticed that in cross-channel profiles over braid and point bars the reflections were parallel to the bar surfaces or they are slightly dipping towards the cut banks. They also constructed a revised facies model for sandy, braided river from their results. Vandenberghe & van Overmeeren (1999) gathered a GPR dataset from former Maas-Rhine confluence area in the Netherlands. They showed distinct radar facies for meandering, braided and transitional river types and confirmed the facies with section and borehole logging. They also notified the difference in the radar facies in the floodplains of the different river types. Best et al. (2003) represented a facies model for modern, growing, mid-channel sand braid bar obtained from 3D GPR, vibracores and trenching from Jamuna River in Bangladesh. The data were combined with the bathymetric surveys.

1.1.2 Deltaic depositional environment

The deltaic depositional environment was one of the first in which the radar facies and radar stratigraphical approach was applied. The studies from this environment were performed by Jol & Smith (1991), Smith & Jol (1992; 1997), and Asprion & Aigner (1999), among others. Jol & Smith (1991) studied six different types of river deltas in Canada. They noticed that GPR provides a 'big picture' of the subsurface for the sedimentologists and geomorphologists in areas where section and borehole logs are not available. Their study provided the framework for GPR investigations in deltaic environment and for radar facies analysis. Later Smith & Jol (1992) studied the Lake Bonneville delta in Brigham City, Utah, USA. Here they noticed the striking similarity of the inclined strata in the exposures and GPR profiles, and interpreted both to represent foreset beds. Smith & Jol (1997) subsequently noticed a similarly inclined reflection pattern from Peyto Lake delta in Canada. They also described a radar facies representing braided river topset facies and bottomset facies. The radar facies assemblage was interpreted to represent a Gilbert-type delta. Asprion & Aigner (1999) combined 3D GPR survey and outcrop information to characterise heterogeneities in a glaciofluvial delta in Singen Basin, Southwest Germany. They also showed that the spatial distribution of the heterogeneities in aquifers can be reconstructed using 3D GPR.

1.1.3 Glaciofluvial depositional environment

Glaciofluvial sediments underlie vast areas in recently glaciated terrains, such as in Finland. They are important groundwater reservoirs and therefore, it is important to understand their internal structure and depositional environment. Glaciofluvial depositional environments have been studied using GPR by Sutinen (1992), Olsen & Andreasen (1995), Beres et al. (1995; 1999), Mäkinen & Räsänen (2003) and others. Sutinen (1992) used GPR to determine meltwater palaeoflow patterns in eskers and end moraines in Northern Finland for his PhD thesis. Olsen & Andreasen (1995) studied the Kronhede sandur in Jylland, Denmark using a grid of GPR transects and sediment logging to characterise the sediments and the 3D geometry of the jökulhlaup deposit forming the top part of the sandur. Their interpretation of the GPR data was achieved using the radar facies approach. Beres et al. (1995) showed that 3D GPR studies can be used both costand time effectively to study the geometries and facies of sedimentary units. They studied proglacial braided-river gravels and sands in Switzerland, and noticed that 3D data provides more detail and more reliable information on the heterogenities of the subsurface compared to 2D GPR data. They defined the palaeocurrent directions, the boundaries between different sedimentary facies and the level of the ground-water table. Beres et al. (1999) studied the same area again using 2D GPR. They correlated 2D and 3D GPR data with their section logging and noticed that the time slices of the 3D GPR amplitude blocks shows structural trends not visible in 2D GPR and section logging. Mäkinen & Räsänen (2003) studied the fan-like Virttaankangas enlargement of the Säkylänharju glaciofluvial ridge in Southwest Finland. They used a combination of section logging, drilling, GPR, seismic and gravimetric methods to describe the stratigraphy, morphology and depositional history of Virttaankangas. As a result they were able to show that Virttaankangas formed as a spit-platform and superimposed nearshore sediments deposited during the glacio-isostatically-driven forced regression of the Baltic Sea Yoldia and Ancylus stages.

1.1.4 Glacial depositional environment

Glacial depositional environments consist of deposits directly deposited by a glacier, i.e. tills. The identification of the radar facies representing till can be difficult because it usually includes fine-grained sediments, which causes the attenuation of the electromagnetic wave. Therefore, in this study the glacial depositional environment takes also into account the secondary structures in sediments caused by glaciotectonic deformation (subglacial and proglacial). Glaciotectonised deposits can give additional information of the depositional environment and glacier behaviour in recently glaciated terrains. Glacial depositional environments have been studied using GPR by Sutinen (1992), Lønne & Lauritsen (1996), Van Overmeeren 1997, Overgaard & Jakobsen 2001, Jakobsen & Overgaard (2002) and Bakker (2004), among others. Sutinen (1992) used GPR to study internal structures of morainic landforms, drumlins and Rogen moraines, in addition to glaciofluvial formations mentioned above. From the results he identified three Weichselian ice advances in Northern Finland. Lønne & Lauritsen (1996) studied the geomorphology and internal structure of a modern push-moraine in Svalbard in Spitsbergen using GPR and section logging. They noticed reflections from primary bedding, buried ice blocks and thrust faults. In their study the present-day morphology of the push-moraine was controlled by: 1) zones of thrust faults and 2) the position of ice blocks. Van Overmeeren (1997) used GPR to image abrupt 'steps' in the groundwater level in push-moraines close to the village of Epe in the Netherlands. With borehole logging he confirmed that the 'steps' are caused by inclined clay strata which acted as sliding planes during the glaciotectonic deformation. Overgaard & Jakobsen (2001) and Jakobsen & Overgaard (2002) studied the ice-pushed ridge in northwest Zealand, Denmark using the radar facies approach on closely spaced GPR transects. They correlated their radar facies with the section logging, geological maps and borehole data. The facies they identified include a glaciotectonised glaciofluvial facies, a penecontemporanously deposited facies and a post-deformational facies. The structures interpreted from their GPR data include thrust planes, major folds and minor faults. They concluded that the deformation style is a thin-skinned proglacial thrust complex and constructed a structural geological map from the radar facies. In a later study from the same area (Jakobsen & Overgaard, 2002) they also concluded that the thrust complex suffered a shortening of 4% and that the original morphology of the complex is controlled by thrusting and folding of earlier glaciofluvial sediments, similar to the observation of Lønne & Lauritsen (1996). However, they noted that the modern morphology is smoothed penecontemporaneously to the deformation and by post-deformational sedimentation. Bakker (2004) studied the internal structure of a push-moraine in the Veluwe area of the Netherlands in his unpublished PhD thesis. The methods used in his thesis comprise GPR, borehole logging, cone-penetration tests, high-resolution reflection seismics and gamma logs. He differentiated three different glaciotectonic styles with GPR. The distribution of these glaciotectonic styles coincides with the geomorphological units. The glaciotectonic styles consisted of: 1) imbricated thrusts, 2) imbricated thrusts and folds and 3) large-scale folds. He concluded that the Veluwe push-moraine was caused by a single major push event, which is expressed by distinct zonal distribution of glaciotectonic styles. He also concluded that the current geomorphology of the push-moraine is a direct reflection of the internal architecture and glaciotectonic mechanisms.

