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An approach to palaeoseismicity in the Olkiluoto (sea) area during the early Holocene

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Keywords: northern Baltic Sea, Holocene, palaeoseismicity, acoustic-seismic survey, glaciation, bedrock, fracture, modelling, dating, pockmarks, faults, turbidites, nuclear waste disposal, safety assessment

Abstract

Olkiluoto Island is situated in the northern Baltic Sea, near the southwestern coast of Finland, and is the proposed location of a spent nuclear fuel repository. This study examined Holocene palaeoseismicity in the Olkiluoto area and in the surrounding sea areas by computer simulations together with acoustic-seismic, sedimentological and dating methods. The most abundant rock type on the island is migmatic mica gneiss, intruded by tonalites, granodiorites and granites. The surrounding Baltic Sea seabed consists of Palaeoproterozoic crystalline bedrock, which is to a great extent covered by younger Mesoproterozoic sedimentary rocks. The area contains several ancient deep-seated fracture zones that divide it into bedrock blocks.

The response of bedrock at the Olkiluoto site was modelled considering four future ice-age scenarios. Each scenario produced shear displacements of fractures with different times of occurrence and varying recovery rates. Generally, the larger the maximum ice load, the larger were the permanent shear displacements. For a basic case, the maximum shear displacements were a few centimetres at the proposed nuclear waste repository level, at proximately 500 m b.s.l.

High-resolution, low-frequency echo-sounding was used to examine the Holocene submarine sedimentary structures and possible direct and indirect indicators of palaeoseismic activity in the northern Baltic Sea. Echo-sounding profiles of Holocene submarine sediments revealed slides and slumps, normal faults, debris flows and turbidite-type structures. The profiles also showed pockmarks and other structures related to gas or groundwater seepages, which might be related to fracture zone activation. Evidence of postglacial reactivation in the study area was derived from the spatial occurrence of some of the structures, especial the faults and the seepages, in the vicinity of some old bedrock fracture zones.

Palaeoseismic event(s) (a single or several events) in the Olkiluoto area were dated and the palaeoenvironment was characterized using palaeomagnetic, biostratigraphical and lithostratigraphical methods, enhancing the reliability of the chronology. Combined lithostratigraphy, biostratigraphy and palaeomagnetic stratigraphy revealed an age estimation of 10 650 to 10 200 cal. years BP for the palaeoseismic event(s).

All Holocene sediment faults in the northern Baltic Sea occur at the same stratigraphical level, the age of which is estimated at ~10 700 cal. years BP (~9500 radiocarbon years BP). Their movement is suggested to have been triggered by palaeoseismic event(s) when the Late Weichselian ice sheet was retreating from the site and bedrock stresses were released along the bedrock fracture zones. Since no younger or repeated traces of seismic events were found, it corroborates the suggestion that the major seismic activity occurred within a short time during and after the last deglaciation.

The origin of the gas/groundwater seepages remains unclear. Their reflections in the echo-sounding profiles imply that part of the gas is derived from the organic-bearing Litorina and modern gyttja clays. However, at least some of the gas is derived from the bedrock. Additional information could be gained by pore water analysis from the pockmarks.

Information on postglacial fault activation and possible gas and/or fluid discharges under high hydraulic heads has relevance in evaluating the safety assessment of a planned spent nuclear fuel repository in the region.

HUTRI Kaisa-Leena. Olkiluodon (meri)alueen varhaisholoseenikauden paleoseismiikkatutkimuksia. STUK-A222. Helsinki 2007, 64 s. + liitteet 55 s.

Avainsanat: pohjoinen Itämeri, Holoseeni, sedimentti, paleomaanjäristykset, akustis-seismiset luotaukset, jäätiköityminen, kallioperä, rakoilu, mallinnus, ajoitus, purkausaukot, siirrokset, turbidiitit, loppusijoitus, käytetty ydinpolttoaine, turvallisuusanalyysi

Tiivistelmä

Tutkimuksessa selvitettiin Olkiluodon ja sitä ympäröivien merialueiden jääkauden jälkeistä maanjäristyshistoriaa kallioperän jäätiköitymissimulaatioiden, merenpohjan akustis–seismisten luotausten ja sedimenttitutkimusten avulla. Olkiluodon saaren kallioperä koostuu pääasiassa syväkivien lävistämistä migmatiittisista gneisseistä. Ympäröivän merialueen pohja muodostuu paleoproterotsooisesta kallioperästä, jonka päälle mesoproterotsooiset sedimenttikivet ovat kerrostuneet. Useat ikivanhat ruhjeet ja raot halkovat alueen kallioperää.

Kallioperän käyttäytymistä simuloitiin erilaisten jääkausiskenaarioiden mukaisesti. Kalliolohkojen suurimmat siirtymät liittyivät yleensä suurimpiin jäätikön kuormituksiin. Perusskenaariolla siirtymät loppusijoitussyvyydellä, noin 500 metriä, olivat muutamia senttimetrejä.

Merkkejä mahdollisista maanjäristyksistä merenpohjan sedimenttikerrostumissa kartoitettiin akustis–seismisillä menetelmillä. Holoseenin aikaisista kerrostumista löytyi erilaisia liukumarakenteita, siirroksia, maanvyörymiä, turbidiittisia rakenteita ja pohjaveden tai kaasujen purkautumisaukkoja, jotka saattavat olla kytköksissä maanjäristyksiin. Merenpohjan kerrostumissa esiintyvät siirrokset ja purkautumisaukot sijaitsevat kallioperän ruhjeiden läheisyydessä, mikä viittaa ruhjeiden uudelleenaktivoitumiseen jäätikön vetäytymisvaiheessa.

Olkiluodon alueella löydetyt savisedimenttien siirrokset ajoitettiin paleomagnetismin, piileväanalyysin ja litostratigrafian avulla syntyneen noin 10 650 – 10 200 kalenterivuotta sitten. Myös muilla tutkituilla merialueilla havaitut siirrokset esiintyvät samalla stratigrafisella tasolla. Merkkejä nuoremmista tai toistuvista siirroksia ei havaittu, mikä vahvistaa käsitystä siitä, että jääkauden jälkeinen seisminen aktiivisuus on ollut suurimmillaan heti jäätikön vetäydyttyä alueelta.

Kaasu- ja/tai pohjavesipurkausten alkuperä ei tutkimuksessa selvinnyt. Luotausprofiilien perustella voidaan päätellä, että osa purkauksista on peräisin savikerrostumista mutta osa voi tulla myös kallioperästä. Lisätietoa purkausten alkuperästä voitaisiin saada purkauskaasujen ja/tai -veden analyyseillä.

Tutkimuksessa saatuja tietoja voidaan käyttää hyväksi käytetyn ydinpolttoaineen loppusijoituksen turvallisuusanalyysin ennusteiden ja oletusten verifioimisessa.

Contents

List of original publications

This is an article dissertation, based on the material and results originally presented in the following papers referred to in the text with Roman numerals. This thesis includes some additional data as an annex.

I Hutri K, Antikainen J. Modelling of bedrock response to glacial loading at Olkiluoto site, Finland. Engineering Geology 2002; 67 (1–2): 39–49.

II Kotilainen A, **Hutri** K. Submarine Holocene sedimentary disturbances in the Olkiluoto area of the Gulf of Bothnia, Baltic Sea: a case of postglacial palaeoseismicity. Quaternary Science Reviews 2004; 23 (9–10): 1125–1135.

III Hutri K, Heinsalu A, Kotilainen AT, Ojala AEK. Dating early Holocene palaeoseismic event(s) in the Gulf of Bothnia, Baltic Sea. Boreas 2007; 36: 56–64.

IV Hutri K, Kotilainen AT. An acoustic view into Holocene palaeoseismicity offshore southwestern Finland, Baltic Sea. Marine Geology 2007; 238 (1–4): 45–59.

Annex: Hutri K, Kotilainen AT, Rantataro J, Hämäläinen J, Alvi K, Sonninen E. Gas studies in the Olkiluoto sea area. The Finnish Research Programme on Nuclear Waste management (KYT) 2002–2005, Final Report. VTT Research Notes 2337. Espoo: VTT; 2006: 147–154.

Author's contribution to the articles

I The study was planned by K. Hutri who was responsible for the scenarios and data gathering. J. Antikainen performed the rock mechanical simulations. K. Hutri wrote the article with contributions from J. Antikainen.

II The study was planned by K. Hutri and A. Kotilainen. A. Kotilainen carried out the acoustic-seismic data interpretations. The article was written by both contributors.

III The study was planned by K. Hutri and A. Kotilainen. A. Heinsalu carried out the diatom analysis and A. Ojala compared the PSV curves and provided original data from Lake Nautajärvi. K. Hutri and A. Kotilainen did the lithostratigraphical description and paleomagnetic interpretations. K. Hutri wrote the article, which was commented on by the other contributors.

IV The study was planned by K. Hutri, who also carried out the acoustic-seismic data interpretations. K. Hutri wrote the article, which was commented on by A. Kotilainen.

Annex The study was planned by K. Hutri and A. Kotilainen. They carried out the field studies together with J. Hämäläinen and K. Alvi. E. Sonninen did the methaine concentration measures. K. Hutri wrote the article, which was commented by the other contributors.

1 Introduction

1.1 Palaeoseismicity and postglacial faulting in Fennoscandia

During the Weichselian glaciation the bedrock of Fennoscandia underwent massive loading and depression followed by strong isostatic rebound (Kakkuri, 2001). This had an important influence on the development of stress fields of rock masses, and consequently on earthquake intensity in former glaciated terrains (Mörner, 1991; Fjeldskaar *et al.*, 2000; Muir-Wood, 2000; Stewart et al., 2000).

In northern Fennoscandia, several large-scale (up to 160 km long) bedrock faults (Pärve, the Lansjärv, Lainio-Suijavaara, Venejärvi, Ruostejärvi, Pasmajärvi, Suasselkä, and Stuoragurra) have been found cutting and displacing into Quaternary deposits overlaying the fault zone (a.o.t. Tanner, 1930; Kujansuu, 1964, 1972, 1992; Lundqvist & Lagerbäck, 1976; Olesen, 1988; Muir-Wood, 1989; Lagerbäck, 1990; Olesen *et al.*, 1992a and b, 1995; Lukashov, 1995; Dehls *et al.*, 2000). They are suggested to be old fracture zones, which became reactivated within the retreating stages of the ice sheet (Lundqvist & Lagerbäck, 1976; Kuivamäki *et al.*, 1998), when the rate of isostatic land uplift from postglacial rebound was considerably higher than that continuing today (Ristaniemi *et al.*, 1997). All these faults are reverse faults orientated NE-SW and dipping to SE. In view of the length of the faults, Arvidsson (1996) has estimated that the causative earthquakes would have had magnitudes of about 8 between 8500 to 9000 years ago. The magnitude estimation of earthquakes that caused the postglacial faults[1] in northern Finland is less, from 6 to 7 (Kuivamäki *et al.*, 1998). In Finnish Lapland, the postglacial faults are surrounded by several landslides that involved sudden mass movements of till deposits about 8000 years ago (Kujansuu, 1972; Kuivamäki *et al.*, 1998).

In southern Fennoscandia there are only a few postglacial faults, e.g. along the Norwegian Trench (Hovland, 1983). Some minor postglacial faults and pop-ups have also been found in eastern and southerwestern Finland (Kuivamäki et al., 1998). The postglacial faults located on the southwestern coast of Finland (in Linjen, Lambholm, Lanskeri and Pukeenluoto) are some millimetres to one metre in the vertical dimension and their length varies

[1] In the following text, the term "postglacial fault" means that the fault has been (re)activated during the Holocene.

from some metres to tens of metres (Edelman, 1949; Kuivamäki *et al.*, 1998) (Figure 1). They have been found on outcrops polished and scratched by the Weichselian ice sheet. Similar faults and pop-ups have also been reported in Canada (Rampton *et al.*, 1984; Dionne *et al.*, 1988; Adams 1988; Shilts *et al.*, 1992a). However, no postglacial faults deforming Pleistocene or Holocene deposits have been observed in central or southern Finland. There the ice cover was probably thinner and lasted for shorter times, and the deglaciation in the south was a much slower process (Sauramo, 1929; Lunkka *et al.*, 2001; Johansson & Kujansuu, 2005) leading to a slower rate of isostatic rebound than in the north. During and just after the last deglaciation, as large areas of the present land were also below the highest shoreline, the water cover may have dampened potential earthquakes (Saari, 1998). Possible evidence may also have been later wiped out or blurred by processes modifying the morphology of the earth surface (e.g. weathering, erosion, human action).

