Working Report 2011-07

Proceedings of a Seminar on Sea Level Displacement and Bedrock Uplift, 10-11 June 2010, Pori, Finland

Editors:

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January 2011

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Working Reports contain information on work in progress or pending completion.

ABSTRACT

This working report is the proceedings of a seminar on Sea level displacement and bedrock uplift held on 10-11 June 2010 in Pori, Finland. The seminar included invited oral presentations, as well as poster presentations, addressing the causes and mechanisms, observations, modelling and implications of the sea level change and crustal uplift still continuing after the last glaciation in the Baltic Sea region. In the proceedings, a total of 14 papers are included, in addition to foreword and a summary of seminar discussions.

Keywords: land uplift, post-glacial crustal rebound, global isostatic adjustment, sea level change, GIS modelling, radiocarbon dating, historical maps, archaeological findings, landscape reconstruction.

Seminaari merenpinnan muutoksesta ja kallioperän kohoamisesta

TIIVISTELMÄ

Tähän työraporttiin on koostettu Porissa 10.-11. kesäkuuta 2010 pidetyn seminaarin *"Sea level displacement and bedrock uplift"* kirjallinen anti 14 seminaaripaperin, alkusanojen ja keskustelujen yhteenvedon muodossa. Seminaarissa kuultiin kutsuttuja esitelmiä sekä tutustuttiin posteriesityksiin jääkauden jälkeisen, yhä jatkuvan, merenpinnan muutoksen ja maankuoren kohoamisen syistä ja mekanismeista, havainnoista, mallintamisesta ja seurauksista Itämeren alueella.

Avainsanat: Maankohoaminen, jääkauden jälkeinen kallioperän palautuminen, merenpinnan muutos, GIS-mallinnus, radiohiiliajoitus, historialliset kartat, arkeologiset löydöt, maiseman rekonstruointi.

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FOREWORD: FUTURE OUTLOOK REGARDING RESEARCH ON LAND UPLIFT AFTER THE ICE AGE

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A seminar was organised in Pori on 10–11 June 2010 on land uplift after the Ice Age. The seminar arrangements were organised by Biosphere assessment Group manager Ari Ikonen of Posiva Oy and Professor Tarmo Lipping of the Pori Unit of Tampere University of Technology. The lecturers came from Finland and Sweden.

The subjects of the lectures included the mechanisms of post-glacial land uplift, models for modelling the movement of coastline and results obtained from them. Maps showing uplift were also analysed from the historical and archaeological perspectives, and the possibilities for utilising them in the light of current research were discussed. The diversity of the lectures provided a comprehensive picture of research on land uplift after the Ice Age.

This review discusses the future outlook of land uplift research on the basis of the seminar lectures and the results obtained from the GeoSatakunta project (these proceedings; Korhonen 2010). The objective of the GeoSatakunta project in progress during 2000–2009 was to establish the need for geological information in community planning for the province of Satakunta. Satakunta was chosen as the subject area due to its particular geological characteristics. Its bedrock geology is characterized by Jotnian formations, millions of years younger that the bedrock itself, strong land uplift that is constantly altering the landscape of coastal regions, as well as the associated large variations in sediments, the Kokemäenjoki River estuary and Posiva's bedrock construction project in Olkiluoto, the focus of much international attention. Post-glacial uplift has been found to be one of the key elements of natural phenomena in Satakunta. The uplift of bedrock that constantly alters nature must be further studied in future community planning, not forgetting human activities.

Methods associated with gravity research were developed during the GeoSatakunta project for determining the bedrock topography and the thicknesses of different soil layers. A clear example of the importance of bedrock topography is the way the developments in the river channel of Kokemäenjoki depend on rock basins. Bedrock topology has a deciding effect on landscape changes when assessing the impacts of land uplift, and it opens totally new perspectives in structural geology research, also helping to predict future changes taking place in nature. Gravity research has also provided more accurate information on the relationship between calculated and measured geoid data. Accurate determination of exact geoid is essentially important for land uplift research.

Seppo Elo has studied the regional stress field in bedrock as this has been an internationally known problem (Korhonen 2010). According to results obtained by Elo, the effect of density variations on the state of stress in the upper layers of bedrock is 8.5

MPa, which represents a significant part of the horizontal stress field in the upper layers of bedrock. The bedrock in Satakunta has exceptionally large density variations. In addition to the above, the fragmented coastal region that borders the Bothnian Sea has bedrock with a density altogether different from that in the mainland. Further studies are necessary to establish what the implications are of Elo's research results on the equilibrium of bedrock in general, during the Ice Age and after it. Studies indicate that gravity research can provide plenty of new perspectives and information on the equilibriums and structures of bedrock. As measurements taken from ground level are slow and the network of measuring points too scarce, more gravity measurement flights would be required in the future.

The trend towards mathematical modelling was mentioned in almost all seminar lectures discussing modelling. However, that requires a dense network of measurement points. A combination of geological and mathematical modelling is a prerequisite for producing comprehensive models. This also applies to archaeological and geological studies on land uplift and coastline movements after the Ice Age. Pollen analysis should not be omitted from modelling based archaeology and geology; besides land uplift, it can also be utilised for studying the history of human habitation and for producing a view on climate change, for example.

Several studies indicate that the bedrock in Satakunta is exceptionally fragmented. Another indication of this was the statement made by Markku Poutanen in the seminar, according to which the nationwide network of measurement points for land uplift after the Ice Age has too large distances between adjacent measurement points in order to help establish the current movements in Satakunta bedrock (these proceedings). The above is one reason why the most comprehensive GPS network in Finland was built in Satakunta. Seismic deep scans have revealed fault zones in Satakunta that would appear to intersect the crust. The location of fault zones should be taken into account more precisely in order to establish the current movements in bedrock. In parallel to establishing the current movements, the research should also focus on movements that have taken place after the Ice Age in general.

The diverse and living geology of Satakunta attracts researchers to study land uplift after the Ice Age and to produce predictions for the future. Finland has diverse Precambrian bedrock and geological formations that date back to the Ice Age and time after that; they are rather exceptional in the whole of the EU. Systematic research on bedrock developments and mechanisms of post-glacial uplift has been going on in Finland for a hundred years. That is also exceptional, even outside Europe. The seminar lectures and reports produced by the GeoSatakunta project have led to the conclusion that research on post-glacial uplift requires geodetical, geological, geophysical and archaeological methods and mathematical modelling exercises. That is the only way to establish the whole picture of land uplift after the Ice Age and its impact on other natural phenomena. Considerably closer cooperation between researchers than is currently the case will be required in order to obtain a consistent picture. A consistent project should be initiated in Satakunta on the basis of the results for carrying out a multifaceted study on post-glacial uplift. The need for such a consistent project is also obvious when considering the challenges faced in community planning for Satakunta. Research on land uplift has more than just scientific goals. There are several practical applications associated with it, such as; rock construction projects; building construction in general and local planning; understanding the human activities after the Ice Age, today and in the future; survey of significant natural resources (of which groundwater resources are also challenges for the future); research into climate change; and several objects of natural preservation and conservation.

The enhancement of land uplift research will also require that education in the related subjects is boosted, particularly in upper secondary schools. In conjunction with the GeoSatakunta project, many geography teachers of upper secondary schools have expressed their concern regarding the lack of suitable, up-to-date educational material. When planning the future research on post-glacial land uplift, the matters to be considered include the division of responsibilities between different organisations and the historical developments that have led to the current situation. That will require the history of research on land uplift after the Ice Age to be studied.

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SEMINAR PROGRAMME

1 Oral presentations and discussions

Session 1: Causes and mechanisms	
Last glaciation and past stages of the Baltic	Natalia Pimenoff
Geological background: Bedrock in Satakunta	Matti Pajunen
Session 2: Observations	
Dating of past coastline positions - challenges of using the various data types as input to modelling	Jari Turunen
Present bedrock movements and land uplift	Markku Poutanen
Summary discussion on Day 1*: Starting point for land uplift modelling*	

Session 3: Modelling methods	
Påsse's semi-empirical model re-implemented	Jari Pohjola
Comparison between a new and an old semi-empirical Fennoscandian shore-level model	Tore Påsse
Reconstruction of landscapes around relic sites	Kari Uotila
Session 4: Implications	
Past, present and future distribution of Quaternary deposits and land use at the Forsmark site	Gustav Sohlenius
Development of the Olkiluoto site and implications to disposal of spent nuclear fuel	Ari Ikonen
End discussion*: Understanding and modelling of land uplift*	

2 Posters

Posters were invited on the topics of the seminar and the posters presented at the seminar, in connection to the coffee and lunch breaks, are listed below. The authors of all the posters submitted also a paper contribution to the proceedings at hand. The papers on the poster topics are presented below after the papers on the oral presentations.

Posters	
Kuuskajaskari – a daughter of the sea	Pekka Huhta, Riitta Korhonen, Kalevi Korsman
Development of the Olkiluoto site and implications to disposal of spent nuclear fuel	Ari Ikonen, Jani Helin [supplementary material to the oral presentation of the former author]
Estimated coastline in Satakunta, years 1100-1700	Ari Ikonen
Bothnian Sea shore-level displacement data and use of GIS tool to estimate isostatic uplift	Anne-Maj Lahdenperä, Arto Vuorela, Teea Penttinen
Historical maps in the study of shoreline displacement	Jyrki Lehtinen
Analysing the local deformations at Olkiluoto using GPS and levelling time series	Sonja Nyberg, Ulla Kallio, Pekka Lehmuskoski
Archaeological radiocarbon dates and ancient shorelines – resources and reservoirs	Petro Pesonen, Juhana Kammonen, Elena Moltchanova, Markku Oinonen, Päivi Onkamo

ORAL PRESENTATIONS

LAST GLACIATION AND PAST STAGES OF THE BALTIC

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1 Glacial-interglacial variability and dynamics

The climate of the last 500,000 years has varied from glacial to interglacial conditions with strong approximately 100,000 year cyclicity (EPICA community members, 2004). Past glacial-interglacial variations are largely driven by the Earth's orbital changes (figure 1). The Milankovitch theory proposes that glaciations are triggered by minima in summer sunshine in northern latitudes enabling winter snowfall to persist all year and therefore accumulate to Northern Hemisphere glacial ice sheets. For example the onset of the last glaciation, about 117,000 years ago (figure 1e), corresponds to insolation minima in the Northern Hemisphere high latitudes (figure 1a).

The climatic interactions (feedbacks) at the global scale also are involved in the processes of glacial inception and deglaciation (Crucifix et al., 2006). Shifts in the northern treeline, expansion of sea ice at high latitudes and warmer low-latitude oceans as a source of moisture for the ice sheets provide feedbacks that amplify the local insolation forcing over the high latitude continents and allow for growth of ice sheets. The Antarctic ice core data shows that the atmospheric CO_2 concentration (Figure 1d) has been low during glacial times (~190 ppm), and high during interglacials (~280 ppm). This leads to a weaker greenhouse effect during glacial times and a stronger greenhouse effect during warm interglacial times.

Within the glaciations the climate varied from cold periods, stadials, to relatively warm periods, interstadials, that lasted several hundreds or thousands of years. During the cold stadials ice sheets usually grew and during the warmer interstadials ice sheets usually shrank. In figure 1e interglacials of the last 140,000 years are marked with grey shading on a timeline along with the marine isotope stages (MIS). MIS are warm and cool periods of the past, derived from the oxygen isotope data of the deep ocean core samples.

2 Sea level variations during the last glaciation

The glaciations have impact on the global sea level. The water to form the ice sheets originates from the oceans. Thus, as the global ice volume increases, the global sea level decreases and vice versa (figures 1d and 1e). During the coldest stage of the last glaciation, the last glacial maximum, about 20 kyr BP the global sea level was fallen about 120 meter lower than today (Waelbroeck et al., 2002; figure 1d). During deglaciation the ice sheets melt and the water returs back to the oceans increasing the sea level again.

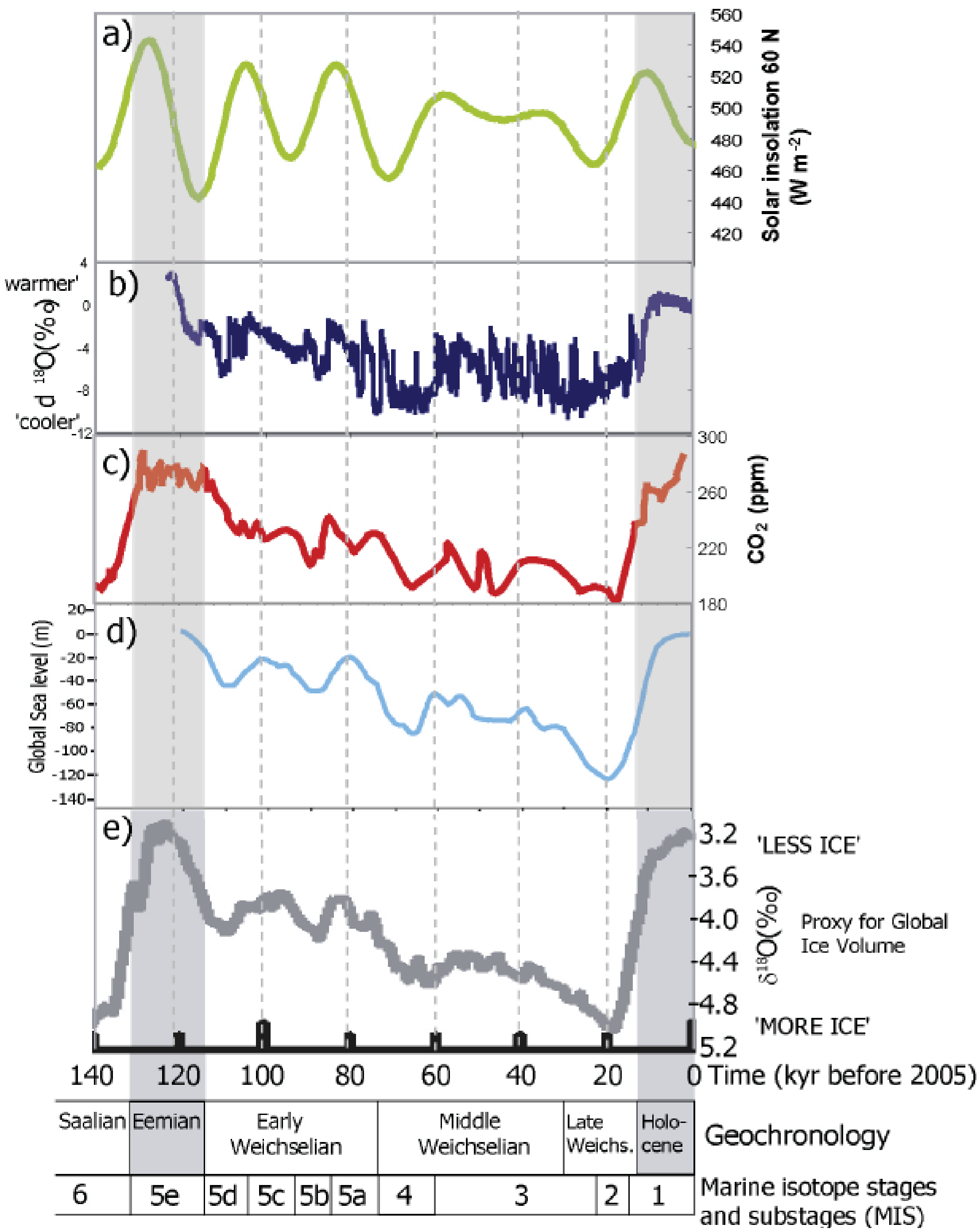

Figure 1. ***a)*** *June solar insolation of 60 °N (Berger & Loutre, 1991),* ***b)*** *measured anomaly of the* ^{18}O *concentration from the NGRIP ice core, a proxy for local temperature,* ***c)*** CO_2 *concentration from the Vostok ice core,* ***d)*** *a reconstruction of the global sea level by Waelbroeck et al. (2002) based on deep ocean* ^{18}O *and temperature records,* ***e)*** *Glacials and interglacials of the last 150,000 years along with the marine isotope stages (MIS) and a proxy for global ice volume. Modified from (Jansen et al. 2007).*

The ice sheets affect the local sea level by depressing the land masses beneath the ice sheet by even hundreds of meters. As the ice sheet retreats, the load on the lithosphere and asthenosphere is reduced and they *rebound* back towards their equilibrium levels. The rebound movements are slow and the uplift caused by the ending of the last glaciation is still continuing e.g. in the Baltic Sea area.

3 The last glaciation in Fennoscandia

In Fennoscandia evidence for the impact of glacial advances is obtained from the most recent glaciations, the Saalian (Marine Isotope Stage 6; MIS 6) and the Weichselian (MIS 5d-2). During the Saalian (which began about 200,000 years ago), an ice sheet covered whole Fennoscandia and large parts of the North Eurasia. The Saalian glacial was terminated by the Eemian interglacial (MIS 5e) about 130,000 years ago. During the Eemian the climate warmed rapidly, the Saale ice sheet retreated and Finland became ice free. However, due to isostatic depression of the crust, large parts of west and south Finland were submerged in the saline Eemian Sea (see figure 2). During the Eemian the global sea level is estimated to have been 4 to 6 m higher than today (Jansen et al., 2007).

The Eemian interglacial ended by a rapid cooling of climate about 117,000 years ago and the Weichselian glaciation started. During the Early Weichselian stadials MIS 5d and MIS 5b Northern Fennoscandia became covered by ice. Most of the Southern Finland, however, remained free of ice (e.g. Svedsen et al. 2004). The Early Weichselian stadials MIS 5d and MIS 5b were separated by a warmer interstadial MIS 5c, and the stadial MIS 5b was followed by a warmer interstadial MIS 5a.

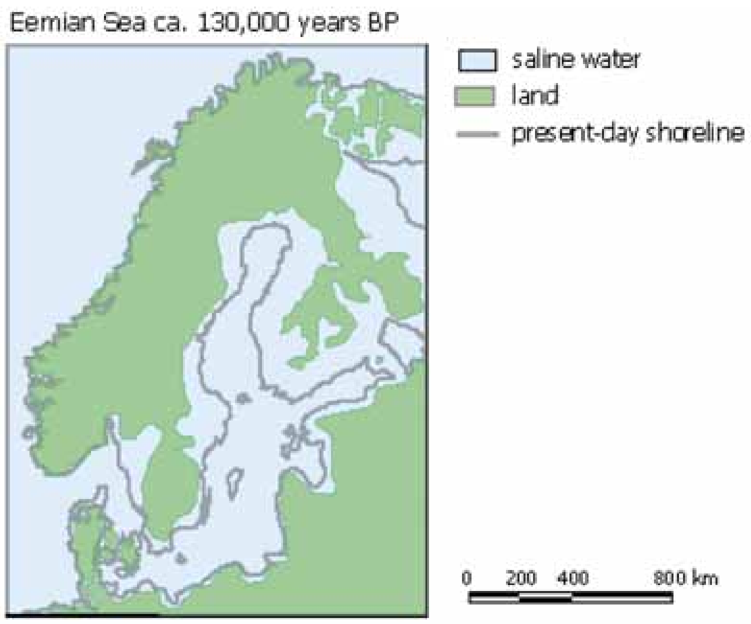

Figure 2. *Schematic figure of the Eemian Sea modified from Funder et al. (2002).*

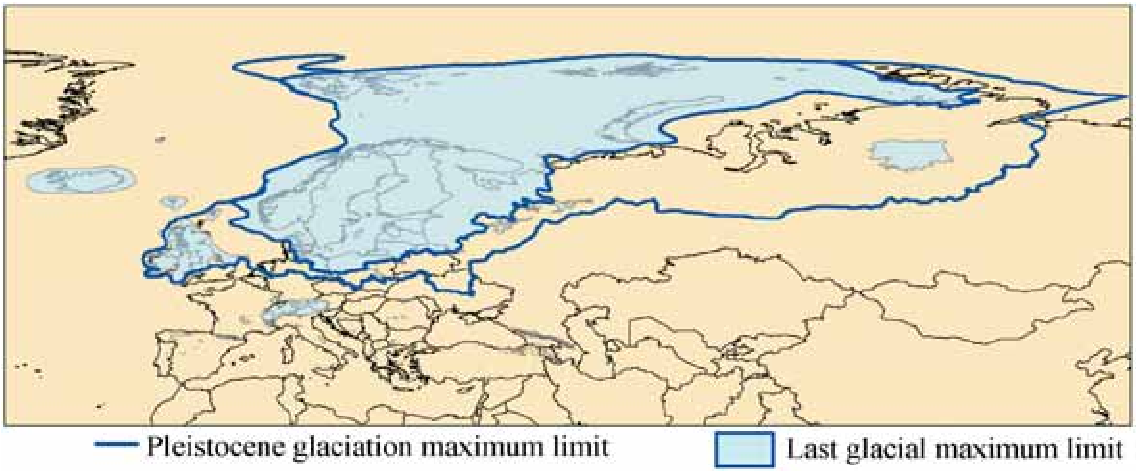

Figure 3. *The maximum ice sheet extent during the Pleistocene (the epoch from 2.588 million to 11,500 years before present) and the last glaciation (data source: Ehlers & Gibbard, 2004).*

The climate cooled again during the cold stadial MIS 4 (ca. 70,000-60,000 years ago) and the Fennoscandian ice sheet spread over most of the Fennoscandia. After the MIS 4 the glacier retreated at least from southern Finland. During a warmer MIS 3 the climate varied from interstadial to stadial conditions and ice free conditions with tundra type vegetation prevailed in the Southern and Central Finland and for several thousands of years (Ukkonen, 1999, Lunkka, et al., 2001).

During the coldest stage of the last glaciation, the MIS 2, about 20,000 – 18,000 years ago the Fennoscandian ice sheet grew to its maximum during the Weichselian (see figure 3). In Fennoscandia the maximum thickness of the ice sheet was 2.5-3 km. After the glacial maximum, about 18,000 years ago, the climate warmed and the glaciers started melting fast until the Younger Dryas stadial (about 12,700 – 11,500 years ago) when the retreat of glaciers stopped for about 1000 years. After the insolation maximum of the Northern Hemisphere 11,500 years ago the climate warmed so much that the Earth entered the current interglacial, the Holocene.

4 Past stages of the Baltic Sea

The Baltic Sea experienced rapid and extreme changes as the Fennoscandian ice sheet retreated (see figure 4). About 12,600-10,300 years BP a fresh water lake, the Baltic Ice Lake (fig 4a), was gradually formed in the Baltic Sea basin. As the Fennoscandian ice sheet retreated from Central Sweden about 10,300 years BP, straits opened from the Baltic Sea basin to the ocean. This started the brackish water Yoldia Sea stage (figure 4b). Due to isostatic land uplift the straits closed up about 9,500 years ago and the Yoldia Sea became fresh water Ancylus Lake (figure 4c). The Ancylus Lake became Litorina Sea (figure 4d) about 7,500 years BP when the eustatically rising ocean levels broke through the Danish Straits (Björck, 1995). After this the Baltic Sea turned little by little to a brackish water body.

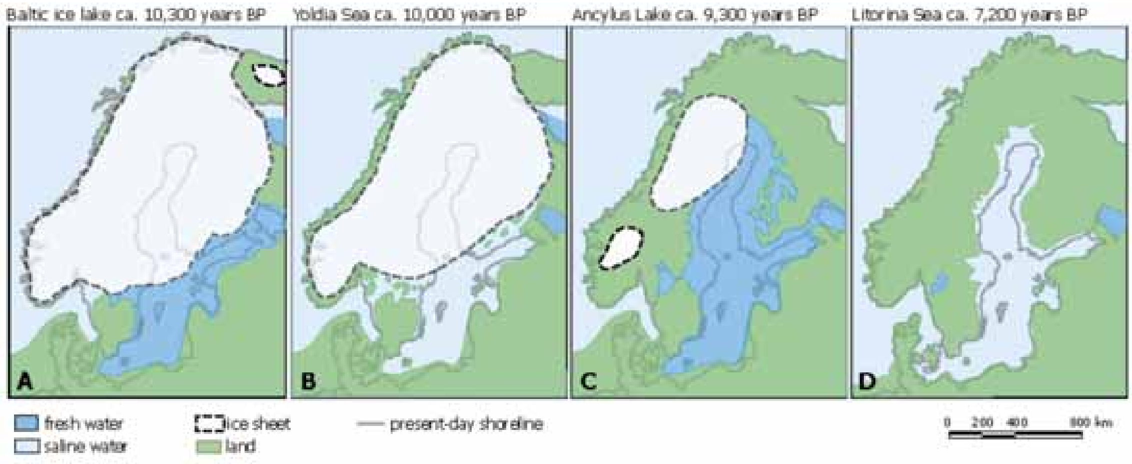

Figure 4. *Schematic figure of the Baltic Sea development* ***a)*** *Baltic Ice Sea,* ***b)*** *Yoldia Sea,* ***c)*** *Ancylus Lake modified from Björck (1995) and* ***d)*** *Litorina Sea modified from Eronen (1990).*

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DATING OF PAST COASTLINE POSITIONS - CHALLENGES OF USING THE VARIOUS TYPES OF DATA AS INPUT TO MODELLING

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Abstract

The dating of the past coastline positions is essential in order to model the land uplift correctly. However, the sizes of various datasets are usually very small and in some cases some of the parameters in datasets are rather 'well educated guesses' than actual real data. Also undocumented man made artefacts, such as river bottom cleaning and deepening efforts may cause lake level lowering and thus error to the dataset and modelling. In this article the uncertainties in the datasets and the possible solutions to overcome these uncertainties in the modelling are reviewed.

1 Introduction

The Baltic coastline position and its dating are directly related to post-glacial rebound. When the land rises in the Scandinavian area the Baltic sea level loosely follows the eustatic sea level revealing approximately 7 km² new land per year in Finland (Kejonen 2007, p 73). The current land uplift rate will cause northern part of the Baltic Sea to be a lake in around 2000 years (Geologia 2007). This is because the Vaasa (Finland) - Umeå (Sweden) sea area is a shallow water region (see figure 1) and the inflow from the northern rivers is greater than inflow from the remaining Baltic sea through the narrow Vaasa-Umeå strait. The 'höga kusten' (high coast) near Umeå and archipelago in Vaasa region are the only places in the world where the effects of isostatic uplift can be observed with bare eye annually (Geologia 2007).

The land uplift effects can be seen in the Baltic coast, but in order to make an accurate land uplift model which is needed, for example, nuclear waste management purposes the existing direct and indirect data must be collected and reviewed. Before the datasets can be reviewed there are some fundamental aspects that will affect to the model itself, for example the bedrock movement dynamics.

There is a debate going on among geologists how homogeneous the bedrock plate might be: can the bedrock blocks move individually or do they act like a leaf upon a wave during lithospheric movements? In figure 2 the well-known bedrock tectonic lines are shown. It is also known that there have been individual block movements in Finland, for example (Kejonen 2007, p. 128). This raises questions about individual block movement, its dynamic linkage to other bedrock blocks and their movements, time span and cause of the movements. These aspects are important because they will point the guidelines whether the bedrock movement and its dynamics can be considered as a whole or not.

Figure 1. *Northern Baltic Sea with the Vaasa-Umeå region (Merenkurkku/Kvarken) marked. Data: Baltic GIS portal (gis.ekoi.lt).*

Figure 2. *Tectonic lines in Finnish bedrock. Data: Geological Survey of Finland, Geological and geophysical maps of the Fennoscandian Shield, 1:1 000 000, Finnish-Russian-Swedish-Norwegian co-operation project.*

Also the map in figure 2 shows some blank areas where the bedrock tectonic lines are not shown. Geological expertise is needed for making at least a 'well-educated guess' about the behaviour of the bedrock blocks and tectonic line continuations in the blank areas.

There is also new evidence about the northern Baltic Sea dynamics. The results of the study presented in (Ymparistö 2006) where mud samples taken from the bottom layers near Svedjehamn, Sweden, have been analyzed that 60,000 years ago the northern Baltic sea was a freshwater basin. The research also suggests that this freshwater basin could have been higher than the surrounding environment 60,000 years ago thus giving new insights to the northern Baltic Sea bottom dynamics and possible tectonic movements.

The annual Baltic sea level change sets a challenge to land uplift rate determination. In figure 3 annual measurements from Kemi and Mäntyluoto are shown. As it can be seen, the differences between annual sea level maximums and minimums are beyond 1 meter. The annual land uplift rate in Finland varies between 2-9 mm / year (Eronen et al. 1995, p. 4), so it is not possible to separate the effect of land uplift from that of annual sea level change. Sea level change measurements have been performed since late 18th century and systematically since 1920's at coastal observation points (FMI 2010a, FMI 2010b), but the time scale is too short to extrapolate the long-term (10,000 years) land uplift from these data. Also, there are a few individual examples in addition to the routine measurements in Finland where lighthouse keepers have painted sea level marks to the nearby rocks (near Sälskär lighthouse in 1900, for example; Stenros 2007, p. 66). The water level is now approximately 40 cm below the lighthouse keeper’s mark so this also falls within the limits of current annual sea level change. Furthermore, it is not known whether the lighthouse keeper has marked the maximum, minimum or average sea level of the year 1900. When the number of data points is small, every possible measurement must be taken into account from different parts of Finland. Evidence also exists that the isostatic land uplift rate changes with time (Vuorela et al. 2009, p. 7-10) so more information on past land and sea level changes is needed.

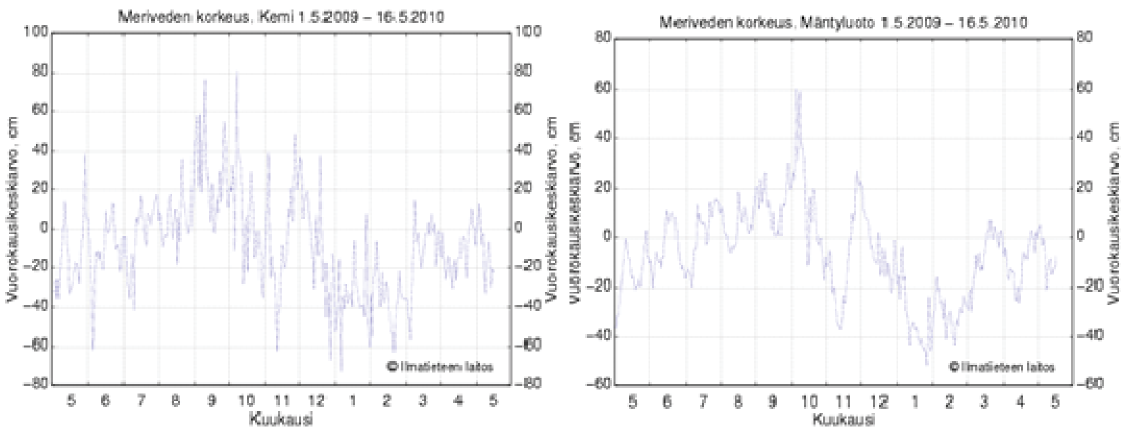

Figure 3. *The 12-month Baltic sea level variation charts in Kemi and Mäntyluoto. Daily data point in the chart is 24-hour average value (FMI 2010b).*

For long time period estimation, the Baltic sea level changes and the eustatic sea level changes must be compared and evaluated. The Baltic Sea has had several lake-phases after the ice age (for example Baltic Ice Lake, Ancylus Lake) where the water level deviates significantly from the eustatic sea level (Fairbanks 1989, Tikkanen & Oksanen 2002). Nowadays the Danish straits will compensate or stroke the eustatic sea level variation in Baltic Sea.

2 Datasets

For the land uplift models, two parameters at minimum are needed: the time and the elevation. The accuracy of the model is related to the accuracy of the data. For example, the radiocarbon age determination is always a distribution within certain limits. In figure 4, the ^{14}C radiocarbon dating was found to be 5500 ± 180 years Before Present (BP) and using "OxCal" conversion program, the highest peak in distribution lies around 4,300 calibrated years Before Christ (calBC). The 'correct' result lies with 95.1% accuracy between years 4,728 – 3,961 calBC.

The georeferencing of old objects is also concern: how much the natural causes, for example floods and landslides, have modified the landscape by adding or removing material from the place of interest. Also man has made modifications during the centuries by drying the lakes and swamps and by deepening the river channels for agricultural purposes. Expertise is needed for estimation and compensation of these modifications. In many cases, such as ancient house foundations, the floor and ground level can be sufficiently well estimated from the site.

In the next subsections the datasets, for which the georeferenced coordinates and timing are known, are presented. These include archaeological evidence data, maps, lake isolation data and lake tilting data. There also exist several indirect observations, but the accuracy is somewhat questionable.

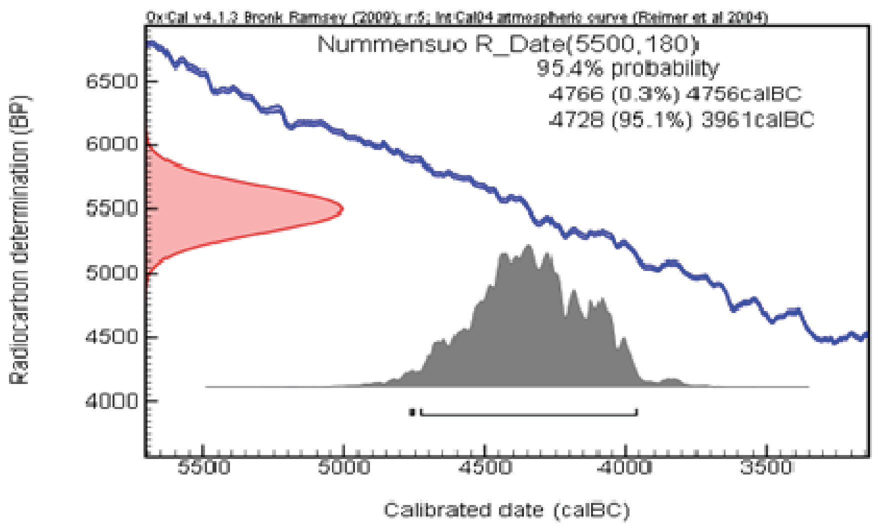

Figure 4. *The example of radiocarbon date calibration.*

2.1 Archaeological evidence

The archaeological data consist of dating and georeferencing of house and village sites, graves, fishermen's and hunters' fireplaces, hidden treasure findings etc. (Tallavaara et al. 2010). Unfortunately, archaeologists are more interested in cultural aspects than georeferencing, and the X-, Y- and Z- coordinates are merely informative, especially in village areas. Sometimes the Z-coordinate (elevation) is completely missing, and the best guess must be obtained from the digital elevation map that itself has been produced with error limits.

In Finland there are two types of graves, the underground graves and piled rock graves on the ground. Concerning the burial sites, there is also the uncertainty how deep the grave was. Regardless of the dating and positioning uncertainties this archaeological evidence gives the upper limit of the sea level at the particular time.

2.2 Maps

There are a few local shore area maps in Finland dating from the 16th century. For example, old map of the sea area of the city of Rauma presents small islands, but unfortunately they are drawn using very generic and artistic style and the georeferencing is almost impossible without some specific landmark details. The time is known but the exact coordinates will set a challenge for using this kind of data to model making.

2.3 Lake isolation data

Eronen et al. (1995) made an effort to determine the time when the lake basins in Finland were isolated from the Baltic Sea due to land uplift. The dating is based on mud samples taken from the bottom of the several lakes. From the drilled core sample the layer is defined where the saltwater algae have been replaced by the freshwater algae. This layer is then radiocarbon-dated. The estimate of the water level is based on empirical observations from the surrounding environment. The timing of the algae and the empirical water level observations do not necessarily correlate to each other. That is why the combined dating and positioning of the empirical observations may include very large errors. The concern is the current water level in lakes and the estimated in swamps etc. natural erosion, man-made modifications in the riverbeds and riverbanks (both inflow and outflow) and the land uplift may have changed the water level in the lakes.

2.4 Lake tilting data

Påsse (1996) has made lake tilting observations in southern Sweden. The water level dating was made by drilling the *Carex* peat samples from the lakes and by performing the 14C dating of the samples. The *Carex* peat is suitable for the water level dating because it forms continuously and the current water level is approximately the same as the new *Carex* peat layer. This data is very good and it gives local model parameters with high confidence. With the current knowledge of the authors this method has unfortunately not been used in Finland.

2.5 Indirect observations

There are plenty of different marks in Finnish nature which are related to the shore level, for example ancient shorelines i.e. washed rock fields all around Finland, wave marks in Salpausselkä sand areas and so on. However the dating of these formations is very difficult and usually it is done by iteration from the water level estimations.