1.2 The aim of the thesis and contents

The aim of this thesis is to study the internal structures of the clastic, coarse-grained deposits using radar facies analysis, radar stratigraphy and traditional sedimentological methods, including section and borehole logging with the main emphasis on the GPR method's radar stratigraphical interpretation. The internal structure, and the depositional environments derived from the internal structure, in the study sites in Finland, England and Northwest Russia and their implications are discussed. The implications include the reconstructions of the glacial limit and palaeoelevation, for example. Despite of the fact that, in places deeper penetration depths, provided by reflection seismics, would be needed because of the large thickness of the deposits, 2D GPR was chosen as the only geophysical method used in this thesis because of its better vertical resolution and faster data collection.

Papers I and III represent the East Anglia, England contribution to this study. Paper I concentrates on the study of a fluvial sequence at Redhill, Thetford, Norfolk using section and borehole logging, GPR and biostratigraphy. The study was undertaken to determine the depositional environment and to date the sediments. In Paper III coarse-grained sediments overlying Chalk bedrock hills on the eastern margin of the Fenland were studied using section logging, borehole records and GPR to determine the depositional environment and the position and nature of the glacial limit.

Papers II and IV concentrates on the glaciotectonised deposits in the Oulu region, Finland. In Paper II deposits were studied using conventional sedimentological techniques including clast-fabric and structural measurements in Isoniemi, Haukipudas and Hangaskangas, Oulu to gain information on the glaciotectonic shear-stress directions and to shed light on the deposition of the sediments. In Paper IV the Isoniemi area was studied using 2D GPR. The radar stratigraphy of the area was determined and the depositional environments were interpreted and correlated with the sedimentological study in Paper II.

Paper V concentrates on the proglacial deltas in Russian Karelia, Northwest Russia. The glaciofluvial plains earlier interpreted as delta planes in Kalevala end moraine were studied using geomorphological and GPR methods. From the results the extent of the White Sea Basin during the late Younger Dryas Stadial was reconstructed.

2 Study areas

Three areas in England, Finland and Russia (Fig. 1), consisting mainly of fluvial, glacial, glaciofluvial, glaciodeltaic and littoral depositional environments, have been studied in this thesis. The study area in Papers I and III was East Anglia in England. In Paper I, Redhill site (52°25’28N 0°43’18E) in Thetford, Norfolk was investigated (Fig. 2). The study area consisted of fluvial terraces and a modern river floodplain incised into the Chalk bedrock (Upper Cretaceous). In Paper III nine sites in Cambridgeshire, Suffolk and Norfolk were studied during 2007 (Fig. 2). The sites were geomorphologically interpreted to represent proglacial deltas or fan deltas on top or on the distal side of the Chalk bedrock hills. The interpretation was confirmed with GPR survey in five sites. In two of the sites geomorphological interpretation suggested that the steep proximal slope represented ice-contact slopes.

Fig. 1. Map of northern Europe and the study areas mentioned in the text. The shaded boxes show the areas covered in Figs 2-4.

Papers II and IV represent the studies in the Oulu region (Fig. 3). In Paper II the till-covered, glaciotectonised, glaciofluvial sequences in Isoniemi, Haukipudas (65°09'N 25°15'E) and Hangaskangas, Oulu (63°37'N 43°13'E) were investigated. The Isoniemi area represents the northern part of the 25 km^2 broad glaciofluvial Isoniemi-Virpiniemi complex. Also in the Isoniemi area the steep slope dipping towards the west at the Runteli Ridge was interpreted geomorphologically to represent an ice-contact slope. The Hangaskangas area is situated 20 km south-east of the Isoniemi area. Here the formation occupies approximately 9 km^2 and on its' flanks littoral deposits, formed in the Litorina Stage of the Baltic Basin, occur (Helle & Ylinen, 1965; Eronen et al., 1995). The bedrock below the sediments in the Isoniemi and Hangaskangas areas consists of sedimentary siltstone, called the Muhos Formation (Korsman et al., 1997). In addition, the northern part of the Isoniemi site occurs on the mica-schists of the Palaeoproterozoic Kiiminki Schist-belt. The bedrock contact between the Muhos Formation and Palaeoproterozoic granites is close to the Hangaskangas site.

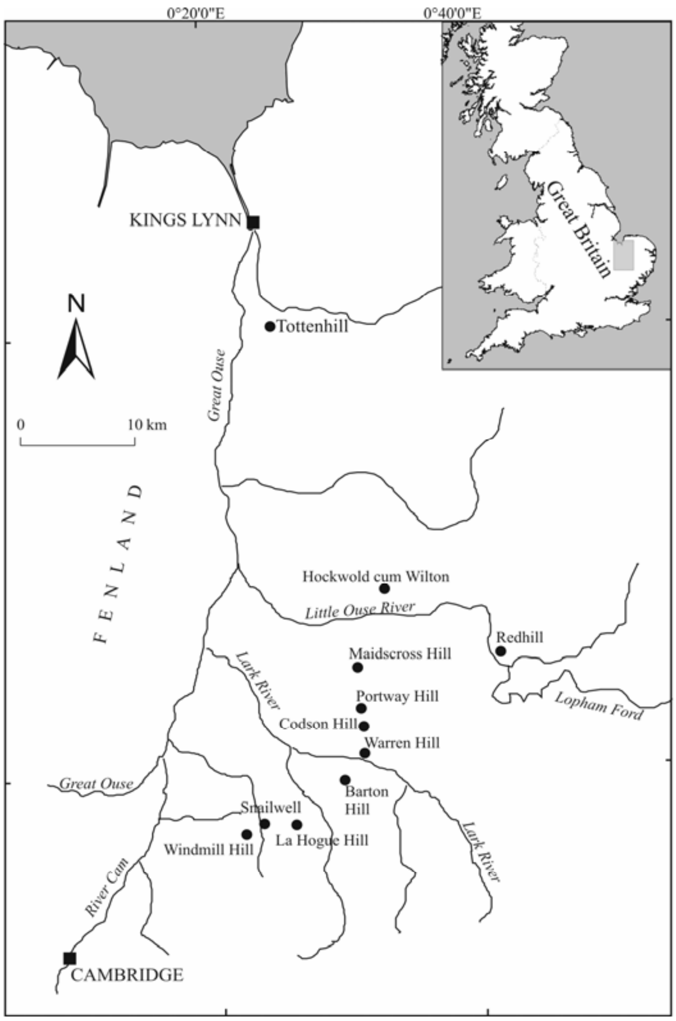

Fig. 2. Study sites in East Anglia, England. In Paper I the study site was Redhill. The other sites are situated on the eastern margin of the Fenland and are discussed in Paper III. The major cities are marked with squares and the rivers with italic font.

The study area in Paper V is the Kalevala end moraine in Russian Karelia, Northwest Russia (Fig. 4). The Kalevala end moraine represents a Younger Dryas-age ice-front position (Rainio et al., 1995) and is a topographical continuum of the Pielisjärvi end moraine in Eastern Finland. Putkinen & Lunkka (2008) mapped the glacial and glaciofluvial landforms in the area. Two of the study sites (64°58’N 32°08’E) were situated south of Shonga village and two sites (65°14’N 31°37’E and 65°16’N 31°46’E) between the town of Kalevala and the village of Kepa. The sites showed glaciofluvial plains which were geomorphologically interpreted to represent delta plains. The other geomorphological features seen were steeply inclined slopes interpreted to represent delta fronts or palaeoshorelines, kettle holes and discontinuous palaeochannels. The bedrock below the deposits consists of Archaean basement rocks of the Fennoscandian Shield. The lithology consists of gneisses with local granitic intrusions and tholeitic basalts on the schist belts at the eastern side of the Kalevala town (Koistinen et al., 2001).