1.2 Indirect sediment records of palaeoseismicity

Soft-sediment deformations, such as postglacial clay liquefaction and varve disturbance, and mass transport features from former glaciated environments in Sweden (Lagerbäck, 1990; Mörner *et al.*, 2000; Tröften, 1997, 2000; Tröften & Mörner, 1997), Norway (Bondevik *et al.*, 1997), Scotland (Ringrose, 1989) and Canada (Piper *et al.*, 1985; Shilts et al., 1992a, 1992b; Eyles *et al.*, 2003) have been discussed in possible connection with palaeoseismicity. Boulder caves may also be connected to palaeoseismicity (Mörner *et al.*, 2000). In southern Sweden, recurrence seismicity at the time of deglaciation has been claimed (Mörner, 1996; Tröften, 1997). All these features may also result from other, non-seismic processes (e.g. Shilts *et al.*, 1992b; Tröften, 1997) and thus need to be carefully considered case by case. In Finland, Sauramo (1918, 1923) and Niemelä (1971) have described some disturbance structures in laminated sediments in south-western Finland, but no relation to earthquakes has been suggested[2]. Recently, Virtasalo (2006) considered a disturbed sediment unit, Trollskär Allomember, in the Archipelago Sea to be connected with palaeoseismic activity.

In pre-Quaternary deposits of the Baltic Sea, faults with vertical displacement of layers are common (e.g. Sviridov, 1981; Winterhalter *et al.*, 1981), and there are a few submarine and lacustrine indications of disturbance structures in Quaternary sediments that may reflect earthquake deformation (Sviridov, 1981; Winterhalter *et al.*, 1981; Vangkilde-Pedersen *et al.*, 1993; Jensen *et al.*, 2002). Vangkilde-Pedersen *et al.* (1993) connected the disturbance structures of the Holocene sediments in the Kattegatt region to the Sorgenfrei-Tornqvist

[2] The sediment cores of Sauramo (1918, 1923) and Niemelä (1971) were found to have suffered during the years thus they could not be used further for this study.

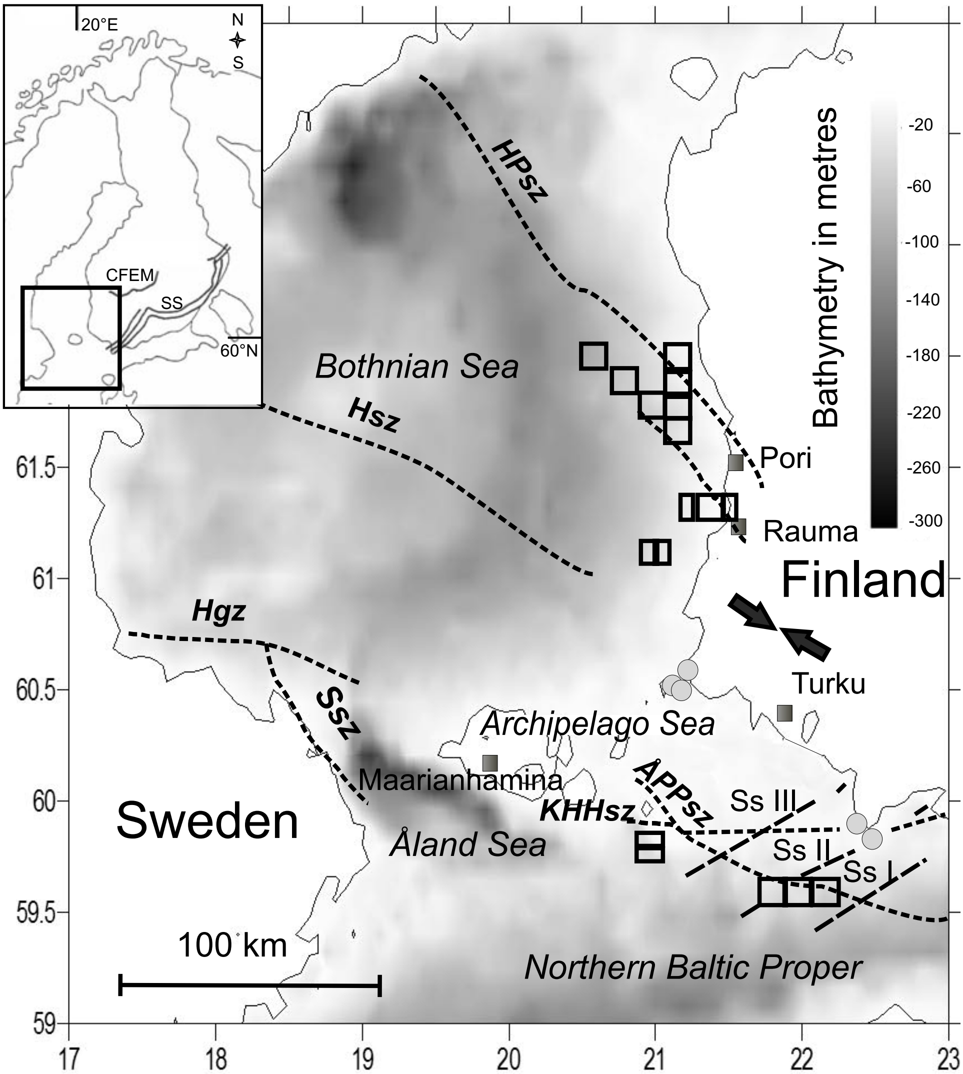


Figure 1. Bathymetric information on the study area and some major tectonic zones in the northern Baltic Sea region according to Korja and Heikkinen (2005), Koistinen *et al.* (1996), Koistinen *et al.* (2001) and Flodén (1982). Hsz = Hassela shear zone, Hgz = Hagsta deformation zone, Ssz = Singö shear zone, ÅPPsz = Åland-Paldiski-Pskov shear zone, HPsz = Härnösand-Pori shear zone, KHHsz= Kökar-Hanko-Helsinki shear zone. The study area is marked with a rectangle in the icon and the surveyed map sheets are marked with 10 km × 10 km squares. The letters Ss I–III refer to the Salpausselkä End Moraine formations and CFEM to the Central Finland End Moraine formation. The regional stress field is marked with arrows. The locations of the small-scale postglacial faults are marked with grey circles (Kuivamäki, 1998).

tectonic zone. However, it has to be remembered that high-resolution acoustic profiles have been scarce so far (Winterhalter *et al.*, 1981).

Seafloor pockmarks formed by gas and groundwater escapes (Hovland & Judd, 1988) are also recognised as possible indicators of palaeoseismicity, since movements along bedrock faults have been found to facilitate gas escapes (Hovland *et al.*, 2002; NGU, 1998; Söderberg & Floden, 1991, 1992; Duck & Herbert, 2006).

1.3 Mechanism for postglacial faulting

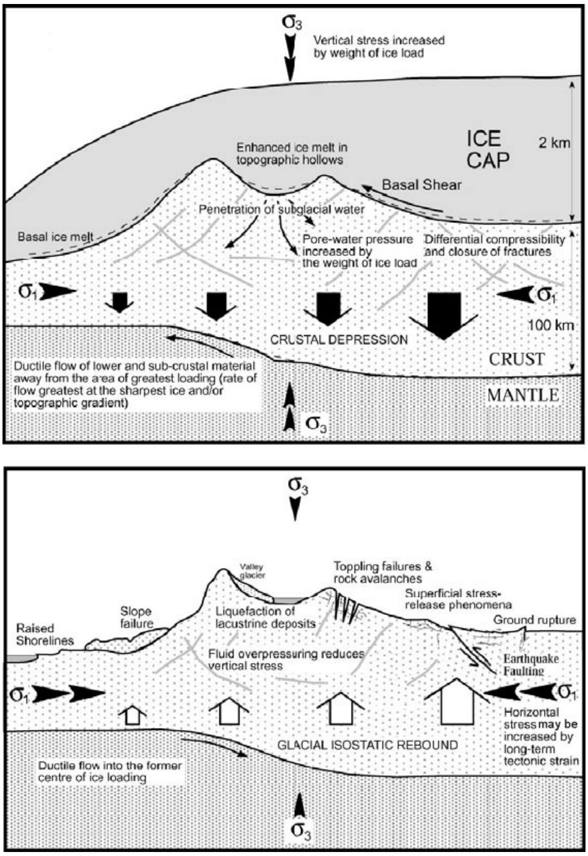
In Fennoscandia, and also elsewhere in northwest Europe and North America, all postglacial faults have been found in areas with currently low to moderate seismicity (Fenton, 2003). In Fennoscandia, the areas of postglacial faulting are still seismically the most active areas (Ojala *et al.*, 2004). Bedrock failures caused by pronounced changes in the stress field as a consequence of the growth and decay of the Weichselian glaciation have been analysed by several scientists (e.g. Adams, 1989; Muir-Wood, 1989; Wu *et al.*, 1999; Johnston, 1998; Stewart *et al.*, 2000).

According to Adams (1989), the most likely location for postglacial (PG) faults is in front of the ice sheet, where the regional stress adds to the stress caused by the ice load, assuming that the maximum horizontal stress (σ_H) direction is perpendicular to the ice margin. However, large postglacial faults should then also exist in central and southern Finland.

Muir-Wood (1989) suggested that during the glaciation the material in the lower crust and mantle flows towards the ice margins. When the ice retreats the material flow in the lower crust and mantle turn back towards to the retreating ice margin, causing friction. The additional stress from friction together with the horizontal stress creates shear stresses in the crust, resulting in thrust faulting in the areas free of ice. This is illustrated in Figure 2 a, which is modified after Muir-Wood (1989) and Stewart (2000) by Ojala *et al.* (2004). This model explains successfully the large postglacial thrust faults in Northern Fennoscandia.

A model of Stewart *et al.* (2000) suggests that directional variability in stress field can result in different types of faulting (Figure 2 b). Modelling by Johnston *et al.* (1998) suggests that different scales of glacial load may have induced different crustal responses. According to the viscosity model of Johnston *et al.* (1998), within the former glaciated region thrust faulting is predicted to occur at the end of deglaciation and normal faulting is predicted to occur in peripheral regions for the entire period since the last glacial maximum. The onset of instability is predicted around 12 ka BP and fault instability is predicted to reach maximum values around 9 ka BP (Johnston *et al.*, 1998).

a)



b)

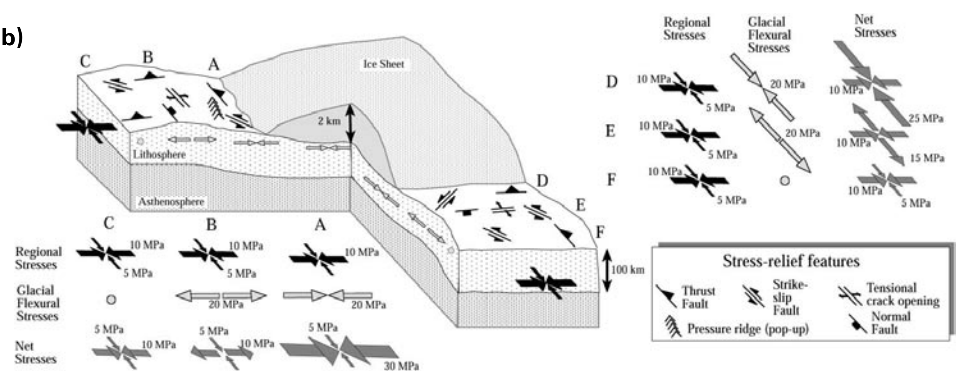


Figure 2. a) The theory of postglacial faulting according to Ojala *et al.* (2004) modified from Stewart *et al.* (2000), Muir-Wood (1989) and Fenton (1992), **b)** to Stewart *et al.* (2000) modified from Adams (1989) and Walcott (1970).

In northern Fennoscandia, the postglacial faults generally strike NNE-SSW and dip to SE. In some cases they have been formed either perpendicular or parallel to the former ice margin at the glacial maximum, but fairly perpendicular to the greatest principal stress. According to Wu (1998), in those cases where the faults are parallel to the former ice margin, it is unclear whether the faulting was determined by postglacial rebound or by plate tectonics. The model by Wu *et al.* (1999) considering tectonic stress, overburden pressure, gravitationally self-consistent ocean loading, and the realistic deglaciation history and compressible Earth model suggests that postglacial rebound is the most likely cause of the large postglacial thrust faults observed in Fennoscandia. Fjeldskaar *et al.* (2000) interpreted the present glacial isostatic uplift in these areas to be overprinted by a weak (approx. 1 mm/a or about 10%) tectonic uplift component.