There also exist man-made marks in rocks that have moved and been modified by the means of expanding urban plans in cities. These marks lack confidence in the elevation and the modifications in the water mark history are often untraceable.

Also several canvas art paintings are available, but the sea water elevation is very difficult to determine based on them. The canvas paintings cover mostly the modern era and there are better measurements from that time.

There are also Stone Age rock paintings such as in Astuvansalmi where the oldest can be dated to circa 3000-2500 BC when the lake Saimaa water level was it its highest. Astuvansalmi paintings are now 7-11 meters above current Lake Saimaa level. It is known that Lake Saimaa was already isolated from the Baltic Sea (Ancylus Lake) about 6,000 BC and the estimated 4 - 4.5 meter drop is explained by Vuoksi River breakthrough in near Imatra approximately 3000 BC. The remaining 5 meters are best explained by painting from scaffolds at time in question (SLL 2010, Kivikäs 2005, Wirilander 1989 p. 18–20, 23, 31–34)

3 Challenges in modelling

The ^{14}C dating will automatically give distribution in the calibration phase. Geospatial error is usually assumed to follow Gaussian distribution with some preselected accuracy. Also, as discussed earlier there are still several questions: how accurate the local model parameters can be assumed to be in X and Y directions and how many neighbouring points and how far they can be taken into account? These questions are directly related to plate tectonics and crustal changes.

When working with data with distributions, Monte Carlo simulation is a useful tool for predicting model parameters. With this method when the distributions (error limits) are known the output confidence limit is obtained by randomly selecting a number from each distribution of the selected neighbouring points. This process is then repeated for obtaining sufficient distribution for the output data set.

The possible error in data can also be rejected by using sufficient set of neighbouring points and leave the outlier(s) out. Also using competitive methods for parameter estimation will give more accurate estimation than using single parameter selection method.

The iterative adjusting can be combined with the previous methods. If one dataset does not allow such water level, the water level is decreased until all datasets are in suitable water level tolerance.

4 Discussion

The selection of model parameters based on sometimes sparse, vague or widely distributed data may pose a real challenge. Fortunately, statistical methods, such as Monte Carlo simulation method, will give confidence and error limits for the model parameters. Also the supporting algorithms mentioned in previous chapter will narrow the confidence limits significantly thus providing parameter values of reasonable accuracy for estimation and modelling.

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PRESENT BEDROCK MOVEMENTS AND LAND UPLIFT

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Abstract

Postglacial rebound and the related crustal motion and gravity change in deglaciated areas are observed with high-resolution geodetic techniques. Geodesy provides accurate measurements of contemporary deformation and gravity change. In Fennoscandian area we have systematic uplift observations for more than 100 years based on repeated precise levelling and tide gauges, geodetic high-resolution observations of contemporary movements based on decade-long GPS time series, extensive network of repeated absolute gravity measurements, and possibilities to monitor postglacial faults and local movements. Networks of permanent geodetic GNSS (Global Navigation Satellite Systems, including GPS) stations provide an accurate method to determine contemporary crustal 3-D deformations over continent-wide areas. Horizontal velocities can be measured at a millimetre/year level and vertical rates simultaneously about 2 times less accurately. For a more detailed study of the intra-plate deformation a denser set of GNSS stations or episodic GNSS campaigns are necessary. Detailed 3-D motion with an accuracy of sub-millimetre is already achievable in a small local network as demonstrated in the Posiva network or in the GeoSatakunta project. We describe these measurements and give some general results on the Fennoscandian area.

1 Introduction

There are systematic postglacial uplift observations in Fennoscandian area over last 100 years. Traditional geodetic observations consists repeated precise levelling, tide gauge data, gravity change and monitoring postglacial fault activity. Based on this data and time series over several decades one is able to construct maps of vertical motion. Horizontal motions could not be observed accurately over large areas without modern GNSS techniques. GNSS observations are accurate enough to allow the construction of 3-D motions in a mm-level already in a decade-long time series.

Land uplift is just one consequence of the whole physical process called the Glacial Isostatic Adjustment, GIA. Due to the slow processes, we see not only contemporary effects but we can also retrieve information through the Holocene back to the late Pleistocene. GIA offers information both on the physics and dynamics of Earth's upper mantle and crust, mass variation of glaciers and on the long-term climate change. Most of the GIA-related phenomena originate to the large-scale mass transportation and geodetic observations of the geometry and gravity field of the Earth and their temporal and spatial variation are fundamental for understanding the dynamic Earth. No single technique or observing network will give enough information on all aspects and consequences of GIA and a need for integrated multi-technique observing systems is evident.

The mass transportation within the solid Earth is an enormous phenomenon. Waxing and waning of the Northern hemisphere glaciers in about 100 000 year cycles cause up to 135 m of global sea level rise and fall. This alone corresponds about 5×10^{19} kg of mass (almost 10^{-5} of the total mass of the Earth; e.g. Poutanen & Ivins, 2010). The mass transportation causes cyclic variation on the surface load resulting in the viscoelastic mantle flow and elastic effects on the upper crust (Fig. 1). Increased mass of the glacier changes the geoid in its vicinity and the sea level is changed less than elsewhere. And opposite, when the glacier is melted, most of the melt water flows far from the glacier causing sea level rise there, and less near the melting glacier.

The GIA signal, however, is contaminated by several other spatially and temporally varying mass changes and crustal deformation. These include seismic deformation, mantle convection and plate tectonics (e.g. van Dam et al., 2008). Separating GIA-induced contributions from the other sources is not straightforward. Sea level change is an example of a phenomenon which is related to GIA but mixed with other signals. The

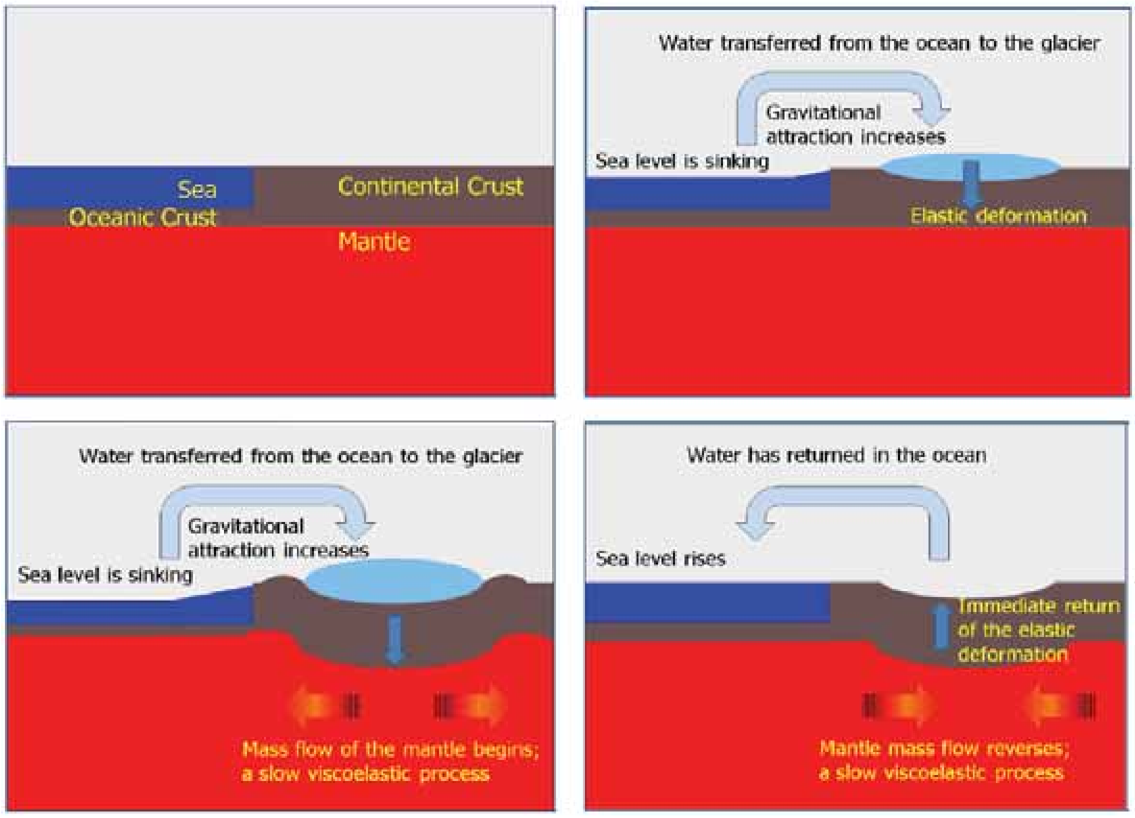

Figure 1. *A schematic diagram of the Glacial Isostatic Adjustment (GIA), seal level change and gravity change. (Top left): Situation before the glaciation. (Top right): The glaciation has begun. Water from ocean is transferred to the glacier. Sea level sinks except near the glacier where increasing mass attracts more water. Immediate crustal subsidence is due to the elastic deformation. (Bottom left): Maximum of the glaciation. Viscoelastic process is causing a slow mass flow of the mantle and land uplift outside the glacier. (Bottom right): End of glaciation, current situation in Fennoscandia. Elastic deformation has recovered but the slow viscoelastic rebound continues.*

observed sea level change relative to the benchmark on the ground contains components of GIA related crustal vertical motion, eustatic rise of the sea level, changes in semi-permanent sea surface topography and geoid changes.

2 Regional observations

Maps of vertical motion have traditionally been based on long time series of tide gauges and repeated precise levellings over several decades. Tide gauge time series reflect both vertical motions of the land and variations of the surface of the sea. Uplift maps for Fennoscandia were published by e.g. Ekman (1996), Kakkuri (1997), Mäkinen and Saaranen (1998), Saaranen & Mäkinen (2002), Vestøl (2006), and Ågren & Svensson (2007).

GNSS observations allow the construction of 3-D motions from less than 10 years time series. The project BIFROST (Baseline Inferences for Fennoscandian Rebound Observations, Sea Level, and Tectonics) was initiated in 1993 taking advantage of tens of then-established permanent GPS stations in Finland and Sweden, see e.g. Milne et al. (2001), Johansson et al. (2002), and Scherneck et al. (2002). 3-D deformation maps based on GPS time series were published e.g. by Mäkinen et al. (2003) and Lidberg et al. (2010), see Figs. 2-4.

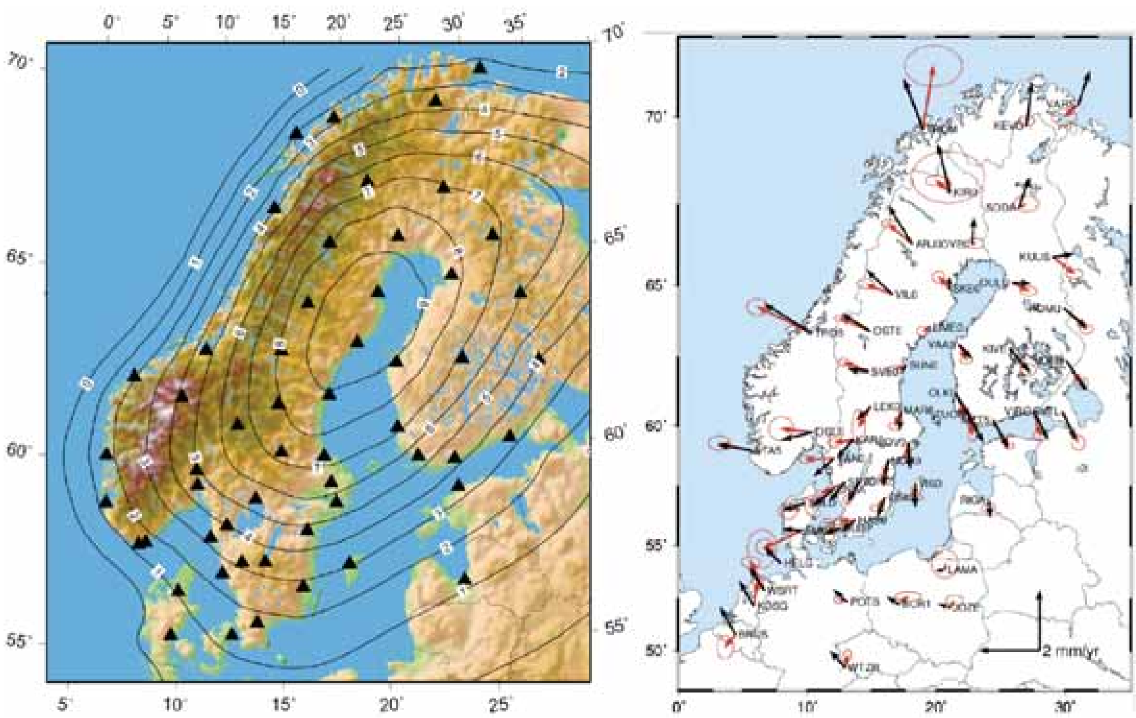

Figure 2. *(Left): Postglacial rebound rates (mm/y) relative to the centre of mass of the Earth. Triangles are permanent GPS stations. (Right): Observed (red) and modelled (black) rates of horizontal displacement in Fennoscandia based on a model of Milne et al. (2001) and the GPS-derived velocity field of Lidberg et al (2006), based on Nordic permanent GPS stations (Lidberg et al., 2006).*

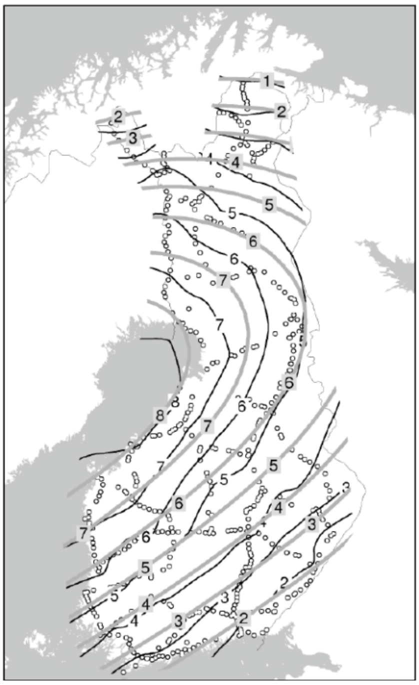

Figure 3. *Comparison of the Nordic land uplift model NKG2005LU with observed velocities [mm/y] in Finland. Vertical velocities are estimated from the three precise levelling. Open small circles represent levelling bench marks in bedrock. The thick grey isobases come from the NKG2005LU and the thin black isobases from the three precise levellings in Finland. (Mäkinen at al. 2005)*

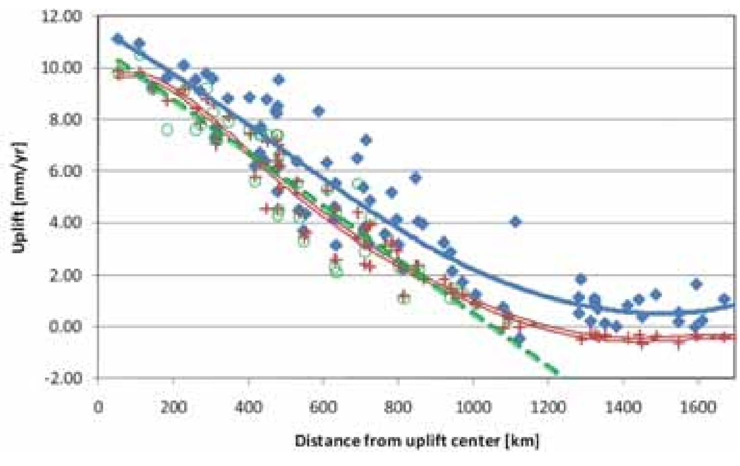

Figure 4. *Vertical rates of Fennoscandian rebound as a function of distance to the uplift maximum. GPS data (diamonds) are based on latest BIFROST results of Lidberg et al. (2010), tide gauge data (open circles) are from Ekman and Mäkinen (1996), and GIA model (crosses) is based on revised model constructed by Glenn Milne (Lidberg et al. 2010). All fitted trend lines show similar slope (solid line: GPS; double line: GIA model; dashed line: tide gauges). Difference between GPS and tide gauge uplift values amounts the eustatic rise of the Baltic Sea; GPS uplift values are relative to the mass centre of the Earth. (Poutanen & Ivins 2010)*

There are also other ongoing projects utilizing data collected over decades. These projects include DynaQlim (Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas; Poutanen et al. 2009; Poutanen and Ivins 2010), COST Action ES0701 “Improved Constraints on Models of Glacial Isostatic Adjustment” (COST, 2010), SPP1257 “Mass transport and mass distribution in the system Earth” (Ilk et al. 2005), and many more.

3 Local observations

Local GNSS observations are based on the existing background of regional or global networks and stable reference frames. The Finnish permanent GPS network FinnRef® consists of 13 permanent GPS stations. The distances between the stations are 100-200 km. The network is the backbone of the Finnish realisation of the European coordinate reference system ETRS89, referred as to EUREF-FIN. Most of the stations have been operational since 1996 offering now a possibility for 10-year long time series (Koivula 2006). All FinnRef® stations are used in the computation of the joint Nordic GNSS network and they enable the study of the crustal motions. Although this network is too sparse for local deformation studies (e.g. in Olkiluoto or in the Satakunta project), it forms the basic reference for all geodynamics studies. Stability of the network is of ultimate importance to any GNSS-related work.

Finnish Geodetic Institute has made GPS based deformation studies at the investigation areas of Posiva since 1994, when the network of ten GPS pillars was established at Olkiluoto (Chen & Kakkuri 1995). The network of seven GPS pillars was built at Kivetty and Romuvaara during the year 1996. The GPS network at Olkiluoto was extended in 2003 and 2005. Including the new pillars the local GPS network at Olkiluoto consists of 14 stations (Fig. 5). The new pillars were built close to Kuivalahti, Taipalmaa and Hankkila villages and on a small island of Iso Pyrekari. The whole network at Olkiluoto is measured twice a year, and the total number of campaigns at the end of 2009 was 28 (Kallio et al. 2009).

About 30 % of the baselines at Olkiluoto have statistically significant change rates at the confidence level of 95 %. The rates between any two pillars are smaller than ± 0.20 mm/y; the most significant change rate is 0.18 ± 0.03 mm/y (Figs. 6 and 7).

GPS measurements are suitable to determine horizontal deformations, but the accuracy of height determination is not adequate. The FGI started to determine possible vertical deformations at Olkiluoto with precise levelling in 2003. Levelling campaigns will be performed every second year (Lehmuskoski 2008).

The Finnish Geodetic Institute, the Geological Survey of Finland, Posiva Ltd and cities of Pori and Rauma launched the GeoSatakunta research program in 2002 to carry out interdisciplinary studies on regional bedrock stress field and to apply the results e.g. in land use planning in the Satakunta area. As a part of the project FGI established a regional GPS network in 2002 which was expanded at its southern part by six new pillars in 2005-2006. The current network covers the area of interest to obtain the movements in the area (Poutanen et al. 2010).

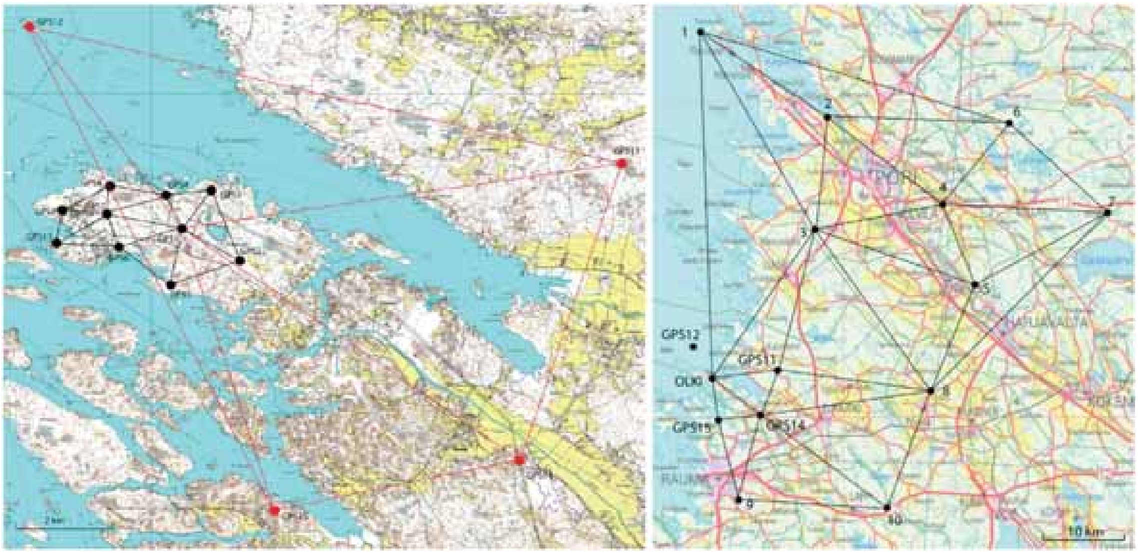

Figure 5. *(Left): The local GPS monitoring networks at the investigation area of Olkiluoto. Black: Original network has been established in 1994 (GPS13 in 2003). Red: Pillars have been established in 2003 and 2005. (Right): GeoSatakunta GPS network. Base map ©National Land Survey, license number 51/MML/09.*

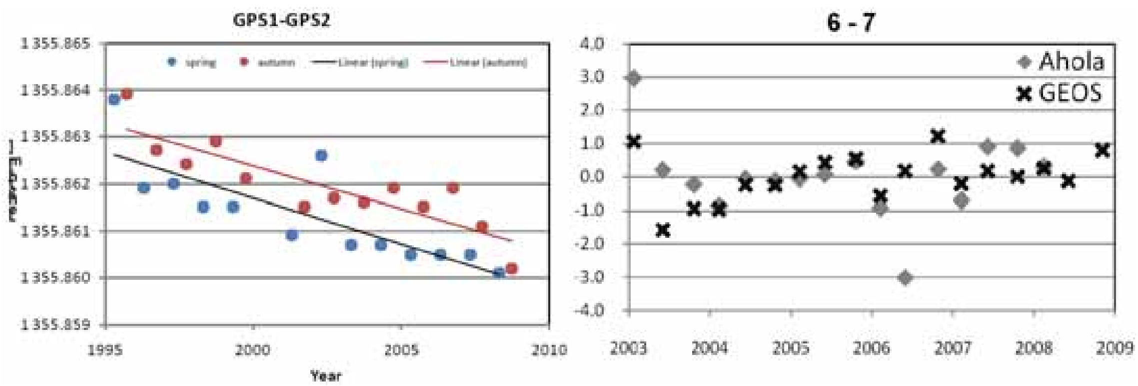

Figure 6. *(Left): GPS time series at Olkiluoto, the length between pillars 1 and 2 is changing 0.18 mm/y ± 0.03 mm/y. There is an annual signal in the data because autumn and spring observations seem to systematically deviate from each other. (Kallio et al. 2009) (Right): In time series of GeoSatakunta network, similar annual signal is not visible. Diamonds are the preliminary solutions computed after each campaign, crosses are the final solution computed in 2009 for all campaigns. Y-axis is the deviation from the mean (mm). (Poutanen et al. 2010)*

There have been three annual GPS campaigns between 2003 and 2008. In five years it was reached the accuracy where any large movements can be excluded. There is, however, a possibility for 0.2-0.5 mm/y inter-station movements which can remain unobserved in the current data. Especially in the southern part of the network, which was established later than the northern part, the time series are too short to draw any definite conclusions (Fig. 7). GPS observations will be continued also in the future.

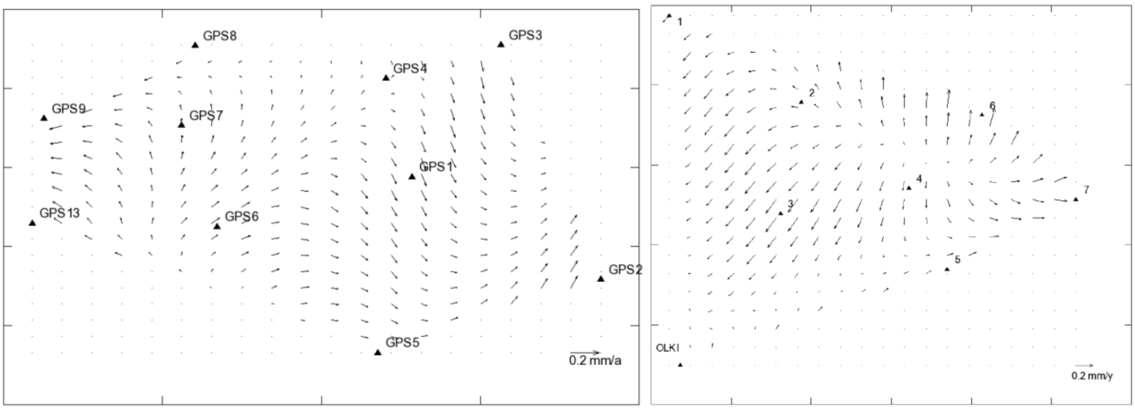

Figure 7. *(Left): Horizontal velocities obtained from 15-year GPS time series of Olkiluoto network. (Kallio et al. 2010). (Right): Velocities obtained from GeoSatakunta network. Only the northern part of the network is shown here. (Poutanen et al. 2010)*

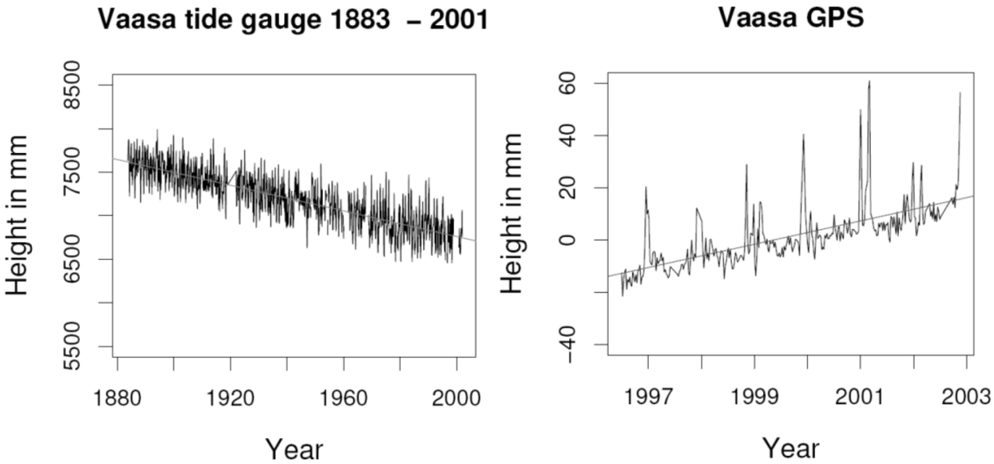

Figure 8. *Sea level time series of Vaasa tide gauge and land uplift of Vaasa GPS station. Note, that the scale of the GPS time series is 10 cm and the scale of the tide gauge time series is 3 m. Spikes in GPS time series are due to the snow on the antenna radome in winter time. (Tervo et al. 2006)*

No single observing technique can detect all aspects of the GIA related phenomena. In addition to the GPS measurements, there exist also other geodetic data in the area. These include repeated precise levelling (Lehmuskoski et al. 2008), uplift values computed from levelling data (Mäkinen et al. 2003) and gravimetric data (Kiviniemi 1980; Kääriäinen & Mäkinen 1997). For the land uplift and sea level change, one needs long time series of tide gauge observations (Fig. 8).

4 Conclusions

The crustal deformation caused by rebound and other phenomena changes the stress field of the crust. Other processes can be slower or smaller in magnitude than the glacial-related processes but they can play an important role in long time scales or they can cause abrupt motions (earthquakes) when monitored over very long time spans. These include erosion and sedimentation redistributed surface loads and stress on the crust, plate tectonic forces, including the Mid-Atlantic push that can contribute to the regional stress, geological anomalies of the crust and lithosphere causing them to be in a non-equilibrium state and therefore introducing stress fields. Climate-change processes will cause actual changes in the sea level and water mass in addition to the relative sea level change due to the postglacial rebound (Poutanen et al. 2010).

The present-day intra-plate seismicity in Fennoscandia is low and tectonic stress rates are small. Melting of the glacier at the Pleistocene-Holocene transition caused earthquakes with magnitudes up to 8. The risk for large intra-plate earthquakes inside the Fennoscandian Shield during the current slow viscoelastic phase is unknown. The largest historical earthquake in Fennoscandia occurred in the Rana region of northern Norway in 1819 with a magnitude of M = 5.8. However, during last 200 years we know several intraplate events in Northern America and China up to magnitude 8.

Regional and local GNSS observations are needed also in the future to monitor crustal deformation. The observing accuracy is now about 0.5 mm/y but the permanent GNSS network is too sparse to make any detailed conclusion. Therefore, episodic campaigns are needed to maintain dense local networks. Also if deformation is not continuous, one may see nothing for a long time until the accumulated stress is released in an abrupt event. We do not know the GIA mechanisms well enough to predict such events.

On the local level (e.g. Olkiluoto network) combined GNSS observations with associated regularly repeated precise levelling offer best combination to monitor crustal 3-D deformation. Weakness of GNSS in vertical direction is partly eliminated by levelling but this can be applied in a small network only. Already in the size of GeoSatakunta network (with distances of some tens of kilometres) levelling is too slow and laborious. New emerging techniques, such as SAR Interferometry or airborne lidar observations may in future improve our ability to monitor crustal deformation with better spatial and temporal resolution.

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PÅSSE'S SEMI-EMPIRICAL MODEL RE-IMPLEMENTED

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Abstract

In this paper we present a new method for improved estimation of the parameters of the semi-empirical land uplift model of Fennoscandia introduced by Tore Påsse. The land uplift model serves as an input predicting the development of the landscape in 10 000 years' time span for safety assessment of disposal of spent nuclear fuel at Olkiluoto site in Finland. The research was carried out as an assignment by Posiva Oy, the company responsible for the repository program. The ongoing land uplift in the Baltic Sea region is due to the rebound of glacial stress caused by the most recent ice age 115 000-10 000 years before present (BP). The rebound is known to contain two phases: the fast and the slow uplift. The fast uplift took place about at the melt of the glacier but the slow uplift is still in progress. The improved methodology for the land uplift model parameter estimation presented in this study is based on regional variations in bedrock properties and download. The parameters were computed using ancient shore level positions and their radiocarbon dating. Also information about prehistoric population history in Finland was used in the research. Because of the uncertainties and inaccuracies in the dating and the shore level estimations, Monte Carlo simulation was employed for the estimation of the parameter distributions.

1 Introduction

The effects of the most recent ice age 115 000-10 000 years before present (BP) are clearly visible in Fennoscandia: the land is still rising due to glacio-isostatic uplift (glacial rebound) with estimated annual rates shown in figure 1. Reliable estimates of the land uplift are essential in assessing the long-term safety over millennia of the spent nuclear fuel disposal as the hydrological conditions in the bedrock and the potential exposure pathways of humans and other biota to possible releases of radioactivity are affected. There are several physical models available for land uplift estimation like, for example, those presented in Cathles (1975), Clark et al. (1978) and Lambeck & Purcell (2003). However some of the parameters of these models are very difficult to obtain and the meaning of the parameters also differs between the models. The approach proposed by Påsse (2001) uses a different point of view. In this model the unknown parameters can be estimated from fairly well known data describing the coastline displacement. Swedish Nuclear Fuel and Waste Management Company and Posiva Oy have accepted in co-operation to use Påsse's model in their analysis (Lindborg & Rubio Lind 2006).

According to the Finnish regulations (STUK 2001) the time window of estimating the doses in the safety analysis of the spent nuclear repository has to be at least several thousands of years, which is interpreted by Posiva to be 10 000 years from the present. The repository site, Olkiluoto Island, resides in the glacial rebound area and the annual land uplift rate is approximately 6 millimetres per year.

In this paper we present a method for improved estimation of the parameters of the land uplift model introduced by Påsse (2001). The method is based on shoreline information collected from lakes and prehistoric population information. The study covers the area of Finland.

2 Påsse's uplift model

In Påsse's (2001) model the shore level displacement is estimated from the variables:

$$S = U - E \tag{2-1}$$

$$U = U_s + U_f \tag{2-2}$$

where S is the shore level displacement, U is the total glacio-isostatic uplift, U_S is the slow component of the glacio-isostatic uplift, U_f is the fast component of the glacio-isostatic uplift, and E is the eustatic sea level change (all in meters). The eustatic sea level change is either subtracted or added depending on the sign in the eustatic data.

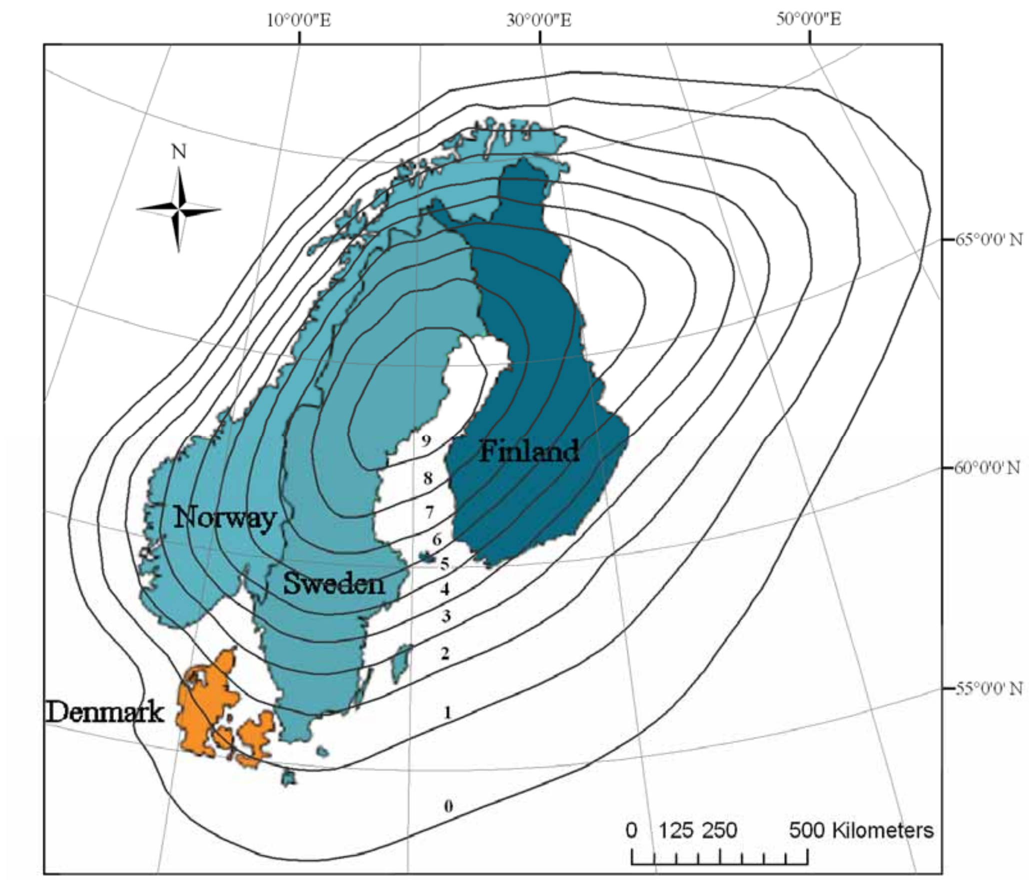

Figure 1. *Absolute annual land uplift in millimetres in Scandinavia.*

The slow uplift is modelled using a linear combination of two arc tangent functions (Påsse 2001):

$$U_s = \frac{2}{\pi} A_s \left[\arctan\left(\frac{T_s}{B_s}\right) - \arctan\left(\frac{T_s - t}{B_s}\right) \right] \tag{2-3}$$

where A_s is the download factor (in meters), T_s is the time for maximal uplift rate (i.e. the symmetry point of the arc tangent function, in years), t is the time (in years) and B_s is the inertia factor (years^{-1}).

The fast uplift component is expressed:

$$U_f = A_f e^{-0.5\left(\frac{t-T_f}{B_f}\right)^2} \tag{2-4}$$

where A_f is the total subsidence (in meters), B_f is the inertia factor (y^{-1}), T_f is the time for maximal uplift rate (i.e., the symmetry point of the function; in years) and t is time (in years).