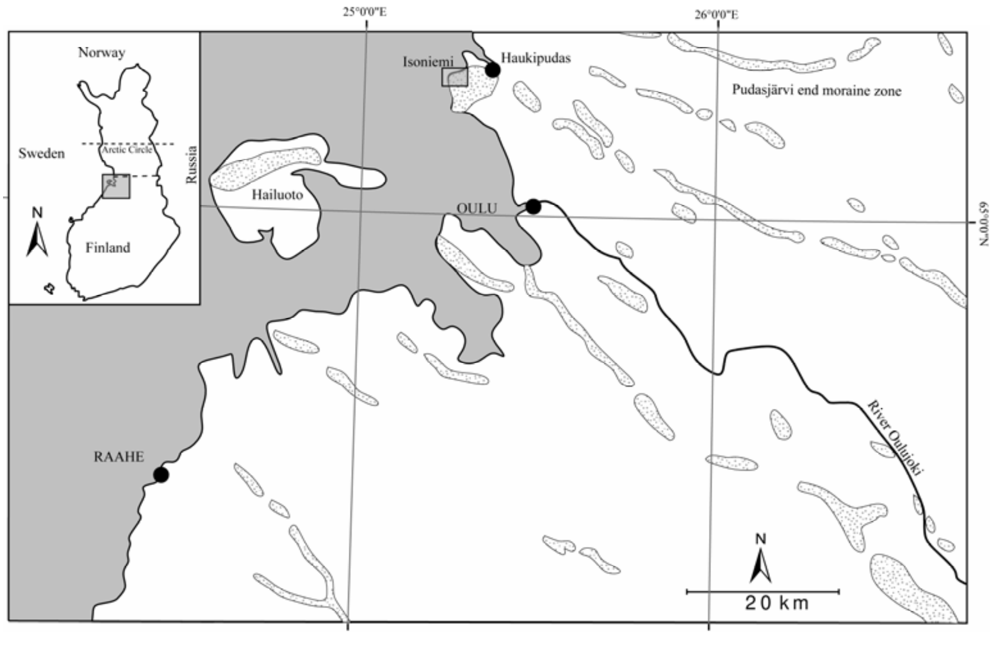

Fig. 3. Study sites in the Oulu region, Finland, presented in Papers II and IV. The sites are marked with circles and towns with squares. The dotted areas represent major glaciofluvial formations. The Pudasjärvi end moraine zone is proposed by Sutinen (1992) to represent Early Weichselian ice limit.

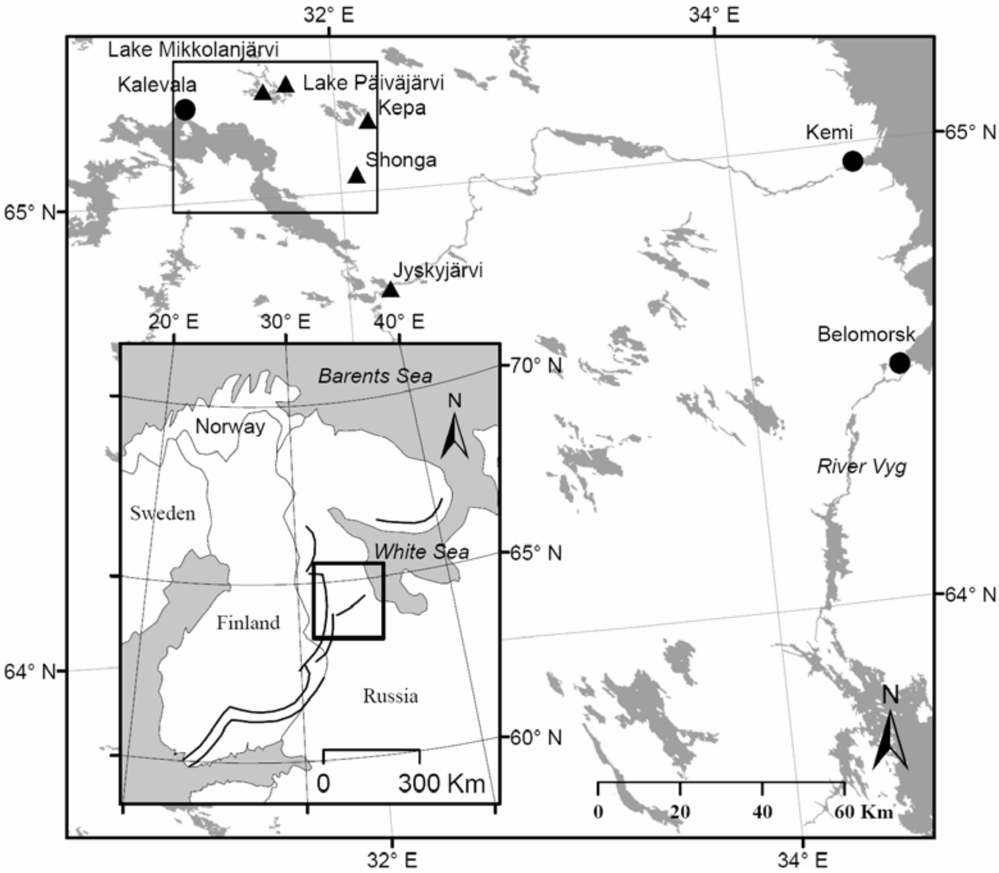

Fig. 4. Lake Mikkolanjärvi, Lake Päiväjärvi and Shonga study sites and additional control sites used in the reconstruction of the White Sea Basin during the late Younger Dryas (Fig. 7) in Russian Karelia, Northwest Russia. The black lines in inset map show major end moraines interpreted to represent Younger Dryas age.

3 Methods

The main methods used in this study comprise geomorphology, sedimentology and GPR. Geomorphology was used mainly as a preliminary surveying method but it also provided many important observations for the interpretation of the depositional environment and deformational style at individual localities. Sedimentological and GPR methods were used to study the internal structure of the sediments and to verify the geomorphological interpretations. These methods were chosen because of the nature of the studied sediments. Clastic, coarse-grained sediments are exploited for civil engineering purposes, such as building, and therefore, sections are readily available in many places in these deposits for sedimentological studies. Moreover, these deposits provide a good penetration depth for the GPR method. Other methods used in this thesis are borehole logging (Papers I, III and IV), clast lithological analysis (Papers I and III) and palaeotopographical reconstruction (Paper V). The main survey methods are discussed briefly below. Discussion of the other methods can be found in original papers.

3.1 Geomorphology

Geomorphological methods were used as a preliminary survey method in all the original papers presented here. They also provided valuable information concerning the ice-front position in Papers III and IV. Geomorphology is based on the recognition of the external form and topography of the landforms. The geomorphological interpretation was done using satellite imagery, map interpretation and field surveys. During the field surveys the grain size of the sediments close to the modern ground surface was determined visually to aid the geomorphological interpretation.