1.4 Aim of the study

Olkiluoto Island, situated off the southwestern coast of Finland (Figure 3), has been selected as the site for a repository of spent nuclear fuel in Finland. In evaluating the safety of the nuclear waste repository, an important consideration is the long-term stability of the surrounding bedrock. According to climate predictions we will encounter a new glaciation episode during the next 100 000 years (Kukla *et al.*, 1981; Imbrie & Imbrie, 1980; Matthews, 1984; Berger & Loutre, 1997; Loutre & Berger, 2000). Postglacial tectonic movements and high hydraulic gradients (related to glacial meltwater intrusion and discharge) are relevant to safety assessment of a spent nuclear fuel repository, since they are the major threats to repository safety related to glacial scenarios (Vieno & Nordman, 1999). However, significant regional fracture zones were already avoided during the site investigations (McEwen & Äikäs, 2000), and large postglacial faulting that could harm the disposal canisters is not expected to occur within or near the repository area (La Pointe *et al.*, 1997).

The aim of this study was 1) to examine by computer simulations how the bedrock might behave during a possible future glaciation and what would be the impact of different glacial scenarios. Olkiluoto Island was also selected as study site for modelling since a conceptual bedrock model was available and a variety of investigations had already been carried out. Further goals were 2) to investigate with acoustic–seismic methods possible traces of Holocene palaeoseismicity and 3) to date the possible palaeoseismic events detected.

Because the possibility of detecting undisturbed relicts of palaeoseismic events is higher in sea-bottom sediments than on land and they are also easier to map there, the field investigations were conducted in the sea areas around Olkiluoto Island. To put the results into a larger spatial context, available acoustic–seismic material within the surrounding 200 km was included in the study (Figure 3). These areas were also regarded as bringing regional representativeness (e.g. with a different deglaciation history and sedimentation environment) to the study.

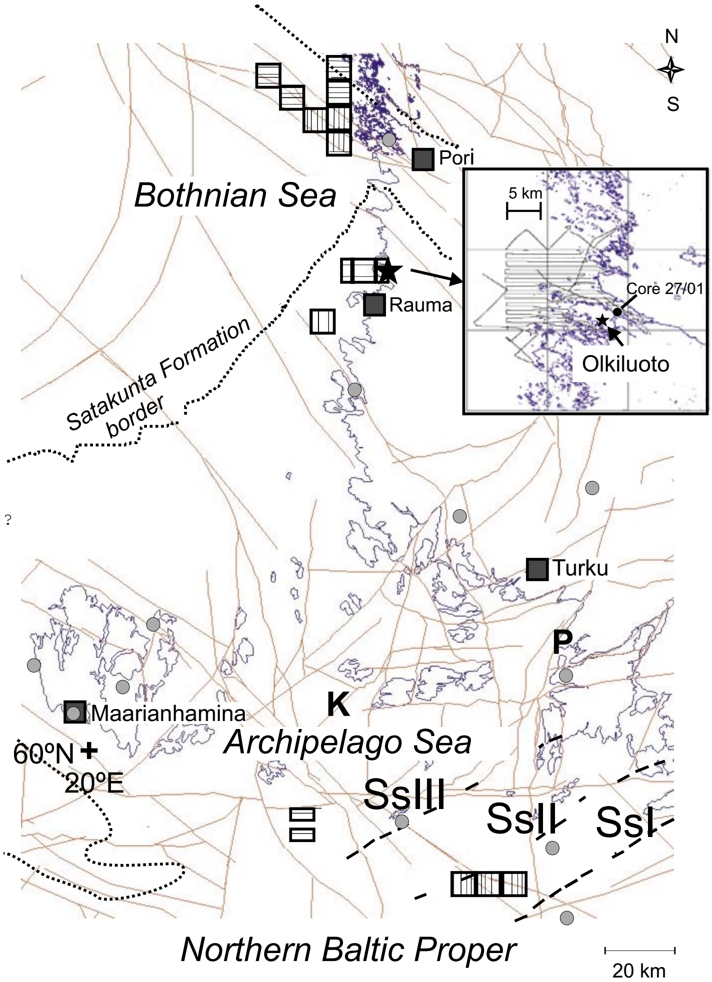


Figure 3. The study areas are indicated on the map with squares according to the Finnish map sheet division. The locations of the survey profiles are marked as horizontal or vertical lines inside the map sheet squares, indicating mainly east-west or north-south directions. The profiles are located about 500 m from each other. The icon shows a detailed survey map near Olkiluoto Island and the sampling site of the core 27/01. The bedrock fracture zones according to Kuivamäki (2005) are shown with reddish lines. The letters Ss I-III refer to the Salpausselkä End Moraine formations. Letters K and P represent Kråkskär and Paimionlahti areas referred to in the text. The earthquake epicentres (1375–1995) with magnitude M ≥ 1.5 in the area (Saari, 1998) are marked with grey dots. The approximate border of the Satakunta Formation is marked with a dashed line (Koistinen *et al.*, 1996).

2 The study area

2.1 Locations

Olkiluoto Island is located off the southwestern coast of Finland (Figure 3). The additional study areas, where the acoustic–seismic surveys were conducted, are located in the southern Bothnian Sea (Finnish map sheets 1132-04, -06, -09, -12, 1124-09, -11, 1142-01, -04, -05, -06, and 1141-06), in the Archipelago Sea (Finnish map sheets 1031-01 and -02) north of the Salpausselkä III end moraine, and in the northern Baltic Proper between the Salpausselkä I and II end moraines (Finnish map sheets 1M44-03, -06 and -09), within a distance of 200 km of Olkiluoto (Figure 3). Figure 1 displays general bathymetric information on the northern Baltic Sea.

2.2 Geological settings

Olkiluoto Island (Figure 3) emerged from the Bothnian Sea about 3000 years ago. The topography is subdued in relief, being usually less than 5 metres above sea level (Eronen *et al.*, 1995). The bedrock of Olkiluoto mainly consists of Precambrian Svecofennian rocks, 1850–1900 Ma in age (Suominen *et al.*, 1997). The most abundant supracrustal rocks are migmatic gneisses intruded by intermediate and felsic plutonic rocks, tonalites, granodiorites, granites and pegmatites. In the northern parts the gneisses are weakly migmatized. Migmatization is stronger towards the southern and southeastern parts of the island, forming vein gneisses. The youngest rocks are diabase dikes (1650 Ma), crossing the older rocks. All rock types, except diabase, have gone through five plastic deformational phases. The main fracture directions from surface mapping are firstly ENE-WSW, which is parallel to the foliation and migmatic banding, secondly a direction perpendicular to the previous one, and thirdly, a direction that intersects these at an oblique angle (Anttila *et al.*, 1999). According to acoustic–seismic studies (Rantataro, 2000), the contact of the sedimentary rocks in the Baltic Sea is at least in some places at Olkiluoto about 6 km from the coastline.

In the Bothnian Sea the depositional basement of the Mesoproterozoic Satakunta Formation consists of Paleoproterozoic (Svecofennian) crystalline rocks (Winterhalter *et al.*, 1981). Presently the Satakunta Formation covers a northwest elongated, fault-bounded area about 15 by 100 km in size in a graben setting (e.g. Kohonen and Rämö, 2005). In the Archipelago Sea and in the northernmost Baltic Proper the crystalline rocks are exposed. They are mainly granites, gabbro, micaschist and gneisses (Koistinen *et al.*, 2001).

According to previous marine geological studies (Winterhalter, 1992; Rantataro, 2000), the following main units can be distinguished in the northern Baltic Sea Holocene sediments. Till (unit 1) was probably deposited by Late Weichselian glacier activity. The oldest glacioaquatic sediments (unit 2) thin upwards into distal varved sediments (unit 3) deposited during deglaciation. Sulphide-bearing clays (unit 4) are commonly associated with the "lower Ancylus Lake" sediments (Ignatius *et al.*, 1968). The upper parts of the unit 4, *i.e*. "Upper Ancylus Lake" sediments, are mainly homogenous, typically (bluish) grey clay containing concretions of marcasite/pyrite. At the onset of the Litorina Sea phase (~8000 cal. years BP), conditions changed from freshwater to brackish (Andrén *et al.*, 2000a, 2000b). This change can be observed across the entire Baltic Sea area as a switch from (bluish) grey Ancylus clays to organic-rich Litorina clay-gyttja or gyttja clays. In the Baltic Sea these sedimentary units (borders of them) are diachronic, i.e. older in the southern than the northern study area. Litorina clays (unit 5) are organic-rich gyttja clays and the recent sediments (unit 6) are affected by anthropogenic activities. The thickness of the glacial and postglacial deposits varies considerably in the study area, being probably thickest in the northern Baltic Proper area, even exceeding 80 m (Häkkinen, 1990).

Sedimentation rates in the study area have greatly varied during the Holocene. The mechanism of deposition depends on several factors, such as water salinity, winds and currents, water depth and bottom topography and also on the amount of suspended material (Nuorteva, 1994). The mean postglacial sedimentation rates are calculated to have been between 0.1–2.0 mm/yr (Ignatius, 1958). The present sediment accumulation rates also vary considerably between different parts of the Baltic Sea, with measured values from 60 to 6160 $gm^{-2}yr^{-1}$ (Mattila *et al.*, 2006). The glacial clays and Ancylus clay smoothly conform to the bottom topography, whereas the younger Litorina gyttja clays are deposited as a "basin fill" type (Winterhalter, 1992).

The timing of deglaciation in the study areas can be estimated according to varve chronologies (Sauramo, 1929; Saarnisto & Saarinen, 2001; Strömberg, 2005), and the Salpausselkä I and II formations (Saarnisto & Saarinen, 2001). The final meltwater discharge of the Baltic Ice Lake to the Atlantic Ocean was a sudden event that is currently dated at 11 590 ± 100 cal. years BP (Saarnisto & Saarinen, 2001), also being the zero varve in the Finnish varve chronology. Applying this information, the whole study area deglaciated between ~12 250 and ~ 10 890 cal. years BP.

2.3 Seismotectonic setting

The current stress field in Fennoscandia is dominated by the tectonic forces sustained by the Mid-Atlantic Ridge push. The NW-SE direction of tectonic compression is dominant (Reinecker *et al.*, 2005) (Figure 1). However, the maximum horizontal stress also depends on depth, and the regional stress fields may include components of tectonic and local effects (e.g. glacial rebound) (Martin *et al.*, 1990). Creeping movement along old faults striking from NW to SE is regarded as a normal mechanism for releasing this stress (Saari, 1998).

During and just after the latest deglaciation the whole study area was submerged from 40 m to more than 160 m (Eronen *et al.*, 2001). The present land uplift varies from ~3 to 6 mm/yr (Ekman & Mäkinen, 1996) from south to north. Studies of Kakkuri (1985), Veriö *et al.* (1999) and Lehmuskoski (1996) suggest that the present uplift in Finland can be considered plastic on a regional scale, but on a local scale there can be small block movements. Small bedrock movements may also due to temperature changes in the rock (Lehmuskoski *et al.*, 2003).

The major fracture zones of the Baltic region (Figure 3) provide a basis for seismotectonic correlation (Flodén, 1982; Koistinen *et al.*, 1996, 2001; Saari, 1998, 2000; Korja and Heikkinen, 2005; Kuivamäki, 2005). Several NW-SE and NE-SW trending tectonic zones and fracture zones are typical for the whole study area, most of them being very old. Many faults denote tectonic zones that have been activated during several geological events since the Archean (Winterhalter *et al.*, 1981).

The present seismicity in the study area is low, and according to the Fennoscandian earthquake database (Ahjos & Uski, 1992; Institute of Seismology, University of Helsinki, 1998) only approximately ten small (M<3) earthquakes have occurred in the area since 1375. Most of these have been located along the NW-SE trending fracture zones (Figure 3). The 600 km long and 150 km wide Åland-Paldiski-Pskov shear zone (Figure 1) has a somewhat higher seismicity (Saari, 1998, 2000). Small earthquakes may occur in the lengthening of quietly creeping fractures, reflecting ongoing bedrock deformation processes over a time span of thousands of years (Saari, 1998). Recent GPS measurements carried out in the Olkiluoto area (Ollikainen *et al.*, 2004) have affirmed very small crustal movements indicating the motion of the Eurasian plate, and the horizontal crustal velocity vectors in southwestern Finland are SE-NW (Milne et al., 2001).