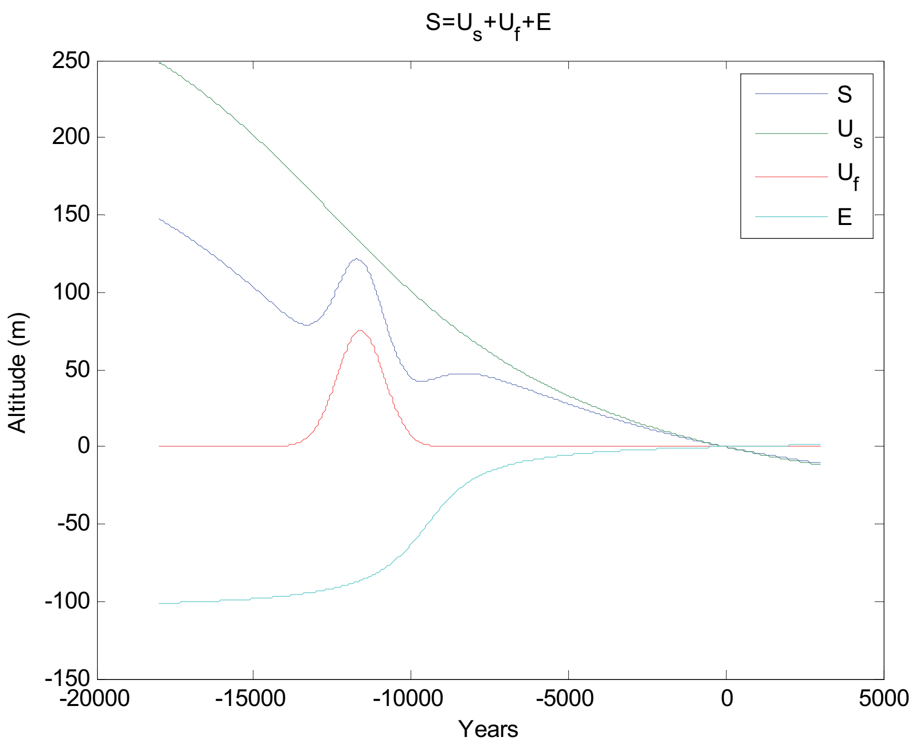

Figure 2. *An example of shore level displacement, slow and fast uplift and eustatic sea level rise following an illustration by Påsse (2001).*

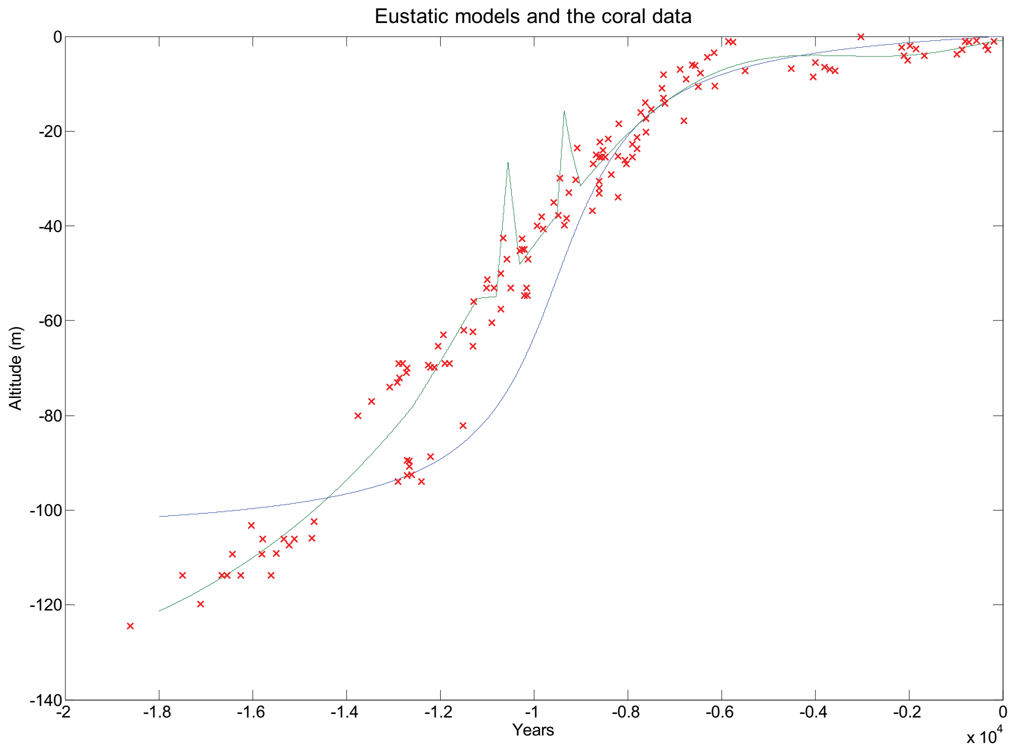

Figure 3. *Sea and lake level estimates. The blue curve is the eustatic rise according to Påsse (2001). The red crosses are the coral data collected by Fairbanks (1989), Chappell (1991) and Bard (1996). The green curve is fitted to the coral data with the addition of the Baltic Sea lake phases. These include the Baltic Ice Lake (12600-10300 BP) and the Ancylus Lake (9500-9000 BP) (Tikkanen & Oksanen 2002). During the lake phases the water level in the Baltic Sea area differed from the global sea level.*

The eustatic sea level rise (E) is originally modelled using the radiocarbon-dated coral data collected by Fairbanks (1989), Chappell (1991) and Bard (1996). Påsse (2001) derived an arc tangent based function using Fairbanks' data. He also discussed about the effects of the lake phases of the Baltic Sea but concluded that the evidence is insufficient in some cases and that the influence of these lakes might be negligible in long-term studies (Påsse 2001). This is true if only the future land uplift is in the interest and the parameter values are fully known. In our study the lake phases – more specifically, the duration and the estimates of the altitude of the lake levels – were taken from (Tikkanen & Oksanen 2002) and incorporated into the analysis since they do have a significance in deriving the model parameter values from the shore level observations dated within the time span of these lake phases. Both curves can be seen in figure 3.

The parameters A_s and T_s play a significant role and they can be estimated from the existing data. A_s can be interpreted as half of the total isostatic uplift and T_s is the maximum uplift rate correlating with the glacial retreatment (Vuorela et al. 2009). To find out the inertia factor B_s, a Moho (Mohorovičić discontinuity) map of Europe is used (Grad et al. 2009). The Moho map describes the depth of the boundary between the

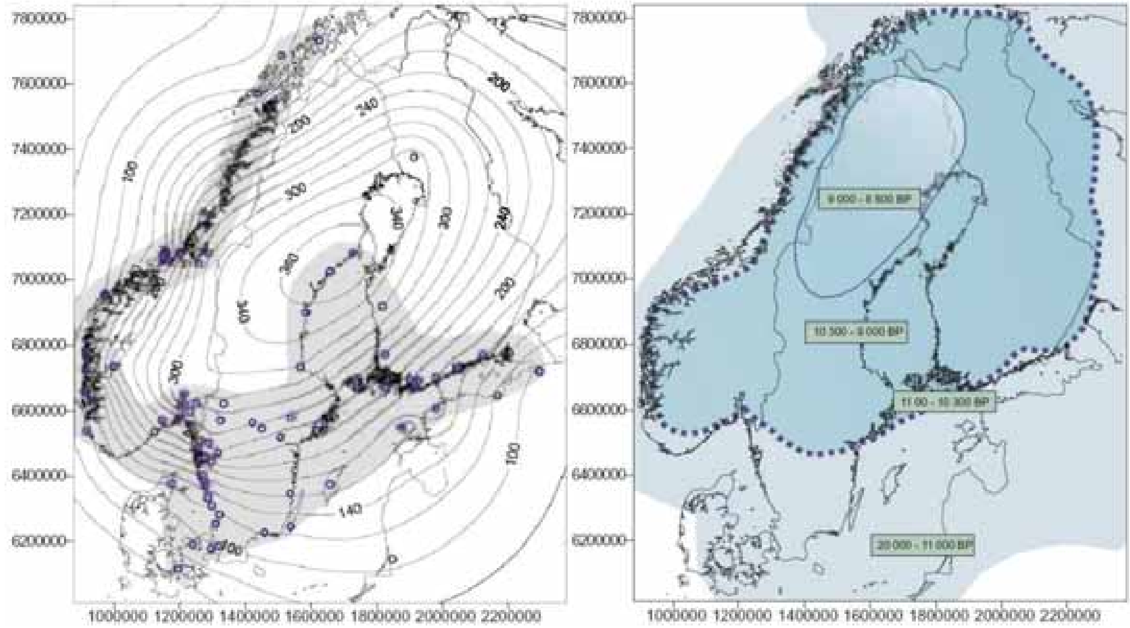

Figure 4. *A_s estimates (left) and the ice recession $(\cong T_s)$ map in Fennoscandia according to Påsse (2001).*

Earth's crust and the mantle. Based on this the Moho depth can be thought as the crustal thickness of the Earth. The inertia factor B_s is calculated using formula (2-5) (Vuorela et al. 2009), where ct is the crustal thickness (Moho depth) in kilometres.

$$B_s = 302e^{0.067ct} \quad (2\text{-}5)$$

In figure 4 estimates of A_s and T_s (ice recession) are presented.

3 Refinement of Påsse's uplift model

For defining and iterating the local As and Ts parameter values, 94 collected point data values (x,y,z and ^{14}C radiocarbon age) of the shore level were used in this study. The data used is from Vuorela et al. (2009) and it was gathered from lakes. Also another data set of prehistoric population history was used (x,y,z and ^{14}C radiocarbon age) in the iteration. This data set included 264 data points and is based on the study of Tallavaara et al. (2010). The points of both data sets are shown in figure 5. The ^{14}C radiocarbon ages together with corresponding uncertainties were converted into calendar year probability distributions using "OxCal" software by Oxford Radiocarbon Accelerator Unit (2010). In figure 6 an example of the calibration of the point data from Lake Vähäjärvi in Eura is presented. As both the ^{14}C radiocarbon dating as well as the height (z) value contain uncertainties, the Monte Carlo simulation was used for determining the probability distributions for the A_s and T_s parameter values. The Monte Carlo simulation was based on 1000 realizations of elevation values generated according to Gaussian distribution (z ± 3 m) and the age distributions from OxCal.

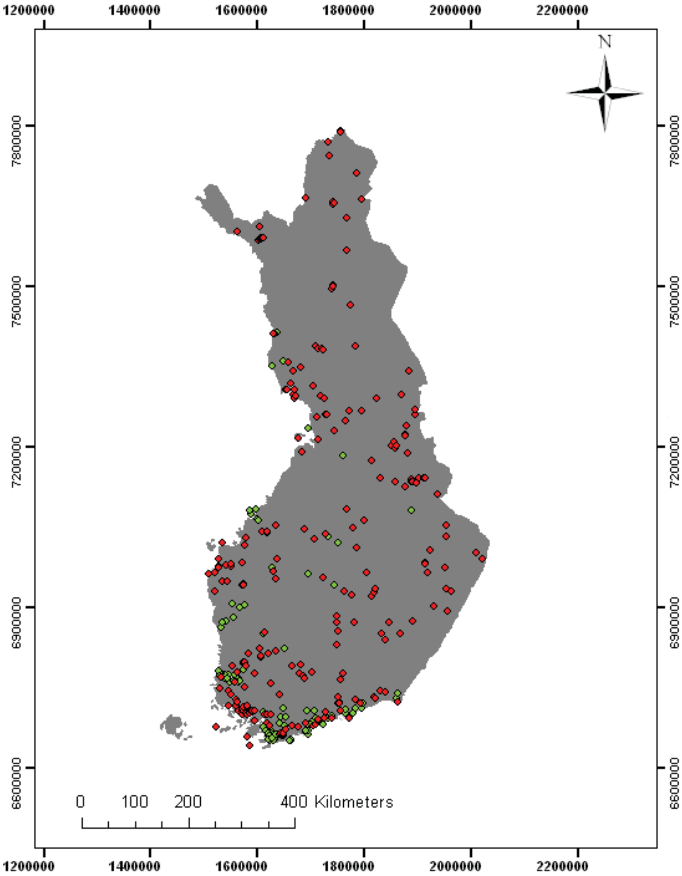

Figure 5. *Point data locations in Finland. The green dots indicate the points from the data set of lakes and the red dots indicate the points from the prehistoric population data set (Tallavaara 2010). The map is in a Finnish KKJ map projection.*

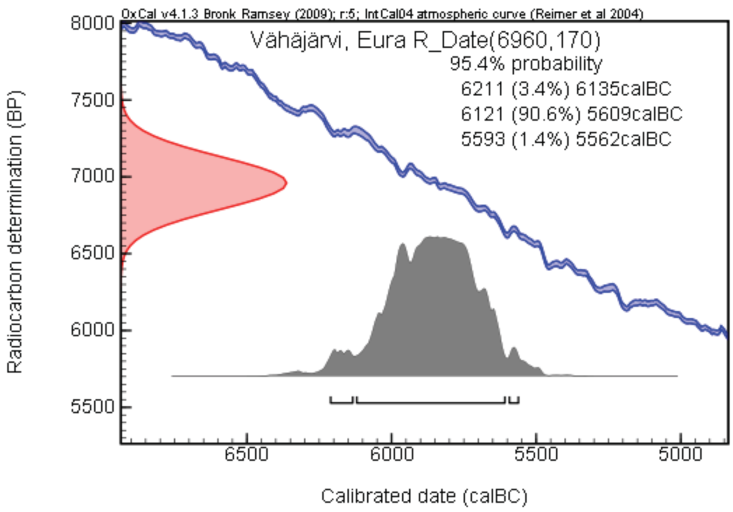

Figure 6. *Screen capture from OxCal program. The* ^{14}C *age (6960) and the standard uncertainty (170) are the inputs. The blue line indicates the calibration curve while the error distribution of the calendar age (95.4 % confidence) is shown in grey.*

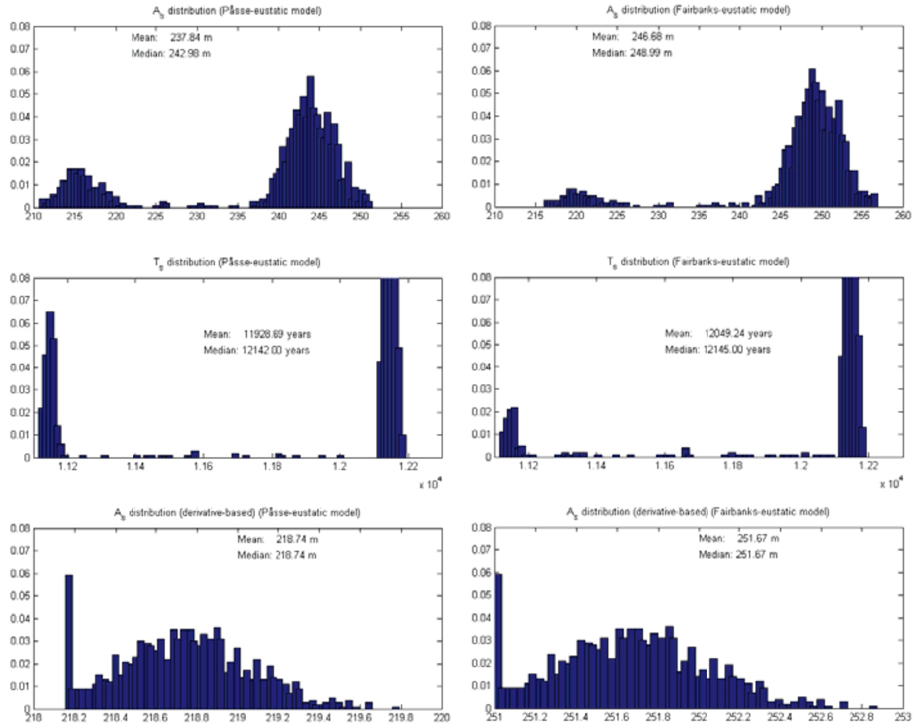

Figure 7. *The simulation results for Lake Vähäjärvi in Eura.*

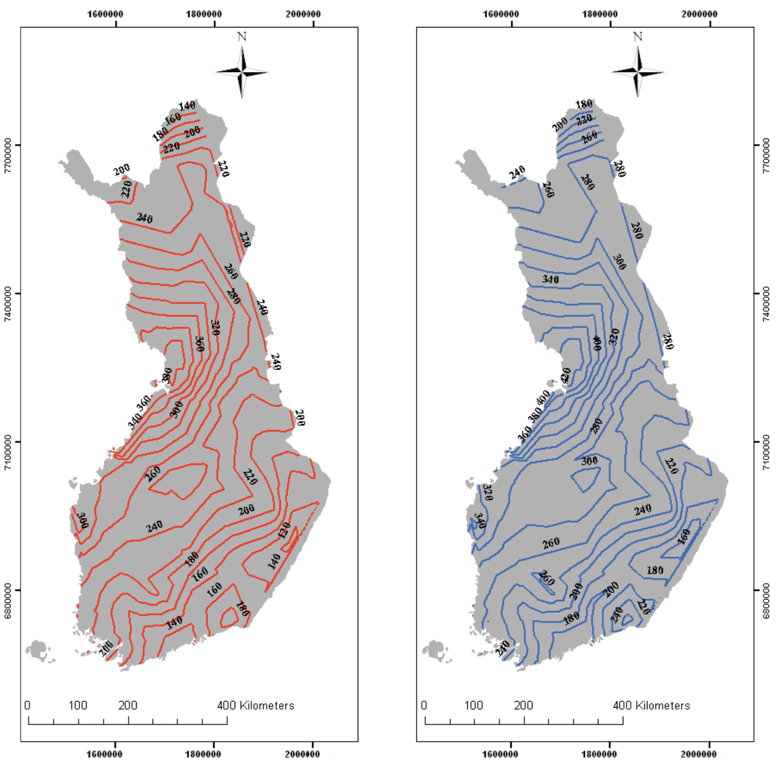

Figure 8. *Iterated A_s values calculated with the derivative-based process described in Vuorela et al. (2009). The left-hand side is calculated using Påsse's eustatic model and the right-hand side using Fairbanks eustatic model.*

In the iteration process the point data from the prehistoric population data set was used as an upper limit for the shoreline displacement. Then the local A_s and T_s parameter values were iterated using the shoreline displacement information gathered from the lake basins. A_s values were also calculated using the derivative-based process described in Vuorela et al. (2009).

4 Results and discussion

The results of Monte Carlo simulation for Lake Vähäjärvi in Eura are shown in figure 7. According to figure 4 (Påsse 2001) the A_s value for Lake Vähäjärvi is 249 and the T_s value is 11 621. When comparing the simulation results in figure 7 with the A_s and T_s values from figure 4, it can be noted that the iterated A_s values (mean and median values of the distribution) are quite close to values according to Påsse (2001). The derivative-based method presented in Vuorela et al. (2009) gives results that differ more from the values from figure 4. It can be also noted that the Fairbanks eustatic model gives a little bit higher results for A_s parameter compared with the results calculated with Påsse's eustatic model. The T_s distributions are about 1000 years wide but the mean and median of the distributions are in the same range as the T_s value from the map in figure 4.

In figure 8 are presented the A_s value contours drawn based on the results from the iteration process. The values have been calculated using the derivative-based method. From the figure can be seen that A_s values calculated using Fairbanks' eustatic model tend to be a bit larger than the ones calculated using Påsse's eustatic model and also the shapes of the contours differ from each other.

Overall the results show that there might have been local variations also in timing of the ice recession, download stress of the ice sheet and bedrock response properties etc. and these will be studied further in the present project.

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COMPARISON BETWEEN A NEW AND AN OLD SEMI-EMPIRICAL FENNOSCANDIAN SHORE-LEVEL MODEL

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Abstract

Shore-level displacement and glacio-isostatic uplift in the area affected by the Fennoscandian ice sheet is calculated from empirical data. Besides 80 shore-level curves from Fennoscandia, the calculations are also based on some detailed lake-tilting investigations as well as information concerning present relative uplift recorded by precision levelling and tide-gauge data. Our shore-level modelling allows the course of glacio-isostatic uplift to be expressed in solely mathematical terms. Maps showing the distribution between ice, land, lakes and sea at different times are produced by the GIS model. These maps can be designed to show changes of the hydrography through time including changes in lakes, glacial lakes, rivers and drainage basins.

1 Background

There are principally two different methods for modelling shore-level displacement. The most widely used method is to model the shore-level displacement by combining information concerning the geophysical structure of the Earth with information concerning the evolution of surface loading from dated shorelines and ice-sheet reconstructions. The temporal and spatial evolution of ice sheets must be accurately known to receive a detailed model of the glacial-isostatic adjustment within a geophysical modelling. This information is not satisfactorily known today, which means that geophysical methods are not yet able to produce high-accuracy shore-level models within Scandinavia. An alternative method is to exclusively analyse empirical shore-level data, with spatial statistics and mathematical calculations.

A semi-empirical shore-level method has successively been developed by Påsse (1996a, 1997, 2001) and Påsse & Andersson (2005). A further development of the model has recently been concluded by Påsse & Daniels (manuscript). The semi-empirical models have been developed using empirical data from three sources: Lake-tilting data, shore-level curves, and information about present relative uplift (mm/y) recorded by precision levelling in combination with tide gauge data.

Shore-level data is an effect of two movements, land uplift and rise of sea level. If the models were developed solely from existing shore-level data they could have been designated as plain empirical. However, as these two movements are differentiated in the models, means that the models should be designated as semi-empirical. However, the method is very close to be empirical as the course of land uplift partly is known by lake-tilting data (Påsse 1990, 1996b, 1998).

2 Land uplift within the latest model

The Earth behaves as an elastic material for stresses of short time scale and as a fluid for stresses of long duration. The semi-empirically modelling follows the concept, originally used by Cathles (1975) and Peltier & Andrews (1976), that a Maxwell viscoelastic material could be used as a plausible rheological model for explaining the glacio-isostatic movements. The behaviour of this material is analogous to an elastic spring together with a viscous dashpot.

In the latest model land uplift following unloading of ice (*U* in m) is calculated with the general function:

$$U = \frac{2}{\pi} \cdot A_v \cdot \left[\arctan\left(\frac{T}{B_v}\right) - \arctan\left(\frac{T-t}{B_v}\right)\right] + \frac{2}{\pi} \cdot A_e \cdot \left[\arctan\left(\frac{T}{B_e}\right) - \arctan\left(\frac{T-t}{B_e}\right)\right] \quad \text{(Eq. 1)}$$

where A_v is a down load factor (m) for the viscous uplift, *T* (years) is the time for the maximal uplift rate, i.e. the symmetry point of the *arctan* function, *t* (year) is the variable time and B_v (y^{-1}) is the relaxation factor for the viscous uplift. In the calculations *T* and *t* are counted in calendar years. The variables A_e, and B_e correspond in a similar way to the elastic uplift. In this formula there are 5 unknown variables.

As a result of the modelling, it is possible to reduce the variables in the general function to only two unknown variables, A_e (m) and *T* (years). The down load factor (m) for the viscous uplift A_v (m) is derived from the down load factor (m) for the elastic uplift by the linear relation:

$$A_v = A_e \cdot 1.9 - 4.6 \quad \text{(Eq. 2)}$$

The relaxation factor for the viscous uplift B_v (y^{-1}) is related to A_v (m). B_v (y^{-1}) is thus calculated from:

$$B_v = A_v \cdot 7.67 + 6233 \quad \text{(Eq. 3)}$$

The relaxation factor for the elastic uplift B_e is given a constant value of 600 (y^{-1}).

The history of the land uplift is somewhat more complex then outlined above as the uplift was somewhat slower during the interval 13 500 – 11 500 BP. This irregularity has given a condition where the uplift is most easily modelled by two uplift formulae, which means that uplift can be calculated by four unknown variables i.e. two down load factors for the elastic uplift and two times for the maximal uplift rate. In the latest model this variables are named A_1 and A_2 respectively T_1 and T_2.

3 Deglaciation and the highest coast line

The shore-level model does not include deglaciation chronology but a GIS layer, comprising a record of the deglaciation, has been used for drawing the paleogeographical maps produced by the model. The shore-level model actually provides a new method to map the recession of the Scandinavian ice sheet by using data from the highest coastline.

The highest coastline has in most areas been formed continuously at the ice border during deglaciation. Because of isostatic uplift, sea-level regresses immediately as a local becomes ice free. Thus the highest shoreline is roughly synchronous with the time of deglaciation. A locality where evidence of the highest shoreline is recorded is a point with latitude, longitude and elevation. When these three parameters are known, the model makes it is possible to calculate the time when the highest coastline was formed at each specific site. A data base with levels of the highest coastline, including more than 1000 levels in Sweden, has been compiled at the Geological Survey of Sweden. Each single level within this data base has been transformed to a date, which means that this method created more than 1000 new dates of the ice recession.

4 Land uplift within the previous model

The expression for the land uplift, which was used in the previous model (Påsse & Andersson 2005), is quite similar to the expression reported above. In the previous model the ‘viscous’ component was named the slow component and the ‘elastic’ component was named the fast component. However, the ‘elastic’ land uplift within the new model is a faster and more short-lived process then the fast land uplift in the previous model.

In the previous model the slow and the fast components were assumed to be two different movements with different dates of the T -factors. The T –factor for the fast uplift was thus related to the deglaciation, while the T –factor for the slow uplift was given a constant date of 12 000 cal BP. In the new model the viscous and elastic components are regarded as one movement, with one and the same T –factor, which is related to the deglaciation. However, this problem is more complex as the new model uses two uplift events for calculating the irregular land uplift. There are also differences between the relaxation factors within the two models. In the previous model the regional differences for the relaxation factors were correlated to the thickness of the lithosphere. In the new model the relaxation factor for the viscous component is linearly related to the down load factor, while the relaxation factor for the elastic component is clearly different, with a constant value around 600 (y^{-1}). That means that the elastic component respectively the fast component is given quite different values within the two models.

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RECONSTRUCTION OF LANDSCAPES AROUND RELIC SITES

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1 Introduction

Archaeological landscape models done with computers are a form of archaeological perception and interpretation that present many practical and theoretical challenges. Models and current ideas about landscapes of the past are necessarily always ideational constructs. As well as being an issue related to archaeological theory, landscape rendering is also a relatively new combination of scholarly representation and communication, as are other forms of digital modes of mediating scholarly information (Bowker 2005, Borgman 2007).

Like scholarly databases, data archiving and other digital methods, landscape models are instruments of scholarship and archaeological storytelling. They open up new avenues for research and help to address earlier research questions in new ways. However, at the same time, such models also profoundly change the nature of many aspects of scholarship. A model can be viewed simultaneously both as a device of external communication to other researchers and the general public and as an active participant in the scholarly work (Uotila et al. 2006). A model explicates that which has been done and that which is known, but it is also an instrument that constructs new knowledge.

2 Landscape rendering

Since the beginning of the 1990s, the use of GIS – and later rendering software – has made it possible to create different re-enactments of historical landscapes. Significantly, such advancements also meet the needs of graphic designers and motion picture industry. During the pioneer years the emphasis was primarily on the recreation of important historical objects and monuments, particularly the more significant objects of antiquity (Renfrew 1997, Forte 2000). Little by little, other themes and objects – less well known but interesting from a research perspective – began to be explored (Lock 2003, Valenti & Nardini 2004, Gabucci 2005, Jerpåsen 2009). Digital reconstructions made it possible to combine measurement data and interpretations in seamless renderings.

The two-dimensional GIS-analysis of a landscape and its many tools has been in use for more than twenty years. GIS-analysis is an effective research method and a way of analyzing and "academic" visualizing archaeological landscape data. In addition to the traditional tools for diagrammatic visualizations, the present GIS-software packages also tend to have limited tools for quasi-realistic visualization. The emphasis of the GIS-based graphics is, however, on cartographic and diagrammatic presentation rather than qualitative visualization.

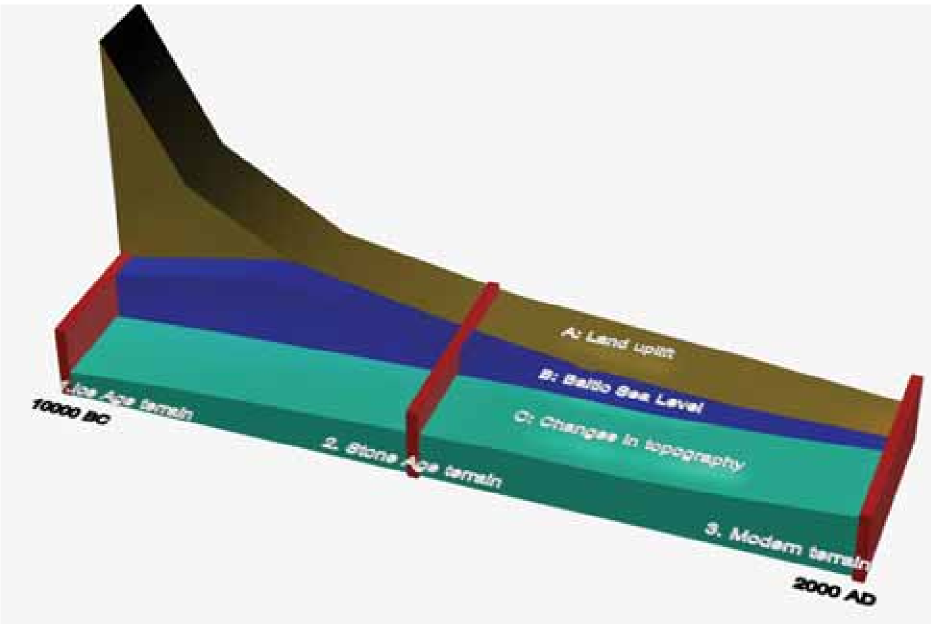

Figure 1. *Different elements in landscape modelling. From the early 1990's to the 2000's only A and B were used as a variation in time and C has represented a stabile modern grid. In 2010's C will probably gain a bigger role as new data processing techniques make deeper analyzes possible. The weight of sectors A, B and C is varying in time.*

The cartographic mode of presentation has many advantages in presenting and communicating both overviews and carefully chosen details and sub-sets of data. One could argue that the 'serious' mode of explicating the data might have also added to the perceived credibility of the material. The diagrammatic mode of presentation strikes a note of a precision and high quality; whereas an aesthetic visualization is more likely to give an impression of approximation and imprecision (Roussou & Drettakis 2004).

The visualization of large geographical areas through the use of three-dimensional rendering software has only been possible since the beginning of the twenty-first century. Before this time, the capacity of workstation-level computer hardware limited the size and detail of models to relatively small or simple objects. Same was the situation with programs. Larger renderings were less detailed (Renfrew 1997, Uotila & Sartes 2000, Uotila et al. 2002). During the early 2000s, functions for the creation and presentation of landscape models were added to the major rendering software packages. At the same time, the ability to combine the GIS-based geographic information with three-dimensional modelling was introduced. To a contemporary viewer, the results were high quality three-dimensional images, virtual models and animations, all of which will seem very crude and simplified in soon future. The aesthetic appeal of visualization has changed and will continue to evolve. Furthermore, the more fundamental qualities of what is perceived to be 'realistic' are equally transient. In the 1990s, a plane surface was a natural and scientifically sound solution to represent the ground level in a rendering of a building. The idea of rendering the surroundings and its form in the same detail as the reconstruction of a building is fairly new in virtual archaeology.

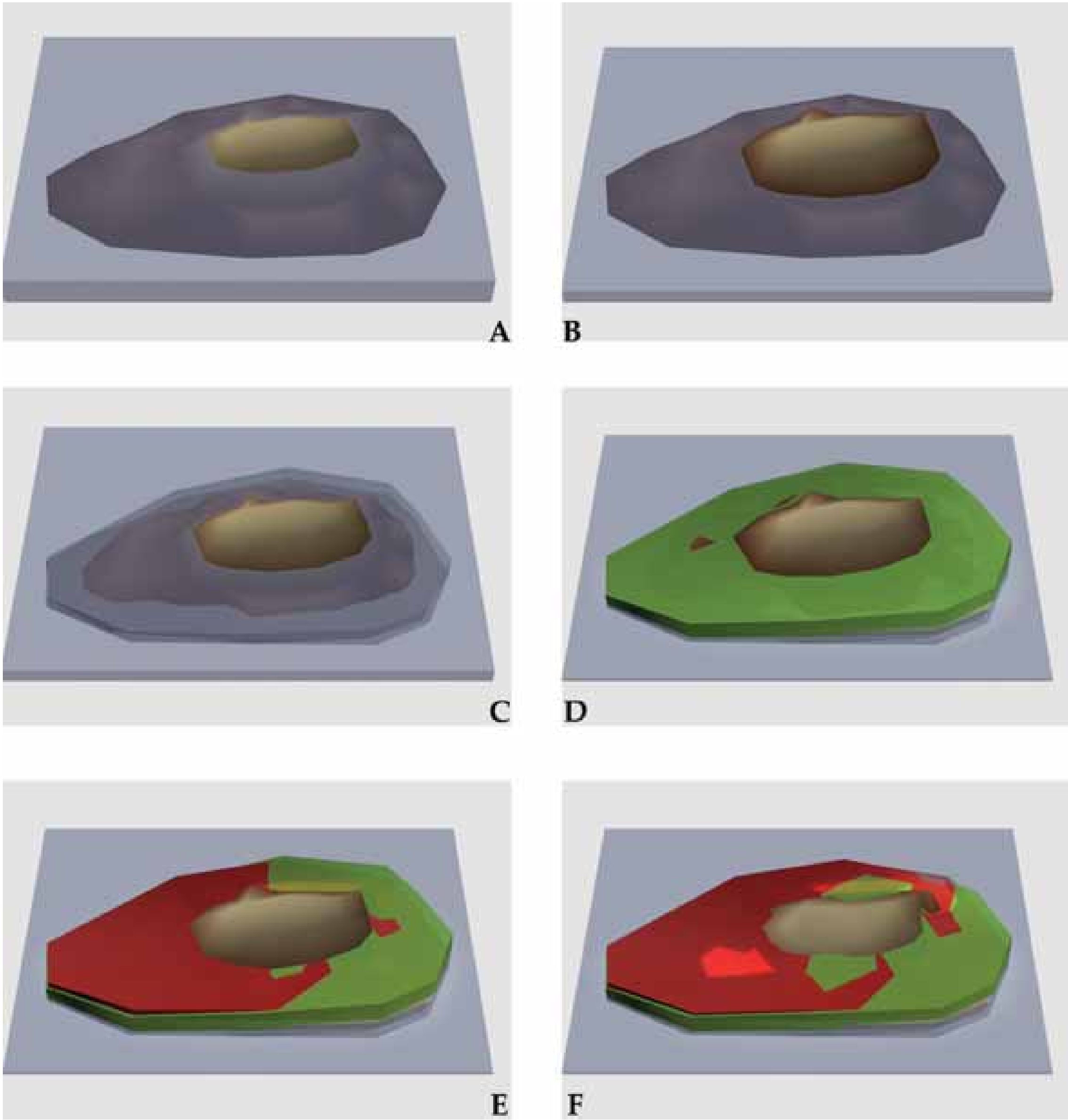

Figure 2. *Thematic model of landscape in time. Phases A and B represent a rocky and sandy island growing as the Baltic Sea level is changing and land uplift is very fast (10 000 - 6 000 BC). In phase C, meters of clay sediments settle and grow in thickness in layers around the bedrock area (6 000 BC - 1 000 AD). In phase D, the bedrock and adjoining clays are covered by mixed soils (2 000 BC - 2 000 AD). In phase E, cultural layers of varying consistence grow over the underlying layers of bedrock, clay and soils (1 200 - 2 000 AD). Finally, in phase F, a grid of the terrain in 2010 AD is presented with parts of the rock, clay, soil and cultural layers cut away in different historical processes during the last 100-200 years.*

The act of visualization inevitably simplifies data as part of the process (Pletinckx 2008). This is partly a question of a limited computing power and partly the deliberate effort to create an example, a representation of reality rather than the whole of reality.