3.2 Sedimentology

Sedimentology was the main method adopted in Paper II. In other papers the method was used in conjunction with the GPR technique, except in Paper IV where results of sedimentological study from Paper II were used to correlate with the GPR results. In this method, the structure, texture, thickness, lower contact and lateral continuity of the sedimentary units are determined. By determining these elements in each unit a vertical profile could be drawn and the facies and depositional setting interpreted. The texture, structure and lower contact of the units were described using the lithofacies codes and contact descriptions modified after Miall (1977; 1985), Eyles et al. (1983) and Eyles & Miall (1984). In addition, deformational structures were measured and clast-fabric analysis was performed in Paper II. The structural studies consisted of the measurement of the direction and angle of the dip on fold axis, fold planes and fault planes of the thrust faults. Also the folding types were defined. Clast-fabric analysis consisted of measuring the dip angles and directions of 40-50 clasts in diamicton with the axis ratio *c.* 2:1. The significance of the clast-fabric analysis results were studied using Eigenvalue 1/Eigenvalue 3 method described by Woodcock & Naylor (1983).

3.3 Ground penetrating radar

3.3.1 Operational principle

GPR provides a high resolution, electromagnetic technique for the study of the shallow subsurface. Because of its non-intrusive nature, it can be used in delicate areas, such as nature reserves, and in places where the use of intrusive methods is not allowed or possible.

In reflection profiling, common offset antenna configuration is the most commonly used in sedimentological and engineering applications. In common offset studies the transmitter and receiver antennae separation remains the same and the transmitter-receiver pair is towed, in the continuous method, or moved in predefined steps, in the step method, along the survey line. Common mid-point (CMP) or common depth-point (CDP) studies, where the transmitter and receiver are moved away from the common central point, can be used to estimate the electromagnetic wave velocity of the first subsurface layer. Many modern shielded antennae are encased in a single casing making this type of survey impossible. Other instrument configurations consist of a common source, common receiver, wide-angle reflection and refraction and tomographic configurations. As a consequence of the instrument limitations and ease of data post-processing and interpretation, only the common offset configuration was used in this thesis.

In GPR reflection profiling in sediments a pulse of high frequency (usually 25-1000 MHz) electromagnetic energy is transmitted to the subsurface. Part of the pulse is reflected from the electrical boundaries while part of it travels through the boundary and reflects from the boundaries at a lower elevation or attenuates or scatters. The amplitude and the two-way travel time (TWT) in nanoseconds are recorded at the receiver antenna. The obtained data are shown at the data logger in a diagram where the vertical axis represents TWT and the horizontal axis survey time or distance depending on the equipment used.

The properties of the material controlling the behaviour of the electromagnetic wave in a medium are dielectric permittivity (ε), electrical conductivity (σ) and magnetic permeability (μ). At the discontinuities of ε_r (relative dielectric permittivity), μ_r (relative magnetic permittivity) and σ in the subsurface, some of the energy is reflected back to the surface. The higher the contrast below and above the discontinuity, the higher the reflection amplitude recorded. Van Dam & Schlager (2000) and van Dam et al. (2002 a; b) noticed that abrupt changes in ε_r are the main reason for the reflections in GPR surveys. The value of the ε_r for dry, coarse-grained sediments is between 2.5 and 7.5, whereas for fresh water it is 80 (Neal, 2004). Therefore, the reflections are caused where the sediment's porosity and ability to hold water changes. Van Dam & Schlager (2000) and van Dam et al. (2002 a; b) also noticed that that goethite iron oxide precipitates and organic material caused reflections in GPR images. The reflections were caused by the higher water retention capacity of goethite and organic material compared to that of the surrounding sediment. Van Dam & Schlager (2000) and van Dam et al. (2002 a; b) noticed that μ_r and σ were not significantly altered and therefore, μ_r and σ were not responsible for the reflections. The sharpness of the reflection received is a function of ε_r transition zone width compared to the wavelength of the survey. The wavelength must be approximately three times the transition zone width to get a sharp reflection (Neal, 2004). In coarse-grained sediments ε_r governs the velocity of the electromagnetic wave. The influence of μ_r and σ can be assumed to be minimal.

The velocity estimation for the subsurface can be done using *e.g.* CMP survey, radar tomography, drilling, hyperbolae fitting and published tables for sediments (e.g. Davis & Annan, 1989; Hänninen, 1991; Gawthorpe et al, 1993; Neal, 2004). The full physical basis for the GPR method and for the propagation, attenuation and reflection of the electromagnetic wave is given, for example, by Annan & Davis (1976), Davis & Annan (1986) Daniels et al. (1988) and Neal (2004).

3.3.2 Radar stratigraphy

The similarity of the propagation and reflection between electromagnetic and acoustic waves allows the principles of seismic stratigraphy to be used in the interpretation of GPR data. In the investigation of sediments with GPR, the concept of parallelism is the basis for the radar stratigraphy. The stratified sediments usually have a greater lateral lithological continuity, as well as physical properties, parallel to the depositional surfaces than across them (Sangree & Widmier, 1979). This allows the assumption that the reflections observed are parallel to the bedding surfaces in the resolution of the study (Sangree & Widmier, 1979). There are also exceptions to this concept. In GPR surveys the most common reflections which are not parallel to the bedding surfaces are caused by the ground-water table, offset reflections, diffraction hyperbolae, reflection multiples and reflections from secondary structures *e.g.* deformation structures. The development of the equipment and shielding of the antenna has resulted in a decrease of these reflections especially from overhead objects. Neal (2004) suggests that when performing a radar stratigraphy interpretation, this type of reflections should be recognised and removed in post-processing or ignored in the interpretation.

The terminology of the building blocks of radar stratigraphy is adopted after Neal et al. (2002). The building blocks consist of radar surfaces, radar facies and radar packages. Radar surfaces are defined as systematic reflection terminations and they represent non-depositional or erosional hiatuses (Gawthorpe et al., 1993). The interpreter must take care when defining radar surfaces because the reflection terminations may be caused by apparent truncation of reflection or interference effects. Gawthorpe et al. (1993) defined radar packages as fundamental stratigraphical units identified from GPR data, which are genetically related packages of strata, defined by radar surfaces. They also defined radar facies as representing changes in reflection characteristics within a radar package. However, in this thesis the definition of radar packages and radar facies is adopted after Neal et al. (2002) and Neal (2004). They defined radar packages as the three-dimensional external geometry of the deposits. The radar facies was defined as 'two- or three-dimensional sets of reflections that lie between the radar surfaces' (Neal et al., 2002).

The geological interpretation of the radar stratigraphy includes the interpretation of the nature of the boundaries (radar surfaces), bed assemblages (radar facies) and geometry of the deposits (radar packages) (Neal et al., 2002). The terminology for the definition of the radar surfaces, radar facies and radar packages used in this thesis follows the terminology gathered by Neal (2004). In this terminology the reflection geometry for the upper boundary can represent erosional truncation, toplap or concordant reflection ending, whereas for the lower boundary it can be onlap, downlap or concordant. The 3D external geometry can be *e.g.* a sheet or a wedge. The radar facies are described by their shape, dip, dip direction and continuity of the reflections. Also the relationship between reflections, amplitude and wave velocity are essential for the description. By defining the radar stratigraphy and using the description presented above the depositional processes and environments, as well as, the relative stratigraphical position between units can be interpreted.