3 Material and methods

3.1 Bedrock behaviour modelling under glacial scenarios (Paper I)

Bedrock stability changes, displacements of rock blocks and the sensitivity of rock properties to block displacements at Olkiluoto were evaluated with the 3DEC (3-Dimensional Distinct Element Code) modelling programme considering four future glaciation scenarios (Paper I, Figures 2–5). Three of the scenarios were developed by Finnish and Swedish nuclear waste management companies according to different future climate predictions (Forsström, 1999; SKB, 1999). These scenarios did not include any ice-free interstadials. The fourth one was drafted by the author according to the Weichselian glaciation scheme (Ukkonen *et al.,* 1999; Donner, 1999) with two interstadials (Paper I). The ice thicknesses are converted to ice load based on an ice density of 900 kg/m^3.

3DEC models rock mass as an assembly of discrete deformable rock blocks, which are separated by planar discontinuities. The discontinuities are regarded as distinct boundary interactions between the blocks, and joint behaviour is determined for these interactions (HCItasca, 1994).

The conceptual bedrock model geometry includes 32 fracture zones (Saksa *et al.,* 1998) from 100 m to 1.5 km. Modelling was first carried out for the outer part (about 12 km × 9 km × 3 km) of the study area following some regional fracture zones to provide realistic boundary conditions for the inner part of the study area (about 7 km × 3.2 km × 2.5 km), which was modelled in more detail. The boundary conditions for modelling are given in Paper I.

Material properties of the migmatized mica gneiss were applied for all rock types in the area (Äikäs *et al.,* 1999; Johansson & Hakala, 1992). Material properties of the discontinuities were evaluated using typical values of similar scale structures in crystalline rock since they are very scale-dependent (Bandis, 1990; Martin *et al.,* 1990). The material properties are summarized in Table 1. Rock stress was applied as *in situ* stresses using the mean values measured at Olkiluoto (Ljunggren & Klasson, 1996; Äikäs *et al.,* 1999) assuming stress to vary stepwise linearly with depth (Table 2).

The model consists of 194 distinct element blocks that are internally divided into 112 735 deformable zones. A linearly elastic material model was used for the blocks and the Mohr-Coulomb strength criterion was applied for

Table 1. Material properties for 3DEC modelling.

Property	Value	Source
Intact rock:		
Young's modulus (inner part of model)	61.5 GPa	Äikäs *et al.*, 1999
Young's modulus (outer part of model)	49.2 GPa	estimated with iteration, see text
Poisson's ratio	0.23	Äikäs *et al.*, 1999
Density	2730 kg/m^3	Äikäs *et al.*, 1999
Discontinuities:		
Cohesion	0	Johansson & Hakala, 1992
Friction angle	15 degrees	Hoek *et al.*, 1995
Normal stiffness	2 GPa/m	Martin *et al.*, 1990
Shear stiffness	0.2 GPa/m	Bandis, 1990

Table 2. The in-situ rock stresses in modeling, z is depth from surface (m).

Parameter	Depth 0 – 300 m (MPa)	Depth 300 – 3000 m (MPa)
Maximum horizontal stress	0.041 z + 2.67	0.060 z + 2.67
Minimum horizontal stress	0.030 z + 2.00	0.030 z + 2.00
Vertical stress	0.0273 z	0.0273 z

discontinuities so that yielding is possible along the discontinuities but not inside the distinct blocks. The Mohr-Coulomb criterion explains the shear strength of the discontinuities (Eq. 1).

$$\tau = c + \sigma_n \tan \phi \qquad (1)$$

where:

τ shear strength
c cohesion
σ_n normal stress
ϕ friction angle

The glaciation scenario imitating the Weichselian glaciation with three clearly-separated loading phases was chosen as a basis for the sensitivity study of changes in cohesion, friction angle, shear stiffness of discontinuities (shear stress/shear displacement-ratio), horizontal rock stress, and rock mass modulus of elasticity (stress/strain-ratio in uniaxial loading). To simplify the study, thermal, hydrological and chemical effects were omitted.

3.2 Acoustic–seismic methods (Papers II, IV)

3.2.1 Acoustic–seismic material

All acoustic–seismic records were collected and interpreted during 1997–2002 by the Marine Group of the Geological Survey of Finland (GSF) by using an

MD DSS sonar system (Multi-Mode Sonar System for Sub-Bottom Profiling, Meridata Finland Ltd) and TOPOS mapping software (Pekkonen, 2000). Geospatial position is based on the DGPS (Differential Global Positioning System) system with ± 2 m accuracy.

The survey lines are situated approximately 500 m apart, drawn either N-S or W-E (Figure 3). Altogether, they cover an area of ~1300 km^2 (2550 profile km). These are the only areas for which modern digital echo-sounding and reflection seismic data were available in the vicinity of Olkiluoto. Although a large number of old acoustic–seismic profiles exist in paper form, examination of these would not have provided any detailed information due to their relatively poor resolution.

The marine geological interpretation of the profiles confirmed by several core drillings comprises the following lithological units: bedrock, till, (glaciofluvial) sand/gravel, washed surficial/erosion remnant sand, glacio–aquatic mixed sediment, glacial silt and/or clay, sulphide clay (Ancylus clay), gyttja clay/clayey gyttja (Litorina) and modern gyttja clay/clayey gyttja.

3.2.2 Echo-sounding, seismic reflection survey and side scan sonar

Echo-sounding is widely used in marine geology to measure water depth and study the internal structures of soft sediments. This is done by measuring the elapsed time between the transmission of the ultrasonic acoustic pulse and the return of a reflection or echo from the sea floor. The sounder measures the two-way time of travel. The depth can be calculated from the formula (Eq. 2):

$$D = V \cdot T/2 \qquad (2)$$

where:
D = depth
V = velocity of the sound in water
T = recorded travel time

The sound velocity in the water column is a function of temperature, salinity and water pressure. The normal sound velocity in the Baltic Sea varies between 1420 m/s to 1470 m/s. The average sound velocity in the Baltic Sea is 1300–1480 m/s in recent gyttja clays (Sviridov, 1977), 1500–1700 m/s in postglacial clays and glacial clays (Solheim & Grönlie, 1983), 1350–1720 m/s in late glacial clays (Sviridov, 1977), 1800 m/s in glacial clays and sands (Flodén & Brännström, 1965) and 1700–1800 m/s in sands (Bell & Porter, 1974; Chapman & Ellis, 1980). It has to be remembered that the dip of the slopes on reflection records is not a true representation of the dip (Nuorteva, 1994) and very steep slopes are not reflected on the profile. The transection of possible faults and other structures at small angles may also hamper their reliable evaluation (Winterhalter *et al.*, 1981). The resolution and the penetration of the acoustic signal are dependent upon the used frequency: the higher the frequency, the greater the resolution but the lower the depth of penetration. In this study, a 28 kHz echo-sounder was applied, which provided resolutions as precise as ~10 cm. The resolution and the digital form of the data made it possible to examine the profiles and their acoustic stratifications on a PC monitor.

A single-channel seismic reflection survey (Electro Magnetic implosion type sound source, ELMA, 400–700 Hz, depth resolution of ± 2 m) was used to determine the thicknesses and internal structures of coarse-grained sediments. A side scan sonar (Klein SA 350, 100 kHz) was used to examine the surface of the sea floor in some areas. The geospatial position has ± 2 m accuracy based on DGPS (Differential Global Positioning System).

3.2.3 Classification of the observations detected on the profiles

In this study, all soft sediment structures were classified according their appearance (Stow, 1994), resulting in the following five categories: 1) debris flows and turbidites, 2) slump and slide structures, 3) pockmarks and buried pockmarks, 4) faulting structures, and 5) others. When possible, the faults were also confirmed on the seismic profiles and subclassified according to their presence in the underlying till/bedrock. The category "others" included unknown observations that could not be classified with certainty in any of the other groups. Observations that could be explained by bottom currents were omitted.

3.3 Sediment material and dating methods (Paper III)

3.3.1 Coring, grain size, loss on ignition and wet water content

One 253-cm-long sediment core (27/01) was retrieved using a piston corer with a diameter of 12 cm (Figure 3). The core was described using standard sedimentological methods (Geological Survey of Finland, 2003) and sub-sampled for later laboratory analysis.

Since the sediment core was visually classified mainly as glacial clay, eleven sub-samples (at depth 60–130 cm) were analysed by using a Micromeritics SediGraph 5100ET to resolve the grain size distributions of the total fine sediment (< 63 µm). Changes in grain size may reflect the change in the distance of the retreating ice sheet.

Wet water content (WWC) was determined as weight loss on drying overnight in an oven at 105 °C from eleven samples between 60–130 cm. Loss on ignition (LOI) was determined from the samples dried for WWC by keeping them in a furnace for 2 h at 550 °C. LOI reveals the approximate content of organic material in the sediment (Bengtsson & Enell, 1986; Boyle, 2004), thus reflecting the sedimentation environment.

3.3.2 X-ray radiography

X-ray radiography was used for accurate varve counting of the core. Plastic electrical installation liners (1.5 × 5 × 49 cm) were used in sub-sampling for stereo X-ray imaging of the cores (e.g. Axelsson, 1983). The sub-samples were X-rayed with a Philips constant potential MG 102 L X-ray machine and the developed pictures were scanned with 400 and 600 pixel (dpi) resolution.

3.3.3 Diatoms

Diatom analysis is commonly used in chronostratigraphical correlations (e.g. Andrén *et al.*, 2000a, 2000b; Heinsalu, 2001) and also to study changing palaeoenvironments within the basin. For diatom analysis, pre-weighed (0.6–1 g) sub-samples at the depth of 56 to 125 cm were digested in 30% H_2O_2 to remove organic material and thereafter fine mineral particles were removed by repeated decantation (Battarbee *et al.,* 2001). Diatom concentrations were determined by adding a known number of commercially-available *Lycopodium* spores to the cleaned sediment slurry. Slides were mounted with Naphrax® medium and analysed for microfossils using a Zeiss Axiolab microscope (oil immersion, phase contrast, ×1000 magnification). Samples with very low microfossil concentrations were observed with ×600 magnification and the whole slide was examined. Diatoms were grouped according to their living habitats into planktonic and littoral (epiphytic and benthic diatoms) taxa (e.g. Snoeijs, 1993; Snoeijs & Vilbaste, 1994; Snoeijs & Potapova, 1995; Snoeijs & Kasperovičienė, 1996; Snoeijs & Balashova, 1998), and with respect to ecological preferences into large-lake, other freshwater and aerophilous taxa, respectively (e.g. Heinsalu, 2001).

3.3.4 Palaeo- and mineral magnetic measurements

Magnetic susceptibility is commonly used to compare cores from different sites and can serve as an indicator of lithological or sedimentation changes. In this study, magnetic susceptibility (κ) (e.g. Thompson & Oldfield, 1986) was measured from the whole length of the core at 0.5 cm intervals with a Bartington MS2E1 surface scanning sensor. Measurement was performed from trimmed sediment surfaces covered with thin plastic film. The intensity of natural remanent magnetization (NRM), declination(D) and inclination (I) were measured by a tri-axial SQUID magnetometer (2G Enterprise SRM-755R, located at GSF) from orientated sub-samples pressed in at every 2.5 cm The technique is described in detail in Saarinen (1994). An alternating field (AF) demagnetization cleaning technique was applied to test the stability of NRM using a value of 20 mT (Thompson & Oldfield, 1986).

Palaeosecular variations (PSV) were measured and compared with PSV records from annually laminated lake sediments of Lake Nautajärvi, central Finland (Ojala & Tiljander, 2003). The Lake Nautajärvi record was chosen for the correlation since it is the longest and best dated core in the vicinity of the study area (Paper III, Figure 1). Lake Nautajärvi contains a nearly 10 000-year-long record of well documented varve chronology and an approximately 11 000-year-long section of PSV curves (inclination and declination).

3.4 Gas sampling and analysis (Annex)

In addition to traditional methods to study Baltic Sea sediments, gas sampling with concentration and isotope analysis was attempted at six sites with gas or groundwater anomalies detected in echo-sounding profiles of Holocene submarine sediments in the Olkiluoto area (Paper II). The locations of the anomalies were verified with a side-scan sonar survey (Annex). Gas concentrations and in particular isotope abundances of carbon and hydrogen may indicate the origin of the gas. Here, the main interest was in determining whether some of the gas was 'deep gas' leaking from bedrock fractures. The main sampling was carried out in summer 2002 with a Söderberg-type sampler that has been developed at the University of Stockholm. Two types of samples were taken: gas samples directly from the sampler chamber equipped with ventilators, and sediment samples from the same sampler, from which additional gas samples were taken. Methane was analysed by gas chromatography at the Lahti research laboratory. Additional sampling was carried out in summer 2003 with a vibrohammer corer and in winter 2004 from the same area through the ice cover using a self-developed sampler, but both samplings failed since the isotope results (conducted at the Dating Laboratory and at the Finnish Museum of Natural History, University of Helsinki) indicated contamination by air. Sampling methods and conducted analysis are described in detail in the Annex.