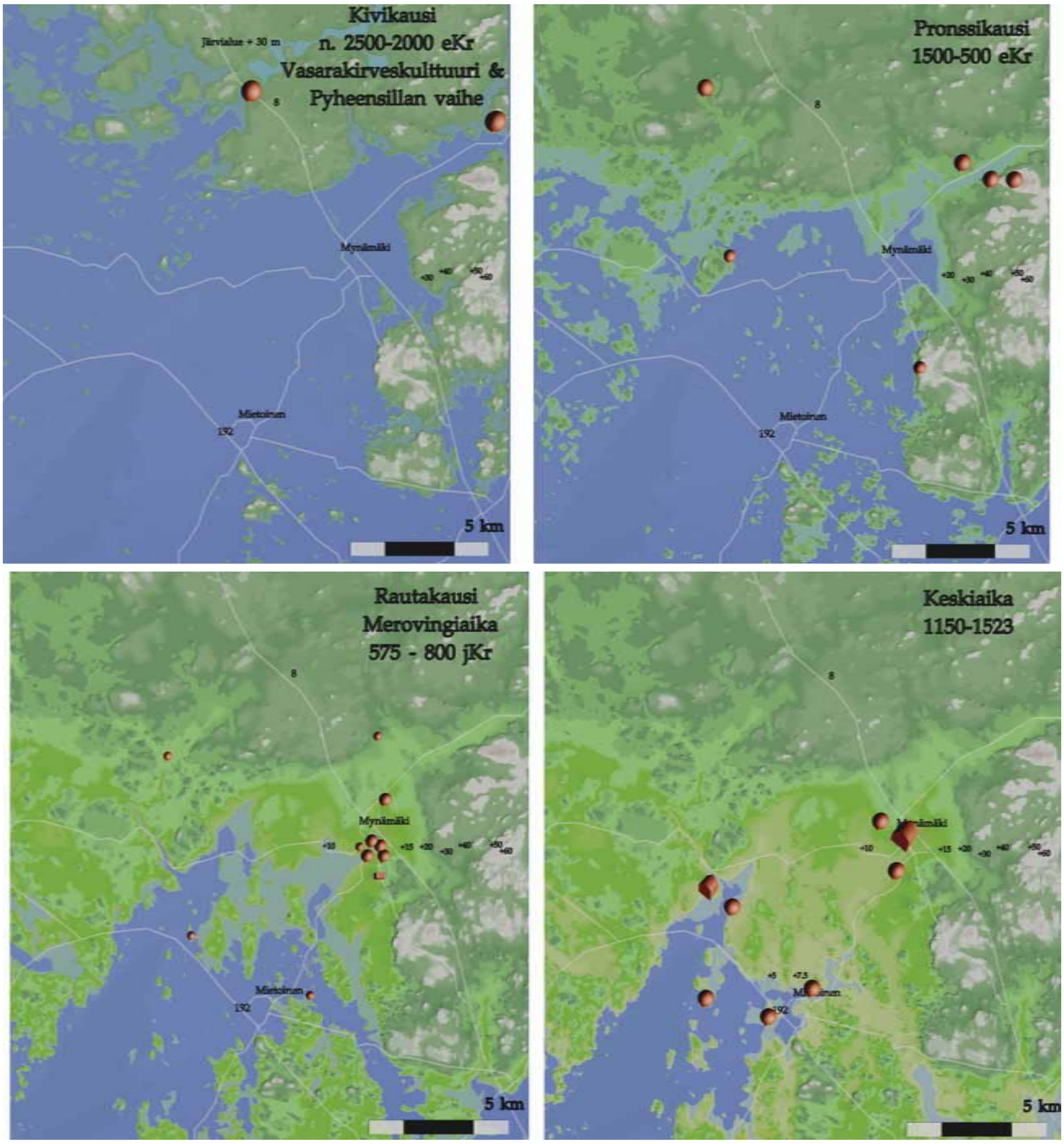

Figure 3. *The bay area of Mynämäki-Mietoinen and the known settlements of the Neolithic (2500-2000 BC), Bronze Age (1500-500 BC), Iron Age (Merovingian Era 600-800 AD) and the Middle Age (1150-1523 AD). The model is based on several different terrain models and geological material, and also contains an estimate of the effect of the shallow delta clay deposits on the present terrain. The elevations of the terrain are presented in colors in relation to present elevations. The series of models is available for viewing in the showcase of the Mynämäki Association presenting the history of the area. The models include a literary reference. (3D model Kari Uotila).*

The simplification is often more difficult to discern, but otherwise comparable to presenting a large forest by reducing it to a few hundred or thousand trees (see e.g. Sogliani et al. 2009). Landscapes used to be represented through painting an impression of a forest using, for instance, watercolours. A rendering is a kind of 'fact sheet' used by its compilers to explain various phenomena to its viewers. The challenge is that it often proves difficult, if not impossible, to interpret small, practically hidden, features like presenting leafy trees without a thorough written interpretation. An inherent problem of visual representations is that each individual will interpret them differently. Even though a text is also open to multiple interpretations, it is more strictly codified and thus leaves somewhat less room for such highly individualized readings.

Even though simplification and interpretation are rather apparent in landscape renderings, geographic information systems also simplify data and present qualitative readings of the past. The unit of analysis during the early 1990s, when earlier forms of software were in use, was typically rather large. The unit size might not be a problem when dealing with a proportionally large total area (Pukkila & Uotila 2005). However, if one was attempting to examine a hamlet or the fields and pastures belonging to a single house, or to evaluate the suitability of various parts of a terrain for agricultural usage, a much more exact grid would be needed in order to obtain even remotely accurate results. It is practically impossible to find a one or two hectare optimal field area for early agriculture using a large background grid. The problem of large grid size became apparent in the early twenty-first century, when rendered field models began to be much more detailed than the corresponding grid data.

3 Challenges with data

Historical (human and nature) accuracy of source material and accuracy of processing are the two central issues raised by source critical scrutiny of renderings of past landscapes. Specific problems vary according to location and depend on the quality and precision of datasets and multiple other factors. In the following discussion, the diversity and complexity of data-related issues is highlighted using Finland and its local conditions as an example.

In Finland, almost all landscape renderings are based on contour data provided by the National Land Survey of Finland (NLSF) and supported by the more accurate local materials provided by municipal or communal organizations. Even more detailed contour data can be obtained using measurements from archaeological excavations, for example. The difference between the 2.5–5 m contour data provided by the NLSF and *in situ* measurements from a total station, GPS equipment and laser scanning is enormous, but as far as rendering is concerned the focus is of course on the objective and on what equipment is in use. When one interprets the rendering, it is vital to know what material it has been based upon.

The method chosen has a profound effect on how accurately the contours of the terrain are presented. In Finland the challenges of countrywide terrain models become apparent when we consider the long coastline and archipelago regions. In some places the lowest mapped contour is +5m a.s.l. (above sea level) and in other places +2.5m a.s.l.; the ±0 m contour is missing and replaced by the shoreline, which in some cases can represent the boundary of an area covered by reeds or rushes. The area of the lowest 2–3m contours is significant in Finland, as many medieval layers and structures were situated quite near the medieval shoreline which was in 2-3 m contours.

In conjunction with this, we should note that in some cases during the 1990s and the early 2000s it was customary to emphasize the size or height of the rendered model with level surfaces or wooded areas to add drama. Moreover, revision of the contours makes it impossible for non-experts unacquainted with such techniques to interpret the resultant images. It is clear that the method has its advantages in research, but when results are presented to a wider public audience the manipulation of contours presents a great risk (see e.g. Koivisto 2004 and Uotila et al. 2002).

One factor that distorts or at least hampers interpretation of the results is the lack of data about lakes or at least depth of them in the rendering data. As result of postglacial land upheaval, Finnish lakes continue to incline towards the southeast at varying velocities. In simple terms, this means that the present shorelines of the lakes and their contours have little or nothing to do with the form of ancient lakes. In spite of this, the lakes are often depicted in models in their modern forms. In a successful rendering of a terrain, the lakebeds – preferably the original shapes rather than the present sediments – should be analysed in addition to the existing contours. This is especially important when presenting interpretations of the oldest terrain forms that were exposed from the sea immediately after the last glaciation. This has not been yet been implemented in any extensive terrain presentation in Finland, but as research and computing advance (and access to the relevant technology increases) it will become possible and necessary to incorporate such analysis within models (Tikkanen & Oksanen 2002, Virkki & Häkkinen 2007).

It has recently become apparent that the effect of soft soil sediments deposited after the last glaciation (~10 000 BP in Finland) should also be taken into consideration. In a natural landscape this involves the natural layers; in archaeological or historical landscapes this also includes the anthropogenic layers, both *in situ* and as secondary deposits. There is awareness of this problem and some attempts have been made to address the lack of soft soils in the contours, but there is still a great deal of work to be done in this area. It, like other issues, is related to questions about the size and scale of the studied terrain, the accuracy and deepness of the analysis and the objectives of the research.

The sedimentation of soft soils in estuaries and the subsequent land upheaval in shallow areas is one of the most important issues in the history of the Finnish coastline and is also arguably of significant importance in other areas of Finland. Shallow shore meadows and eutrophic[1] estuaries have in all likelihood been important areas for livestock-based economies for the last few thousand years. In Finland, land upheaval has caused these areas to shift over time. In many cases, the population is believed to have followed the upheaval and repeatedly moved their settlements back to the coastline. Those who stayed in the area have been forced to find new sources of livelihood.

This is not only a question of the formation, flourishing and disappearance of reedy areas; when the sea recedes, a new kind of microclimate develops. Recently, various

[1] A body of water with an aquatic ecosystem with high primary productivity or fertility due to an increased amount of nutrients. Eutrophic waters are subject to algal blooms and tend to have poor water quality.

forms of geographic research have been conducted on past, present and future microclimates in the Turku archipelago, but the methodology has not yet been transferred to an entirely different geographical environment (the 3000 BP Bronze Age coast and its evolution, for example) (Kalliola & Suominen 2007).

4 Conclusions

The applicability of virtual realities in an archaeological simulation and their potential usefulness in reviewing and evaluating scholarly propositions has been touched upon briefly in recent literature. Various researchers have proposed that a kind of 'grammar' should be developed in order to express the validity of the virtual reality arguments (see e.g. Ryan 1996, Frischer et al. 2002, Ryan 2001, Niccolucci & Cantone 2003, Vatanen 2003, Beex 2008). In spite of awareness and required technical skills, 'everyday archaeology' is still far from capable or prepared to exploit the potential of methods and techniques based on virtual reality.

In comparison to traditional forms of inquiry and reporting, visual representations of the cultural landscape offer a number of benefits. Through visualization, it is possible to get a visual glimpse of a representative landscape as it might have been. Visualization provides us with an opportunity to explore inconsistencies in the evidence, verify the coherence of sources that describe aspects of landscapes, bring historical and archaeological evidence together, and illustrate and test research findings. Naturally, visualization allows us to communicate research results in a considerably more tangible form than does a traditional textual description. The significance of the communication aspect has been particularly emphasized by younger generations accustomed to digital forms of visual aesthetics.

Earlier studies in landscape archaeology and history have demonstrated that a comprehensive analysis of the relationship between humans and landscape requires a mass of heterogeneous sources. Various scientific and scholarly observations and data sources provide evidence to support contrastingly different sides of a complex cultural and social sphere (see e.g. Tilley 1994, Schama 1995). Using a computer model to weld this material together, and thus create a landscape visualization that depicts an interpretation of the ancient maritime landscape, is hardly a shortcut to clearer understanding of the research subject. Such visualization could be considered another, complementary, tool of analysis, but hardly much more than that.

Although illustration has a long tradition in archaeology, dating back well into the eighteenth century (Adkins & Adkins 1989), a major issue regarding archaeological illustration (with and or without the use of computer modelling) persists: how can we understand and communicate the actual possibilities and extent to which we can visualize the past? Visualizations allow improbabilities and impossibilities to be tested, but they can also lead to the creation of believable images that are based on non-existent information.

Visualization may be a representation of one plausible interpretation, a valuable tool of research or a graphic illustration of research results. But, in essence, it is nothing more than a construct created by a researcher (and some case artist) and viewed through the scholarly-artist lens of interpretation of the past.

Landscape renderings represent a new form of scholarly communication. Borgman (2007) and Bowker (2005) have discussed how databases and digital information infrastructures have changed scholarly inquiry and the communication of scholarship. Landscape renderings represent a similarly challenging form of infrastructure. The data used to visualize the past contain implicit and explicit deficits. Renderings directly affect how scholarly considerations and results are mediated and re-mediated both within the community of researchers and outside to the general public.

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PAST, PRESENT AND FUTURE DISTRIBUTION OF QUATERNARY DEPOSITS AND LAND USE AT THE FORSMARK SITE

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Abstract

The Swedish Nuclear Fuel and Waste Management Company (SKB) has undertaken site characterisation at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective being to site a geological repository for spent nuclear fuel. The site investigations began in 2002 and were completed in 2007. The analysis and modelling of data from the site investigations provide a foundation for the development of an integrated, multidisciplinary Site Descriptive Model (SDM) for each of the two sites. In June 2009 SKB pointed out Forsmark (SKB 2008) to be the site for deep repository.

This presentation includes results from the investigation and modelling of Quaternary deposits and soils at the Forsmark site. The investigations of these deposits include numerous studies of the unconsolidated deposits overlying the bedrock. Theses soils and Quaternary deposits are here referred to as regolith. The spatial distribution and physical and chemical properties of the regolith are important input to modelling the transport of water, elements and various compounds between the geosphere and the biosphere. The knowledge of the genesis of the regolith is of importance for the conceptual understanding of the site and for modelling of future evolution of the area.

Results from drillings and geophysical investigations were used to model the depth and stratigraphy of the regolith. The observed present and modelled past and future distribution of regolith has been used to model the land use during an interglacial. Properties and distribution of past and present regolith are important factors when evaluating which areas that have the potential to be used as arable land in the future. The land use model is used as input to model the human exposure to radionuclides that may reach the surface system during different phases of an interglacial.

1 Quaternary development of Forsmark

The development of the Forsmark area from the latest deglaciation to the present is summarised in Figure 1. The Quaternary deposits in the Forsmark area have been deposited in the varying environments that have been at hand during and after the latest glaciation. At some sites in the Forsmark area a highly consolidated till has been observed. That till may predate the last phase of the Weichselian glaciation (Robertsson et al. 2005). However, most of the regolith in the area was formed shortly before or after the deglaciation. The whole of the Forsmark model area, was situated below the highest

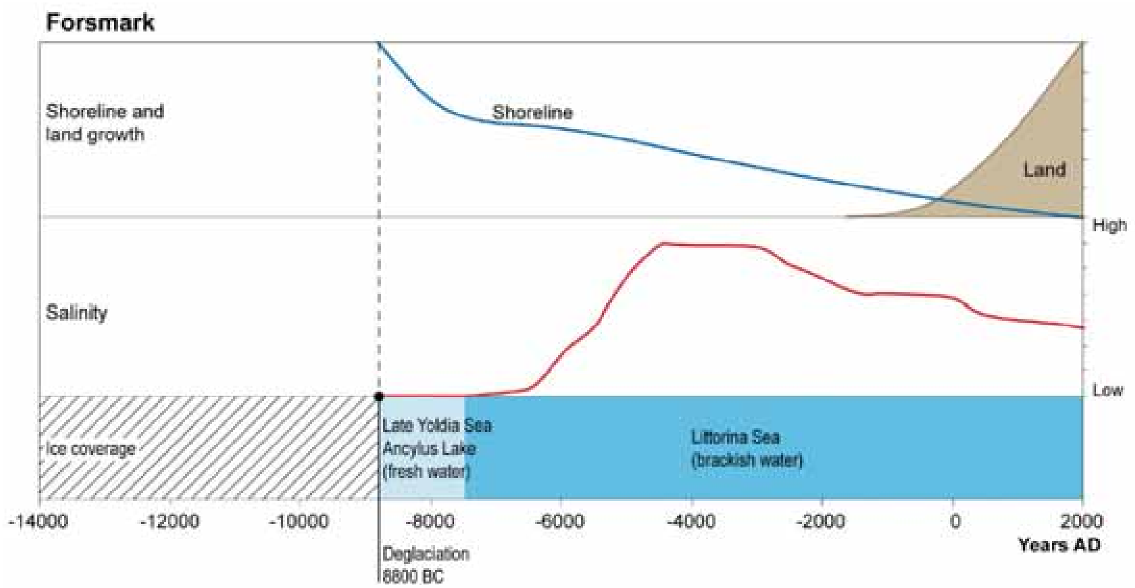

Figure 1. *The development of the Forsmark area from the latest deglaciation to the present. The red curve shows variations in salinity of the Baltic Sea. The brown curve represents the successively increase in land areas (from Söderbäck 2008).*

coastline after the deglaciation, which occurred ca. 8 800 years BC. According to extrapolations between investigations from central and northern Uppland and Åland, the rate of ice recession was ca. 300–350 m per year (Persson 1992).

Since the deglaciation, water depth has successively decreased as an effect of the isostatic land uplift. During the last two thousand years there has been a significant increase of land areas in the Forsmark region (Figure 1). The regolith in the Forsmark area has consequently only been subjected to soil forming processes for a relatively short period and most of the soils are therefore immature and lack distinct soil horizons (Lundin et al. 2004). Since the area is flat the growth of new land is relatively fast. Lakes and wetlands are continuously formed in the uplifted areas. The highest shoreline in the region was formed in connection with the deglaciation during the final freshwater phase of the Yoldia Sea stage of the Baltic. The closest shore/land area at that time was situated ca. 100 km to the west of Forsmark, where the highest shoreline has been identified at ca. 190 m.a.s.l. At the deglaciation, the Forsmark area was initially covered by approximately 150 m of glacio-lacustrine water. The Holocene shoreline displacement in northern Uppland has been studied with stratigraphical methods by (Robertsson & Persson 1989) and (Hedenström & Risberg 2003). The methods used are based on diatom stratigraphy of lake sediments for identification of the isolation event of the basin, together with radiocarbon dating and determination of the elevation of the isolation threshold of the basins. Since there are no elevated (and old) areas close to Forsmark, the stratigraphical investigations only cover the last 6,500 years. Påsse (2001) has described shoreline displacement in Fennoscandia during Holocene in a mathematical model. Påsse's model has been adjusted to the Forsmark site by using input data from sites north, south and east of Forsmark. The modelled curve is presented

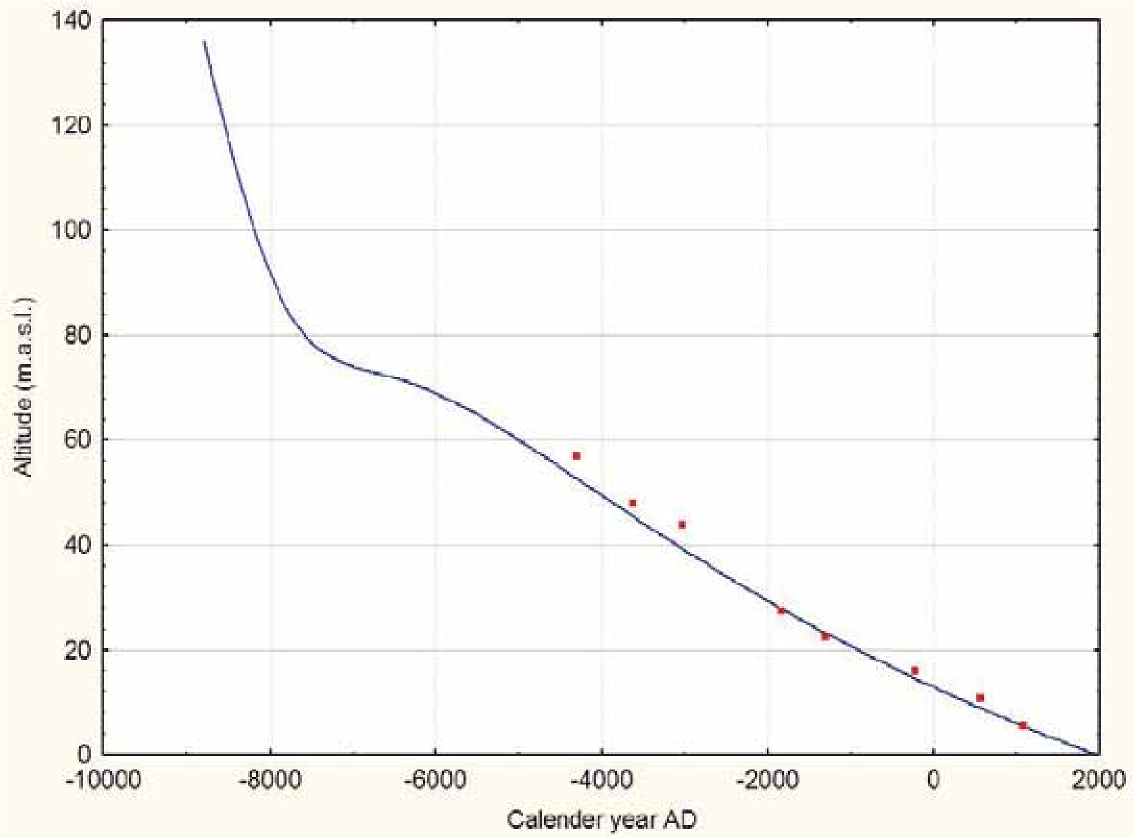

Figure 2. *Shoreline displacement curve for the Forsmark area after the latest deglaciation. The red symbols depict dating of the isolation events of lakes and mires (Hedenström & Risberg 2003). The blue solid curve was calculated using a mathematical model (Påsse 2001).*

in Figure 2, together with the results from dated isolation events of lakes and mires in the vicinity (Hedenström & Risberg 2003). As can be seen, the modelled curve and the ages based on stratigraphical investigations are in agreement. In Forsmark it was not until ca. 500 BC before the first islands started to form. The flat upper surface, in combination with the relatively rapid land uplift (presently 6 mm/year), resulted in a rapid growth of new land areas and major geographical changes over time. One effect of the continuous regressive shoreline displacement is that once the new land areas and lakes have been isolated from the Baltic, they have not been submerged for longer time periods again.

2 Present distribution of regolith

The terrestrial part of the Forsmark area is today dominated by till deposited during the latest glacial. At the floor of the sea, in Öregrundsgrepen, large areas are covered with clay. That general distribution of Quaternary deposits is typical for the County of Uppsala and the region around Lake Mälaren. In that region the topographically high areas are dominated by till and outcrops whereas the valleys are covered with clay. Figure 3 shows the distribution of Quaternary deposits in the central part of the Forsmark area.

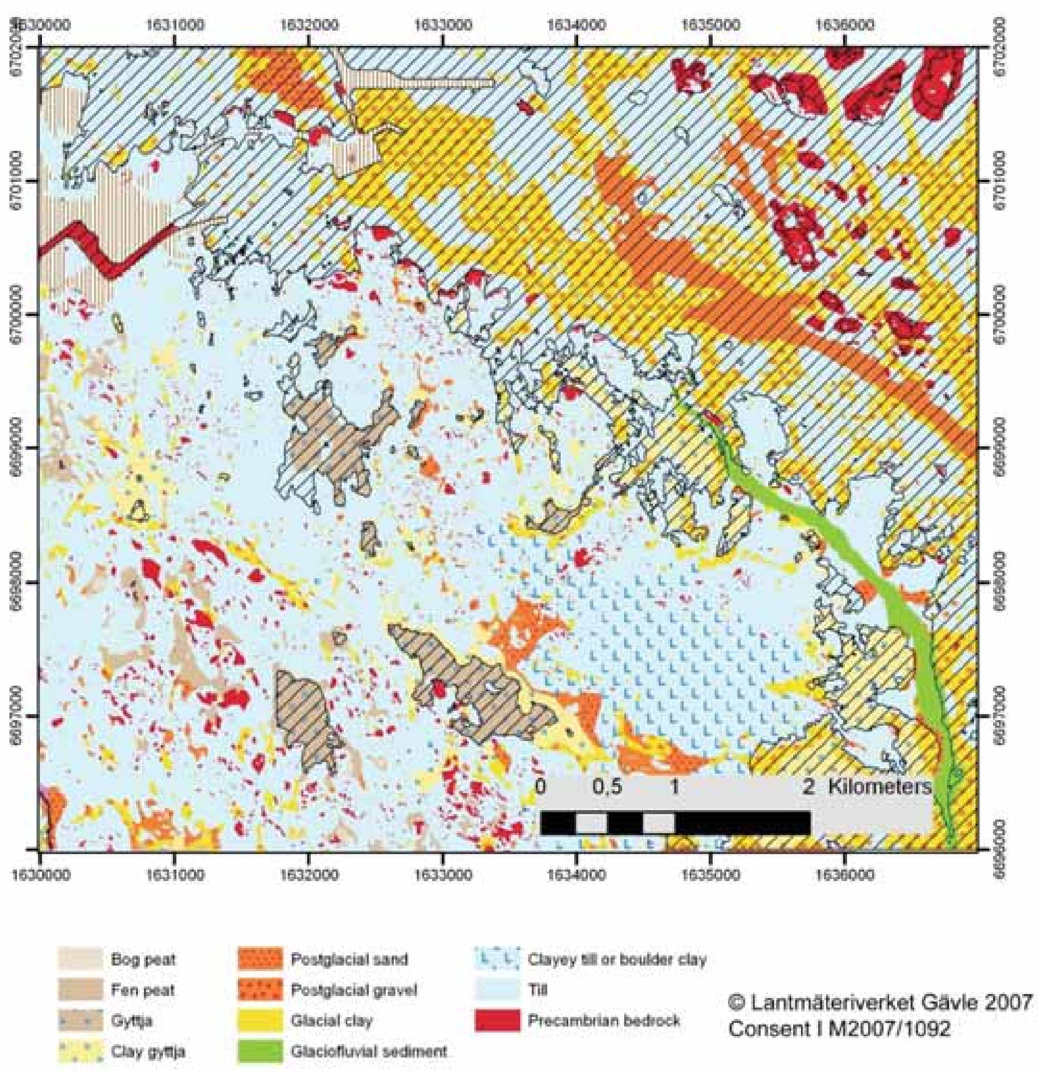

Figure 3. *The superficial distribution of Quaternary deposits in the central part of the area investigated by SKB. Areas covered by water are marked with a raster (modified from Hedenström & Sohlenius 2008).*

Figure 4. *Different types of till in the Forsmark area. A) Sandy till with a normal frequency of boulders, B) Clayey till with a low frequency of boulders, C) Till with a high frequency of large boulders.*

In Forsmark the dominating recorded ice flow directions were from north and northwest. The till in the area consists consequently of material that has been transported from these directions. In the terrestrial part of the Forsmark area three main types of till have been defined (Figure 4). In certain areas clayey till occurs, which is partly used for agriculture whereas the other two till types are dominated by forest. The till contains $CaCO_3$ which emanates from limestone, which has been transported from the floor of the Bothnian Bay and has consequently been transported several tens of kilometres. Most of the material in the till from the Forsmark area emanates, however, from the local bedrock (Bergman & Hedenström 2006).

Glacial clay covers a large proportion of the present sea floor (Figure 3). It can consequently be assumed that the area with glacial clay will increase in the future due to the ongoing land upheaval. As the till the glacial clay in the Forsmark area, contains a relatively high content of $CaCO_3$, which emanates from the floor of the Bothnian Sea, north of the model area.

After the deglaciation the water depth was around 150 meters deeper than at present, well below the wave base, so postglacial clay started to settle and covered large parts of the sea floor. These sediments were deposited after erosion and redeposition of older Quaternary deposits, such as glacial clay. The erosion of older deposits often occurs in areas which have been subjected to wave washing when the water depth has decreased as an effect of the land upheaval. The relative sea level decrease brought the shallowest part of the sea above the wave base and caused the postglacial sediments to resuspend. These particles were transported out of the area into the Bothnian Sea or re-settled on deeper bottoms within the study area. When the area became even shallower, the wave power decreased and postglacial clay started to accumulate in sheltered positions, such as bays. As is the case with the glacial clay, the area with these postglacial deposits will increase in the future terrestrial areas.

A large proportion of the terrestrial area has been above the sea level for less than thousand years. The landscape is consequently young and $CaCO_3$ which is easily subjected to weathering is still present in the uppermost soils (Lundin et al. 2005). The high concentration of $CaCO_3$ has resulted in high pH values in the near-surface groundwater and a rich flora. In the future the $CaCO_3$ will be leached out from the soils, pH will decrease and the flora will change. Since the Forsmark landscape is young the time to form a distinguished peat layer has been too short in many of the fens. Large parts of the present lakes and wetlands, however, will be covered by peat during the next coming thousand years.

3 The regolith depth model

During SKBs site investigation numerous drilling and geophysical investigations were carried out and provided information of the depth and stratigraphy of the regolith. These data were used to model the total depth and stratigraphy of regolith at the Forsmark site (Hedenström et al. 2008). The model is based on the general stratigraphy of the Quaternary deposits in the area. Seven layers where used and each layer can be given certain properties by the user of the model (Figure 5). The uppermost layer, Z1,

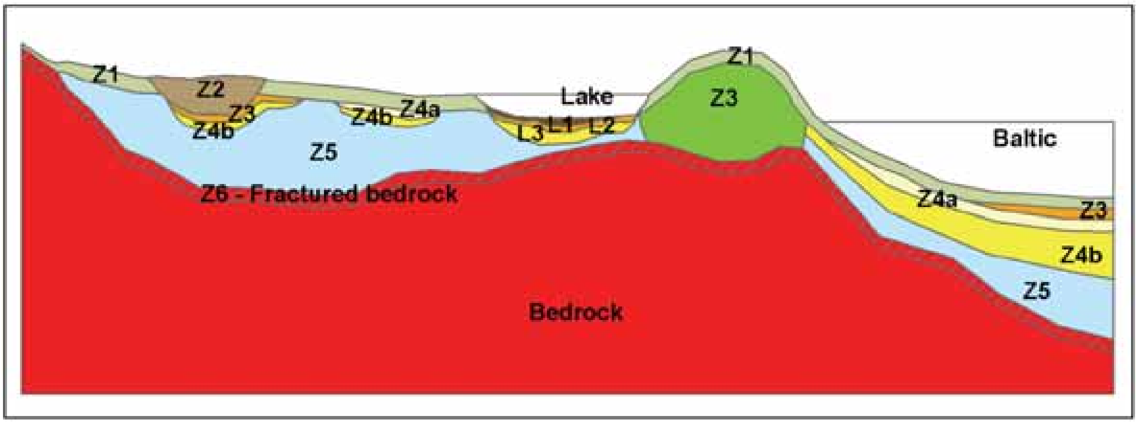

Figure 5. *The stratigraphical model used for modelling the depth and stratigraphy for regolith in the Forsmark area. The Z1-Z6 and L1-L3 layers are explained in the text (from: Hedenström et al. 2008).*

represents the layer that may have been influenced by the impact from surface processes, e.g. bioturbation, frost action and chemical weathering. Next layer, Z2 represents peat. After that follows Z3 that represents sand/gravel, glaciofluvial sediment or artificial fill, followed by Z4a which corresponds to postglacial clay and clay gyttja/gyttja clay. Z4b consists of glacial clay while Z5 symbolizes till. The bottom layer, Z6, represents the uppermost bedrock, which have a high frequency of fissures and fractures. The lower level of Z5 constitutes the bedrock surface. The water laid sediments in eight of the lakes have been modelled separately according to three classes of deposits; L1 corresponding to different type of gyttja, L2 corresponding to postglacial sand and gravel and L3 that represents glacial and postglacial clay.

The resulting depth model (Figure 6) clearly shows that the regolith depth reflects the large scale morphology of the bedrock surface. There is a general difference between the regolith depth in the terrestrial and marine area: the average depth in the terrestrial area is 4.0 m and 8.3 m in the marine part. Some of the major lineaments in Forsmark are characterised by deeper regolith. The maximum depth of regolith in the model is about 42 m. The average regolith depth within the model domain, including bedrock outcrops is 5.6 m.

4 Future models

The future distribution of Quaternary Deposits and land use has been modelled separately. This work is still in progress and will be presented in SKB reports published before the end of this year (Lindborg (ed) in prep., Brydsten & Strömgren in prep.). Preliminary results will, however, be presented during the oral presentation. The first model will show how present and future lakes are filled with sediment and peat during an interglacial equivalent to the present. That model will also show the successive increase in land areas due to the land upheaval. The results from were used to model the distribution of Quaternary deposits during different time steps. The land use model will show in what manner humans may use the landscape for e.g. agriculture and forestry. That model is to a large extent based on the modelled maps of Quaternary deposits from different time steps during an interglacial. The preliminary results clearly show that the area which potentially can be used for agriculture will increase in the future as more clay covered areas are uplifted.

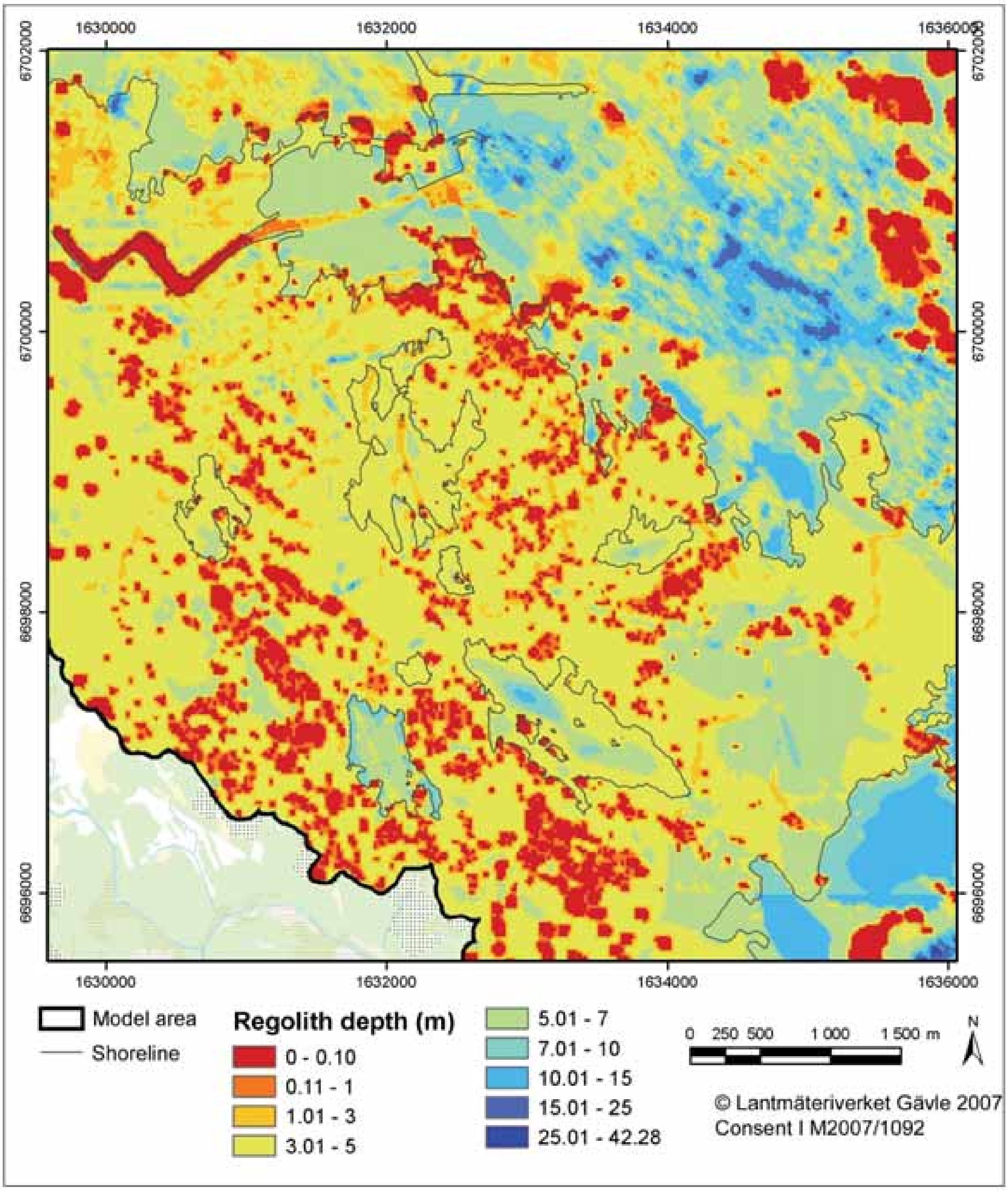

Figure 6. *The modelled regolith depths in the central part of the Forsmark area (from: Hedenström et al. 2008).*

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DEVELOPMENT OF THE OLKILUOTO SITE AND IMPLICATIONS TO DISPOSAL OF SPENT NUCLEAR FUEL

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Abstract

For the safety case of the deep repository for spent nuclear fuel in Olkiluoto, Finland, a biosphere assessment is needed that includes also a prediction of the effects of land uplift and sea level change within the several millennia in the future. For such predictions, a toolbox named UNTAMO has been developed to the ArcGIS environment. In this paper the main results from simulations carried out in 2009 are summarised together with remarks on their implications to the safety case of the spent nuclear fuel disposal; making predictions for the future millennia is plausible and provide a sound basis for site-specific modelling of the transport and fate of radionuclides possibly released from the repository.

1 Introduction

Posiva is implementing a deep repository for spent nuclear fuel in Olkiluoto, Finland. A site-specific safety case (Posiva 2008) is being produced, of which biosphere assessment (Hjerpe et al. 2010) is an integral part. As the Olkiluoto site is located on the coast of Gulf of Bothnia, Baltic Sea, the post-glacial crustal rebound shapes the landscape continuously – the future development of the area needs, and can, be predicted for the next several thousands of years in the context of the land uplift as possible anthropogenic sea level rise, societal factors etc. are treated with scenario methodology (adequate number of alternative plausible lines of evolution); the possible releases from the repository would transport from the deep bedrock to the biosphere at least hundreds or thousands of years.