3.3.3 Equipment, data collection and post-processing

The antenna centre frequency used in this thesis was 100 MHz. This frequency was selected because of its good balance between the penetration depth and vertical resolution. A 250 MHz centre frequency antenna was also tested on sites in Finland and Russia, but because of the inadequate penetration depth, it was not used systematically. In addition, because of the higher vertical resolution of the 250 MHz centre frequency antenna, the amount of reflections and diffractions increased compared to those from the 100 MHz centre frequency antenna making the post-processing and interpretation challenging. The shielded antennae were manufactured by Malå Geoscience. The antennae were controlled by the same manufacturers X3M controller unit and the data was logged with Panasonic Toughbook CF-29 rugged laptop. The data collection was performed in a time trigger mode because the equipment was not equipped with a measuring wheel. The antennae were towed by hand and by a vehicle. The horizontal positioning was done using Garmin e-trex, hand-held, global positioning system (GPS) device and markers to mark known positions on the map. The vertical profile was recorded using the calibrated altimeter of the GPS device and enhanced with elevation data obtained from the map contours, markers of the highest and lowest positions and by adjusting interpreted horizontal reflectors such as the groundwater table. In Paper I the vertical profile was obtained using levelling data. Because of the relatively high survey speed, the stacking was low; usually two scans were combined into one.

The raw data was post-processed in GeoDoctor 2.054 software manufactured by Roadscanners Oy. The post-processing steps included: 1) data editing, 2) depth conversion, 3) topography correction 4) adjustment of the time-zero level, 5) amplitude zero-level correction, 6) automatic background removal, 7) vertical high- and low-pass filtering, and 8) automatic or exponential gain control. Post-processing is essential for the improvement of the data quality and interpretation. Neal (2004) has discussed the different filters and post-processing steps used in sedimentological applications of the GPR in more detail.

4 Review of the original papers

Paper I

Paper I presents results of a study on a late Middle Pleistocene (Palaeolithic) sequence at Redhill, Thetford, Norfolk, England. The studies of post-Anglian-age fluvial sediments in Eastern England (equivalent to the post-Elsterian-age in Central Europe) are important because of their environmental significance but also because of the prolific artefactual finds during the last two centuries. The old diggings on the banks of River Little Ouse have been studied since the late 19th century by several workers. The site was then forgotten but rediscovered in 2004 and the diggings were opened for section logging. In addition to this, a transect of boreholes was put down adjacent to the diggings, GPR study was performed in the area and the sediments were sampled for clast lithological analysis. The section logging and borehole records, together with the historical descriptions, suggested that the sediments were deposited by flowing water, most probably by a gravel-bed stream of variable flow energy and abundant sediment supply above the Chalk bedrock. The GPR survey showed seven radar facies which were interpreted to represent bedding planes in the Chalk bedrock, a solution hollow filled with fluvial sediments, point bars, mid-channel bars, fluvial channel fill, cross-cutting channel-floor scours and colluvial deposits. The sediments overlying the Chalk bedrock were divided into three depositional environments. The sediments on the higher terrace were interpreted to represent deposition in a shallow, gravel-bed braided river facies. Downslope sediments that occur between the higher and lower terraces, the deposition was interpreted to have caused by the mass-movement of the sediments, probably in periglacial conditions. The lower terrace was interpreted to represent deposition in modern river floodplain. Palaeolithic artefacts, vertebrate remains and mollusc shells were found in the sediments by earlier workers. The artefact and vertebrate assemblages show a striking similarity to those of the Lynch Hill/Corbets Tey Member in the River Thames valley suggesting a late Middle Pleistocene Wolstonian (Saalian) age. The Redhill terrace sediments are incised into the Anglian Stage glacial deposits. The age determination is supported with the similar artefact findings and optically stimulated luminescence dating (OSL) from the late Saalian Stage deposits in the Netherlands. It was also concluded that the valley sides provided a source of flint for the Palaeolithic humans.

Paper II

In Paper II glaciotectonised glaciofluvial deposits underlying till were studied at Isoniemi and in the Hangaskangas areas in the Oulu region, Finland. The study of the glacial sediments in the central area of the glaciation is important when trying to understand the behaviour of the ice sheet. The stratigraphical investigations suggest that the Oulu region was covered by the Scandinavian Ice Sheet (SIS) twice during the Weichselian Stage. It has been hypothesised that the Isoniemi area represents a part of the Early Weichselian ice limit. The deposits were studied using conventional sedimentological techniques including clast-fabric and structural measurements. The sedimentary strata in the Isoniemi area consisted of: 1) deformed sand and gravel facies, 2) diamicton facies 3) cobble gravel facies and 4) sand and pebble gravel facies. The strata seen in the Hangaskangas area were similar, except the cobble gravel facies was not observed. Facies 1 and 2 are the most important for the study of the glaciotectonic and ice-movement history in the Oulu region. The deformed sand and gravel facies was interpreted to represent glaciotectonically deformed glaciofluvial, possibly fan-delta sediments. The diamicton facies was interpreted to represent deformation till originated from reworked earlier sediment and glacially transported sediment. The cobble gravel was interpreted to represent washed till during the subsequent littoral phase. The sand and pebble gravel facies was interpreted to represent littoral reworking of the earlier sediments. The glaciotectonic deformation consisted of thrust faults and tight to isoclinal folds which are gently inclined or recumbent. In the Isoniemi area, two shear-stress directions were observed (from northwest and southwest) but the clear time relationship between the directions could not be determined. The main direction was from the northwest and it was thought that this was the latest. The same directions were also seen from the clast-fabric analyses from the till.

Similar shear-stress directions were observed in the Hangaskangas area. Here the southwest-aligned shear-stress direction was observed cutting the sediment strata suggesting that it was the latest direction.

It was hypothesised that the fan-delta sediments may represent pre-Late Weichselian deposits whereas the glaciotectonic deformation occurred in the Late Weichselian. During the deformation the deposits were saturated with water and the water depth exceeded 200 m. The glacio-isostatic uplift raised the area to the water level and littoral reworking occurred.

Paper III

In Paper III coarse-grained sediments overlying the Chalk bedrock hills on the eastern margin of the Fenland were studied using section logging, borehole records, clast lithology and GPR. In Eastern England the deposits of the Middle Pleistocene Wolstonian (Saalian) glaciation have been masked by the Late Pleistocene Devensian (Weichselian) glaciation in places. The controversy on the number of glaciations observed from terrestrial sequences in Eastern England is caused because the Wolstonian glacial deposits are thought by some authors to represent a pre-Wolstonian age event. This paper presents the evidence for the eastern limit of the glaciation at the eastern margin of the Fenland and contemporaneous glaciation in Britain and mainland Europe during the Wolstonian Stage. For the sedimentological studies and clast-fabric analysis old diggings, studied in late-19th and mid-20th century, together with new sections were opened at four sites. In addition to this borehole data was obtained from five sites. The simplified overall sequence observed consisted of horizontally bedded sands, interpreted to represent bottomset facies of a delta, overlain by tabular cross-bedded sands, and gravels interpreted as foreset facies of a delta, both of these lying on the Upper Cretacious Chalk bedrock and clay. The alternative interpretation of regressive shoreface deposition for the tabular cross-bedded sands can also be considered. However, the facies association and upwards coarsening sequence observed does not support this interpretation. The sedimentological study and the clast lithological analysis showed a high abundance of Chalk clasts and diamicton balls, latter interpreted to represent till. The occurrence of the fragile materials provides evidence to confirm the short transport distance and glaciofluvial origin of the deltas. In the course of the study new sites were found using geomorphological methods and the total number of sites used in this study reached nine. GPR survey was performed in six sites. The results confirmed the sedimentological interpretation, but also new radar facies, not seen in the sedimentological study, were observed. The most important features for the determination of the position of the ice margin and ice-sheet behaviour, which were not observed in the section logging, were the channel facies continued to the delta core facies, and thrust faults and folds in the Chalk bedrock. The channel facies was interpreted to have formed below the ice-front, whereas the delta-core facies was interpreted to have formed outside it, most probably simultaneously with the channel facies. The origin of the thrust faults and folds were interpreted as being of glaciotectonic nature. A steep proximal slope at two of the sites was interpreted geomorphologically to represent ice-contact slope. In one of the sites thrusting and folding seen in the GPR survey supports this interpretation. The glaciodeltaic sediments were then correlated with the Wolstonian Tottenhill glaciodeltaic sediments in North Norfolk and with the sequences and artefacts from the Netherlands. The correlation and two separate OSL dates giving *ca.* 160 ka from Tottenhill and Warren Hill (the latter was earlier interpreted as pre-Anglian fluvial sequence) sites supported the Wolstonian age. It was concluded that the ice-sheet advanced to the Fenland basin from the north damming the westward-flowing rivers. The deltas were formed in front of the glacier in a proglacial lake of which water level was dropping during the deposition. The current position of the fan-deltas shows the Wolstonian ice-limit in the eastern Fenland. The lake reached the maximum level of *c.* 32 m OD before draining.