4 Results: overview of the papers

The main results obtained and conclusions drawn in separate papers of this volume are presented in the sections below (4.1–4.4). These results are further discussed and summarized in the context of previous postglacial faulting literature in the subsequent sections.

4.1 Bedrock behaviour under a glacial cycle: simulation results (Paper I)

According to the basic scenario, the maximum shear displacements of some of the essential fracture zones at 500 m depth was about 3 cm and the maximum permanent shear displacement was about 3 mm (Paper I, Figures 7–10). There was no significant difference in the magnitudes of shear displacement between the different ice age scenarios, but scenarios with more than one glacial maximum produced displacement in several phases. It is notable that shear displacement along one fracture zone affects the rock stresses and thus the displacements in other fracture zones. Generally, the larger the maximum ice load, the larger the maximum and permanent shear displacements (Paper I, Figure 11). Displacements occurred in fracture zones with all strike directions.

In general, the largest shear displacement developed along long fracture zones with more than 30 degrees dip. The sensitivity analysis of the rock properties indicated that the friction angle and shear stiffness variations resulted in the greatest changes in shear displacement, while effects of cohesion, *in situ* rock stress and rock mass deformability were less (Paper I, Figures 12–16). The effect of the friction angle varies from one fracture zone to another. Shear displacement of a fracture zone with a very small friction angle might be several centimetres or even up to several decimetres (Paper I, Figure 12). The shear stiffness of the fracture zones has strong effect on rock deformation, producing large shear displacements when the joint shear stiffness values are small (Paper I, Figure 14).

In the 3DEC simulation results the surface subsidence was proportional to the glacial load and the subsidence almost completely recovered after the ice load was removed. The maximum surface subsidence according to applied basis scenario was more than one metre when the reference level was set at 3 km depth (Paper I, Figure 6).

4.2 Acoustic–seismic results (Papers II and IV)

4.2.1 Holocene sediment faults and slide and slump structures on the profiles

Several submarine Holocene sediment faults (Figure 4) and slide and slump structures were observed in the acoustic–seismic profiles of ~2550 km of the studied areas in the Baltic Sea (Papers II and IV). The slide and slump structures (Figure 5; Paper II, Figure 8; Paper IV, Figures 8 a–c) mainly occur on slopes, indicating their gravitational origin. They might have also been formed during or after the deposition of sediment layers when the shear strength of the sediment is exceeded, especially in cases where the profiles reveal a gradual transition from varved sediments to a zone with a chaotic seismic signature, or they might also be induced by gas or groundwater escapes from deeper layers or by earthquakes.

The Holocene sediment faults (Figure 6; Paper II, Figures 7 a–c; Paper IV, Figures 11 a–c, 12 a–c) show a spatial distribution (Figure 4), being located along a couple of NW-SE or NE-SW depressions probably reflecting bedrock fracture zones or shear zones, in the Bothnian Sea (Paper II, Figure 3; Paper IV, Figures 3–5) and in the northern Baltic Proper (Paper IV, Figure 3). Two of the depressions are in the vicinity of the Härnösand-Pori shear zone (Figure 4; Paper IV, Figures 3–5) and one is located north of the Olkiluoto Island (Paper II, Figure 3). The fourth is located in the Åland-Paldiski-Pskov shear zone (Figure 4; Paper IV, Figure 3). It is notable that Holocene sediment faulting was not observed in several bedrock depressions and slopes (Paper IV, e.g. Figures 4–7).

This spatial distribution suggests possible seismic reactivation along the old bedrock fracture zones. Their movement may have been triggered by palaeoseismic events when the Late Weichselian ice sheet was retreating from the site and bedrock stresses were released through fracture zones. Unfortunately, poor resolution of the seismic profiles hampered the confirmation of the existence of the faults in bedrock/till in most places. These problems were due to differences between years in the applied sounder and its settings and of course to the weather conditions and the sea floor topography. However, in the Bothnian Sea area, several faults in clay sediments reaching into the underlying bedrock/till were also recognised (Paper II). In the Bothian Sea study area, Holocene sediment faults also occur in the vicinity of pockmarks (Figure 4; Paper IV, Figure 3), suggesting a relationship.

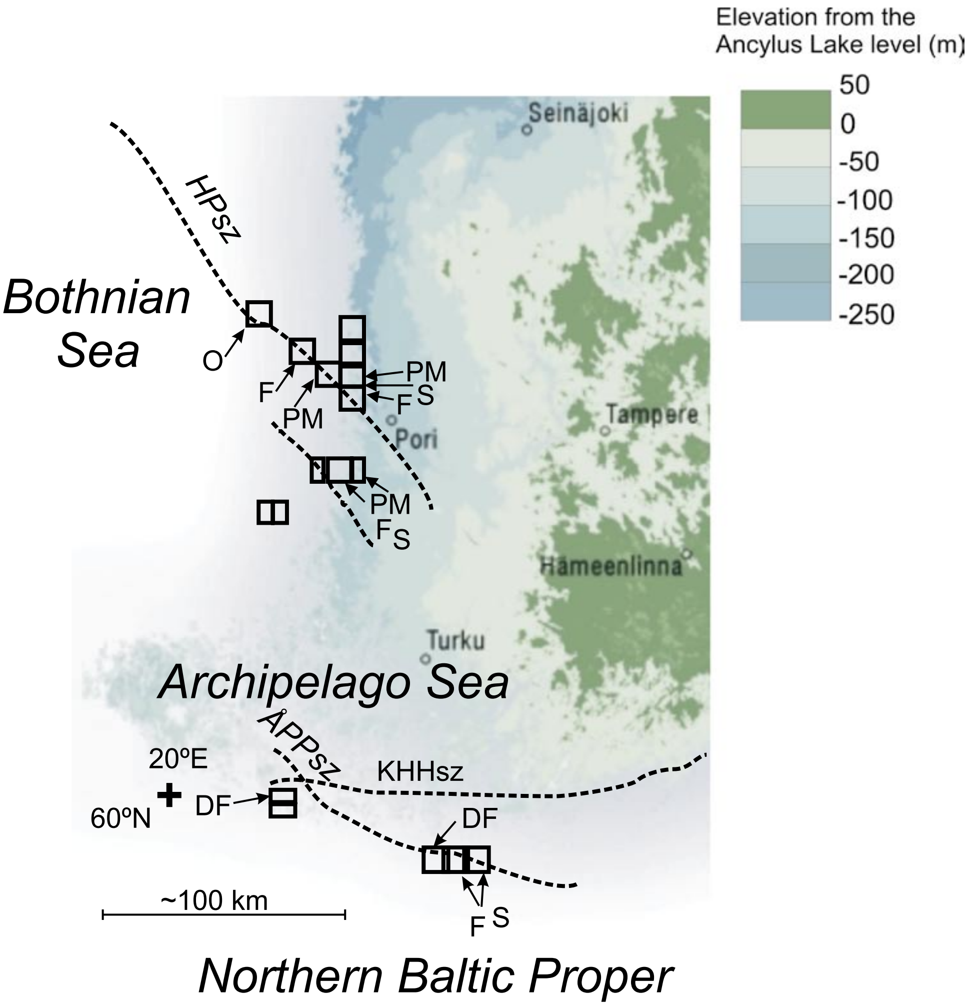


Figure 4. Map showing the estimated bathymetric information for the Ancylus Lake stage (according to Koivisto, 2004; Figure 12-5) and the locations of the detected observations. The more exact locations are found in Papers II and IV. F = faults, PM = pockmarks, S = slide and slumps structures, DF = debris flows and turbidite-like layers, O = other structures. The study areas are indicated on the map with squares according to the Finnish map sheet division. ÅPPsz = Åland-Paldiski-Pskov shear zone, HPsz = Härnösand-Pori shear zone, KHHsz = Kökar-Hanko-Helsinki shear zone (Koistinen *et al.*, 1996).

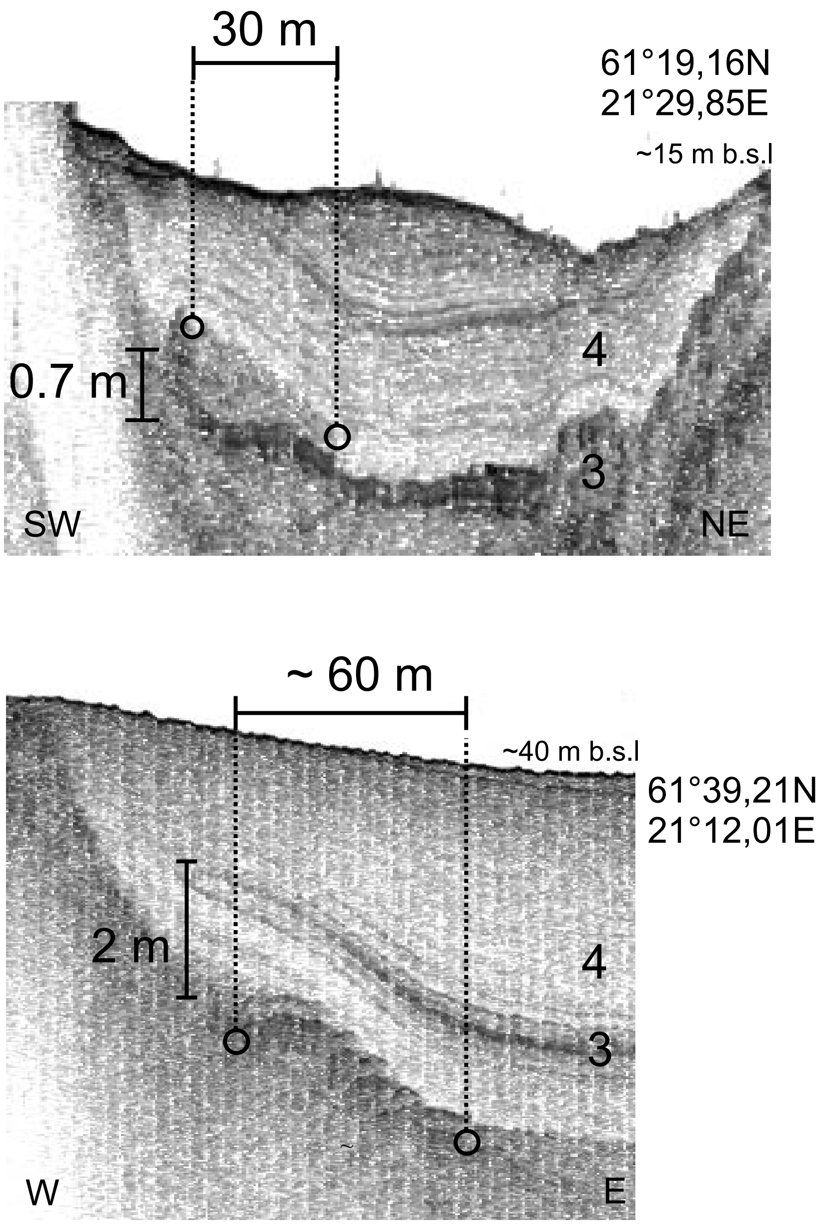


Figure 5. Examples of slide and slump structures in echo-sounding profiles. The water depth (m) and the location of the site (longitude, latitude) are given in the right corner of the figures. Numbers 3 and 4 refer to sedimentary units (3 = distal varved sediments, 4 = sulphide bearing clays) according to Rantataro (2000).