For the 2009 interim assessment (Hjerpe et al. 2010), the development of the site resulting from the post-glacial crustal rebound and related change in ecosystem types was modelled in the TESM-2009 project utilising a set of GIS processing tools, the UNTAMO toolbox. The methodology is summarised and the main results are briefly presented in this paper. For more details, see (Ikonen et al. 2010).

2 Methods

For simulating the land uplift driven or other changes in the biosphere until and beyond the time when the potential releases would reach it, a GIS toolbox named UNTAMO has been developed. Briefly, the toolbox consists of following main parts:

- Topographical and geological initial conditions,
- Land uplift and delineation of the sea area,
- Surface water bodies, runoff formation and flow rates,
- Terrestrial vegetation,

- Aquatic vegetation,
- Terrestrial erosion and sedimentation,
- Aquatic erosion and sedimentation,
- Fauna habitats,
- Land use, and
- Simulation control and auxiliary tools.

The initial conditions consist of a topographical model of the present, for which a statistical model of Pohjola et al. (2009) has been used, and the overburden thickness model, compiled from various data sources.

The land uplift is modelled by utilising Påsse's (2001) model with recently updated input parameter values (Vuorela et al. 2009). In essence, the present and future land uplift is modelled using two s-curves for the isostatic rebound of the crust (*U*) and the eustatic sea level change (*E*), respectively:

$$U = \frac{2}{\pi} \cdot A_S \cdot \left[\arctan\left(\frac{T_S}{B_S}\right) - \arctan\left(\frac{T_S - 1950 + t_{AD}}{B_S}\right) \right] \qquad \text{(Eq. 1)}$$

$$E = \frac{2}{\pi} \cdot 56 \cdot \left[\arctan\left(\frac{9500}{1350}\right) - \arctan\left(\frac{9500 - 1950 + t_{AD}}{1350}\right) \right] \qquad \text{(Eq. 2)}$$

where A_s is the download factor (m) relating to the ice-sheet thickness, B_s is the inertia factor (1/y) relating to the bedrock properties, T_s the timing factor of the maximum of the uplift rate (y) relating to the ice recession time, and t_{AD} is the time in the common calendar years (A.D.).

The effective sea-level change (*S*) is then

$$S = U - E \qquad \text{(Eq. 3)}$$

The delineation of the sea identifies those areas below the sea level resulting from the land uplift or additional sea level changes, and removes such areas that do not have connection to the Baltic Sea, such as depressions and lake bottoms that may have an elevation value below the sea level, too.

Surface waterbodies are identified with conventional GIS analysis of flow accumulation: For each cell of the terrain model, the number of upstream cells is calculated (i.e. from how large area, in grid cell units, water is accumulated to a specific point by surface runoff). Those cells having a larger value are streams and rivers. Cells where all the other cells have a smaller value are bottoms of depressions, which are filled by water. The runoff generation is modelled by a simplified concept of using a constant value for the fraction of precipitation falling on the catchment area that appears as the water flow in the rivers (improvements based on a more detailed water balance analysis will be implemented for later versions). In addition, as two regionally large rivers, Eurajoki and Lapinjoki, discharge to the eastern end of the modelling area, their additional discharge rates are given as boundary conditions to the model.

In the present model version, the aquatic vegetation includes only reed bed prediction. The existence of reed colonies is determined by a depth threshold and degree of exposure to waves (fetch analysis) calibrated with site data. Basically, in shallow enough areas the extent of reed colonies is determined by the openness of the shore to wave action. Also threshold for flow rate can be applied for (almost) closed areas to take into account e.g. the exposure to river discharge to a narrow strait.

The peat growth is simulated with the model of Clymo (1984): peat growth is based on production-driven accumulation constrained by the hydrology (summer droughts) and the decay in deeper layers. The model produces an ellipsoidal bog if the base soil is totally horizontal and flat; in practical applications the actual peat thickness is that predicted by the model subtracted with the elevation difference between the point in question and the centre of the bog in the deepest point of the depression. Mathematically the model can be presented simply as

$$H = \sqrt{\left(\frac{p_c}{\alpha_c \rho_c}\left(1 - e^{-\alpha_c t}\right)\right)^2 - \left(U/k\right)x^2} = \sqrt{H_m^2 - \left(U/k\right)x^2} \qquad \text{(Eq. 4)}$$

where

H	thickness of the peat layer (m) at distance x from the bog axis point
p_c	rate of matter passing to catotelm ($kg_{dw}/m^2/y$)
α_c	peat decay rate in the catotelm (1/y)
ρ_c	bulk density of peat (kg_{dw}/m^3)
t	time from the initiation of the bog formation (y)
U	groundwater discharge from the bog ($m^3/m^2/y$)
k	hydraulic conductivity of the peat formation (m/y)
x	distance from the bog axis point (m)

The axis point, or foci, of the peat bogs are determined by searching for areas that have groundwater table close enough to the ground (10 cm) to sustain peat-producing vegetation. The groundwater table is modelled in the present version with a simple relationship between the long-term observed groundwater table and the elevation of the monitoring tube in Olkiluoto. In the future versions, more elaborate predictions are made based on simplified derivatives of a surface and near-surface hydrological model.

As human land-use, agricultural areas are delineated based on the soil type: in the region, practically all croplands are located on clay and gyttja soils that have adequate thickness for ploughing (0.5 m). This observation has been used in our model also to estimate plausibly largest extent of croplands assuming the present practise also in the future.

3 Results and discussion

3.1 Results of the terrain and ecosystems simulations

The main results of the terrain and ecosystems development modelling of Olkiluoto site, version 2009, are presented in Figures 2 and 3. Figure 1 provides a common legend for the maps in this paper.

The coastline retreats rather rapidly with the post-glacial crustal rebound: after about 1000 years the semi-enclosed sea around the site has been deformed into a long and narrow bay on the northern side and to a complex low-water-exchange bay in the south. 500 years later the latter has already been isolated into two lakes, of which the smaller one will become nearly totally overgrown by reed colonies as it is shallow enough. The larger part of the former bay, however, is deep and wide enough so that it keeps nearly free of reeds until the end of the simulation at year 12020; only the most sheltered small bays of the lake become overgrown.

On the northern side of the site, the Eurajoki and Lapinjoki rivers merge quite early in the development and create a river-lake system with significantly higher discharge than in the southern side (about 13 and 0.7 m^3/s, respectively). The lakes here are shallower, and in many places could be taken as an enlargement or backwater of the river. The shallowest parts are relatively quickly taken over by reed beds where the river flow does not prohibit the growth. Couple of the lake basins are deep enough, though, to remain open until the end of simulation.

Following from the in-growth by the reed, parts of the initial lake areas become mires and some of them dry further to a forested area. The arable land, or the cropland areas in our scenario, emerges on the clay and gyttja areas as the sea retreats, and little happens to them during the simulations as on the dry land there are no processes included in the present version of the model that would change the soil type or thickness. The most prominent change in the landscape after the lakes have been isolated is that the peat bogs become more abundant and grow both in extent and in thickness (oldest ones up to 4-5 m at the end of the simulation). This is consistent with the general understanding of the paludification on the inland areas of Finland, and resembles the pattern of mires in less disturbed areas old enough in respect of emerging from the sea.

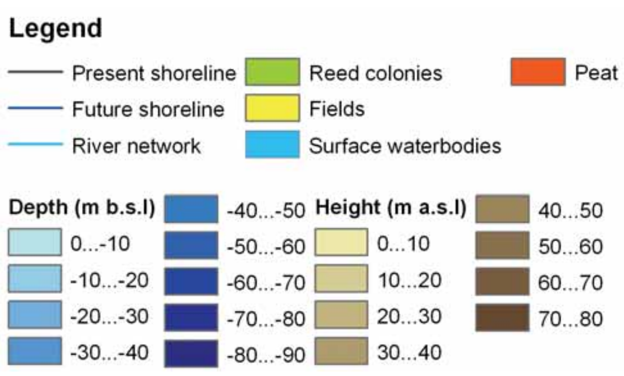

Figure 1. *General legend to maps in the other figures in this paper.*

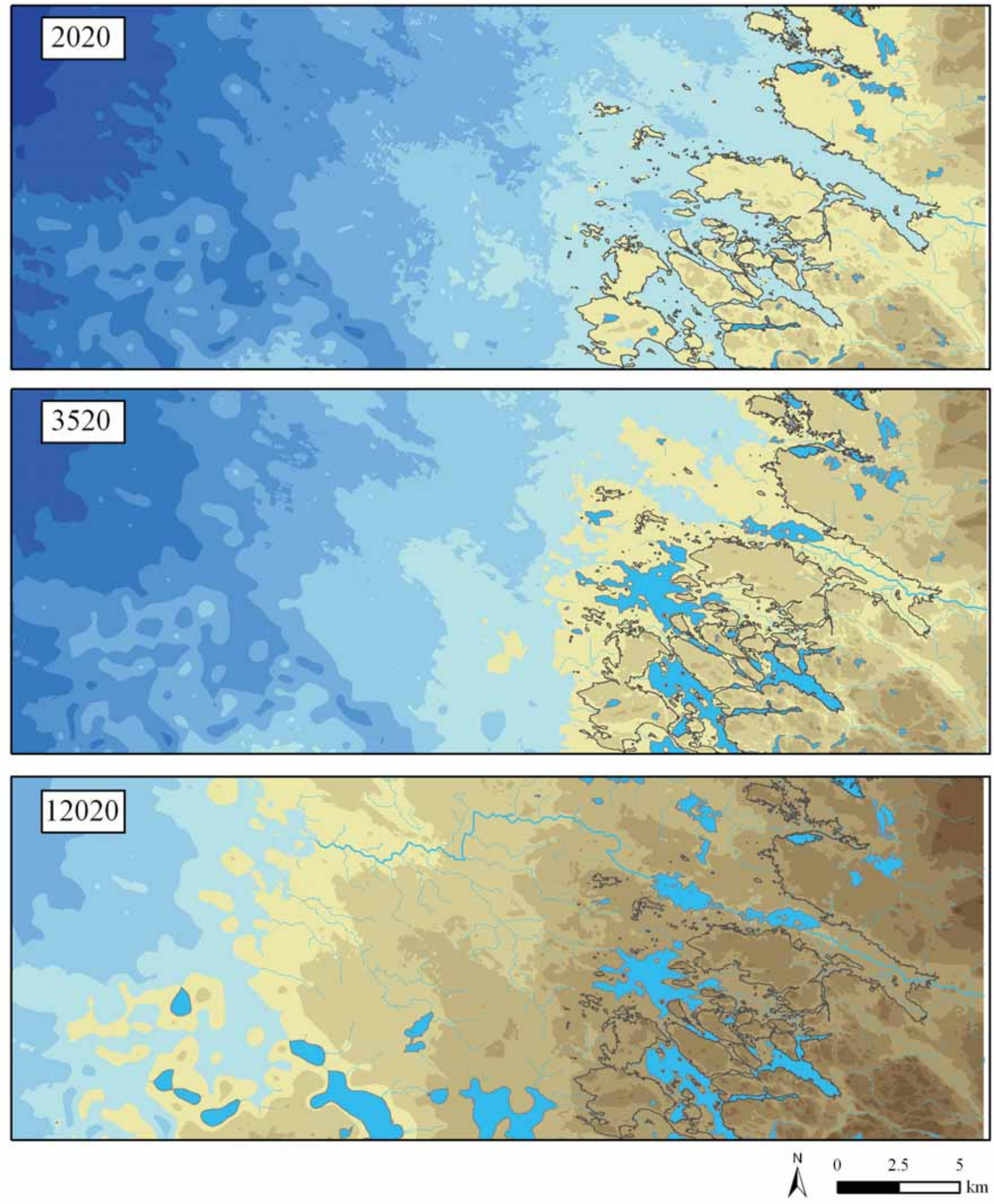

Figure 2. *Development of topography in the full model area from year 2020 to year 12 020. The elevation and water depths are shown with the colour classification of Figure 1, and in addition the predicted surface water bodies are presented in bright blue and the present coastline with grey line.*

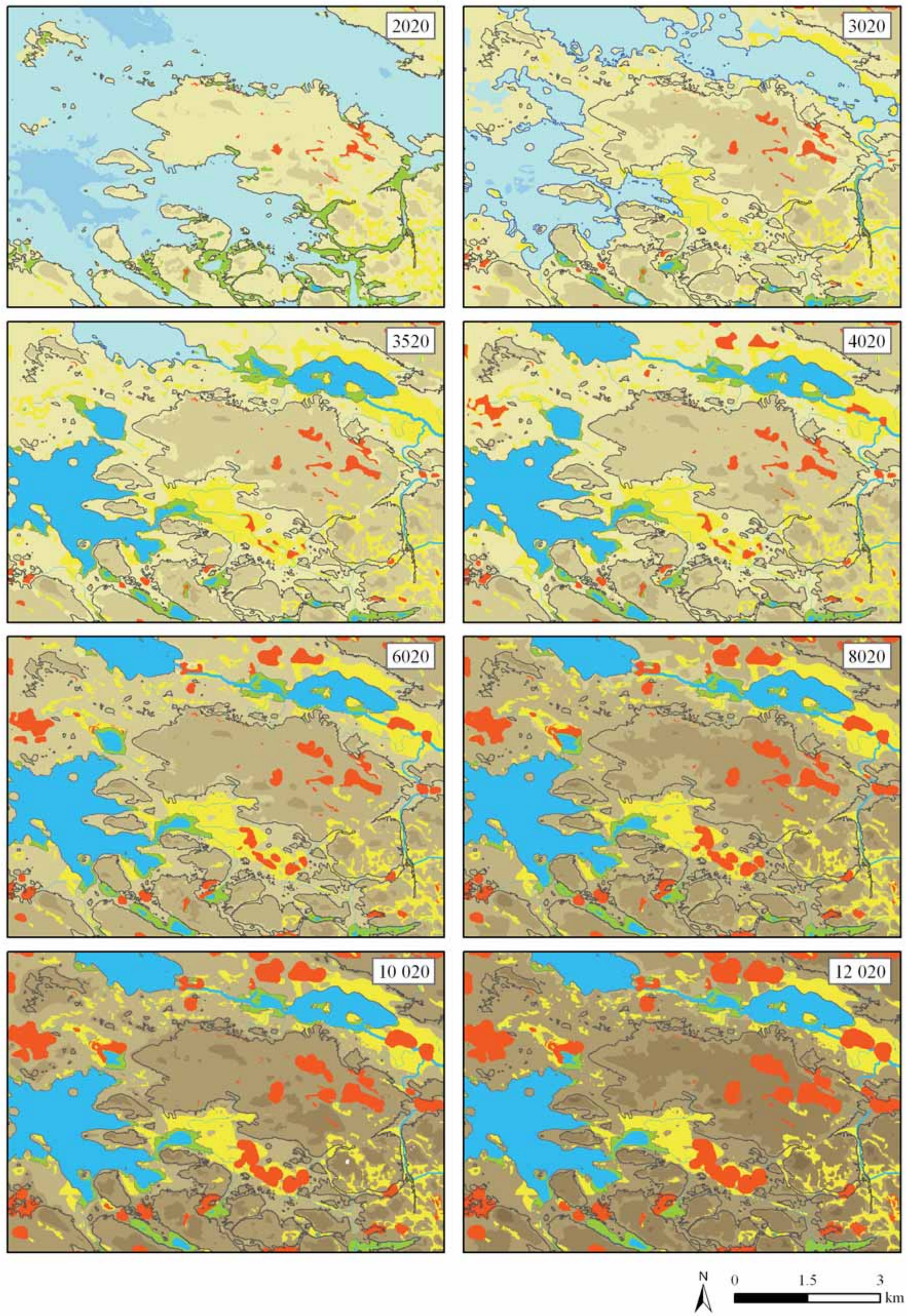

Figure 3. *Predicted topography, surface water bodies, peat bogs and croplands (arable land) in the vicinity of the present Olkiluoto Island from year 2020 to year 12 020. For the legend, see Figure 1.*

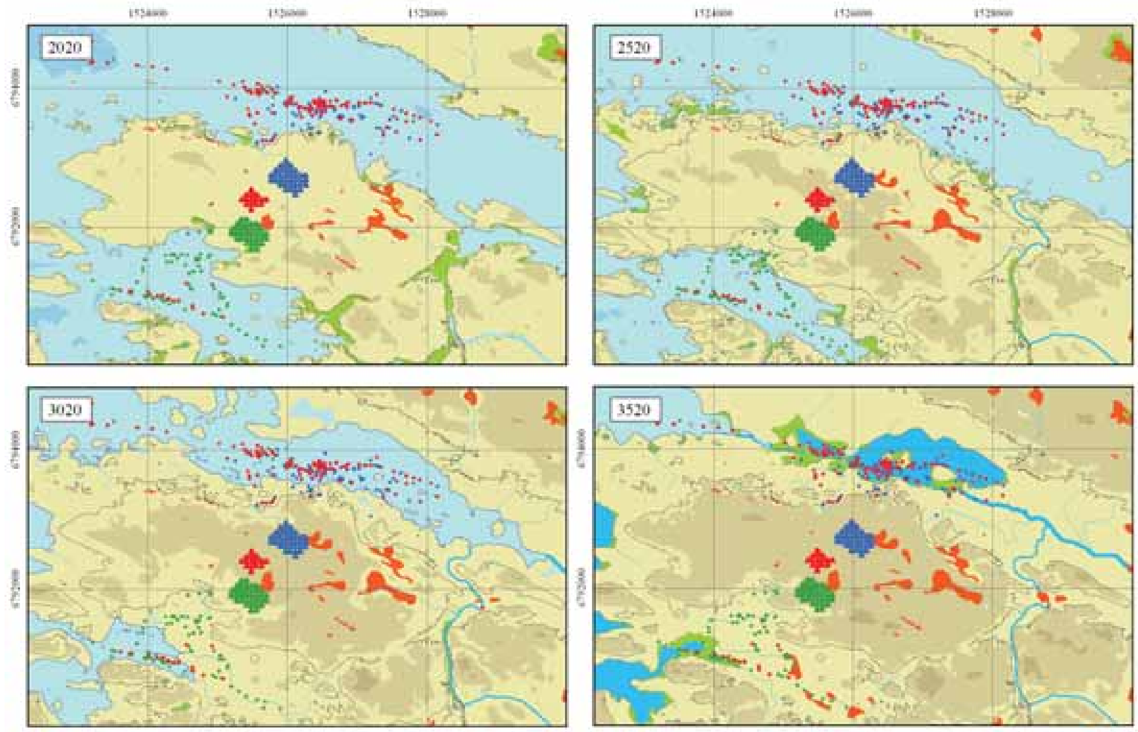

Figure 4. *Release paths from three repository panels (triangles in the middle) to the surface water bodies and rooting zone (dots with colours respective to the originating panel) at three different time points in the development of the surface environment.*

3.2 Implications to the disposal of spent nuclear fuel

Pathways of radionuclides released from the spent fuel disposal canisters deep in the bedrock have been simulated by Nykyri et al. (2008). As the pathways have been nearly identical between the simulations at 1 000 and 10 000 years in the future, only the latter has been used in the biosphere part for simplification. The pathways are continued from the upper bedrock to the surface water bodies or rooting zone with a SVAT (Soil-Vegetation-Atmosphere-Transfer) surface hydrology model (Karvonen 2009), from which the main results are presented in Figure 4.

Following from the rather thin soil and sediment layers, the ends of the release pathways in the surface water bodies and rooting zone ("release points") are close to those simulated for the upper bedrock. In the early development of the site, nearly all release points are located in the sea. With the retreat of the coastline, some release points remain in depressions of ground surface driven by the local-scale hydrological circulation, but majority is found in the sea (year 3020 in Figure 4). After the lakes have formed and developed shoreline vegetation (reed beds), still the majority of the release points is in the lakes, but some occur on the shoreline areas of lakes and along the main streams and rivers, in addition to the local depressions.

From the point of view of the modelling of radionuclide transport in the biosphere, these results simplify the structure of the compartmentalised transport model as the releases can be directed to specific stationary objects (e.g. lake or its reed colony) which transform from sea to a lake and further partly to a wetland type mimicking the reed bed.

4 Conclusions

It is possible to forecast the development of the Olkiluoto site during the future millennia with some degree of plausibility. However, due to the unpredictability of human actions, these can only be examples. Despite of this, the forecasts make a solid ground for assessing the transport and fate of possible radioactive releases in the biosphere and avoid specific justification of more arbitrary reference biosphere models.

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POSTER PRESENTATIONS

KUUSKAJASKARI - A DAUGHTER OF THE SEA: AN EXAMPLE OF GEOLOGICAL POSTERS

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1 Geological data on the Province of Satakunta in Finland

Geological studies, whose aim was to assist in spatial municipal planning, were carried out in three projects entitled GeoPori, GeoSatakunta and InnoGeo from 1999-2009. The study areas were focused in the coastal region between the cities of Pori and Rauma, and especially in the environs of the city of Pori. Topics covered within the projects included the past and future development of the Kokemäki river and its delta, the evolution of the bedrock and especially of brittle deformation, the thickness and composition of the soil, the present movements and equilibrium, the stage of the bedrock, and the formation of wetlands and settled areas associated with the uplift of the bedrock following the last Ice Age. New methods for municipal planning have also been developed within the projects. Gravity measurements and a study of the regional stress field have produced some new fundamental information on the thickness of the soil, the topography and the structure of the bedrock. For the measurement of current bedrock movements and accurate determination of the coordinates, an extensive GPS network was constructed, which has been connected with the network in the Olkiluoto

2 Kuuskajaskari Island

One of the important targets of the projects GeoSatakunta and InnoGeo has been to produce information on the geological features of the province of Satakunta (Korhonen 2010). In connection with this theme, the Jotuni Rock Garden was established, which includes typical rock samples from Satakunta with descriptions. The Rock Garden is a part of the Arkki Natural House situated in the city of Pori. On Kuuskajaskari, a young island near the city of Rauma (Fig. 1), a geological trail has been constructed, including maps with explanations.

Kuuskajaskari Island rose from the Bothnian Sea after the latest ice age. The land uplift began about 11,000 years ago due to the end of the ice age. Because the continental ice sheet was about two kilometres thick the ground had depressed by a few hundred meters. The ground began to rise during the melting of the ice sheet. The very first rock outcrops on Kuuskajaskari Island appeared from water about 2,000 years ago (Figure 2). The land uplift continues still at a rate of about 6 mm per year.

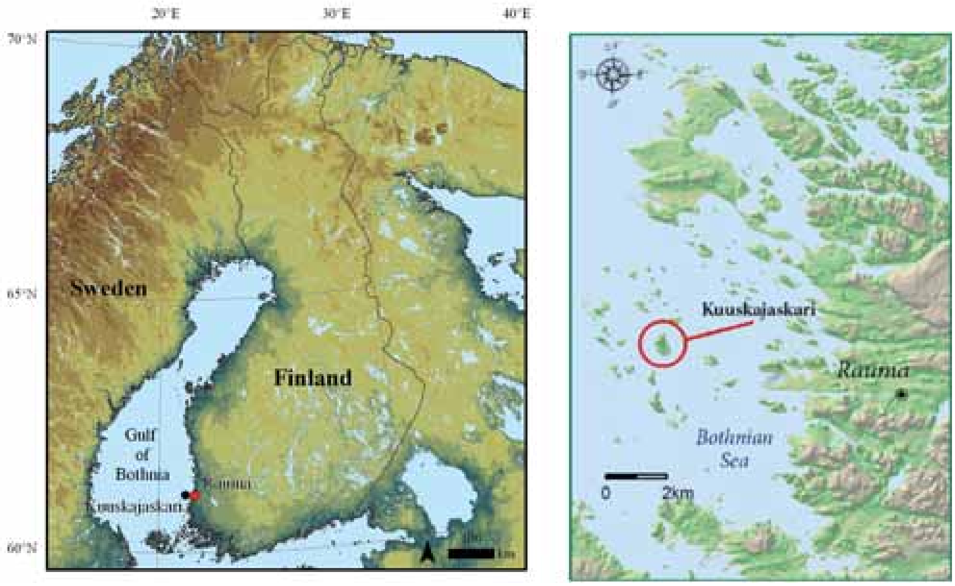

Figure 1. *The location of Kuuskajaskari Island. Data of the map on the right: Baltic GIS portal (gis.ekoi.lt).*

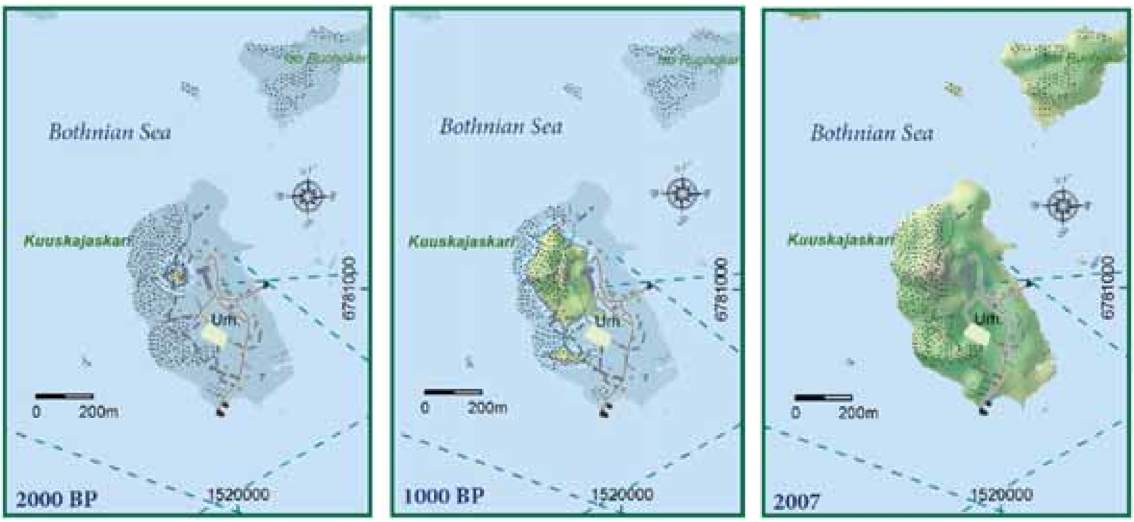

Figure 2. *Kuuskajaskari at 2000 BP (left), at 1000 BP (centre), and in year 2007 (right).*

The landscape of Kuuskajaskari Island is still changing. Due to the land uplift, new, dry land is emerging, islands are enlargening and new islands are rising from the sea. In the accompanying Figure 3, the effect of the land uplift on the surroundings of Kuuskajaskari Island has been forecast for the year 3000 and 4000. The land uplift has been calculated with 6 mm per year in the past 2000 years (Figure 2) as well as in future (Figure 3). Climate warming caused by greenhouse gas emissions and associated rises in sea levels has not been a factor in making forecasts below.

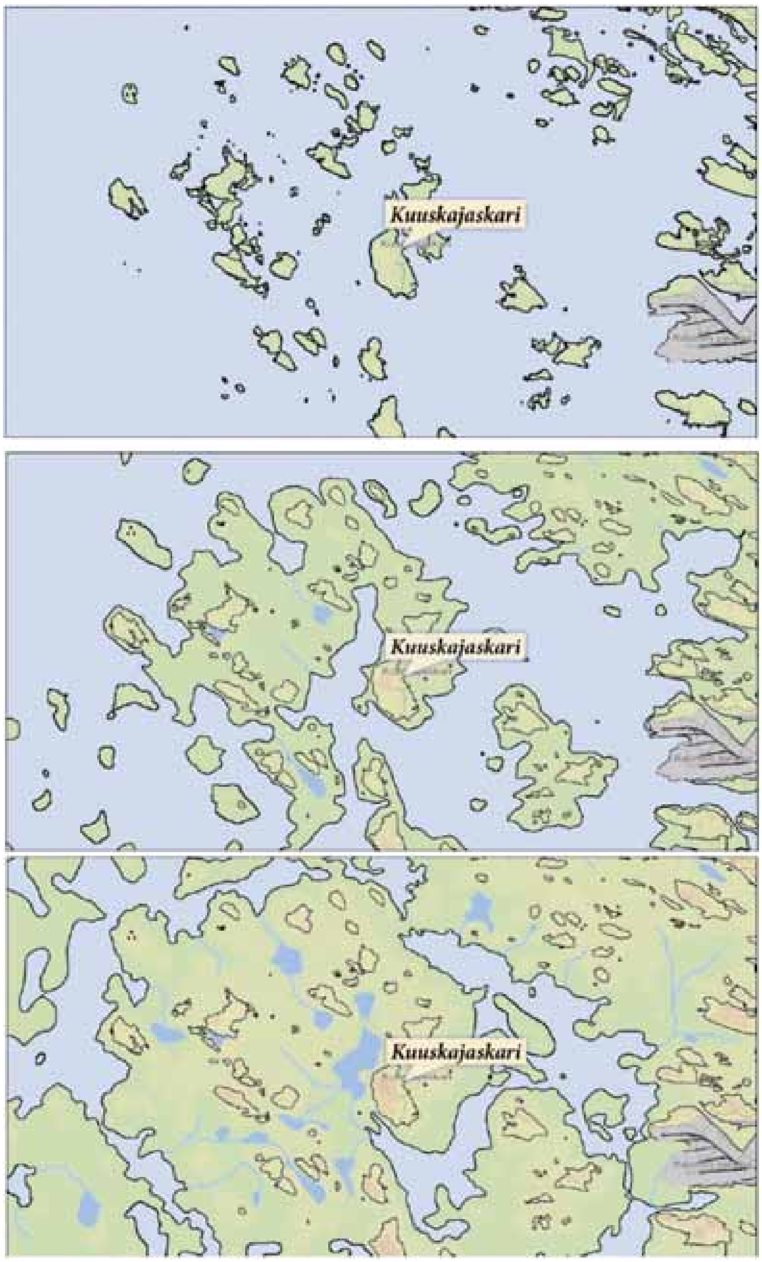

Figure 3. *Kuuskajaskari at year 2025 (top), 3000 (middle), and 4000 (bottom).*

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ESTIMATED COASTLINE IN SATAKUNTA, YEARS 1100-1700

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Abstract

For the biosphere assessment of a spent nuclear fuel repository at Olkiluoto, Finland, the effect of the post-glacial land uplift needs to be estimated for the future several millennia. During this time, lakes and mires will emerge at the site, and analogues of these future ecosystems are needed from a larger Reference Area as they do not exist at the present site. This area covers almost the entire Satakunta Province. To test the land uplift model applied in the Reference Area against historical and other information on the past coastline positions, the past elevations in Satakunta in years 1100-1700 were simulated. In the scale of the whole province, the results seem plausible, but in more detailed scale some uncertainties inherent to the data used and inconsistencies with other information can be observed as expected from the nature of the original land uplift model.

1 Introduction

As a part of the biosphere assessment for a spent nuclear fuel repository at Olkiluoto, the model on post-glacial land uplift presented by Påsse (2001) and provided with improved set of parameters by Vuorela et al. (2009), has been implemented in the ArcView GIS environment to cover the so-called Reference area of the biosphere modelling including most of the Satakunta province and northern parts of the Varsinais-Suomi province. Both to test the outcome of the model with the present parameters, and to provide computational estimates of past coastlines for use in other research projects, the coastlines corresponding the years 1100, 1300, 1500 and 1700 in the common calendar were simulated and are presented here. For further details, see the forthcoming (Ikonen, in prep.).

The shoreline displacement at shallow shores is not only dependent on the crustal rebound and sea level change: The amounts of common reed are increasing due to human-induced eutrophication, and this result in faster apparent shoreline displacement. The displacement is further accelerated by the deposition of materials transported by seawater, ice, rivers etc., but on the other hand also decelerated by shoreline and sea-bottom erosion. Thus it needs to be noted that the estimates presented here are not meant to be precise or accurate, but an indication of the likely overall landscape set-up at the time indicated – comparison with other evidence, such as historical maps, remains important to get the full picture of the past development.

2 Methods

2.1 Mathematical land uplift model

During the last glaciation, the weight of the ice sheet caused the Fennoscandian crust to deform and down-warp several hundred metres. During and soon after the deglaciation, when the ice sheet melted and the load decreased and finally ceased, the initial uplift was rapid. Regionally the uplift rate can be presented in relation to download and inertia factors that depend on local conditions such as the ice-sheet thickness (stress) and the thickness and other properties of the crust, respectively (Vuorela et al. 2009).

Consistent with this, the land uplift module includes an implementation of Påsse's semi-empirical model (Påsse 2001, and its variations) as interpreted by Vuorela et al. (2009), who also provide most updated parameter data for the Olkiluoto site. In essence, the recent past, present and future land uplift is modelled using two s-curves for the isostatic rebound of the crust (*U*) and the eustatic sea level adjustment (*E*), respectively:

$$U = \frac{2}{\pi} \cdot A_S \cdot \left[\arctan\left(\frac{T_S}{B_S} \right) - \arctan\left(\frac{T_S - 1950 + t_{AD}}{B_S} \right) \right] \qquad \text{(Eq. 1)}$$

$$E = \frac{2}{\pi} \cdot 56 \cdot \left[\arctan\left(\frac{9500}{1350} \right) - \arctan\left(\frac{9500 - 1950 + t_{AD}}{1350} \right) \right] \qquad \text{(Eq. 2)}$$

where A_s is the download factor (m) relating to the ice-sheet thickness, B_s is the inertia factor (1/y) relating to the bedrock properties, T_s the timing factor of the maximum of the uplift rate (y) relating to the ice recession time, and t_{AD} is the time in the common calendar years (A.D.).

The effective sea-level change (*S*) is then

$$S = U - E \qquad \text{(Eq. 3)}$$

Vuorela et al. (2009) have reconstructed the future isostatic land uplift model and re-evaluated and complemented the input data which are used also in our simulations as rasters of the slow-phase download factor (A_s) and the inertia factor (B_s), together with the timing parameter T_s, taken as a constant of 12 000 years to the whole model area (Vuorela et al. 2009).

2.2 Elevation model and soil types

The elevation model needed for predicting the past topography was interpolated with ArcView's Topo-to-raster tool from the elevation data in the topographical database of Finnish National Land Survey (in Feb 2009; permission no. 41/MYY/09, Karttakone 2824377) to the resolution of 10 metres.

Surface soil types, for illustration of most uncertain areas in the model, were taken from the digital soil map of Geological Survey of Finland (www.gsf.fi).

3 Results

The estimated coastlines for the Satakunta province in years 1100, 1500 and 1700 in the common calendar are presented in Figure 1 which also contains a generic legend to all the other maps in this paper, too. As examples of more detailed results, the coastal areas of Rauma-Eurajoki and Pori-Ulvila in year 1500 are presented in Figures 2 and 3, respectively (in the latter note the rotation of the layout: the north is 30° counter-clockwise from the top of the page). These more detailed maps include also the coastline of years 1100 and 1700.

4 Discussion

Overall, the results presented in this paper, in the seminar poster and available otherwise (see also Ikonen, in prep.) appear plausible estimates in the light of general knowledge on the development of the region – the better the larger scale is in question, as expected from the formulation of the super-regional-scale land uplift model applied.

However, there are some clear sources of uncertainties and also clear errors arising from the elevation model: Few data are available on the depth of the lakes and thus they have not been used at all. There are also some typos in some elevation data, but there has not been time available to correct or remove these. In some areas, the terrain is so flat that the elevation data is lacking and the interpolation produces a deeper valley like at the mouth of the Lapinjoki River in Figure 2 (the long bay straight west from the Eurajoki main village). This may also be the cause of the Liinmaa castle ruins being covered by the sea still in year 1500 even though they are dated to the change of the 14th and the 15th century. Since the interpolation of the elevation model was done also for other purposes, where hydrological correctness was appreciated, the stream network was used in the interpolation causing some unrealistic narrow bays at the mouth of the streams.

Also the geological environment causes uncertainties: In the maps present areas of gyttja and peat (including peat harvest areas) have been marked as these deposits may have been formed after the retreat of the sea. Known earthfills have been marked, too. In addition, especially in the present constructed areas there have been man-made changes in the terrain that are not known; the more detailed maps show the present infrastructure for reference.

In addition to earthworks, several lakes and mires have been drained in the region mainly to increase agricultural land. Drained lakes and mires known by occasional comparison to historical maps have been marked in the Figures and the other maps produced – no systematic mapping has been done, though.