Paper IV

Paper IV expands the sedimentological work of Paper II from the Isoniemi area which was studied using 2D GPR transects. In the radar stratigraphy 10 radar facies and seven radar surfaces bounding the radar facies were observed. In places the radar transects were undertaken in two directions to obtain a pseudo-3-D view on the deposits. The radar facies was correlated with the sedimentological records obtained in Paper II. The strata recorded in Paper IV showed: 1) glaciotectonically deformed glaciofluvial sediments, 2) till, 3) proglacial channel and channel fill, 4) rip current or proglacial channel and channel fill and 5) littoral reworking of the earlier sediments. In addition to this, separate radar reflections were identified from the glaciotectonically deformed glaciofluvial sediments, which were interpreted to represent glaciotectonic thrust faults. In places old borehole data, obtained for groundwater and aggregate investigations, could be used to verify the interpretations. It was hypothesised that the steep proximal slope of the Runteli ridge represents an ice-contact slope and the genesis of the ridge owes its origin to ice-push. It was thought that after the deposition of the glaciofluvial sediments the order of events was: 1) glacier advance, deposition of till and the first deformation, 2) retreat of the glacier and cutting and infilling of the proglacial channels, 3) further retreat of the glacier, possible readvance or oscillation, formation of the Runteli Ridge and the proglacial deformation cutting the till bed into patchy till and forming the thrust faults on the proximal side of the area, 4) cutting and filling by rip currents and 5) littoral reworking. It can also be the case that the sediments representing cutting and infilling of the channel (2) and cutting and filling by rip currents (4) represent different stages of lower shoreface clinoforms. This interpretation is justified according to the evidence presented but it does not explain the occurence of the large channel forms in the GPR images.

Paper V

Paper V presents the first numerical reconstruction of the extent of the White Sea Basin during the late Younger Dryas Stadial. The White Sea basin was covered by the Weichselian Scandinavian Ice Sheet (SIS) during the last glacial maximum *c.* 17 000-18 000 years ago. The eastern flank of the SIS retreated to the Kalevala end moraine between *c.* 17 000-11 500 years ago. The ice retreat history is relatively well known but the palaeoenvironmental setting, in front of the ice sheet and in White Sea Basin, is poorly understood and partially controversial. The controversies include the extent and the nature of the water body, its connection with the Barents Sea and Baltic Basin and the occurrence of dead-ice masses in deep basins of the White Sea.

In order to shed light on the palaeoenvironmental setting and on these controversies four sites at the Kalevala end moraine, earlier interpreted as glaciofluvial plains, were studied using geomorphological, sedimentological and GPR methods. The geomorphological study showed that the flat plains were incised by discontinuous meltwater channels. Also dead-ice kettle holes and steep slopes from the edge of the flat plain were observed. The shallow test pits showed fluvial facies interpreted as delta topset sedimentation. The GPR survey showed inclined reflections interpreted as delta foreset sedimentation and the deposits were interpreted to represent Gilbert-type glaciofluvial deltaic sediments in three sites out of four. These deposits were overlain by littoral sediments in places. Together the evidence suggests that the deltas grew to the contemporary water level. An alternative interpretation of the inclined reflections representing lower shoreface deposits was also considered. However, the occurrence of fluvial topset facies and littoral facies on top of inclined reflections does not support this interpretation.

The elevations of the deltas in Kalevala end moraine, together with the shoreline elevation at the mouth of the River Vyg, were used to define the shoreline gradient. The gradient, 0.42 metres / kilometre, were then used to reconstruct a relative rebound surface which was added to the present topography of the White Sea Basin and adjacent onshore areas. This was done in order to reconstruct the elevation of the area (relative to the present 123 metre level in the Kalevala end moraine) during the late Younger Dryas.

The reconstruction and the geological evidence suggested that saline water intruded into White Sea Basin before the late Younger Dryas. However, it was thought that glaciolacustrine environment occurred in front of the ice sheet at the west whereas saline or brackish environment dominated at the north and east. It was concluded on the basis of the reconstruction that the water body in the White Sea Basin during the late Younger Dryas was more extensive than today inundating the present onshore areas on the western side of the White Sea and in the Arkhanglesk area. It was also concluded that the water body was connected to the Barents Sea through the Gorlo Strait and it was separated from the Baltic Basin by the Maaselkä – Uikujärvi threshold. The geological observations do not support the assumption that the huge dead-ice masses occupied the White Sea basin during its deglaciation.

5 Discussion

The results presented in this thesis show that GPR has became one of the most useful techniques in the study of the internal structures of clastic, coarse-grained sediments. When using the GPR technique and radar stratigraphical interpretation in conjunction with the well-established sedimentological and geomorphological techniques, knowledge of the subsurface can be dramatically enhanced in comparison to using the latter two techniques alone. Radar stratigraphical interpretation can also be used separately. The interpreter, using this technique, must have knowledge of how the reflections obtained with GPR are formed. In addition to this the sedimentological background must be strong for the sedimentological and geological interpretation of the radar facies, radar surfaces and radar packages.

The post-processing parameters used in GPR have been derived from reflection seismics. In reflection seismics migration is used routinely. Neal (2004) suggests that the use of migration should also be a routine step in the GPR post-processing. Although migration has very good features, such as correction of the angle of the dipping surfaces and removal of the diffraction hyperbolae, the use of migration can sometimes be problematic especially when using time-trigger data collection mode and where no ground truthing is available. Moreover, migration has a tendency to remove weak amplitude reflections and leave only the high amplitude reflections. This can be favourable when performing radar stratigraphy interpretation and the aim is to determine the relative stratigraphic position between the radar facies. When interpreting the depositional environment, migration may mask the radar facies reflection configuration making it impossible to determine the depositional environment. Sometimes, even diffraction hyperbolae, usually caused by outsized clasts, may help in determination of the depositional environment. Therefore, it is suggested that the use of migration in GPR post-processing should always be tested to suit the survey objectives and data collection.