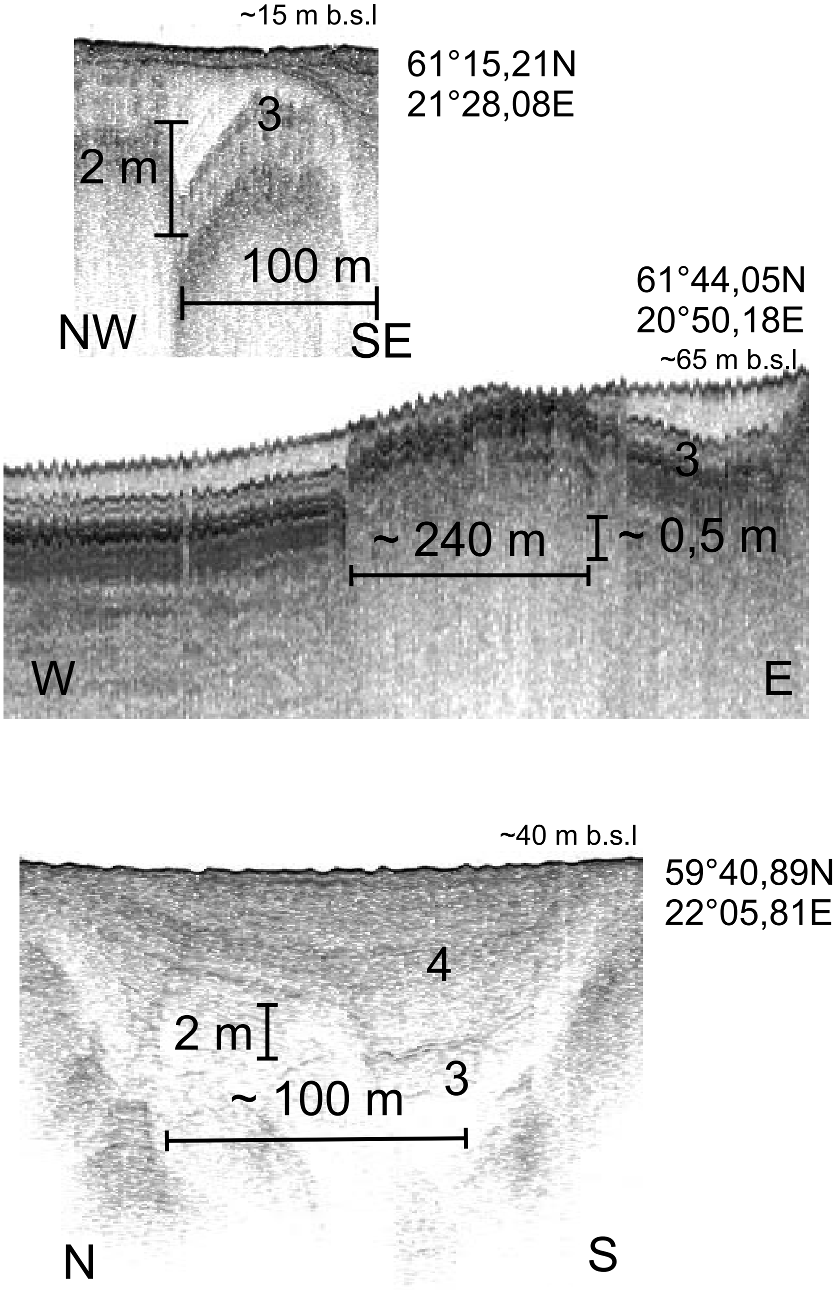


Figure 6. Examples of submarine faults in clayey sediments revealed in echo-sounding profiles. Numbers 3 and 4 refer to sedimentary units (3 = distal varved sediments, 4 = sulphide bearing clays) according Rantataro (2000). The water depth (m) and the location of the site (longitude, latitude) are given in the right corner of the figures.

4.2.2 Pockmarks and some unidentified sediment structures

Various sizes of pockmarks from centimetres to more than one hundred metres in diameter (Figure 7; Paper IV, Figures 10 a–c) occur in the Bothnian Sea approximately 5 km southwest of the submarine Pori-Yyteri esker and near Olkiluoto Island (Figure 4; Paper II, Figure 10; Paper IV, Figures 3 and 4). Most of the pockmarks are buried, but in the profiles near Olkiluoto Island gas bubbles have also been identified in the water column above some of the pockmarks, suggesting ongoing activity (Paper II).

The location of pockmarks at the margins of the Bothnian Sea depressions and along fracture zones associates them with deeper gas seepages from bedrock fractures. Thus, they might be related to bedrock fractures that were seismically reactivated after deglaciation, or they might have been formed due to high hydraulic gradients connected to the meltwaters of the Weichselian ice sheet. Other possible sources for gas seepages could be ancient organic material buried by till (Paper IV).

In Eurajoensalmi north of Olkiluoto Island, reflections in the echo-sounding profiles imply that part of the gas is derived from the organic-bearing Litorina and modern gyttja clays, but some is also derived from the bedrock (Paper II). Further investigations focusing on a comparison of porewater composition at the centre of the pockmarks with the undisturbed sediment profile could indicate increased salinity or other chemical/isotopic signatures.

Profiles recorded in study areas other than the Bothnian Sea revealed no pockmark structures. However, there were numerous observations of large amounts of gas on the sea floor in the Archipelago Sea and in the northern Baltic Proper.

In the Bothnian Sea, approximately 35–40 km from the coast, several unidentified 2–4 m high soft sediment “heaps” were detected (Paper IV, Figures 13 a–c). Because they could not be placed with certainty in any of the other classes, they formed their own class. All heaps were located at a depth of 75–80 m, in an area of 2 × 4 km, and they were covered by 6 to 10 m thick clay deposits.

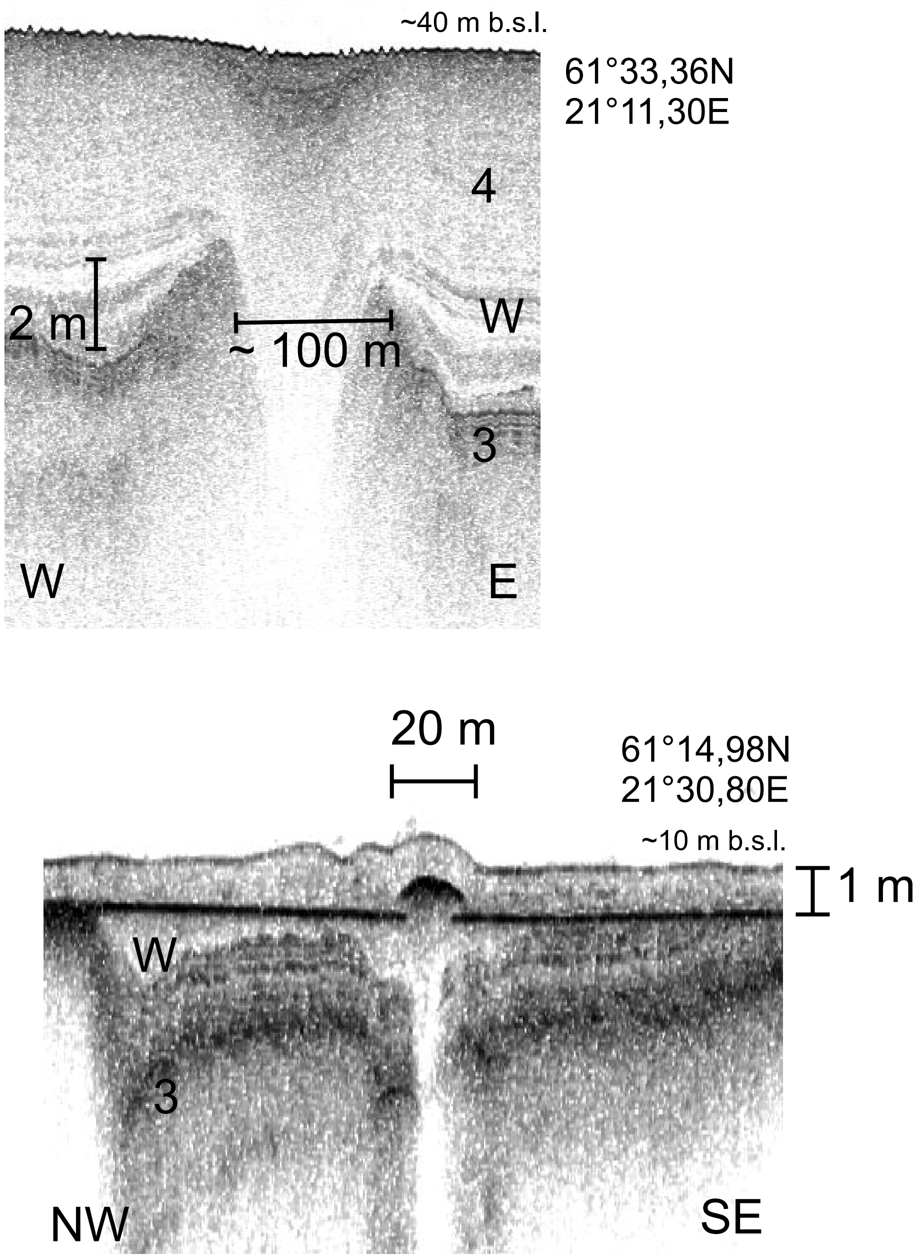


Figure 7. Examples of pockmarks in echo-sounding profiles. The water depth (m) and the location of the site (longitude, latitude) are given in the right corner of the figures. Numbers 3 and 4 and the letter W refer to sedimentary units (3 = distal varved sediments, 4 = sulphide bearing clays and W = Upper Ancylus Lake sediments) according to Rantataro (2000).

4.2.3 Turbidite layer

In the Archipelago Sea and the northern Baltic Proper, 4–6 m thick turbidite-like layers (Figure 8; Paper IV, Figures 3, 7 and 9) were found in the same stratigraphical position (Paper IV). They might also be caused by palaeoseismicity. Other possible causes of the turbidite(s) could include a massive surge from the retreating Weichselian ice sheet or rapid drainage of a dammed ice lake. Yoldia regression might also be considered. Future studies extending to the ice margin of that time may reveal more information on the origin of the turbidite layer.

4.3 Dating results (Paper III)

The suggested palaeoseismic event(s) revealed in acoustic–seismic records near Olkiluoto Island, in the Bothnian Sea, were dated and the palaeoenvironment was characterized using palaeomagnetic, biostratigraphical and lithostratigraphical methods, enhancing the reliability of the chronology (Paper III). Lithostratigraphical correlation gave a maximum age of ~10 700 cal. years BP for the event(s). The time span for the event(s) suggested by diatom stratigraphy was younger than 10 700 and older than 10 200 cal. years BP, and by a palaeomagnetic correlations from 10 650 to 10 100 cal. years BP. The variations in the inclination and declination of natural remanent magnetization (NRM) of the Olkiluoto sediment core showed a very good correlation with the palaeosecular variations recorded in the annually-laminated lake sediment record from Lake Nautajärvi in central Finland (Paper III). These results limit the age of the event(s) between ~10 650 to 10 200 cal. years BP. Combined lithostratigraphy, biostratigraphy and palaeomagnetic stratigraphy revealed an age estimation of 10 650 to 10 200 cal. years BP for the palaeoseismic event(s).

In the other study areas (Paper IV), all faults that could be stratigraphically dated were also formed in the uppermost parts of the glacial distal varves and below or within the lower Ancylus Lake sediments (from ~10 700 to ~10 100 cal. years BP).

4.4 Gas analysis (Annex)

The laboratory analysis confirmed the existence of methane in the sediments. Methane concentrations in the chamber samples were relatively low, from 0.007–1.2 mg/l. In the sediment samples the methane concentrations were higher, from 0.11–18.7 mg/l.