5 Conclusions

Past coastlines of years 1100-1700 were estimated using the land uplift model of Påsse (2001) with updated input data from (Vuorela et al. 2009) together with an elevation model derived from the topographical database of the Finnish National Land Survey (permission, see above). The results are plausible, although in some places

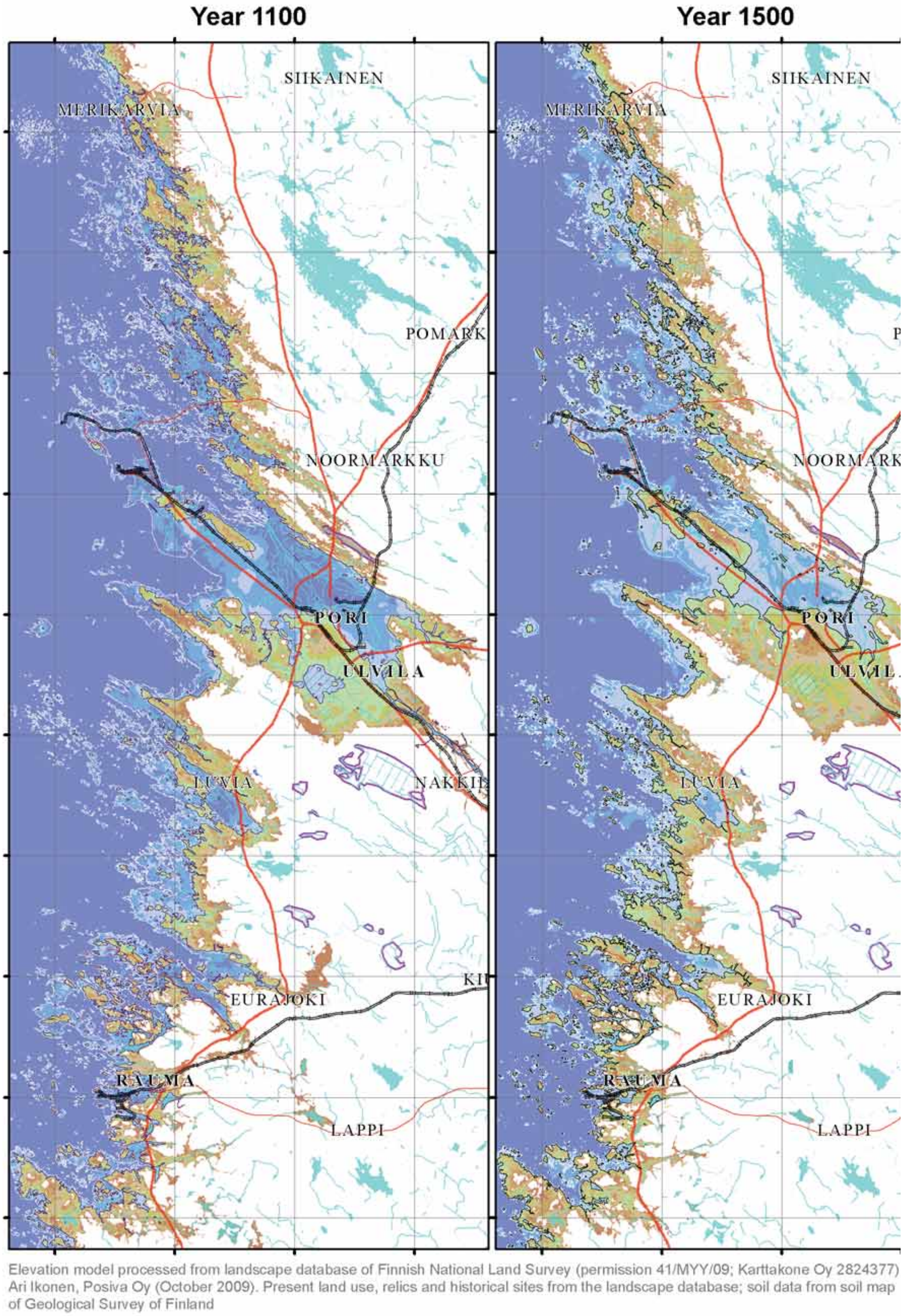
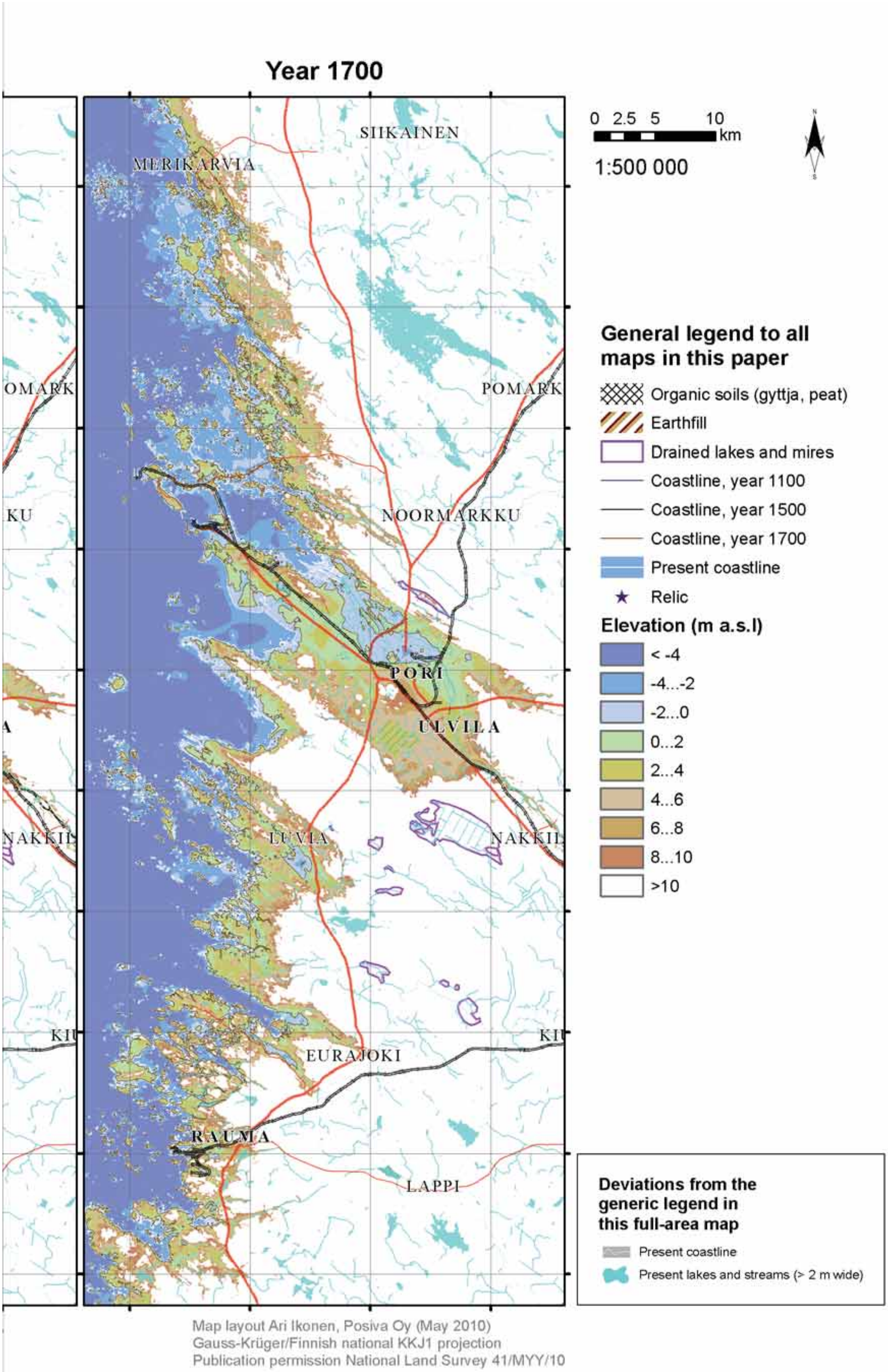


Figure 1. *Coastline of Satakunta in years 1100, 1500 and 1700 in the common calendar.*



The legend is common also to Figures 2 and 3.

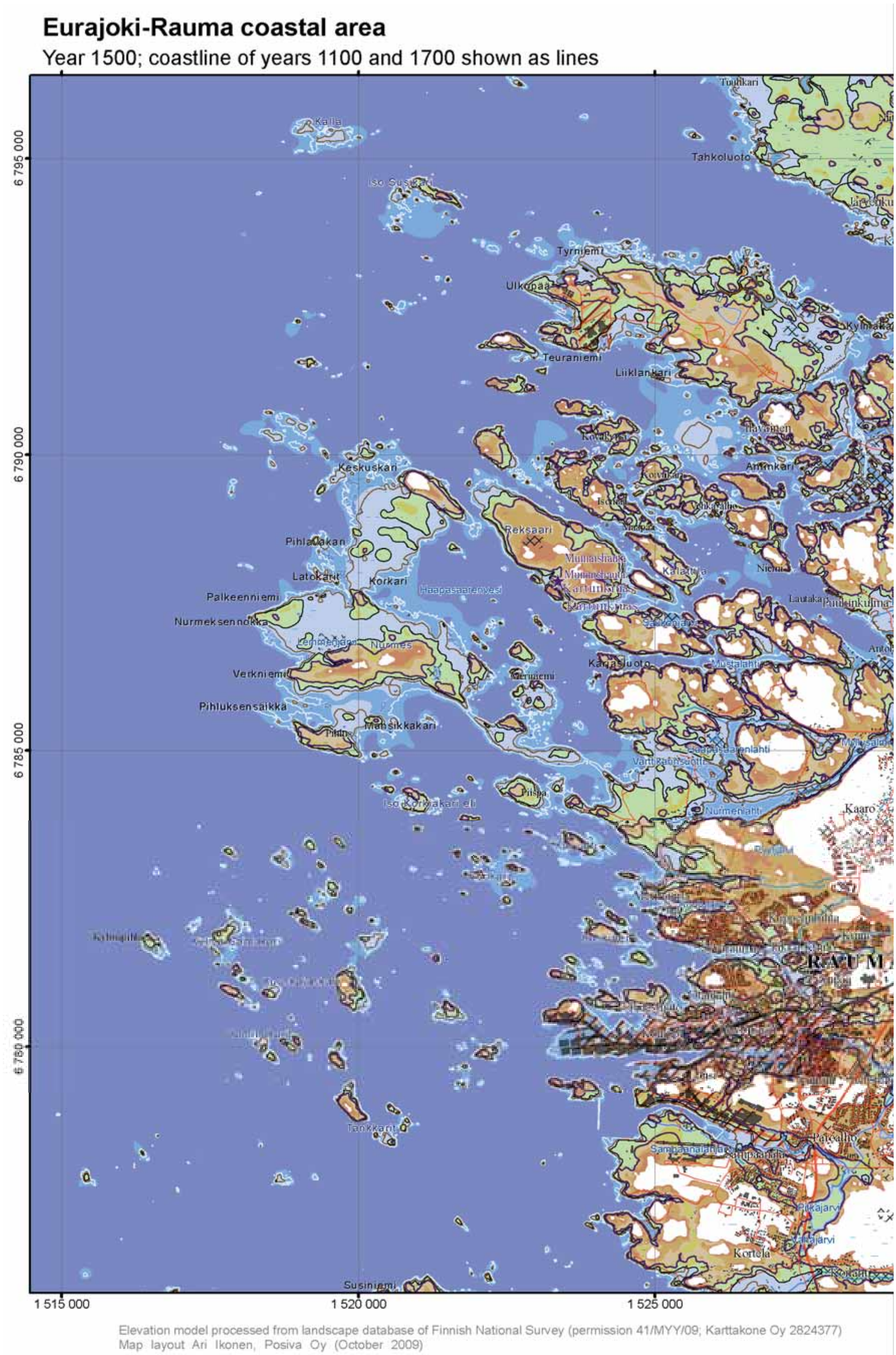
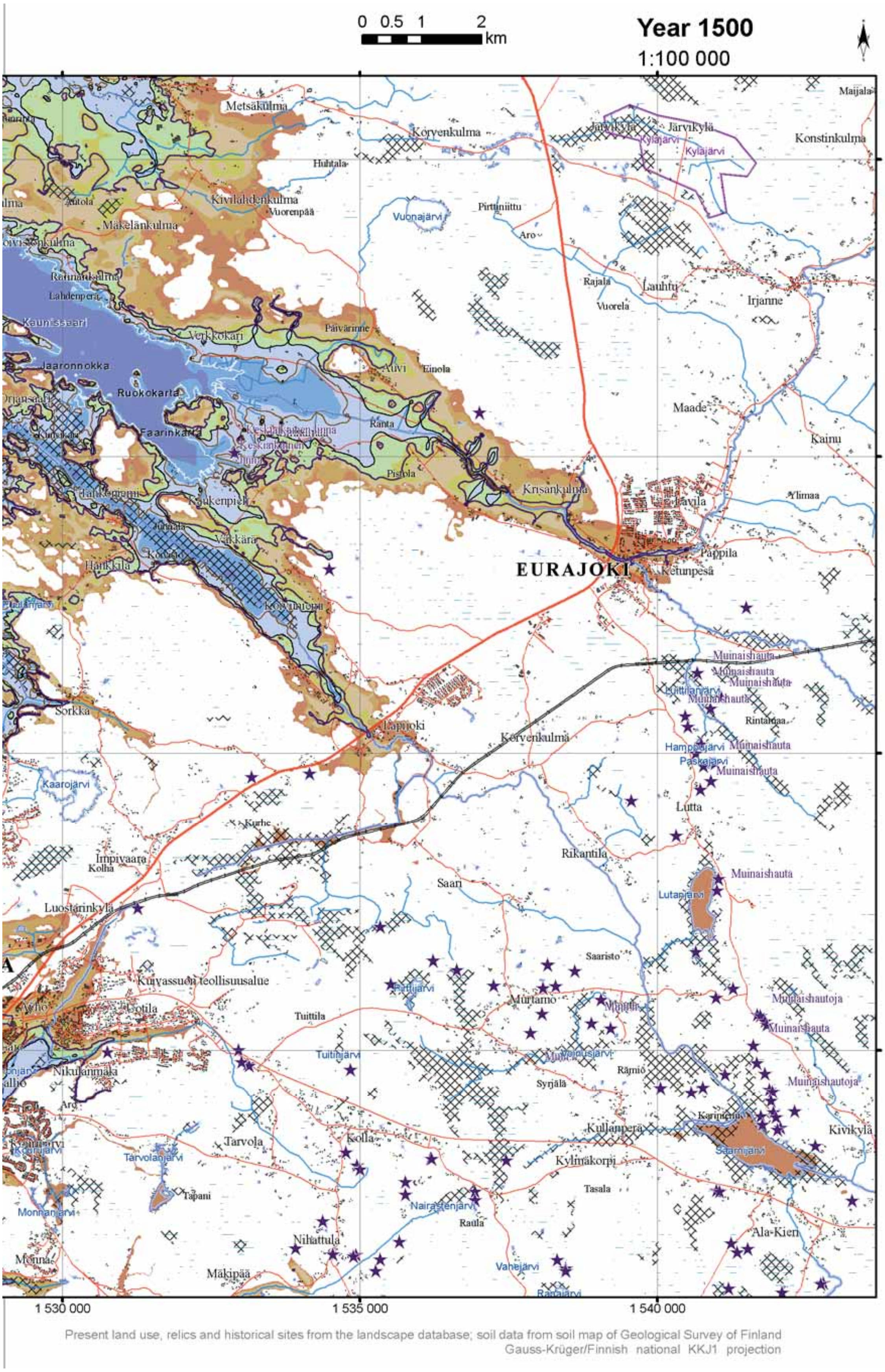


Figure 2. *Coastal area of Rauma-Eurajoki in year 1500. Coastlines of years 1100 and*



1700 are also shown. For the legend of the map, see Figure 1.

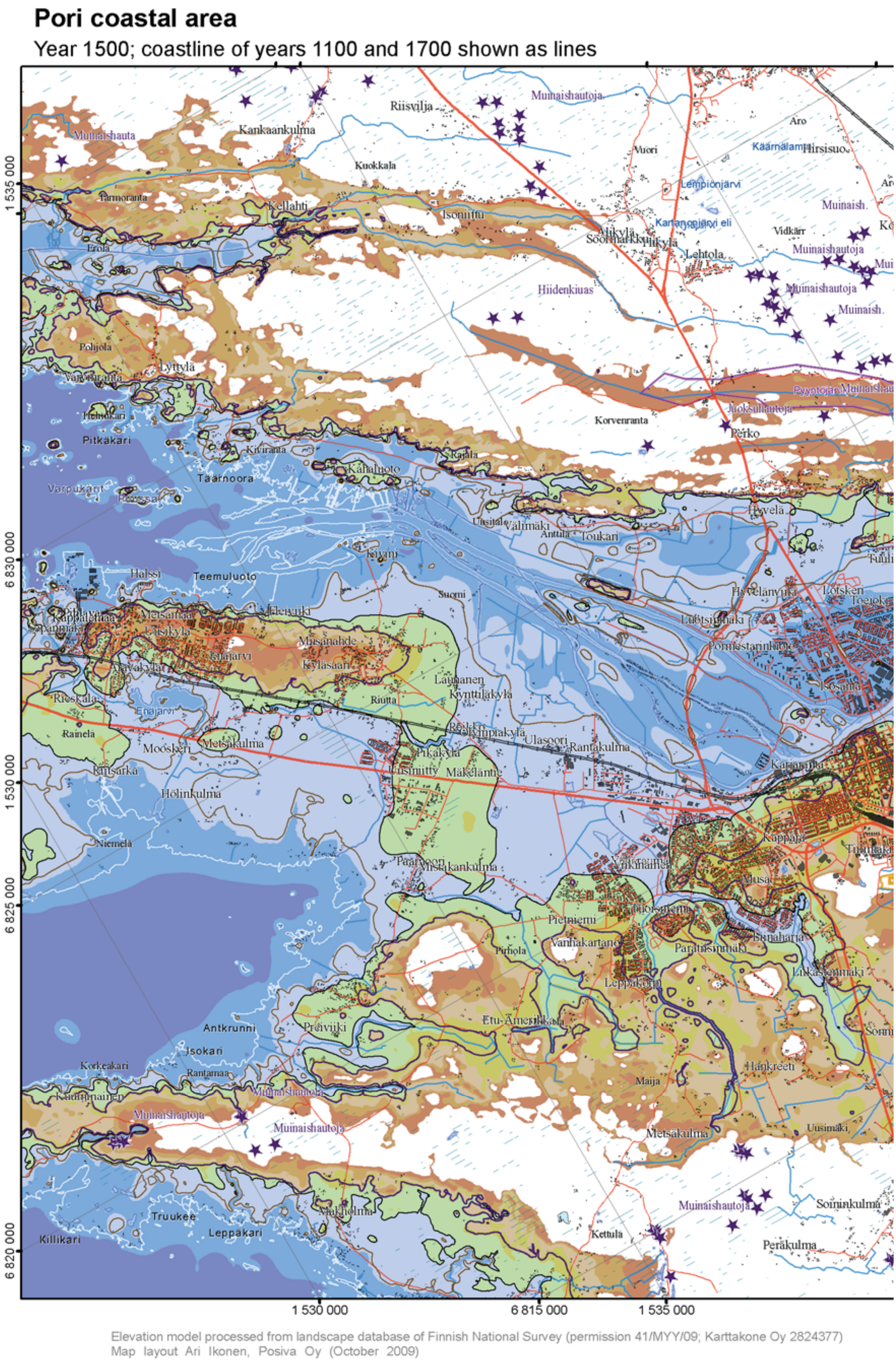
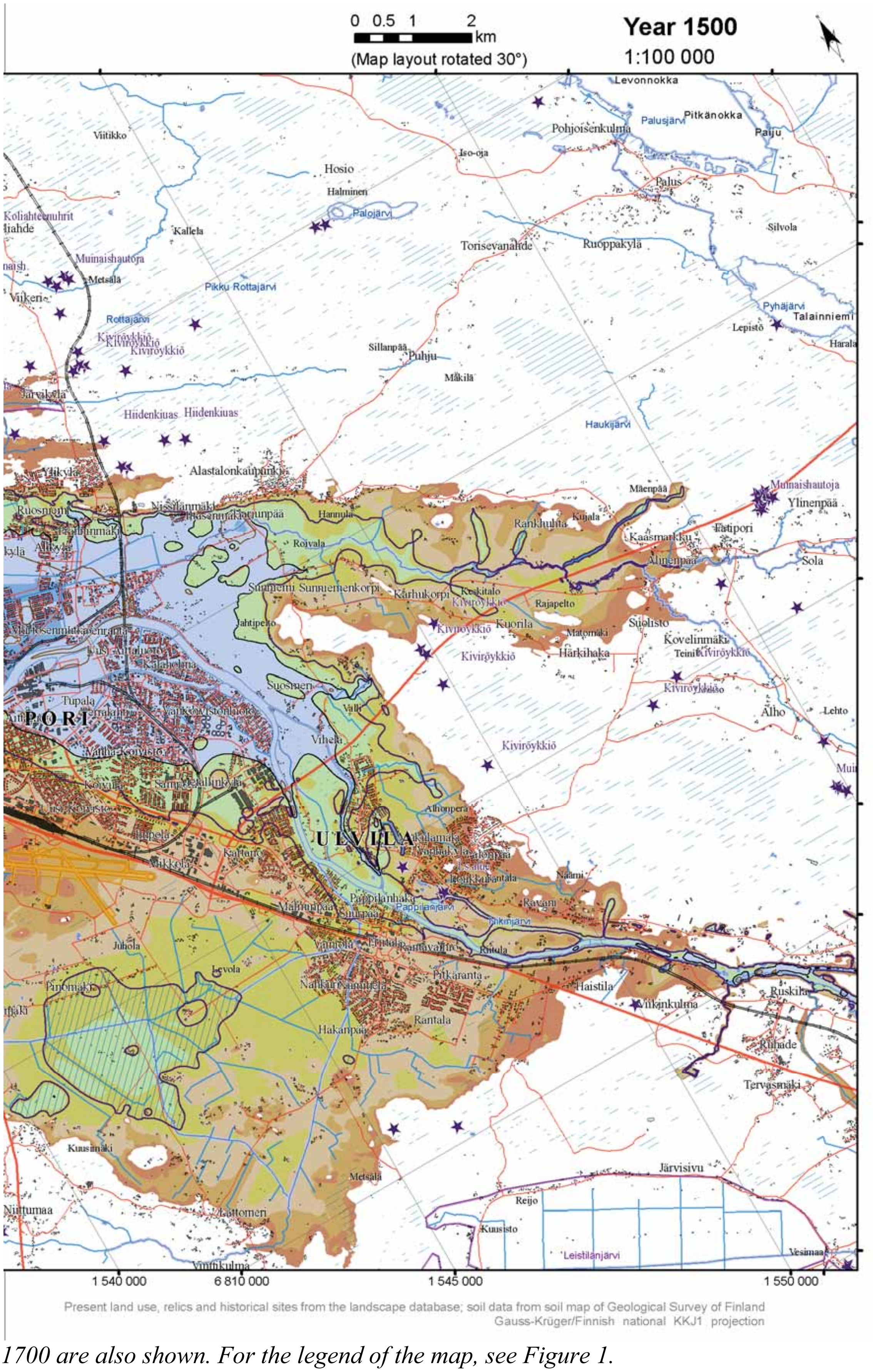


Figure 3. *Coastal area of Pori-Ulvila in year 1500. Coastlines of years 1100 and*



1700 are also shown. For the legend of the map, see Figure 1.

computational artefacts can be seen or the results are known to be anyway inaccurate due to organic deposits largely formed after the retreat of the sea. However, also in some the results are known to contradict with other information (e.g. at Liinmaa castle ruins) - on the other hand, this can be argued to be related to low data density either in the elevation model or in the land uplift model parameters, or both. In any case, the results presented should be taken only as illustrative and requiring iteration with e.g. historical information to improve them.

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SHORE-LEVEL DISPLACEMENT AND BEDROCK UPLIFT NEAR THE OLKILUOTO AREA, BOTHNIAN SEA

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Posiva is preparing to submit the construction license application for a spent fuel geologic repository at Olkiluoto. The safety case (Posiva 2010) is compiled to support that application. The overall aims of the biosphere assessment and reports in the safety case are to describe the present, future and relevant past conditions at, and prevailing processes in, the surface systems of the Olkiluoto site, model the transport and fate of radionuclides hypothetically released from the repository through the geosphere to the surface environment, and assess possible radiological consequences to humans and other biota (Haapanen et al. 2009, Hjerpe et al. 2010).

For the biosphere assessment of 2009 (Hjerpe et al. 2010), Vuorela et al. (2009) have reconstructed the future isostatic land uplift model of Påsse (1996, 2001), and re-evaluated and complemented the input data. The crustal thickness is the dominant parameter controlling the future uplift (Vuorela et al. 2009, Påsse 1997), but the present uplift rate and the dated shore-level points are necessary for calculating the actual input parameters of the model, i.e., the spatially varying inertia and download factors.

One of the consequences of postglacial uplift is the retreat of the Baltic Sea. Vertical shore-level displacement (S) can thus be expressed as a function of glacio-isostatic uplift of land, U, and global eustatic sea level rise, E. Mathematical expressions for U and E as a function of time have been presented by Påsse (1996, 1997 and 2001), Påsse & Andersson (2005) and interpreted by Vuorela et al. (2009).

The study by Vuorela et al. (2009) is based on updating the information on sea-level index points (Fig. 1) from the Bothnian Sea area. This required reviewing the earlier studies of C-14 datings related to the isolation of lakes and mires from the Baltic Sea stages due to glacio-isostatic adjustment. The post-glacial radiocarbon-dated Finnish shoreline data of the Baltic Sea is summarised by Eronen et al. (1993, 1995). The radiocarbon-dated shoreline data included also the data of Eronen et al. (2001), Glückert et al. (1998), Miettinen (2002, 2004), Miettinen et al. (1999, 2007), Seppä et al. (2009) and Seppä & Tikkanen (1998). In addition, some recent Swedish shoreline displacement studies were used, e.g. Risberg (1999), Hedenström & Risberg (1999, 2003), Hedenström (2001), and Berglund (2005).

Terrain development, or reforming of the ground surface on land and under water, and specifying the volumes and exchange rates of surface water bodies, is a direct consequence of the post-glacial land uplift, sea-level changes and hydrological balance. Some effects follow also from formation of shoreline vegetation and peat (Haapanen et al. 2009, Ikonen et al. 2010).

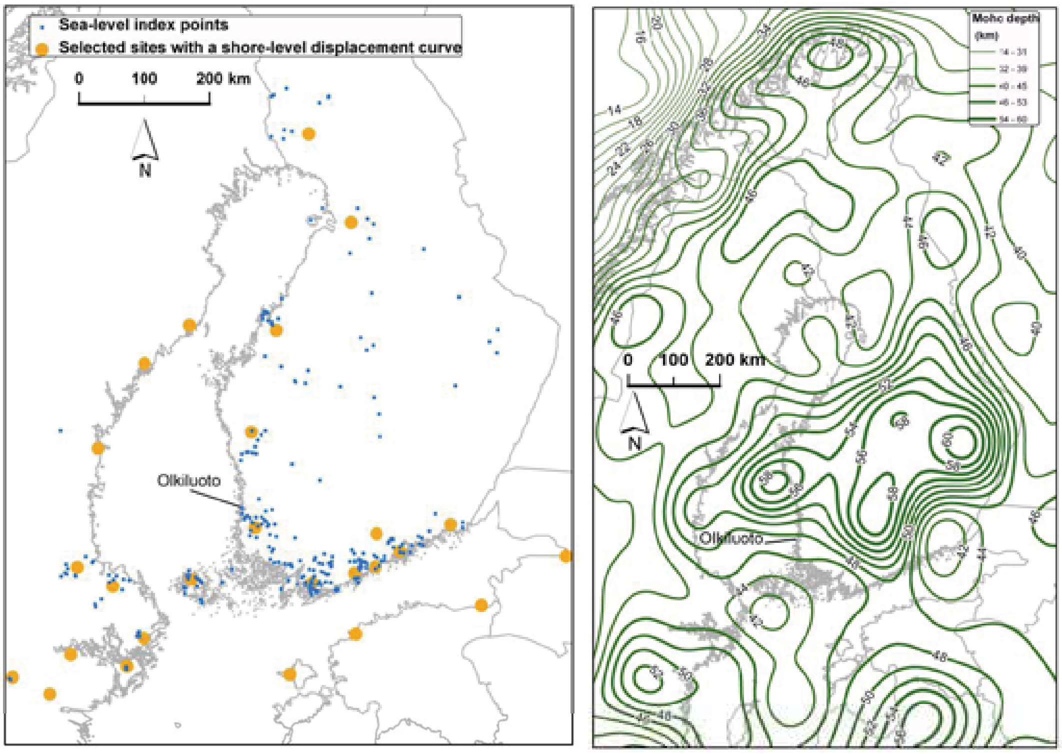

Figure 1. *On the left, locations of the local ancient shoreline and other dating points (blue) and regional sites (orange spots) where a shore-level displacement curves have been fitted to the local points (Vuorela et al. 2009). On the right, the crustal thickness (km ± about 10 %) by Grad & Tiira (2008, 2009). Map projections not reported. Map layout by Arto Vuorela/Pöyry Environment Oy. (Haapanen et al. 2009).*

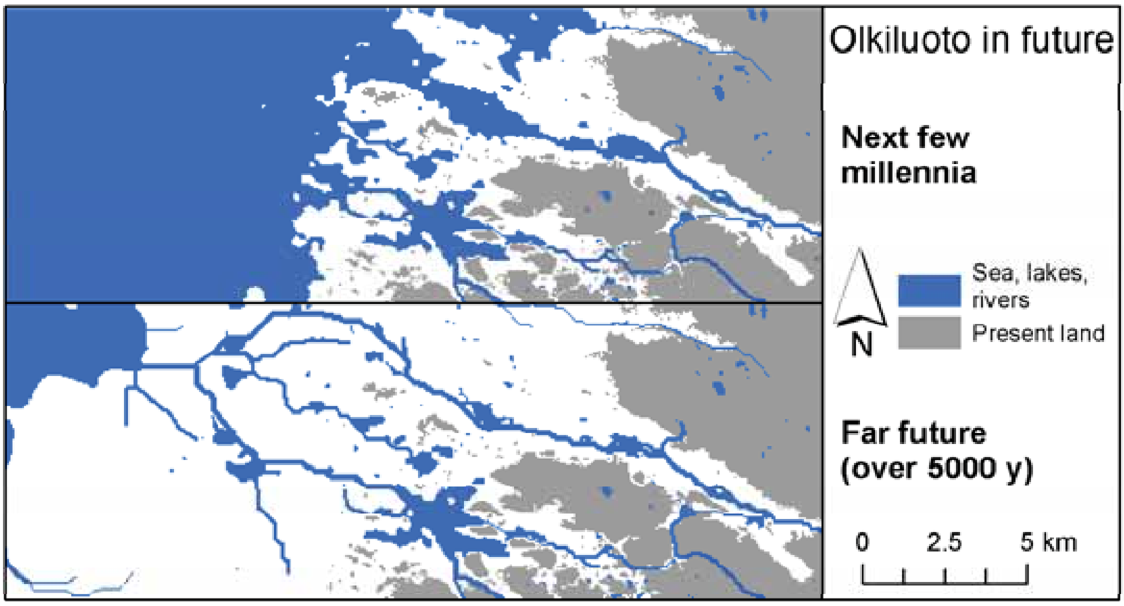

Figure 2. *Conceptual presentation of terrain development at Olkiluoto. The scale given refers to the lower figure only. Map layout by Ari Ikonen/Posiva Oy. (Pastina & Hellä 2010).*

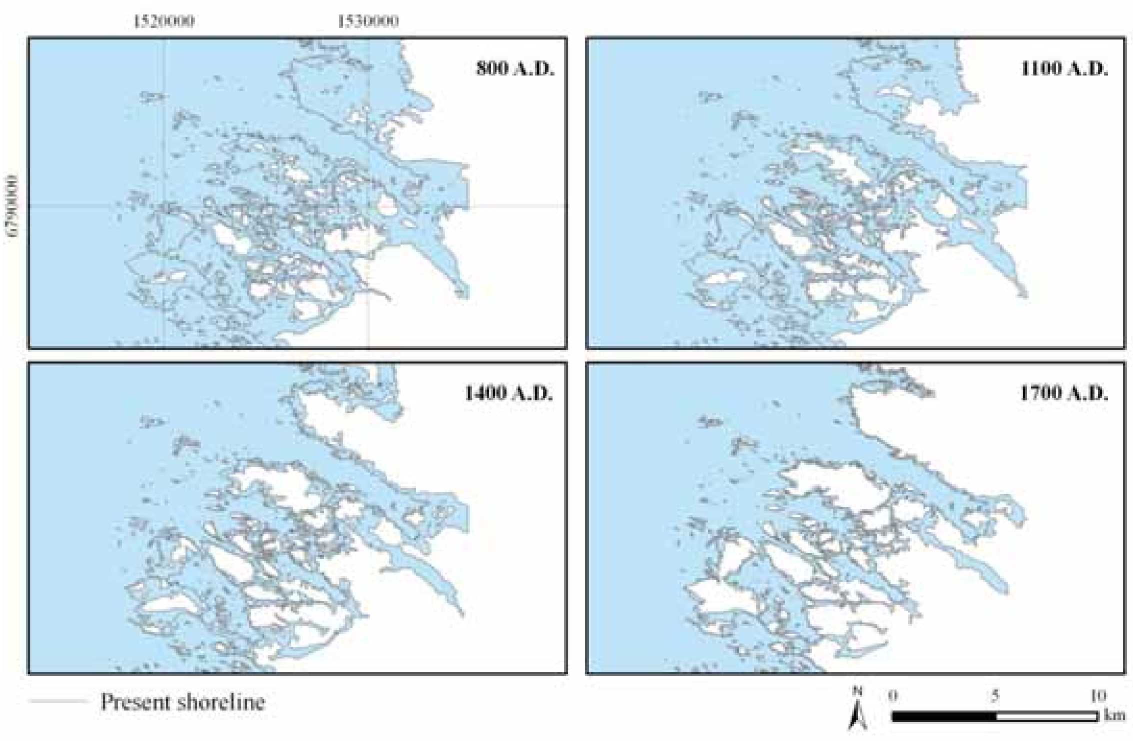

Figure 3. *Shore level displacement at Olkiluoto based on the terrain model by Pohjola et al. (2009) and land uplift model by Påsse (2001), with updated parameter values from Vuorela et al. (2009). Present-day shoreline is from topographic database by the National Land Survey of Finland. Map layout by Jani Helin /Posiva Oy. (Haapanen et al. 2009).*

The present uplift rates in southwestern Finland vary from 5 to 7 mm/y (Alalammi et al. 1995). During the next several thousand years, the bays surrounding the coastal areas of the Bothnian Sea will narrow and become isolated as lakes and further develop toward mires (Fig. 2). The location of the coastline will shift by about 20 km in 6,000 years unless the sea level changes significantly (Mäkiaho 2005, Ojala et al. 2006; Fig. 3). Furthermore, along shallow shores, the extent of common reed beds is increasing due to human-induced eutrophication. This results in a faster apparent shoreline displacement than mere land uplift or changes in sea level would yield (Miettinen & Haapanen 2002). The shoreline displacement is further accelerated by the deposition of materials transported by sea water, ice and rivers.

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HISTORICAL MAPS IN THE STUDY OF SHORELINE DISPLACEMENT

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Abstract

An overview with examples from the Satakunta region, SW-Finland, is given on the use of historical maps in the study of shoreline displacement. In Finland, the time period covered by historical maps begins from the 16th century with rare individual examples and from the 17th and especially 18th century onwards the maps become more numerous and accurate. The oldest maps are, usually, only drafted by the eye and are therefore inaccurate, while the newer maps are based on measurements and are thus more reliable. With the current optimum GIS and image-processing techniques the maps can often easily and with high reliability and good quality be transformed in geospatial datasets and be used together with other geographic information. In the Department of Landscape Studies, University of Turku, historical maps from the Satakunta region have been used widely in teaching and research as well as in publication projects. From the point of view of the study of shoreline displacement the most useful of these are, perhaps, the large scale cadastral maps from the 17th century and onwards, that in some occasions can be very accurate, and the small scale Russian topographic maps from 1900s and 1910s, that cover the entire coastline of Satakunta in an easily manageable format.