In radar stratigraphy, the reflections caused by something other than the original sedimentary surfaces should be removed in post-processing or ignored (Gawthorpe et al., 1993, Neal, 2004). In Papers III and IV, the reflections caused by glaciotectonic thrusting were identified. If the strict definition of parallelism were applied in these cases, the thrusts should have been ignored. In glaciated terrains, glaciotectonic deformation can provide invaluable information on the ice-sheet dynamics and therefore, cannot be ignored. The terminology for such reflections has not been established. In Papers III and IV the reflections are called 'secondary elements'. Bakker (2004) used a term 'glaciotectonic element (thrusts)', whereas Lønne & Lauritsen (1996), Overgaard & Jakobsen (2001) and Jakobsen & Overgaard (2002) merely used the terms 'thrust faults' and thrusts'. This kind of terminology may be confusing because it mixes description and interpretation. Therefore, it is suggested that the term 'secondary element' or 'secondary radar element' should be used in the description and they should be described using the terminology adopted from Neal (2004). It is also suggested that the secondary elements should be recognised and used as part of the facies analysis of the radar stratigraphical interpretation in the sediments where secondary sedimentary or deformation structures may give additional information of the development of the deposit.

Previous studies have shown that geomorphological units can be related to the radar facies (e.g. Lønne & Lauritsen, 1996; Smith & Jol, 1997; Jakobsen & Overgaard, 2002; Bakker, 2004). The geomorphological approach was used in Papers III, IV and V as a preliminary surveying technique to assess the depositional environment. The steep proximal slopes of the Chalk bedrock hills in East Anglia (Paper III) and of the glaciofluvial sediments in Isoniemi (Paper IV) were interpreted to represent ice-contact slopes. It was hypothesised that glaciotectonic deformation should have occurred in the Chalk bedrock and glaciofluvial sediments below these slopes. In both cases, the radar images indeed showed thrusting and folding, which were interpreted to support the geomorphological interpretation (Fig. 5). In Paper V flat glaciofluvial plains on the Kalevala end moraine were geomorphologically interpreted to represent the uppermost surfaces of a delta. The geomorphological interpretation was based on the flat surfaces

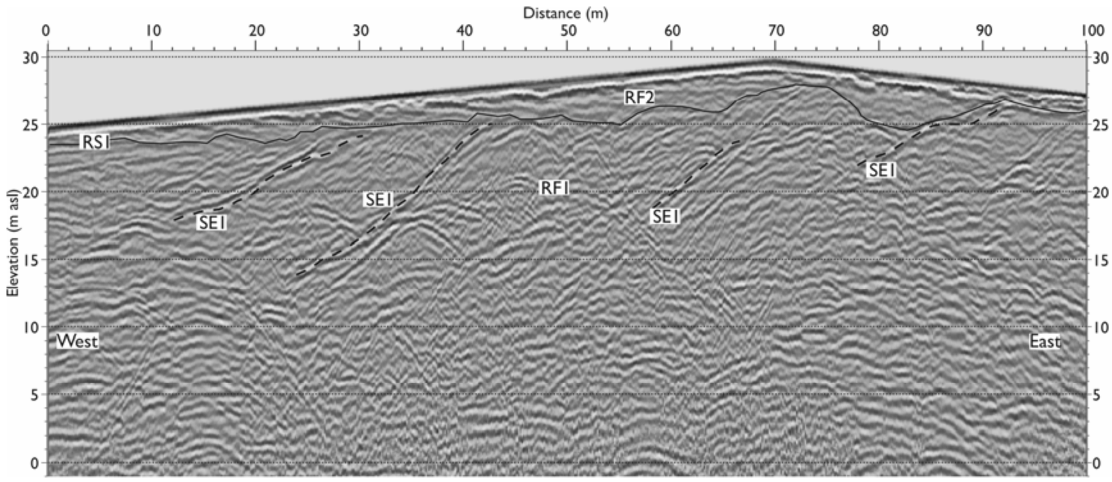

Fig. 5. GPR image from the Isoniemi study site. Radar surface RS1 is marked with the solid black line and it is interpreted to represent a wave-cut surface. Radar facies RF1 is interpreted to represent glaciotectonised glaciofluvial deposit and RF2 is interpreted as littoral reworking deposit. Secondary elements SE1 are marked with dashed black lines and they are interpreted to represent glaciotectonic thrust fault planes.

and inclined landforms interpreted to represent delta fronts. Discontinuous palaeochannels were also identified indicating that the contemporary water level was close to the glaciofluvial plains. This geomorphological interpretation could be confirmed in three sites out of four using GPR, where the survey showed inclined reflections interpreted to represent delta foreset bedding (Fig. 6). In addition to this, horizontal reflections at the top of the radar image were interpreted to represent deltatopset bedding. After the GPR survey it would have been easy to interpret all these flat glaciofluvial areas as representing deltaic surfaces. However, at the fourth site dead-ice kettle holes were seen in the flat surface. The geomorphological interpretation once again suggested the top of the delta which had grown to or close to the water level. In this case, no foreset or topset bedding could be interpreted from the GPR images and it was thought that even though the sediments most probably represent glaciofluvial sedimentation, it was controlled by the bedrock and till surfaces which were observed close to the modern ground surface. Nevertheless, the geomorphological interpretation can provide information about the evolution of the landforms but it should always be confirmed with the study of the internal structures of the sediments beneath.

The applications of the study of the internal structures of the sediments are numerous. The most straightforward applications are the determination of the depositional environment and relative stratigraphic position of the sediments of which the first was mainly used in this thesis. The determination of the depositional environment can lead to other applications. In this thesis these applications included determination of the ice-front position in East Anglia (Paper III) and reconstruction of the palaeotopography of the White Sea Basin during the late Younger Dryas in Northwest Russia (Paper V). In Paper III the deltaic deposits were observed on a north-south orientated curve. These deposits were interpreted as representing glaciofluvial sedimentation in the deltaic deposits in East Anglia implying the water level of a proglacial lake. A similar observation from the Northwest Russia and measuring the current elevation of the deltaic surfaces, formed at the same water level, lead to the reconstruction of the palaeotopography of the White Sea Basin (Fig. 7).