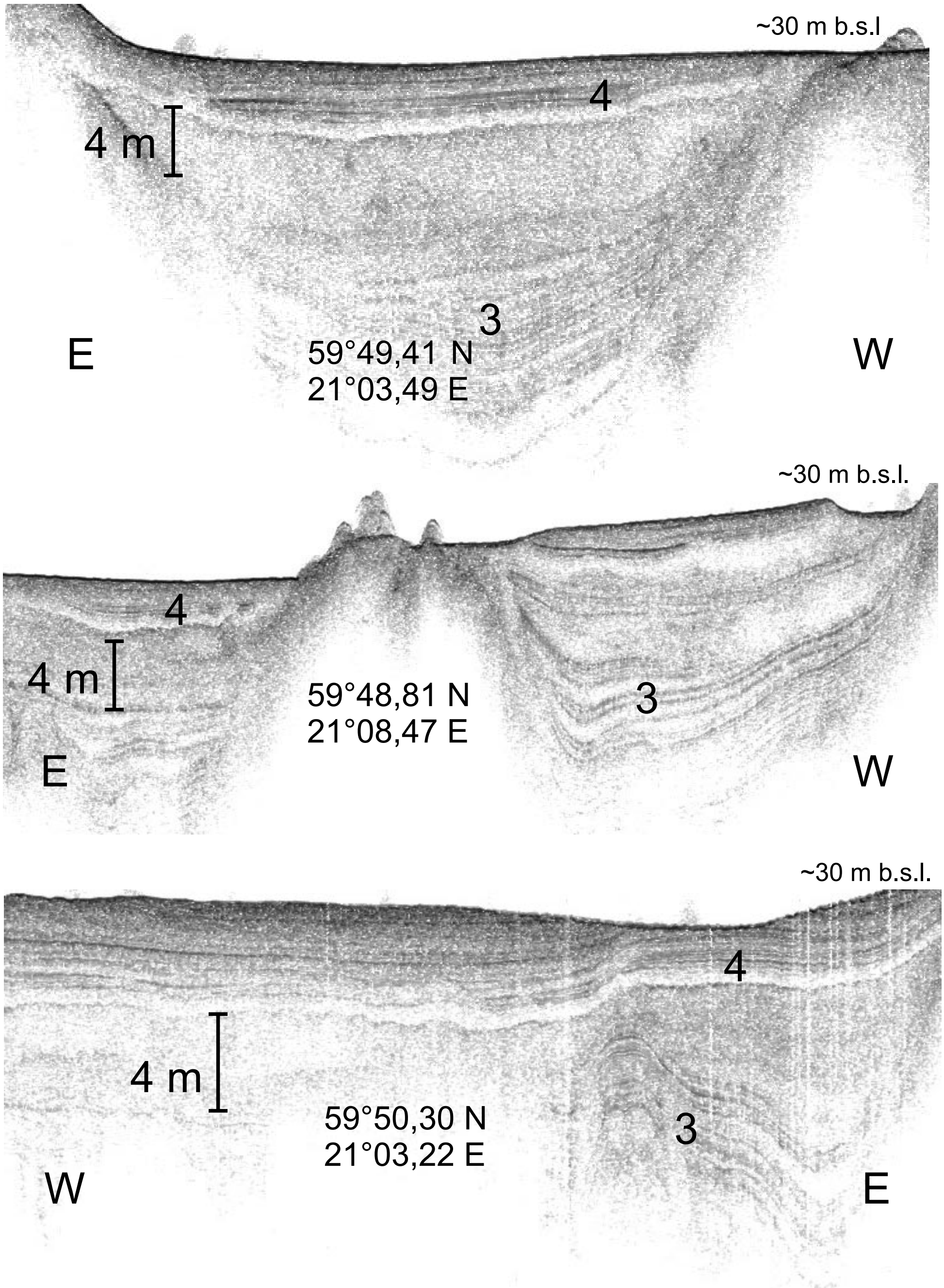


Figure 8. Examples of turbidite layer in echo-sounding profiles. The water depth (m) and the location of the site (longitude, latitude) are given in the center of the figure. Numbers 3 and 4 refer to sedimentary units (3 = distal varved sediments, 4 = sulphide bearing clays) according to Rantataro (2000).

5 Discussion

5.1 Modelling results (Paper I)

According to prevailing knowledge, large postglacial faults in Finland have been found only in the northern parts of the country (Kuivamäki, 1998; Ojala *et al.*, 2004). Small postglacial faults, however, also exist in central and eastern parts of Finland (Kuivamäki, 1998). With linear elasticity, the simulation results suggest that permanent shear displacements of a few centimetres could also occur in the future, according to the applied glaciation scenarios in the study area (Paper I). In reality, the more fractured the rock is, the more non-linearly elastic is its behaviour. However, in general only the uppermost parts of the bedrock at Olkiluoto are known to be more fractured and fracturing diminishes downwards (Anttila *et al.*, 1999; Andersson *et al.*, 2007). The results also showed that displacements might occur in fracture zones with various directions, depending on their orientation to the main stress and their internal geometry.

Fractures that were orientated parallel or sub-parallel to the principal stress directions with the greatest changes in stress had the greatest displacements. Thus, the greatest displacements took place in the steepest fracture zones (60–70 degrees) striking NW(W)-SE(E), i.e. the directions of the main vertical stress and also the presumed direction of deglaciation. It should be remembered that the bedrock conceptual model did not include any horizontal or vertical fracture zones. Hydro–thermal factors including permafrost, which were outside the scope of the simulation, could also have influenced the results.

Land uplift has been proceeding since the last deglaciation and still continues. Kakkuri (1986) has estimated that land uplift will continue for a further 7000 to 12 000 years. Since land uplift and material flows take longer than the melting of the ice sheet, possibilities of thrust faults prevail for longer. It is worth noting that neither changes in the direction of glaciation and deglaciation nor in the stress field were analysed, except the stress caused by ice load in the latter case, since it would have demanded much greater computational resources. Considerable changes in the directions of glaciation and deglaciation were also regarded as unlikely and the push from the Mid-Atlantic Ridge, according present knowledge, is known to have been continuing for millions of years (Torsvik *et al.*, 2005).

Moreover, the material properties of the fractures affected the size of the displacement. The smaller the friction angle or shear stiffness, the larger the displacement under the maximum load. A very small friction angle is typical for a fracture zone filled with clay minerals (Hoek *et al.*, 1995). Thus, fracture zones of this kind should be avoided in the repository area.

The one-metre subsidence is mostly elastic and is almost directly comparable to the depth. Thus, for the average crust thickness of 60 km the subsidence would be 20 m.

The results gained with the applied conceptual model are similar to those derived with generic models (Paper I) and demonstrate that the mechanism of postglacial faulting also works on a small scale. However, constructing a good generic model that behaves in a realistic way is not simple. If a model consists of a regular, systematic fracture network, the results will also show regularity, since the deformation will occur in fractures in a favourable direction with respect to the stress field. In reality, deformation of the fractures is unequal and the displacement is concentrated in the most favourably-oriented fractures. Another possibility is to randomly select the fractures, which could result in a more homogenous model. However, in reality, fractures in the bedrock are not spread randomly, but neither do they form a clear system in a small modelling area. Since the application of a conceptual model by Saksa *et al.* (1989), the model has undergone numerous changes in the number and interpretation of fractures and their properties.

In general, selected boundary conditions and parameters have a considerable influence on the modelling results. Uncertainties in them also cause uncertainties in the results, and they should be verified.

5.2 Palaeoseismicity (Papers I, II, III and IV)

5.2.1 Evidence of palaeoseismicity (Papers II and IV)

According to Shilts *et al.* (1992b), faults extending into and cutting through the postglacial glaciolacustrine sediments may be assigned a neotectonic origin. Other disturbances in sediments (deformation and liquefaction) can also be regarded as the results of palaeoseismic events (e.g. Tröften & Mörner, 1997; Tröften, 2000; Jensen *et al.*, 2002). In a recent study, Virtasalo (2006) attributed a disturbed sediment unit in the Archipelago Sea to palaeoseismic activity.

In the study area, the distribution of Holocene sediment faults along the bedrock fracture zones, sometimes extending into the underlying till/bedrock, together with their large number and limited time-span of occurrence suggests that at least some of these structures were formed by reactivation of fracture zones. In the study area the land uplift, in the form of rapid bedrock block movements, could also have affected slope failures.

Other reasons for the Holocene sediment faults, at least in some cases, could be slope failures due to compaction of the sediments. A rapid sedimentation rate and high pore water content in sediment layers are known to cause instability in the layers. The Ancylus clay layers may be regarded more porous than the underlying layers (Repečka, 2001; Virtasalo *et al.*, 2005). However, Holocene sediment faulting should then be more common, like the slide and slump structures, and not only restricted to certain depressions.

Wave and bottom current activity could also cause erosion and sediment removal. In the Gulf of Bothnia, wave erosion in the open sea prevents the sedimentation of clay in water shallower than 50 m (Ignatius *et al.*, 1980). Before and during the deposition of the disturbed layers, even the most southern parts of the study area were submerged by more than 160 m (Eronen *et al.,* 2001), and it is therefore unlikely that wave erosion caused the observed structures.

Glaciotectonic deformation is also known to cause folding and faulting in sediments (Hart & Boulton, 1991), and disturbance structures in glacioaquatic sediments may also be related to glacial surges (Elverhøi, 1984) or ice-blocks (Shilts *et al.*, 1992b). However, they do not explain the spatial existence of the Holocene sediment fault observations in the vicinity of the bedrock fracture zones. At least at the Olkiluoto site, the Late Weichselian Ice Sheet had already retreated 50 km away (Paper II) at the time of Holocene sediment faulting.

Therefore, the processes discussed above, except palaeoseismicity, do not explain the spatial appearance of the faults in the study area, and thus palaeoseismicity is suggested as being the most reasonable explanation.

In the Bothnian Sea study area, the existence of pockmarks supports the idea of connecting the soft sediment faults to the reactivation of bedrock fracture zones. Several observations around the world e.g. in the Stockholm archipelago have connected deep gas seepages (especial methane) to fault creep and (micro)seismicity (Flodén & Söderberg, 1988; Söderberg & Flodén, 1991, 1992). Similar sediment failures connected to seismic activity have also been reported in the North Atlantic (e.g. Bugge *et al.*, 1987; Mienert *et al.,* 1998; Duck & Herbert, 2006; NGU, 1998; Plassen & Vorren, 2003). The largest pockmarks were not found closer than 1–2 km from the faults. In Skagerrak, a linear concentration of pockmarks has been observed above a fault (Rise *et al.*, 1999). In the Åland Sea, some bedrock fractures could be mapped with the help of gas structures (Söderberg & Flodén, 1991), and gas-induced pockmarks are located in areas along tectonic faults in the sedimentary bedrock sequence (Söderberg, 1993). However, according to Söderberg & Flodén (1992), pockmarks in the Stockholm Archipelago are quite often found within the shallow, peripheral parts of tectonic structures and rarely directly above the central part of the fracture. It should also be remembered that the acoustic network was quite scarce and possible faults parallel to or cutting the survey profiles at small angles may therefore have been undetected.

Although pockmarks were not found in relation to the faults in the northern Baltic Sea area, the possibility that gas escapes (earthquake-triggered or not) caused the other observed disturbance structures (faulting and slide and slumps structures) cannot be ruled out. Pockmarks are believed to be formed by the rapid expulsion of gas and liquid through the sea-bed, which displaces the fine-grained sediment to form craters. Their shape and size depends on the sediment type and the gas and pore-water seepage rate. The grain size, permeability and shear strength of the sea-bed surface sediment, as well as the rate of gas emission are all factors that determine whether pockmarks will form (Hovland & Judd, 1988). If the sediment is fine grained and soft it can be eroded by the escaping gas, but in other cases, for example if the sediment is composed of stiff clays, erosion will not take place and therefore pockmarks will not be visible on the seafloor, even though gas may be actively seeping from the sea-bed.

The lack of sedimentary rocks and the thickness of till may also explain the absence of pockmarks. In the Skagerrak area, pockmarks mainly occur in areas with thin Quaternary sediments (<50 m) (Rise *et al.*, 1999).

The observed turbidite layers in the Archipelago Sea and in the northern Baltic Proper might also be due to palaeoseismicity (Paper IV). A similar layer has been observed in Paimionlahti and Kråkskärd (Figure 3) in the Archipelago Sea and the Åland sea outside of the areas studied here (Virtasalo, 2006; Hämäläinen *et al.*, 2005). In the literature, three mechanisms have been proposed for the initiation of turbidites (Walker, 1994): earthquakes, flooding and sediment failures in rapidly-deposited delta fronts. The Weichselian ice sheet retreated from the northern Baltic Proper and the Archipelago Sea by 10 890 cal. years BP (Saarnisto & Saarinen, 2001; Strömberg, 2005). Since the turbidite layers are located between the glacial clays and the lower Ancylus (whitish unit in the echo-profiles) sediments, they were deposited before or at the onset of the deposition of the Ancylus layer (~10 700 to 9000 cal. years BP). It is not known whether theses observations represent products of a concurrent event or whether they were formed at slightly different times. Immediately after deglaciation the crustal uplift was at its greatest (Ristaniemi *et al.*, 1997) and probably caused earthquakes. In the areas where the turbidite layers were found, no faults were observed. One reason for this might be that no bedrock faulting has occurred in these areas at all or that the turbidite layers were self-triggered by distant seismic event(s) and that might have destroyed or prevented other traces of seismicity. In any case, the amount of material that has been redeposited is considerable. In eastern Canada, in the Saguenay Fjord, similar rapidly deposited layers are interpretated to be connected to earthquakes over the past ~ 7200 years (St-Onge *et al.*, 2004).

Other possible sources of the material could be a huge surge or the splitting off of an ice berg from the deglaciating Weichselian ice sheet, causing a catastrophic wave. Rapid drainage of a dammed ice lake in the Bay of Bothnia could also have caused flood-related turbidite formation. However, the area covered with the turbidite layer is so wide that it should also have left some traces in the ancient shorelines. In Sweden, Mörner (1996) reported a palaeoseismic event and an associated tsunami in 10 430 varve years BP (11 280 cal. years BP) producing the Närke outlet. In western Norway, a turbidite layer found in shallow marine basins and coastal lakes is dated to ca. 7000 BP, which correlates with the tsunami formed by the Storegga slide (Bondevik *et al*., 1997). In Canada, Shilts *et al.* (1992b) concluded that most or all mass transport deposits they studied in the Lac Temiscouata (Quebec) region were generated by postglacial seismic shocks.