1 Studying shoreline displacement with various methods

Shoreline displacement can be studied as an historical and geological phenomenon using techniques from various disciplines: in geology and geography, using geospatial-data technology and elevation models as aids, one can model land uplift (Huhta & Vuorela 2009; Vuorela 2000; Uotila 1998: 79), and data can be supplemented via the study of sedimentation and the composition of organic deposits and via geomorphological observations (Cripps et al. 2009). Additional data can also be obtained via other scientific procedures. Among the humanities, archaeology, inter alia, can help if relics of antiquity are found from which the height of the sea level during a particular period can be estimated (Uotila 1998:79-82). Likewise, there may be information about the extent of water areas in historical sources, and where information cannot be taken from historical sources, place-names may provide information instead. In Pori, such names are, for example, Kyläsaari (Swedish *Inderö*) Yyteri (Swedish *Ytterö*), Pietniemi, Tuorsniemi, Vähärauma and Lattomeri, which contain a common noun relating to the terrain (*saari / ö* = island, *niemi* = cape, *rauma* = strait, *meri* = sea) that describes the character of a place, now located inland, when it was given its name (Jaakkola 1958: 128, 130).

2 Historical maps in the study of shoreline displacement

One historical source is old maps. There are some rare individual examples of historical maps in Finland dating from the 16th century (e.g. Ehrensvärd 2006: 129, 143; Lahtinen

2008: 58-61), but there are greater numbers from the 17th century and there are even more from the 18th century onwards when they become more accurate (J. Lehtinen 2010; J. Lehtinen 2008: 198-226; J. Lehtinen 2003: 88-99; L. Lehtinen 2005). However, the scope of maps both temporally and spatially varies greatly, as does the accuracy of the mapping, and thus the quantity and quality of data available from maps vary. Map availability is generally best for the southernmost part of Finland, but there too the availability of maps varies on a case-by-case basis.

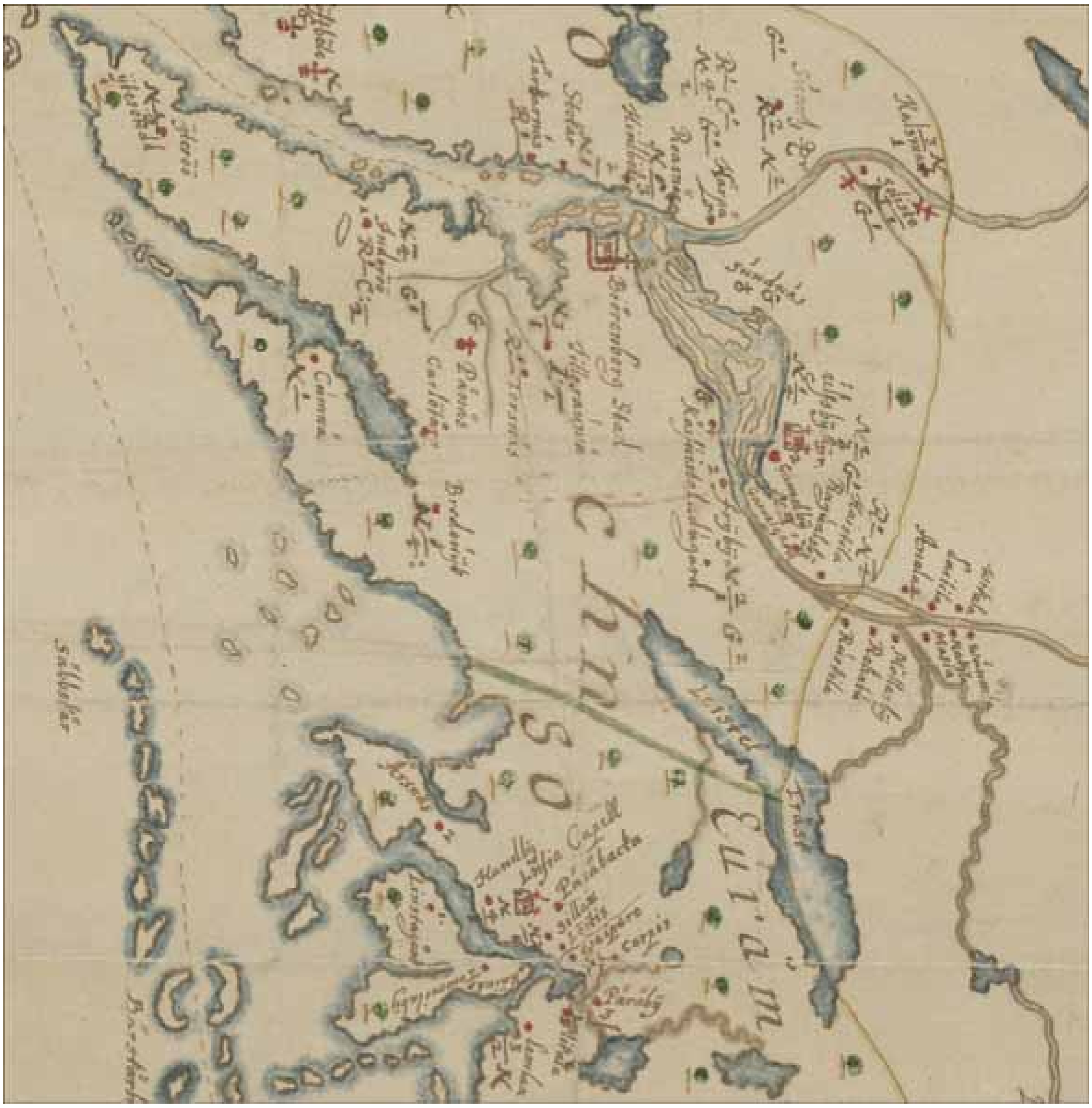

Figure 1. *On the oldest maps the information is often restricted to the existence or absence of particular water and land relationships. A detail from the map of the Satakunta coastline by Hans Hansson from the 1650s. The strait of Luvia, now dry land, can still be seen as a waterway in the map.*

In a study of shoreline displacement, historical maps can provide information about the position of the water surface at the time the map was produced, bound on older maps to a rough time and place and on newer maps to a more precise time and place (cf. e.g. J. Lehtinen 2008: 202, 203, 227).

On the oldest maps, which are often inaccurate and drafted by eye, the information is restricted to the existence or absence of particular water or land relationships at the time illustrated by the map. Examples of this are the strait of Luvia and the bay of Keikvesi in Ahlainen shown on Hans Hansson's map of the Satakunta coastline from the 1650s (Hansson 1650; published in Jaaakkola 1958: 179, Häyrynen et al. 2005: 9, Häyrynen & Lähteenmäki 2009:9) or the oldest maps of the Pori shipping channel (Strengh 1641-1642, published in Häyrynen et al. 2005: 230, Ehrensvärd 2006: 266) and the Kokemäenjoki delta in Pori and Ulvila along with its skerries (Hansson 1663, published in Ruuth 1958: 356; Anon. s. a.). Usually the information included on these maps cannot be transferred directly via geospatial-data procedures to a present-day map, but instead one can look for the water-surface level depicted by the map by comparing an accurate elevation model describing the present day, for example, against the water or

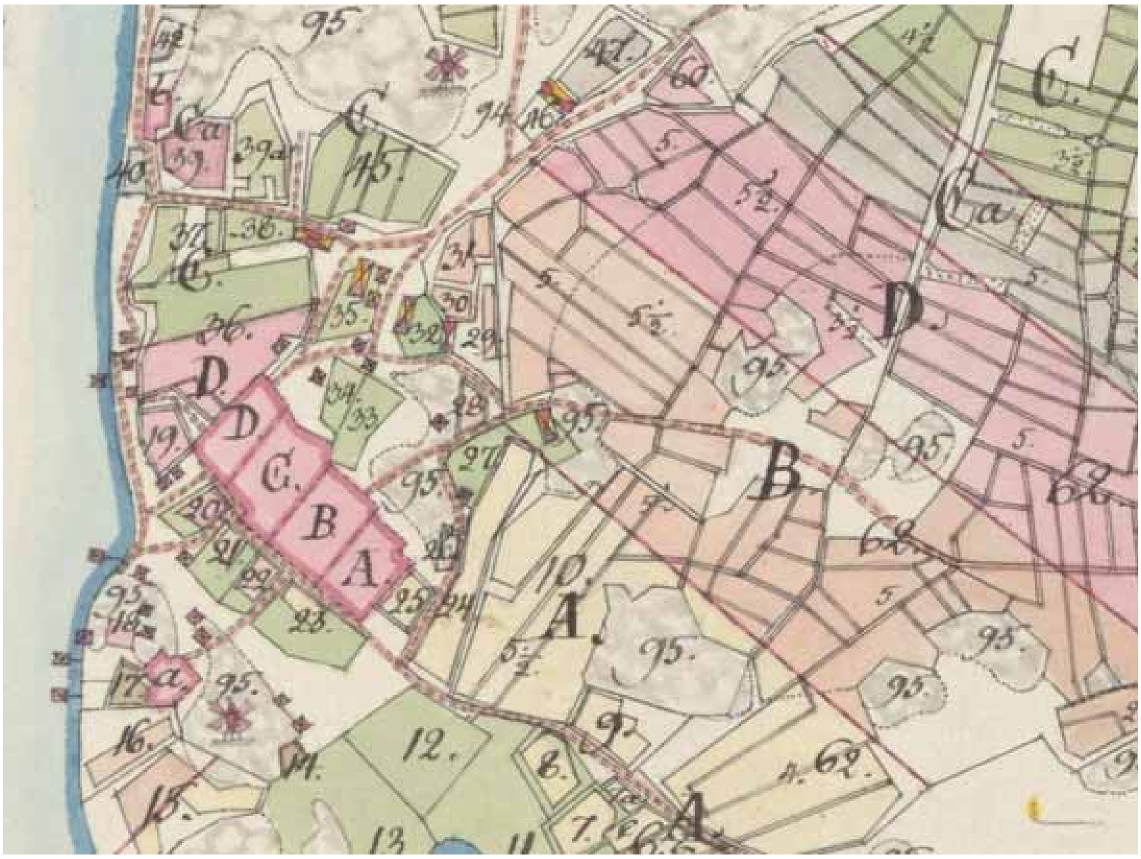

Figure 2. *The newer maps especially from the 18th century and onwards are usually based on measurements and can be very accurate. A detail from an enclosure map from Ilavainen, Eurajoki, Finland, from 1813 scanned with a flatbed scanner at the resolution of 300 ppi by the National Archives of Finland.*

land relationships illustrated by the map. One must note, however, that in addition to land uplift, erosion or deposition/sedimentation has also been able to affect displacement of the shoreline, depending on the location (Cripps et al. 2009; Uotila 2008:43). Sedimentation is particularly strong in river deltas, and erosion and deposition also appear in inland areas, such as old fields (ibid.).

On the newer and more accurate maps, which are, within certain limits, the cadastral maps from the 17th century onwards and in particular the enclosure maps from the 18th century onwards, the information included in the maps is based on surveys, and geospatial-data techniques can be used with these maps. On the oldest or small-scale maps, there are nevertheless mistakes and inaccuracies in the mapping, which it is possible to detect and evaluate by comparison with newer or more accurate maps (J. Lehtinen 2008: 199; Lehtinen 2003: 104-106). On the other hand, on the newer and larger-scale maps, the mapping can be very accurate on maps from the 18th century onwards.

3 Historical GIS: using new techniques to answer the old questions

When compared to base maps that were in use in earlier decades and the procedures for handling location data, the development of geospatial data- and image processing-technology in particular, together with ever more accurate 3D elevation models, has, in recent years, meant significant improvements in the processing of historical spatial data and has increased both its efficiency and improved the quality and usability of the end result (J. Lehtinen 2006a; Tollin 1991, Cserhalmi 1998; Ene et al. 2007; Rentzhog et al. 2002). In particular, this has been made possible by: the use of GIS software developed for the rectification of air and satellite images which, with certain reservations, work almost as well in the rectification of historical maps; fast, large, high-quality flatbed scanners that are cheaper for the end user and that have come into use during the last few years in almost all the most important archives; and, the growth in storage capacity and data processing in recent years, so that it is easier than before to generate, transfer, store and process even large image files. These have all caused a revolution in the usability and availability of historical maps and documents, in the possibilities for generating historical spatial data and in the quality and usability of the end product (J. Lehtinen 2008b). Because progress has happened mainly as computers have become more powerful during the last few years, the opportunities provided by this in the processing of historical maps and historical geospatial data in particular have not yet been fully exploited.

Thus, the results of the excellent research in historical and geographic shoreline displacement conducted in the Pori area over the past decades, for example (Jaakkola 1958: 130; Säntti 1951: 70, 72, 76, 87-88; Eskola 1925: 334; Wahlroos 1890), may not yet have been repeated much at all nor have corresponding datasets been produced using present-day geospatial-data techniques, even though current geospatial-data techniques also enable studies and production of datasets, which were not possible with the old procedures, or the results were significantly less accurate or more limited in their usability.

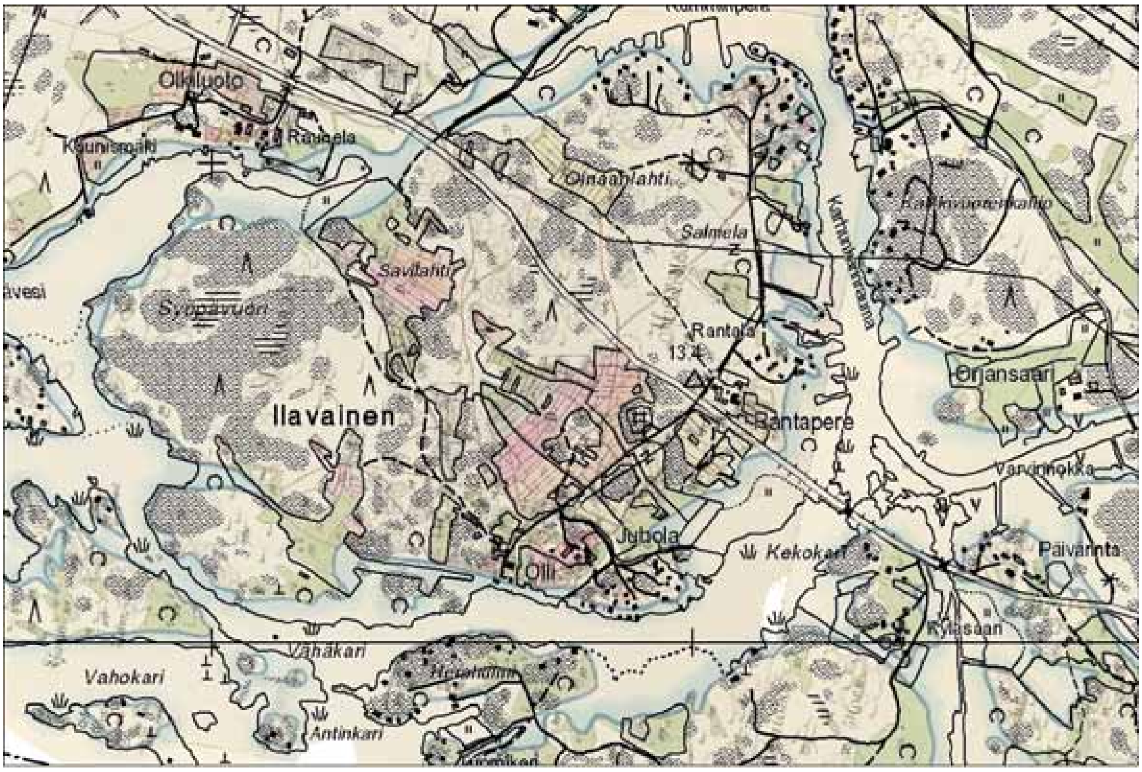

Figure 3. *The enclosure map of Ilavainen, Eurajoki, Finland, from 1813 rectified with GIS software ArcGIS and overlaid with a present day base map.*

These kinds of new techniques include the rectification and use of combined high-quality image files read from maps as a basis for visualisation and additional processing, the creation of vector databases from the contents of maps and the use of these in visualisations and analyses (J. Lehtinen 2008b; Ene et al. 2007; Rentzhog et al. 2002). In processing historical geospatial data, there are still many unused opportunities in both the study and presentation of research results, as well as in education, environmental education, museums and tourism, for example.

4 Use of historical maps in regional level: the case of Satakunta

In the Department of Landscape Studies at the University of Turku, the opportunities presented by new technology have been exploited in research and teaching by acquiring for the use of the department, in collaboration with the regional council of Satakunta and the Southwest Finland Regional Environment Centre, small-scale sheet historical maps from the 1850s through to the 1920s as digital image files for the parts of the Satakunta area that have been mapped, and by rectifying the maps in geospatial-data form in a project financed by the Satakunta regional fund of the Finnish Cultural Foundation. In addition, other large- and small-scale maps for the target areas of the individual projects have been acquired, such as cadastral maps from the 17th to the 20th centuries and parish maps from the 18th and 19th centuries (J. Lehtinen 2006b).

Figure 4. *The mouth of the Eurajoki river in Eurajoki, Finland, in the Russian topographic map in scale 1:21 000 from 1904 overlaid with the current base map.*

For the datasets acquired, the Finnish military topographic map, i.e. the Kalmberg map at a scale of 1:100,000 from the 1850s and the economic map of Finland at a scale of 1:100,000 from the 1910s through to the 1930s are useful as historical general-view and approach maps. In respect of their details, they are not reliable (J. Lehtinen 2003: 97), but when used for education, illustration or in museums, for example, they can be useful because they are illustrative. Maps have been used until now in the department's book projects (e.g. Häyrynen et al. 2006; Grahn & Sivula 2008), for example, and the Kalmberg maps from Satakunta have also been published on the Internet as part of a map service (Lounaispaikka 2010), and they have been used as datasets in geospatial-data teaching in schools (PaikkaOppi 2010).

More detailed information is provided by the Senate map collection's Russian topographic map at a scale of 1:21,000 and 1:42,000 from the 1900s and 1910s and the National Land Survey of Finland's new parish map at a scale of 1:20,000 from the 1920s through to the 1940s. Of these, the Russian topographic map is often very accurate and a versatile source of landscape history for its period (J. Lehtinen 2003: 97-98; for samples of maps see also Häyrynen et al. 2006; Grahn & Sivula 2008; Häyrynen & Lähteenmäki 2009: 11). It includes, amongst other things, the shoreline almost at the scale of a current base map in an easily manageable form and, in addition to this, information about coastal land use and settlement for the whole Satakunta coast during the 1900s and 1910s. On the other hand, the 20th-century parish map is a more heterogeneous source (J. Lehtinen 2003: 98-99; for samples of maps see also Grahn & Sivula 2008), and it is less useful from the point of view of shoreline displacement, because it originates from cadastral maps from different time periods (J. Lehtinen 2003: 98-99), whose data is better and more accurate when taken directly from the original maps.

In the study of shoreline displacement, perhaps most noteworthy are the large-scale historical maps that are generally cadastral maps. These, in the same way as individual small-scale historical maps, like the 18th-century parish maps, have been acquired by the Department of Landscape Studies on a case-by-case basis for different project areas (J. Lehtinen 2006b; for samples of maps see also Grahn & Sivula 2008). In particular, very accurate and detailed information about shoreline displacement is often obtained from cadastral maps, as it also is about land use and settlement, for example. The most important series of land survey maps are: the geometrical land books and the taxation maps from the 1640s through to the 1720s; the land-reform maps from the 1760s through to the 1810s; and the newer cadastral maps, like the land-reform and land-reparcelling maps from the late 19th century and the early 20th century (J. Lehtinen 2003: 88-94; for samples of maps see also Grahn & Sivula 2008).

5 Conclusions: experience thus far and further possibilities

Together with the Russian topographic maps from the 1870s through to the 1910s and the various editions of the present-day base map from the 1950s onwards, from the land-survey maps converted into geospatial-data form, one can create very accurate series of landscape-history cross sections (see e. g. J. Lehtinen 2003, 2008a) where one possible form of data may be shoreline displacement (J. Lehtinen 2008a: 227) and the effects of this, for example, on land use and settlement. As the land-reform maps and also the Russian topographic maps from southernmost Finland are generally available quite extensively, one can with these, if desired, cover long coastal series or wide regional entities, such as the Kokemäenjoki delta or the entire Satakunta coast. On the other hand, the coverage of 17th-century geometrical land books (Rantatupa 2000:74), just like the cadastral maps from the late 19th century and early 20th century, is often more variable. So, the information provided by the 17th-century maps, for example, may be spatially fragmented and may just offer points of reference for extrapolation with elevation models, for example, where no maps are available. On account of the language used and handwriting, interpretation of the oldest maps may also require the expertise of an historian.

In my own projects, I have created series of geospatial-data landscape-history cross sections containing shoreline-displacement data, for the Saari estate area in Mietoinen of Southwest Finland (J. Lehtinen 2008a) and the Vuojoki estate area of Eurajoki in Satakunta (J. Lehtinen 2010), among others.

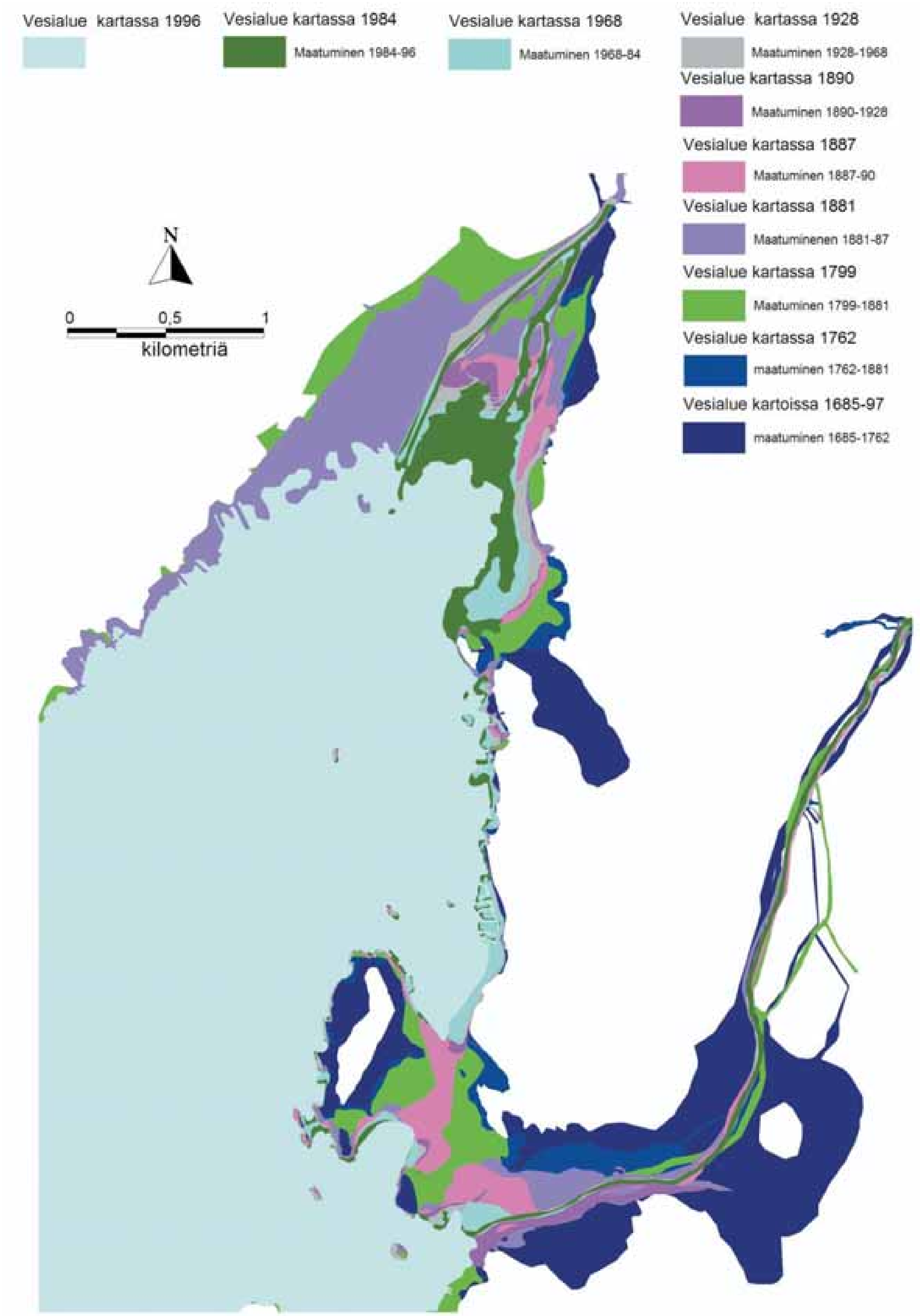

Figure 5. *Shoreline displacement in The Saari estate area in Mietoinen, Finland, between 1685 and 1996 (Source: J. Lehtinen 2008: 227).*

Production of similar datasets would easily be possible, and, because of the exceptional environmental history of the area (Vuorela 2000; Jaakkola 1958: 150; Wahlroos 1890:1), it would also be very interesting for the Kokemäenjoki delta or the Pori coast areas, for example. Furthermore, this kind of data about shoreline displacement would provide valuable information about other environmental history for the area also, such as land use and settlement. When a present-day optimum procedure (J. Lehtinen 2008b) is used, this kind of data would also provide good opportunities for the presentation of environmental-history data and making it known more widely.

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ANALYSING THE LOCAL DEFORMATIONS AT OLKILUOTO USING GPS AND LEVELLING TIME SERIES

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Abstract

The Finnish Geodetic Institute has studied crustal deformations at Olkiluoto since 1995. A local GPS network of 10 pillars has been observed twice a year and the precise levelling has been initiated in 2003 to reach a better vertical control of the network. In this paper we concentrate on the relative movements of the GPS points and briefly analyse the time series. The aim of the study is to combine the results of GPS measurements and levelling. A least squares free network adjustment was applied in order to determine the horizontal and vertical velocities of the points. The analysis show maximum horizontal velocity of 0.10 mm/a and vertical velocity of 0.18 mm/a. The results of the deformation analysis were also presented as a surface plot.

1 Introduction

The Finnish Geodetic Institute (FGI) has studied crustal deformations in co-operation with Posiva Oy since 1995. At the beginning the studies have been carried out at three investigation areas (Olkiluoto, Kivetty and Romuvaara), which were selected as candidates for the final disposal sites of spent nuclear fuel. The studies are now concentrated at Olkiluoto, where the final waste disposal site is being built.

A GPS network of 10 pillars was established on the Olkiluoto Island in 1994 in order to monitor crustal movements (Chen and Kakkuri, 1995, Kallio et al., 2010). The network has been observed twice a year since 1995 except the year 2000 because of high ionospheric activity. One pillar of the network belongs to the Finnish permanent GPS network FinnRef® and is used for continuous GPS observations. The baselines between GPS pillars range from 0.5 to 3.5 km (Figure 1).

The Olkiluoto network was expanded to the north in 2003. Two new pillars (GPS11 and GPS12) were built in order to monitor an old fracture zone, which is passing from NW to SE along Eurajoensalmi (Figure 1). In addition, pillars GPS14 and GPS 15 were established near Olkiluoto investigation area in 2005 in connection with the GeoSatakunta project (Ahola and Poutanen 2006, Poutanen et al., 2010), where regional crustal deformations in the Satakunta area are studied. Measurements at these four pillars surrounding the Olkiluoto Island connect the Olkiluoto and GeoSatakunta networks.

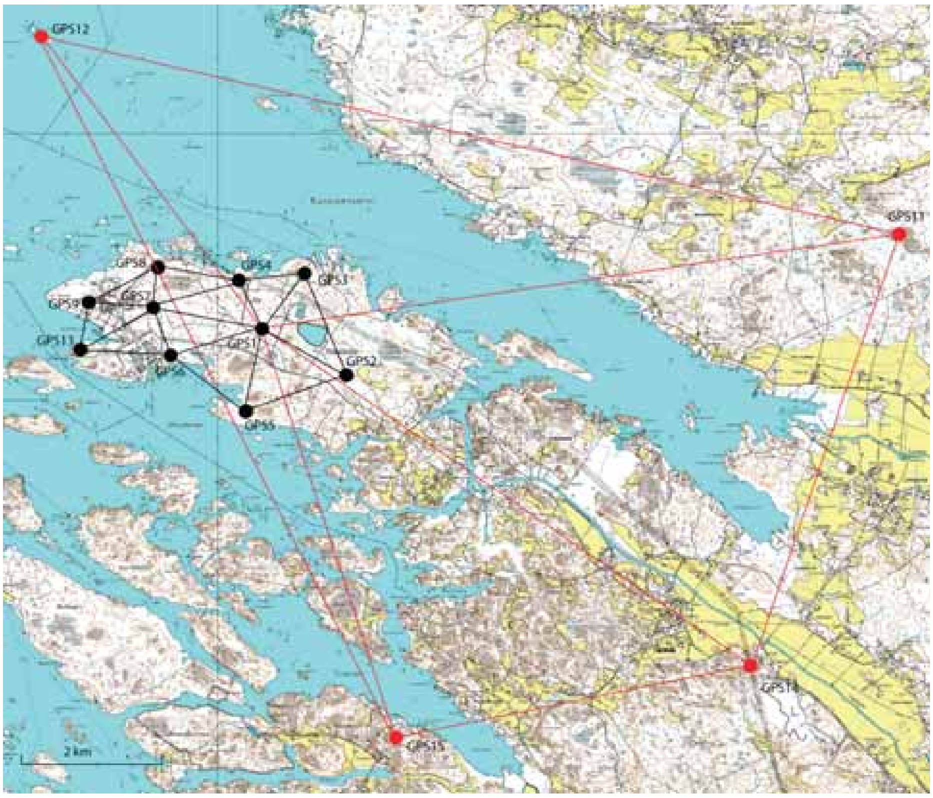

Figure 1. *The GPS networks of the Olkiluoto. The main network on Olkiluoto Island has been observed twice a year since 1995. The surrounding network has been established in 2003-2005.*

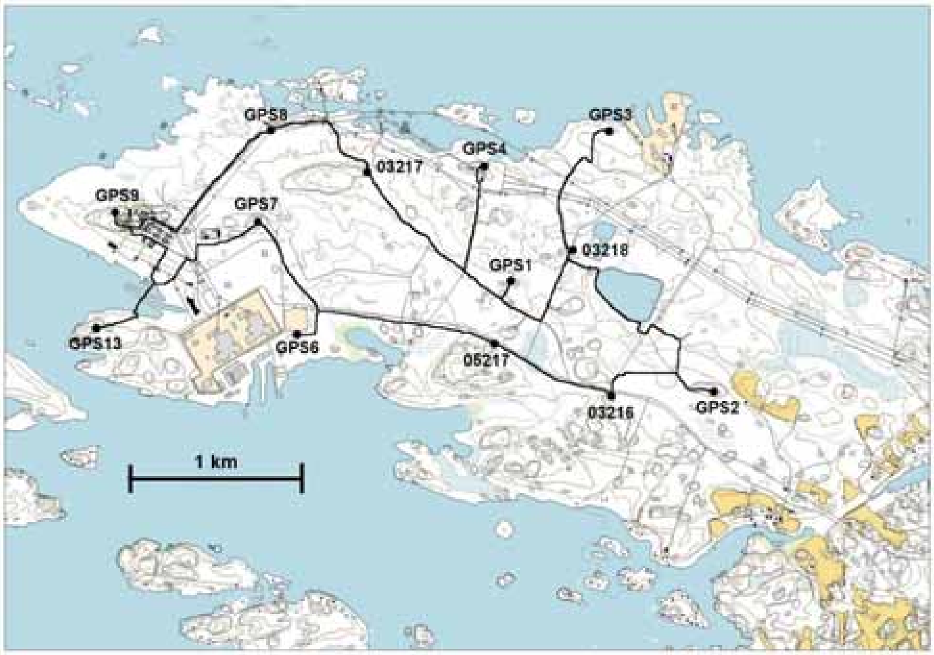

Figure 2. *The GPS network is levelled every second year.*

GPS measurements are suitable to determine horizontal deformations, but the accuracy of the height determination is not adequate. To get a better vertical control of the GPS pillars in Olkiluoto investigation area the precise levelling of the GPS network were initiated in autumn 2003 and repeated every second year (Lehmuskoski, 2008, 2010) (Figure 2).

Here we concentrate on the studies of the Olkiluoto island area. The aim of the study is to combine the results of GPS measurements and levelling. In this paper we concentrate on the relative movements of the GPS points instead of the total land uplift.

2 GPS measurements and data processing

We have carried out a total of 28 GPS campaigns of the Olkiluoto island network using Ashtech Z12 and μZ dual frequency receivers (Leica GX1230 series geodetic receivers since autumn 2009) and Ashtech Dorne Margolin Choke Ring antennas. The same antenna has been set up on the same pillar every time to eliminate the individual antenna phase centre errors. With 24 hour-long observation sessions we try to diminish or eliminate satellite geometry and signal multipath related errors. The campaigns have also been performed at the same time every year to minimize any seasonal effects.

The Bernese 5.0 (Dach et al., 2007) GPS software was used for the data processing (Kallio et al., 2010). All the Olkiluoto data were reprocessed uniformly. The observations from year 1995 were excluded because of the problems with ionosphere modelling. The data processing strategy was based on the double-difference approach. We obtained the best vector solution (smallest rms-values) by using the L1 observables together with local ionosphere model. After computing all vectors in one session, a network adjustment was applied, where the Olkiluoto permanent station was kept fixed. As a result we obtained coordinates of the pillars for each campaign.

We have computed vector lengths from 3-dimensional coordinates obtained from GPS processing. By analysing the vector lengths we get an insight into the variation of the GPS solutions (Figure 3). The scatter of the solution in the best resolved vectors is less than 1.0 mm. The results of the first measurement campaigns deviate significantly in the cases of some vectors, that is probably due to shorter observations sessions before year 2000. On the other hand, the time series plots from a single station revealed obvious seasonal variation i.e. there is a difference in vector lengths between spring and autumn (Figure 4).

3 Precise levelling

The levelling has been carried out with the same method that was used in the Third Precise Levelling of Finland (1978-2004) (Takalo, 1978). The digital levelling system Zeiss DiNi12 and Zeiss Nedo LD13 bar code invar rods were used (Lehmuskoski, 2008, 2010).

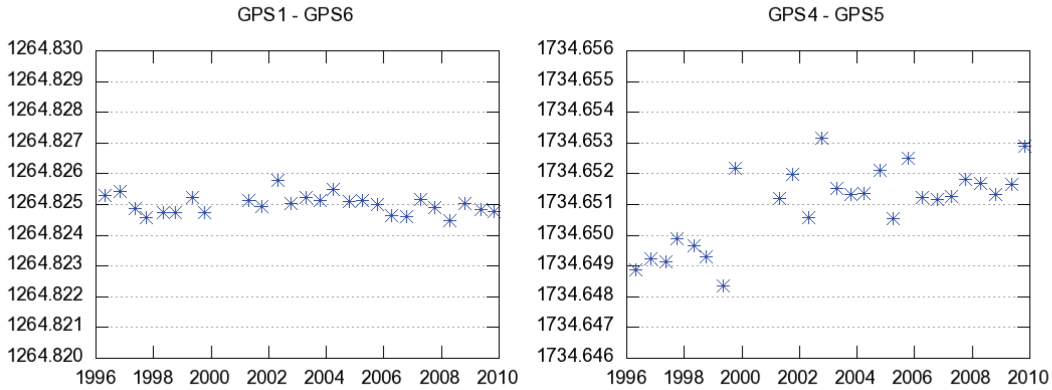

Figure 3. *The time series of vector lengths in metres.*

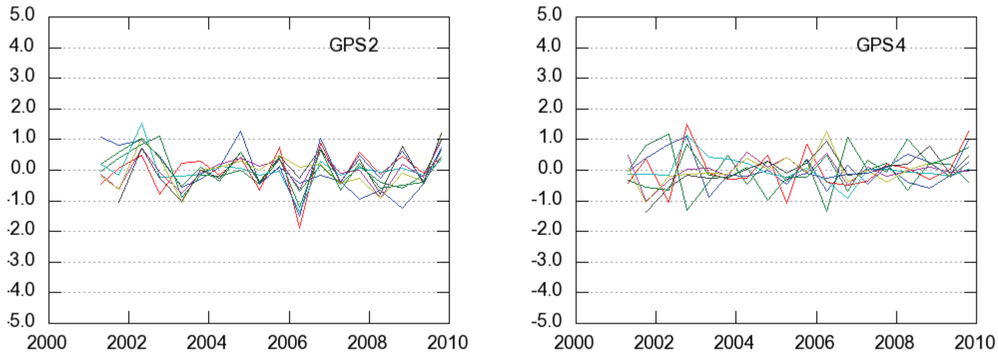

Figure 4. *The seasonal variation is obvious at some of the pillars (e.g. GPS2) but not visible at all sites (e.g. GPS4). Deviation from the mean in millimetres.*

First the GPS network was connected to the precise levelling network of Finland at Lapijoki to control the vertical movements of the whole Olkiluoto Island. Then the GPS network was levelled. Also some micro loops were established and levelled onto the ONKALO (Underground Rock Characterisation Facility) excavations, where the final nuclear waste repository is being built. The micro loops consisted of seven and five bench marks at the mean interval of 300 metres.