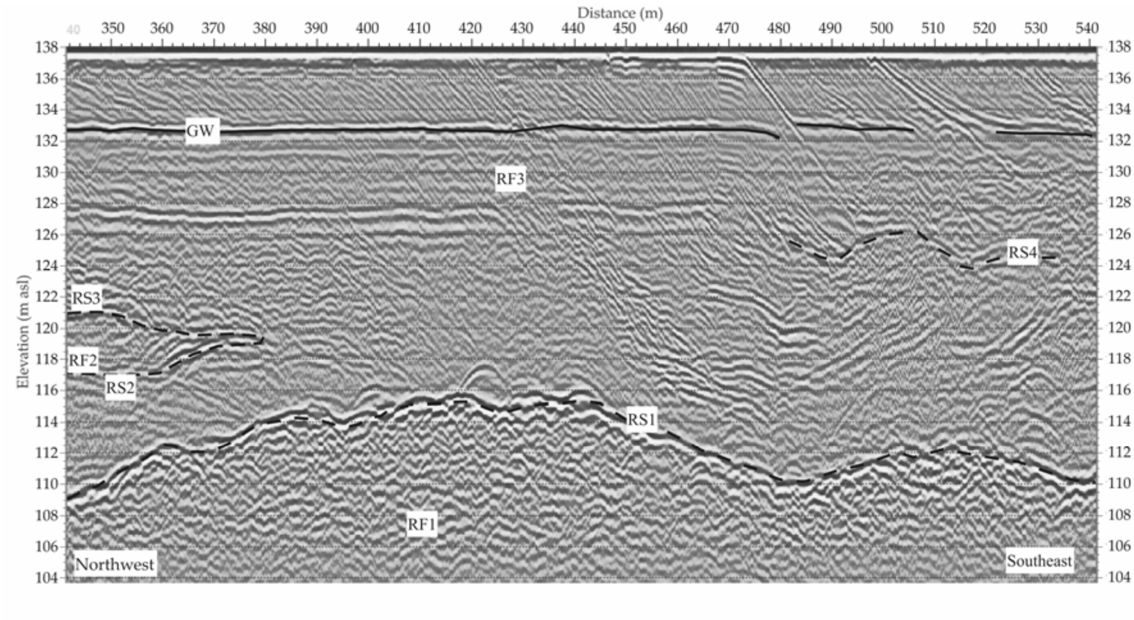

Fig. 6. GPR image from the Lake Mikkolanjärvi study site in the area between the town of Kalevala and the village of Kepa, Northwest Russia (Fig. 4). Radar surfaces RS1-RS4 are marked with dashed black lines and groundwater table GW with solid black line. RS1 is interpreted to represent an erosional top surface of the crystalline bedrock. RS2-RS4 are interpreted as erosional surfaces, probably caused by rearrangement of the flow pattern. Radar facies RF1 is interpreted as crystalline bedrock, whereas RF2 and RF3 are interpreted to represent foreset bedding of the glaciofluvial delta. The different dip direction in RF2 and below RS4 compared to RF3 are thought to be caused by minor changes in the water flow direction and its velocity. The horizontal reflections on top of the image between 340-470 metres are thought to represent topset bedding.

The two decades of the use of GPR in sedimentological studies have produced a large volume of publications and a large dataset from different depositional environments around the world. It would be most advantageous for the people working with GPR in sediments if a radar-stratigraphical atlas of the radar facies in different depositional environments could be collected. This would greatly assist the interpretation but also promote the use of GPR in the study of clastic, coarse-grained sediments, in general.

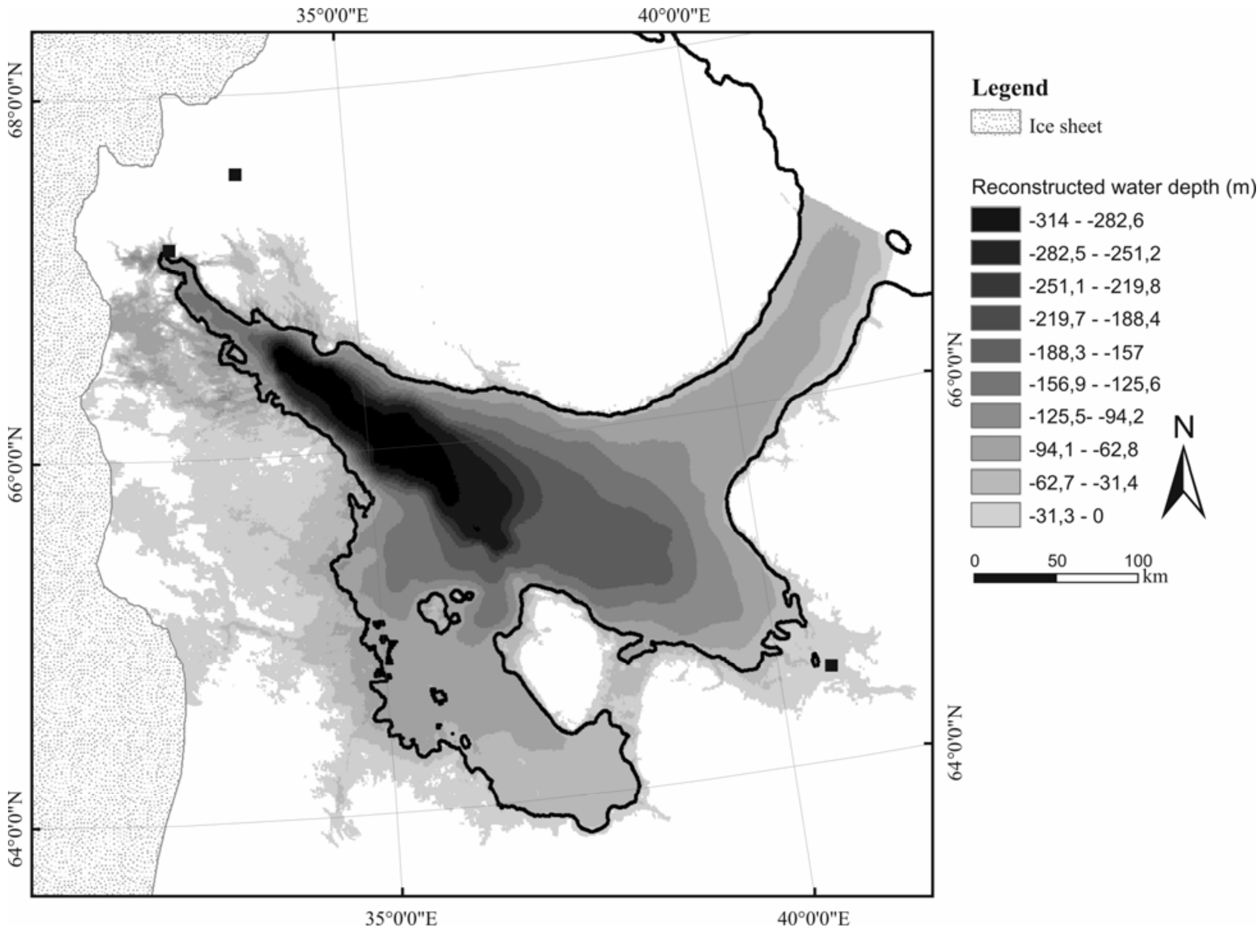

Fig. 7. The reconstruction of the White Sea Basin during the late Younger Dryas. The reconstruction shows that large, currently onshore areas were inundated at the western side of the White Sea and at the Arkhangelsk region.

6 Conclusions

The conclusions presented below illustrate issues important for the radar stratigraphical interpretation and using GPR in clastic, coarse-grained sedimentary successions. These issues are not or are only slightly addressed in the original papers which concentrate on other matters than GPR and radar stratigraphy methodology.

1) GPR has proven to be one of the most useful methods for the investigation of low-conductivity, clastic, coarse-grained subsurfaces to aid with the correlation of the sedimentological data and in the determination of the depositional environment.
2) As a non-intrusive method, GPR can be used in delicate areas and where sections and boreholes are not available or allowed.
3) Where landscape morphology is available, geomorphological interpretation can assist in the interpretation of depositional environments but it should always be confirmed with the study of the internal structures.
4) The outcomes of the use of the radar stratigraphical interpretation are the determination of the depositional environment and the relative stratigraphical position of the sedimentary facies.
5) Secondary elements or secondary radar elements, such as reflections caused by glaciotectonic deformation, can provide valuable information concerning the history of the deposits and should be integrated with the radar stratigraphical interpretation method.
6) The number of studies in which GPR is applied to understand the sedimentology is substantial, consisting of different depositional environments from around the world, and they should be collected into an atlas of radar stratigraphy.

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