Changes in water level can also affect sedimentation rates. One source of the turbidite layer material could have been the rapid drainage of the Baltic Ice Lake when the water level lowered by ~25 m to the ocean level at ~11 590 cal. years BP, affecting sedimentation and redeposition in the Baltic Sea area (Veski *et al.,* 2005). This led to the deposition of gravel and sand layers on glacial varves near the coast of Estonia (Veski *et al.,* 2005). However, at that time the whole study area had not yet deglaciated. The final phase of the Yoldia Sea (11 200 – 10 700 cal. years BP) was also strongly regressive, and the surface waters in the offshore areas such as the Gulf of Finland were turbid (Heinsalu, 2001). If the water level lowered so much that the glacial varved clays were eroded, it is unlikely that a several-metres-thick turbidite layer could have been concurrently deposited.

Changes towards a more proximal sedimentary environment (glacial readvance) could also add to the amount of material, but there should then be glacial varves above the turbidite layer deposited in the new retreat phase. If the retreat of the Weichselian glacier halted for a longer time to allow delta growth at the ice margin, sediment failures of the delta fronts could also have caused turbidites, but then the deltas must have been widely distributed along the ice margin. Such a halt corresponding with the age of the turbidite layer is known to have caused the Central Finland End Moraine formation (~11 000 years BP) within about 100 years (Sauramo, 1923; Rainio, 1996).

5.2.2 Postglacial movements in the study area in the light of palaeoseismic evidence (Papers I, II and IV)

It is suggested here that the soft sediment relicts of palaeoseismicity (especially the Holocene sediment faults, slides and slumps, and pockmarks) indicate that during the Holocene there has been reactivation, either movements or just vibration, in some old large bedrock fracture zones in the studied areas cutting the Quaternary sediments. Thus, these bedrock fracture zones could also be referred to as "postglacial faults", although their history probably dates back to the Precambrian.

These bedrock fracture zones and depressions belong to the Härnösand-Pori shear zone in the Bothnian Sea and to the Åland-Paldiski-Pskov shear zone in the Archipelago Sea (Figure 1) (Flodén, 1982; Koistinen *et al.,* 1996, 2001; Korja & Heikkinen, 2005). The latter shear zone is located inside the Åland archipelago-Paldiski-Pskov seismic belt (Saari, 1998). In addition, there is a smaller bedrock fracture zone north of Olkiluoto Island (lineament interpretations by Kuivamäki, 2005) (Figure 3) with several observations of Holocene sediment faults (Paper II, Figure 3). When modelling the behaviour of Olkiluoto Island under glacial scenarios, this fracture zone was one of the outer boundaries of the model, thus the boundary conditions prevented normal and shear displacements along the zone. The strike of all these fracture zones and depressions is about NW(WNW)-SE(ESE), except in one case where a depression is oriented almost NS, however it is located in the area of the NW-SE oriented Härnösand-Pori shear zone (Paper IV, Figures 3 and 4).

As acoustic–seismic profiles are scarce, it is difficult to estimate the possible lengths of the reactivation along the bedrock faults. In the light of the limited available survey network, the length might be up to some kilometres. The model of postglacial faulting by Muir-Wood (1989, 2000) does not support an idea of large thrust faults in the area. According to the model of Stewart *et al.* (2000) several types of postglacial faulting (e.g. strike-slip faults) might be possible.

The average height of the Holocene sediment faults in the echo-sounding profiles is from 0.5 to 2 m. The bedrock displacement or vibration in the rock mass has probably not been equal but less, since the unconsolidated clays are very sensitive to failure. The magnitude of the event(s) is difficult to estimate. Keefer's diagram (1984) could be used for such estimations by applying the distribution area of the faults and the slump and slide structures along the bedrock fracture zones, but the acoustic network should be denser to produce more reliable results.

5.2.3 Origin of the gas/porewater anomalies (Annex)

On the basis of the laboratory analyses conducted so far in this study, the origin of the gases and their connection to seismic creep cannot be verified. However, the reflections of the seepages in the echo-sounding profiles imply that some part of the gas is derived from the bedrock. Gas and groundwater sampling from the pockmarks in the Olkiluoto sea area revealed the gas to consist of methane (Chapter 4.4). According to Hovland & Judd (1988), seepage gases are generally pure methane and the heavier hydrocarbons appear to be adsorbed on the mineral grains of the clay sediments as the methane passes through. The groundwater samples from the deep drill holes in the island of Olkiluoto contain high volume of gases (methane) (Karttunen *et al.*, 1999; Haveman *et al.*, 2000) and sulphide-reducing bacteria are particularly associated with groundwaters at depth ~250–330 m (Andersson *et al.,* 2007). One possibility is that some of the observations are relicts (buried pockmarks) of strong hydraulic gradients connected with the Weichselian deglaciation (Paper IV). Also gas hydrates – clathrates – might be considered as a potential source.

5.2.4 Origin of the palaeoseismicity (Papers II and IV)

The main strike of the reactivated zones is NW(WNW)-SE(ESE). The only depression with a NS direction is located inside the Härnösand-Pori shear zone, which also strikes NW-SE. According to (Saari, 1998) faulting can happen also in a series of several smaller block movements.

Postglacial faulting is considered to be due to two components: the tectonic and the glacial isostacy component (e.g. Kakkuri, 1986). Fracture zones striking about 25 ±5 degrees from the direction of the greatest principal stress direction, are most likely to be displaced. The greater changes in stress directions under glacial scenarios are due to the movements of the ice sheet (glaciation and deglaciation) and changes in the ice load (vertical direction). According to Muir-Wood (1989, 2000), due to the ice load the material flow in the crust or mantle during glaciation is towards the ice sheet margins. This is reversed when the ice melts and friction resulting from material flow causes additional stress. Together with the horizontal stress it creates shear stresses in the crust and faults develop perpendicular to the flow. According to this theory, presuming that the direction of the Weichselian ice sheet retreat was approximately S(SE)-N(NW) and the direction of the greatest principal stress was about the same as today (NW-SE), postglacial faults in the area should have been formed striking W(SW)-E(NE) rather than NW-SE. A possible reason for this discrepancy might be that the direction of deglaciation was not from S(SE) to N(NW). However, the land uplift contours do not support this suggestion. Another possible reason is that the greatest principal stress was not NW-SE but either vertical or NE-SW. In the first case the faults should develop rather soon during or after the retreat of the ice sheet and be quite steep. In the latter case, thrust faults would form with a gentle dip to the maximum horizontal stress (σ_H). This would also be in concordance with the theory of Adams (1989). The conditions for such faults prevail for longer but are weakened by the land uplift, which causes the horizontal stresses to decrease.

According to Muir-Wood (2000), unusual stress orientations, the ‘stress shadow’, may actually reveal palaeoseismic observations. The small postglacial fault observations with varying strike directions cutting ice-polished bedrock surfaces found within a distance of 200 km from the study area support this assumption (Figure 1). In south-eastern Canada, orientations of the postglacial thrust faults indicate that large postglacial stress rotation occurred (Wu, 1998). The released tectonic stress caused by the Mid-Atlantic Ridge push during and after the deglaciation also might have caused directional variability in the stress field resulting in different type of faulting with various strikes as presented by Stewart *et al.* (2000).

The good correlation between the onset of postglacial faults/earthquakes in eastern Canada and Fennoscandia with the end of deglaciation indicates that postglacial rebound has played an important role in earthquake generation during the early postglacial period (Wu *et al.*, 1999).

5.2.5 Age estimations (Papers (II), III (and IV))

The age estimation for the earthquakes causing postglacial faults in northern Fennoscandia varies from 8500 to 9000 years based on deglaciation estimations (Arvidsson, 1996; Kuivamäki *et al.*, 1998). According to the recent deglaciation results by Johansson & Kujansuu (2005) the postglacial faults might be even older. The age estimations for the palaeoseismic events in southern Sweden are about 10 400 BP for the Stockholm region (Mörner, 1996; Tröften, 2000) and 9663 BP for the Iggesund event north of Stockholm (Mörner *et al.*, 2000). The age estimation for the palaeoseismic event in the Fennoscandian Border Zone in Kattegat region is about 15 000 cal. years BP (Jensen *et al.*, 2002).

The age estimation for the event(s) in the Olkiluoto sea area was dated to be 10 650 to 10 200 cal. years BP (Paper III), thus being of a similar age as in Sweden but younger than in the Fennoscandian Border Zone. The other events/faults in the Bothnian Sea and in the Baltic Proper were dated only litostratigraphically (Paper IV) to have formed after the depositions of the glacial varves but before deposition of the Anclylus sediments. Due to time transgression of the Baltic Sea (deglaciation), the fault in the Baltic Proper is older than the faults in the Bothnian Sea, but all faults appear to have been triggered quite soon after the retreat of the ice sheet. This close relationship is also supported by the modelling results (Paper I; Figures 7–10). Slide and slump structures occurring in the same stratigraphical position in the vicinity of the faults may also be of seismic origin. The time-transgressive formation of “disturbance structures” in the direction of the ice-margin retreat has also been suggested by Virtasalo (2006). When compared to postglacial faults on land the submarine faults in Holocene sediments are in an advantageous position for stratigraphical correlation.

The observations of Holocene sediment faults in the studied Baltic Sea areas occur in areas of tectonic faults (Figure 4), suggesting that postglacial faulting has been more common in southern Finland (sea areas) than thought based on earlier observations. However, the acoustic–seismic profiles are still scarce and only faults not parallel to the survey profiles and not with a very steep dip might have been detected with the echo-sounding method. The events appear to have happened shortly during or after deglaciation of the Weichselian ice sheet, thus being time-transgressive. These are the first observations of postglacial faulting cutting into Quaternary sediments in southern Finland (sea areas) and the results discussed here can be used to verify the boundary conditions in glacial scenarios concerning the long-term safety of nuclear repositories.

5.3 Future research

A better knowledge of mechanical properties and geometry of the fracture zones as well as including the omitted coupled hydro–thermal factors could enable a more accurate modeling and a better prediction of the bedrock behavior under glacial circumstances.

More information would be gained with further acoustic–seismic surveys in other directions, closer to each other and with more channels. Sediment cores from sites with faults, turbidites and pockmarks would be worth investigating. Studies extending to the ice margin at the turbidite layer locations might also reveal more information on the origin of the turbidite layer.

Further investigations focusing on a comparison of pore water composition at the centre of the pockmarks with the undisturbed sediment profile could reveal increased salinity or other chemical/isotopic signatures indicating present-day groundwater discharge along possible palaeoflow pathways.

6 Conclusions

In northern Fennoscandia, postglacial bedrock thrust faults are clear evidence of the bedrock response to the Weichselian glacial loading. Based on spatial and temporal arguments, reactivation of old fracture zones is regarded as a mechanism of stress release. Associated large earthquakes also provide an explanation for the disturbances in Quaternary sediments (land slides).

In southern Fennoscandia, indications of palaeoseismicity and postglacial faulting are fewer and weaker. However, based on present knowledge of the faulting mechanism, there is also a possibility for postglacial faulting in the study area. In this investigation, bedrock stability changes and displacements of bedrock blocks were simulated under simplified assumptions for different glaciation scenarios. Observations in the acoustic–seismic profiles from the sea areas give indications of displacements of glaciotectonic origin also in the studied area. Possible seismic reactivation during the Holocene has been detected in some old bedrock fracture zones in the studied Baltic Sea areas (in the Bothnian Sea, the Archipelago Sea and the northern Baltic Proper). The evidence comes from observations of disturbed sediment structures (slide and slumps, faults, debris flow and turbidite-type structures, and some gas-related structures) and their locations in the vicinity of bedrock fracture zones. Anomalies related to groundwater discharges under high hydraulic gradients and/or to gas seepages (pockmarks), and the evaluated age of the structures also support this assumption.

According to the gained results, postglacial faulting in southern Fennoscandia has been more common than earlier thought, since there have only been a few observations of postglacial faulting found on dry land. The reactivation has occurred within a short time period during or after deglaciation, indicating a glaciotectonic origin. The type of faulting can, however, be ambiguous and needs further investigations.

Observations in nature, analysis of the underlying processes and the time and spatial scales involved, and verified and validated model results can be used as an aid to evaluate predictions and assumptions in safety assessment of the geological repository of nuclear waste and to gain confidence in the selected future scenarios. The results gained seem to be most beneficial for evaluation of the potential risks due to neotectonic bedrock movements and increased ground water flow rates in connection with glacial events.

Further research providing evidence to corroborate the above conclusions is still needed to form a coherent picture of the palaeoseismicity of the Baltic Sea. In particular, acoustic–seismic investigations and pore water analysis of the pockmarks are needed to provide conclusive answers to open questions.

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