The levelling of the GPS network consisted of the reserve marks of eight GPS pillars and four levelling bench marks, which we use in further analysis. We plotted the time series of the height differences point by point in order get to an idea of the nature of the changes (Figure 5).

4 Deformation analysis

We have carried out a similar deformation analysis on both GPS and levelling time series. We used GPS time series from the years 2001-2009. The first time series were excluded because of the outlying behaviour of the results (Figure 3). The time series of the heights and height differences include four epochs: 2003, 2005, 2007 and 2009 except at points GPS13 and 05217 where the starting point was 2005.

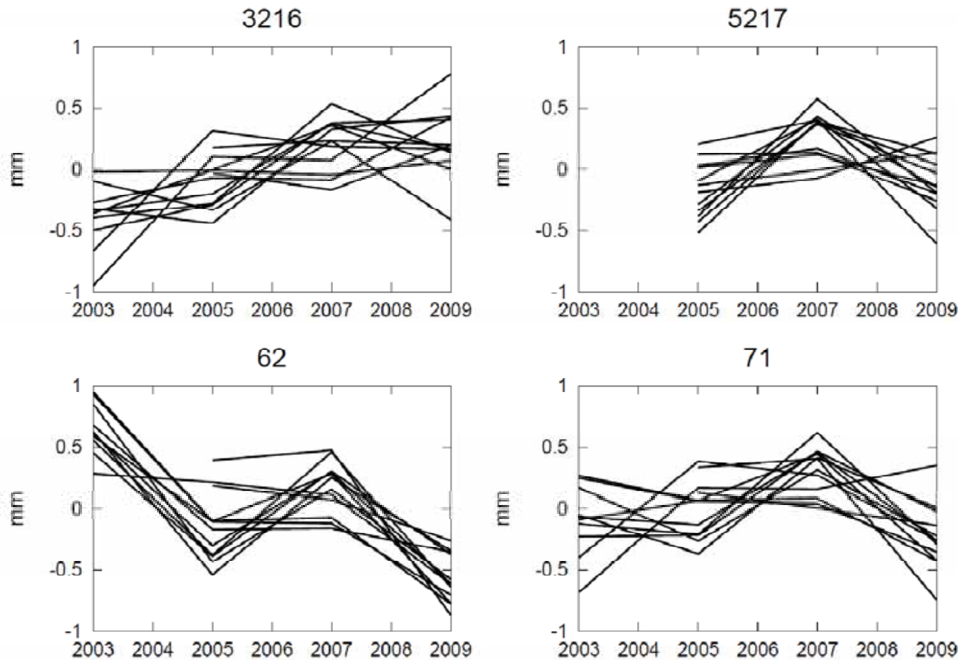

Figure 5. *Change in height difference from the levelling bench marks 3216 and 5217 and the reserve marks of points GPS 6 (62) and GPS7 (71) to the other points of the network. Deviation from the mean in millimetres.*

The deformation analysis was based on the coordinate and height differences between adjacent pillars, which were determined automatically using Delaunay-triangulation. A least squares free network adjustment was applied with station specific velocity parameters (v_X, v_Y, v_Z and v_H respectively) as additional parameters. Because we had no fixed reference coordinates, heights or velocities, there exists a rank deficiency in the normal equation matrix. The solution of unknown parameters was reached by using the pseudoinverse of the normal matrix. In the process the sum of the velocities remains zero.

The results are given in Table 1. The resolved velocities of the GPS time series were transformed to the North-East-Up system. We used a 3σ criterion to test the statistical significance of the estimated velocities, which roughly corresponds the 99% confidence level. The analysis shows statistically significant change rates for five velocity components. However, all estimated horizontal velocities are small (max 0.10 mm/a). For illustration of the results the velocities were interpolated in a grid from the stations values (Figure 6).

If we assume linear continuous vertical movement at each point, the estimated velocities at a point relative to the mean velocity of the points are less than 0.18 mm/a as shown in Table 1 and Figure 6. Because we have only four epochs most of the vertical velocities of the points are not statistically significant. The statistically significant velocities are highlighted. The change in the height difference between the points GPS6 and GPS13 can be due to the construction work of the Olkiluoto 3 nuclear power station.

Table 1. *Estimated horizontal (from GPS) and vertical velocities (from levelling) and the standard deviations (3σ). Statistically significant velocities in bold.*

	North (mm/a)		East (mm/a)		Vertical (mm/a)	
Pillar	Velocity	St.dev x3	Velocity	St.dev x3	Velocity	St.dev x3
1	**-0.086**	**0.062**	0.035	0.048	0.011	0.077
2	**0.104**	**0.081**	0.048	0.063	-0.075	0.096
3	**-0.079**	**0.069**	0.014	0.053	0.064	0.085
4	0.018	0.060	0.017	0.047	**0.080**	**0.075**
5	-0.015	0.069	0.045	0.053	-	-
6	0.038	0.060	**0.064**	**0.046**	**0.162**	**0.073**
7	0.053	0.066	-0.004	0.051	0.016	0.080
8	-0.026	0.070	-0.036	0.054	-0.017	0.075
9	-0.042	0.079	**-0.103**	**0.061**	0.024	0.097
13	0.034	0.150	-0.080	0.116	**-0.176**	**0.125**
3216	levelling bench marks				**-0.087**	**0.077**
3217					0.030	0.070
3218					**-0.012**	**0.072**
5217					-0.021	0.111

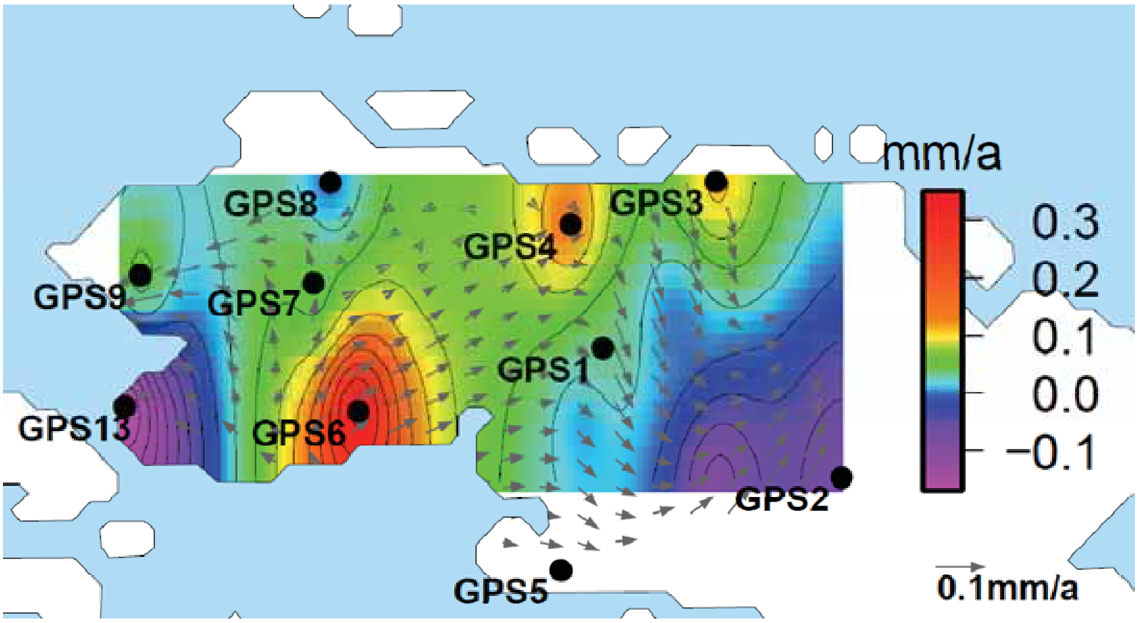

Figure 6. *Horizontal and vertical velocities in Olkiluoto GPS network. The contour lines are at 0.02 mm/a interval and the size of the maximum velocity arrow corresponds roughly 0.1 mm/a.*

5 Conclusions and future

Analysing both the horizontal and vertical velocities gives an insight into the observed total deformations at Olkiluoto. On the basis of ten years GPS measurements horizontal movements larger than 0.3 mm/a can be excluded. The vertical velocities are more uncertain because of fewer measurements and shorter time series. In future the structure of the GPS network will improve, when new permanent stations will be established at Olkiluoto. After a few years of continuous observations we will achieve the current precision level of the velocities for the new pillars. We will also continue with the regular precise levelling campaigns. The joint analysis of the GPS and levelling results may reveal potential interesting sub-areas for the further analysis and interpretation.

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ARCHAEOLOGICAL RADIOCARBON DATES AND ANCIENT SHORELINES – RESOURCES AND RESERVOIRS

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Abstract

The shore displacement of the Baltic Sea has been one of the major dating tools for the prehistoric archaeologists in Finland, and the application of radiocarbon dating has largely improved the quality and the accuracy of the age determination of the prehistoric cultures. The newly compiled archaeological radiocarbon dates database has been used to study ancient population history of Finland. This paper considers the possibilities and challenges of using the archaeological radiocarbon database to study the ancient shorelines of the Baltic Sea. Preliminary results from spatial analyses are presented. In addition, due to complex history of the sea, time-dependent reservoir effect is considered. In this contribution a joint interdisciplinary project is suggested to evaluate this complication.

1 Background

From the beginning of the 20th century, archaeological sites on the shores of the Baltic Sea have been dated with the help of the shore-line chronology (e.g. Europaeus 1930). The co-operation between geologists and archaeologists has been bidirectional: it has not been unusual to date shore-lines according to archaeological sites. This might easily have led to a circular argument, a dilemma which was eventually relieved by the advent of the radiocarbon dating method. The new techniques have also facilitated dating of isolation events of the lake basins with higher accuracy than before. The current shoreline chronology of the Finnish side of the Baltic Sea is based mainly on radiocarbon dates of isolation basins (e.g. Eronen et al. 2001; Miettinen 2004; Miettinen et al. 2007) and archaeological sites are compared with the dated shoreline diagrams. Currently, archaeological radiocarbon dates form an independent database, which could be used together with the isolation contact based shore-line chronology.

Archaeological radiocarbon dates are being used for the study of ancient population sizes. During the last years, summed probability distributions of radiocarbon dates from the archaeological contexts have been used as proxies for the population history events (e.g. Gamble et al. 2005; Shennan & Edinborough 2007). This approach has now been applied also in the Finnish context by collecting and analysing all the available archaeological radiocarbon dates (Tallavaara et al. 2010; Oinonen et al. 2010).

The spatial and temporal distributions of all archaeological finds, whether radiocarbon dated or not, are being utilized in assessing the population history in Finland. Argeopop (http://www.helsinki.fi/bioscience/argeopop/) is a multidisciplinary project aiming at more detailed elucidation of Finnish population history via application of Bayesian spatio-temporal modeling methods to archaeological and (human population) genetic data (Sundell & Onkamo 2010). Archaeological features, especially those that have been radiocarbon dated, can be utilized as an indication of human activity and occupancy in space and time. The Bayesian methodology, on the other hand, provides sophisticated tools to cope with uncertainty inherent in archaeological data (Buck et al. 1996). In the case of Fennoscandian shorelines, the sea level displacement and bedrock uplift processes, as well as the plausible reservoir effect, add extra dimensions to the challenge of assessing the ancient population movements and densities. Not only did they provide newly exposed land for settlement, but also they might have necessitated changes in the sources of livelihood. Together with gradual climate change, these might in turn have affected the (maximum) density of population.

In this contribution, we present examples of radiocarbon-dated (4000-3500 calBC) spatial distributions of archaeological finds as well as ceramics finds over the Eastern Fennoscandia. Based on these we discuss on the status of the spatio-temporal modeling performed through Argeopop project. Within the above-described framework, we also foresee an extensive added value to emerge from tighter collaboration of the experts in dating methodology, spatio-temporal modeling and sea-level displacement. We hope this contribution will prove a trigger of such collaborative efforts. As an example of issues needing more attention, we would like to stress the importance of studies of reservoir effect to improve the present state of the land uplift chronologies within the northern Baltic.

2 Materials and methods

The archaeological radiocarbon analyses performed at the Dating Laboratory (Finnish Museum of Natural History / University of Helsinki) forms the backbone (80%) of the radiocarbon data set. The data has been published as date lists (Jungner 1979; Jungner & Sonninen 1983; 1989; 1996; 1998; 2004) up to Hel-4132 and Hela-154. The data set was extended to cover – as thoroughly as possible – the other published archaeological radiocarbon dates on the eastern Fennoscandian territory measured either at the Dating Laboratory or elsewhere. In addition, the data contains also those unpublished dates that have been kindly released for our use by most of the Dating Laboratory customers.

Altogether, the collected database consists of 2588 individual radiocarbon dates forming a timeline for the period from the earliest colonization in ca. 9000 calBC to the modern era. The database is strongly governed by charcoal finds: of the original data, 55% is from charcoal dates. Wood samples represent another large fraction of dates amounting to 13.5%. The data within the set have been more thoroughly discussed by Oinonen et al. (2010).

As another proxy, we use the prehistoric ceramic database, which was constructed by one of the authors during the late 1990s (Pesonen 1999). From ca. 5200 cal BC onwards, Finnish Stone Age and Bronze Age (ca. 1500-500 cal BC) sites are most easily recognised via pottery finds, which form the basis for the chronological and geographical division of the archaeological cultures. The database is a compilation of information from several sources, the most important being the collections of the National Museum of Finland. The database is described in detail by Tallavaara et al. (2010).

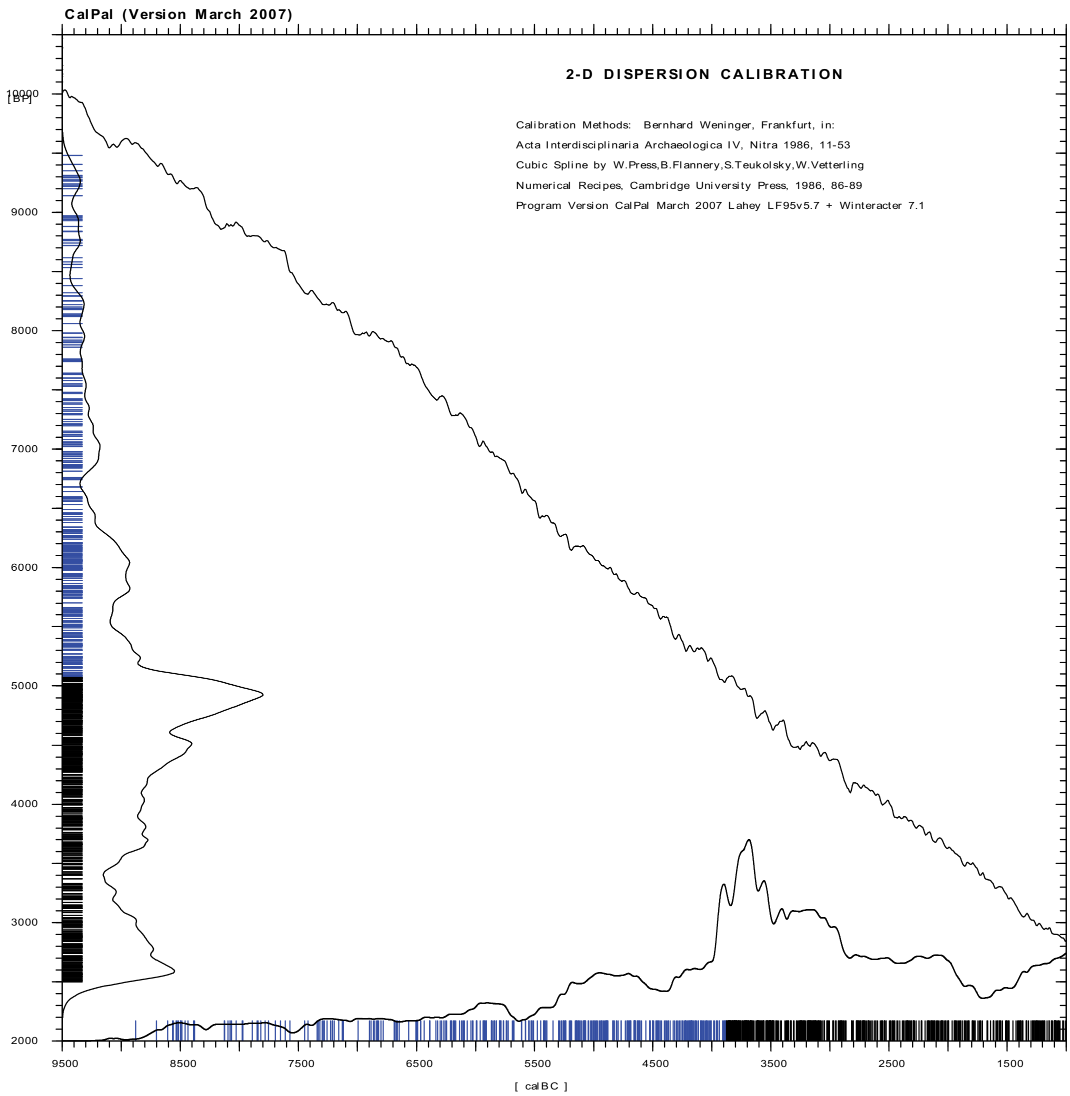

Figure 1. *Summed probability distribution of the radiocarbon dates from Finnish Stone Age and Early Bronze Age contexts between 9500-1000 calBC (n= 889) showing the characteristic maximum at 4000-3500 calBC (cf. Tallavaara et al. 2010; Oinonen et al. 2010). The datings from same sites have not been combined as e.g. in Tallavaara et al. (2010).*

The estimated spatial distributions for the presented maps were produced by a spatio-temporal model based on the Bayesian hierarchical methodology for small area analysis (Besag et al. 1991). The territory of Finland was divided into a grid of 10km x 10km square cells, and each square was given the value 1 or 0 depending on whether there was a find or not. The local probabilities of a find were then given a conditional autoregressive (CAR) prior, which assumes that areas closer together (neighbours) are more alike than the areas farther apart. In this application any cell adjacent through either side or corner was considered a neighbour, resulting in up to 8 neighbours for each cell. The model was estimated using the WinBUGS software (Lunn et al. 2000). A burn-in of 5000 iterations was deemed sufficient upon visual examination of paths and further 5000 iterations were run for monitoring. The estimated posterior means for the probability of a find were then plotted on a map using R-software. (http://www.r-project.org/)

3 Results

For this occasion, we have produced maps describing the Stone Age radiocarbon date maximum ca. 4000-3500 calBC coinciding with the onset of Typical Comb Ware culture (Tallavaara et al. 2010; Oinonen et al. 2010). This phenomenon is recognized as a complex set of “new” features arriving in the archaeological record in the form of exotic materials, sophisticated artefact types, rich grave goods as well as a sturdy house building tradition and it has been speculated, whether this peak prosperity was a consequence of immigration or a local development (e.g. Meinander 1984; Carpelan 1999; Halinen 1999; Pesonen 2002). Whatever reasons there may have been in the background, it is plausible that this probable population expansion has coincided with particularly favourable conditions in the utilization of the resources, both coastal and inland.

The first set of maps (Figs. 2-3) shows altogether 187 radiocarbon datings falling between 4000-3500 calBC and the posterior analysis drawn on the basis of these datings. The second set of maps (Fig. 4) is constructed similarly using the ceramic database, where the 842 records containing Typical Comb Ware, Late Comb Ware or Kierikki Ware were selected. Some of the sites contain several of these ceramic types and consequently, the number of points shown is less than 842. The mentioned ceramic types occur also between 4000-3500 calBC, though not all of the types simultaneously (the datings of the phases, e.g. Tallavaara et al. 2010, p. 253).

4 Discussion

The ceramic database produces quite useful posterior distribution and, particularly, reproduces reasonably well the observed finds near the ancient shoreline. The future evaluation of the prehistoric collections will complement the database significantly. The posterior analysis drawn on the limited radiocarbon database on 4000-3500 calBC still suffers from the lack of data points. The ceramic database and the typological dating of the ceramic phases are not as accurate as the radiocarbon dating usually is, but these databases complement each other. Consequently, one future prospect is a combination of different kinds of datable archaeological signals in the analysis.

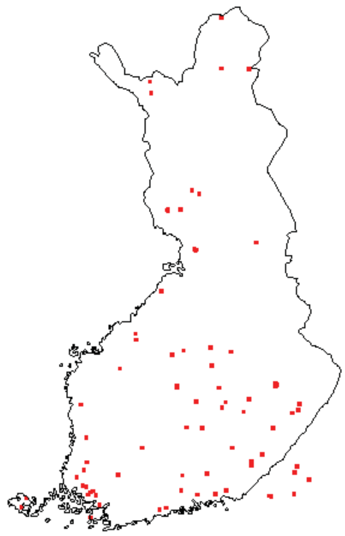

Figure 2. *Places of discovery of the archaeological radiocarbon dates falling between 4000-3500 calBC (population peak) plotted on the map of Finland (n= 187). In this and the following maps the data from the region of Finland and northwestern Russia (the Karelian Isthmus and southwestern parts of the Karelian Republic) are included. Due to map resolution of each square being 10 x 10 km some spots overlap on the map. In addition, some radiocarbon dates derive from the same sites. Thus, the number of places of discovery visible in the figure is less than 187.*

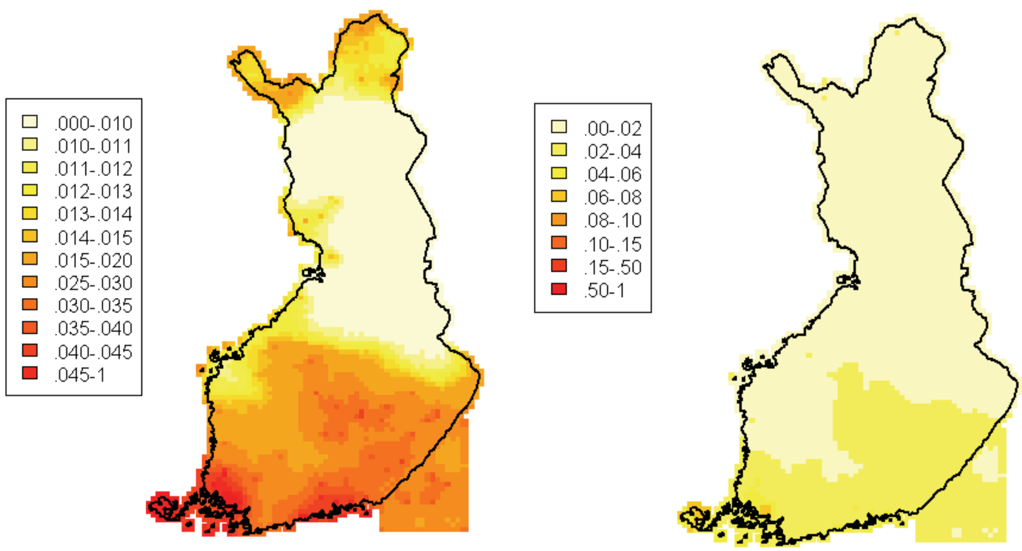

Figure 3. *Posterior analysis of the archaeological radiocarbon dates falling between 4000-3500 calBC. Resulting maps are constructed by introducing the spatial model using data in Fig. 2 as model data and plotting estimated posterior means on the map of Finland. The color of a single square on the map grid is determined by the posterior probability ($0 \leq p \leq 1$) of having a sample that dates between 4000-3500 calBC in the square in question. The colors are specified in the legend. In the right hand map the scale of the posterior probability is changed to correspond the scale used in Fig. 4.*

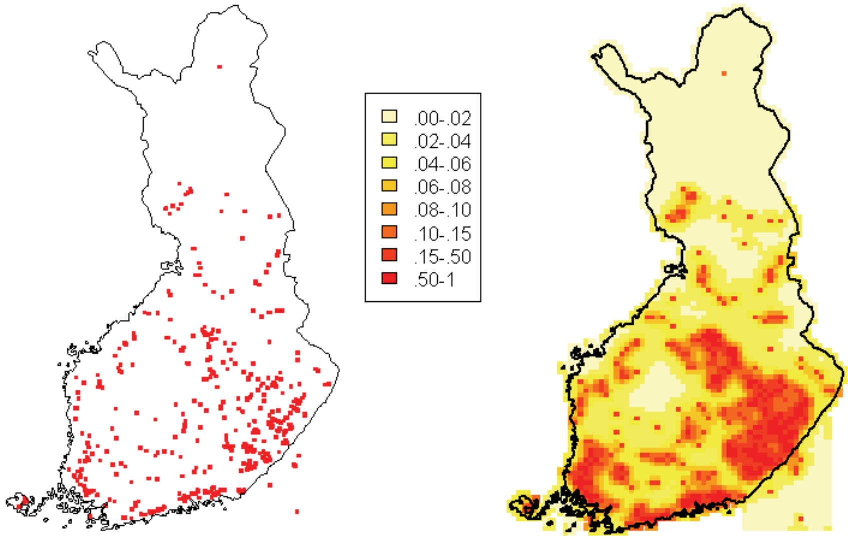

Figure 4. *On the left hand side: places of discovery of Typical Comb Ware, Late Comb Ware and Kierikki Ware between 4000-3500 calBC according to Pesonen (1999) plotted on the map of Finland (n= 842). Some places of discovery overlap due to the map resolution (10 x 10 km squares). Furthermore, some sites are known to harbor more than one ceramic type. The spots follow the ancient coastline of the Baltic Sea especially in the Bothnian Bay. On the right hand side: posterior analysis of the finds of Typical Comb Ware, Late Comb Ware and Kierikki Ware between 4000-3500 calBC. Resulting map is constructed by introducing the spatial model using discovery place data as model data and plotting estimated posterior means (p) on the map. The color of a single square on the map grid is determined by the posterior probability ($0 \leq p \leq 1$) of having ceramic finds between 4000-3500 calBC in the square in question. The color classes are as specified in the map legend.*

In the future, the Bayesian model will also be refined to accommodate e.g. covariate information such as information on whether a full archeological inventory has actually been made on the areas in question, etc. Furthermore, the model for probability in the neighboring squares will be fine-tuned. The grid size might be refined so that instead of using a map grid of 10 km x 10 km squares one might prefer using a map grid of e.g. 1 km x 1 km squares. This should increase the resolution of the analyses significantly.

The settlement sites of the hunter-gatherers were almost exclusively in the immediate vicinity of the water, whether it was sea, lake or river. This basic impression was noted already long ago, but it still seems to hold true, although some exceptions occur (e.g. Jussila & Kriiska 2006). Thus, the settlement sites can be considered to mark the actual location of the shoreline at the time of the occupation. This is seen in the Fig. 4, where the ancient coastline of the Baltic Sea is outlined by the ceramic site dots and the corresponding posterior distribution. The ceramic sites are also partially located within the area of the greatest land uplift and are thus highly relevant for shoreline chronology.

The settlement sites situated in close proximity of the shoreline for obvious reasons: the basins provided waterways for transportation, the lakes and rivers meant a steady supply of water, and most important of all, the aquatic environment is a source of several food resources. The most important of these were seal, fish and water birds (e.g. Nuñez 1990; Ukkonen 2001). The diet of the hunter-gatherers occupying the shores of the Baltic Sea was based on aquatic resources and this should be reflected also in the radiocarbon datings conducted on the materials derived from these sites. This especially holds true for the bone and charred crust datings, both of which may be affected by the reservoir carbon.

Terrestrial plants and the food chains they support acquire most of their carbon from the atmosphere, whereas marine food chains mainly acquire dissolved carbon from the seawater. Therefore marine organisms may be relatively depleted in ^{14}C compared to terrestrial specimen, and modern marine plants and animals can yield apparent ages of hundreds of years. This discrepancy is called the reservoir effect (Morlan 2005). Several factors affect the magnitude of the reservoir age: the geomorphology and the bedrock of the area in question (Olsson 1996). Particularly, limestone bedrock – made of calcium carbonate - acts as a considerable fossil carbon reservoir. If carbon reservoirs are available, the effect may also exist in the freshwaters, though the conclusions of these studies have been somewhat controversial (e.g. Fischer & Heinemeier 2003; Hart & Lovis 2003; Cook et al. 2001).

The size of the reservoir effect may vary both geographically and temporally. The history of the Baltic Sea is characterized by mixing of freshwater and saltwater. Initially, melting of continental ice sheets supplied freshwater and the Baltic Ice Lake was formed probably without significant carbon reservoirs. When saline ocean water started to burst into the lake (Yoldia Sea stage), it probably increased the amount of stable carbon within the basin food chain. Progressive uplift of land cut the central Sweden connection to the ocean transforming the basin to Ancylus Lake ca. 8700 calBC. Thus the oceanic carbon flow stopped although the possible local reservoirs continued to supply carbon into the basin. A new contact was opened to the sea through Danish Straits ca. 7000-6800 calBC, after continuing uplift of land at north. This started again to supply saline and carbonaceous water into the basin transferring it - together with river flows and rainfall - slowly to the brackish Baltic Sea as we now know it. All the above should manifest itself within geological Baltic Sea sediment layers. Furthermore, this all happened in the course of the hunter-gatherers settling their sites at the basin shorelines. Thus, changes in the magnitude of the reservoir effect should be observed also within the archaeological contexts.

Pioneering study within Baltic Sea (Olsson 1980, also in http://intcal.qub.ac.uk/marine) provides estimates of corrections for northern Baltic Sea. The observed values between 300 (Gulf of Finland) and close to 400 radiocarbon years (Bothnian Bay / south of High Coast Archipelago) are in agreement with the globally accepted radiocarbon calibration curve that provides 300-450 years correction for the last 3000 years (Hughen et al. 2004). However, in a geological study of the Lake Lilla Harsjön near Stockholm (Hedenström & Possnert 2001) the authors were able to deduce era-dependent reservoir ages between 1100 and 700 radiocarbon years for Littorina stage, 400 years shortly after the lake isolation and later the effect diminished to zero in the lake – due to ceasing of the marine input. The reservoir age near Gotland, during 2900-2500 calBC seems to be between 70 and 200 years (Possnert 2002; Lindqvist & Possnert 1999; Eriksson 2004).

Summarizing, complex history of the Baltic Sea induces also complex effects of carbon reservoirs.

Salinity within the present Baltic Sea varies from ~ 3‰ to close to the oceanic 35‰ and provides a measure of the oceanic input. However, its power in indicating the magnitude of the reservoir effect is limited by possible local reservoirs. Stable isotopes may provide help for both geological and archaeological samples. For example, Hedenström & Possnert (2001) observed a correlation of natural mass fractionation of carbon isotopes ($\delta^{13}C$) of the bulk sediment and the lake isolation. Bones and food remains in archaeological contexts should behave accordingly: terrestrial diets induce lower $\delta^{13}C$ and $\delta^{15}N$ values compared to marine.

Such indirect studies would support direct determinations of magnitude of the effect – performed on geological, archaeological or paleontological samples. Since the reservoir ages are time-dependent and may vary hundreds of radiocarbon years, we foresee a project combining multidisciplinary expertise to be of high importance in order to get a more accurate picture on the development of the Baltic Sea and population history around the basin.

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SUMMARY

SEMINAR SUMMARY

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In this section, the most prevailing items in the two overall discussions in the seminar and the versatile, lively discussions during the oral and poster sessions are summarised. In the discussion on day one, the main topic was around the starting point for the modelling, i.e. which inputs seem realistic to be available and are there important factors that have been totally omitted from the models. In the end discussion on the second day, a summary was pursued from the viewpoint of understanding and modelling of the sea level displacement and crustal uplift; what is the level of understanding and how it could be improved. The following is a personal synthesis of public discussions during the seminar regardless of their venue.

First of all, the crustal rebound is a result from the weight of the glacier. In more mechanistically oriented models, a key question is how well the pressure by the last glaciation can be hindcast. Some information on the past loading may be extractable from the Eemian deposits e.g. in Seinäjoki and especially in Lapland. Even more uncertain is the possible residual effect of the even earlier glacial events, an issue related to the time between the glaciation and the recovery time of the crust from such effects (apparently much longer than ten millennia since we are still experiencing the rebound from the last depression). However, as long as the need to simulate crustal uplift does not extend over the onset of the future glaciation, empirical and semi-empirical models derived from the various types of observations of the present and past movements seem adequate, at least in (supra)regional scale.

In the large scale, the uplift appears to behave rather smoothly over the Fennoscandia. However, already in national scale, for example, some anomalies start to arise from the general picture, and these may be explained not only by the local variations in the glacial loading (thickness, duration and other properties of the ice sheet) but also by geological formations and structures of the bedrock. There is evidence of post-glacial movements of the bedrock across fracture zones, and tectonic evolution[1] has its role, too. Present stress field in the bedrock has been studied especially in the Satakunta province together with tracking present movements with GPS network and precise levelling. However, the data on vertical movements is more uncertain than on horizontal ones. Datasets used less in the interpretation of the factors related to the crustal rebound include seismic and micro-seismic observations. Anyway, there is potential for new, co-supporting information and thus a clear need for iteration and feedback between the land uplift modelling and lithosphere research.

Third factor affecting to the shore level is, of course, changes in the global sea level reflected further in the water level of the Baltic. The present and past connections to the ocean have limited the water exchange, and indeed the Baltic was a lake (the Ancylus

[1] Pajunen, M. (ed.) 2008. Tectonic evolution of the Svecofennian crust in southern Finland – a basis for characterizing bedrock technical properties. Special Paper 47. Geological Survey of Finland. 326+1 p. http://www.gsf.fi/geotieto/julkaisut/Uusimmat/Julkaisut/SpecialPaper47.html

Lake) for a time. As for example the well-known Fairbanks' curve provides a compendium of global sea level observations in the interglacial time scale, there should be a careful selection of data to be used to derive the Baltic water level curve. For example, the changes of the geoid (see the paper of Markku Poutanen in the present proceedings) should be taken into account in addition to limitations to water exchange. Lake tilting data, when properly considering accumulation processes of bottom sediments and possible water level regulation, would be free from the eustatic (i.e. sea level) component but at least in western Finland most lakes and mires are not large enough to save from sensitivity to the vertical positioning. Overall, methods and data exist to overcome the issues, but the task is not straightforward.

Current challenges in the model development and input data for simulating the crustal rebound and sea level displacement include bedrock block movements[2], sediment dynamics, and variable reliability of past records[3]. Also, reliability and projection issues of historical maps[4] were discussed for the mining of data from the last few centuries. How important issues these are, does depend on the purpose and simulation time window of the model. It was noted that most participants were interested more in the consequences, not in detailed understanding of the mechanisms per se.

The actual land uplift modelling has been done in several scales, e.g. Fennoscandia, Finland, coastline of Satakunta province, spent nuclear fuel repository sites and an island have been represented in the present proceedings. Also several different approaches have been used, including "short-term" estimates using the present land uplift rate, semi-empirical fitting to available datasets, statistical approach etc. In the newest version of the semi-empirical model of Påsse, a separation of peripheral and central area has been introduced resulting in greater differences not in the northern Baltic but near the fringe of the last ice sheet. In despite of the various approaches, models, implementations and input data, the results appear to be in rather good agreement. Is this too good to be true: could it be an artefact of everyone using the same relatively few data? New research is ongoing on the topic, and anyway for practical applications, not least for assessing the future evolution of the nuclear waste repository sites in Fennoscandia, modelling with results is needed with realistic expectations on uncertainties involved and on the reliability of the results. A hold on the sources and effects of the uncertainties is a central issue, as well as testing the models with independent datasets which could be qualitative, too (e.g. indirect or spatially or temporally too imprecise observations to be used as input data to the models).

As a way forward towards further improvements, two lines of development were identified in the discussions: co-operation of land uplift modelling with 1) upper mantle dynamics and lithosphere geology, and with 2) archaeological and pollen studies (latter were unfortunately not well represented in the seminar). In any case, closer Finnish-Swedish co-operation would be useful - it is the same Baltic Shield that is rebounding - preferably involving other countries in the land uplift domain, too.

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[2] It is known that there have been such but data is scarce.

[3] Natural and man-made, especially connecting to accurate enough elevation especially in case of long isolation time of a basin or of archaeological finds.

[4] Before the era of proper clocks there was strong east-west distortion in the maps but in the north-south direction the disctances were easier to determine accurately from stars with rather primitive apparatus.