Working Report 2007-05

Search for Glacio-Isostatic Faults in the Vicinity of Olkiluoto

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ABSTRACT

Glacio-isostatic land uplift continues in Finland at a moderate rate of 2 – 9 mm/year and is at its greatest in the Quarken area. In the vicinity of Olkiluoto Island the rate is 5 mm/year. This land uplift is thought to happen along the ancient fracture zones of the earth's crust and continues without creating new faults. Possible glacio-isostatic faults near Olkiluoto could give new information about the movement of bedrock. In this work the aim was to find out if there exist significant postglacial faults.

Research included the mapping of all long fractures and faults at the shore outcrops of islands surrounding Olkiluoto. During the mapping all such marks were observed, which could be exposed if the fault has been active after glaciation. Most of the observations were made on the south and west side of Olkiluoto, because on the north side there are only a few islands. In addition, the work included some targets from Kustavi and Korsholm, where (by personal communication) some possible postglacial faults have been observed.

Observations were done on 136 outcrops and 619 fractures and faults. Only 30 were true faults. The shortest measured fractures were 4 m long and the longest 58 m. The average length was 11 m.

From the observed 30 faults 13 were located in a rapakivi area in Kustavi and 17 around Olkiluoto. In the rapakivi area some mylonites and one clear fracture were deep and old features, except the fault, which possibly was reactivated also after glaciation. Other young faults in the rapakivi do not reach deeper than the first horizontal fracture. In the vicinity of Olkiluoto Island there were no post-glacially active faults, which has undisputedly been active after glaciation. Marine forces and frost have moved some small blocks on outcrops.

Keywords: fault, fracture, glacio-isostasy, land uplift, post-glacial, Olkiluoto, Eurajoki

Glasio-isostaattisten siirrostumien kartoitus Olkiluodon lähialueella

TIIVISTELMÄ

Mannerjään painaman maankuoren palautuminen alkuperäiseen asemaansa jatkuu edelleen. Tämä maankohoamisena tunnettu ilmiö on Olkiluodon alueella noin 5 mm/v. Maankohoamisen ajatellaan tapahtuvan kallioperän ikivanhoja ruhjevyöhykkeitä myöten jokseenkin joustavasti ja uusia siirroksia aiheuttamatta. Glasio-isostaattisten siirrosten löytyminen Olkiluodon lähiympäristöstä voisi antaa viitteitä kallioperän aktiivisuudesta. Niinpä työssä pyrittiin selvittämään, onko Olkiluodon lähialueella tapahtunut jäätiköitymisen loppuvaiheessa tai sen jälkeen merkittäviä kallioperän siirrostumia.

Työ toteutettiin kartoittamalla kaikki pitkät raot ja siirrokset Olkiluodon lähisaarten rantakallioilta. Työn aikana tarkkailtiin merkkejä, jotka ilmaisisivat siirroksen olleen aktiivinen jäätiköitymisen jälkeen. Suurin osa havainnoista kertyi Olkiluodon länsi- ja eteläpuolelta, koska pohjoispuolinen Eurajoensalmi on lähes saareton. Lisäksi työhön sisällytettiin muutama kohde Kustavista sekä yksi Mustasaaren Raippaluodosta. Nämä kohteet esiintyvät kirjallisuudessa suullisina viitteinä, joita ei ole tarkemmin dokumentoitu.

Kaikkiaan havaintoja tehtiin 136 kohteesta ja 619 raosta. Näistä 30 oli siirroksiksi luokiteltavia. Lyhimmät raot olivat nelimetrisiä ja pisin 58-metrinen. Kaikkien rakojen keskipituus oli 11 m.

Havaitusta 30 siirroksesta 13 sijaitsi rapakivialueella ja 17 Olkiluodon läheisyydessä. Rapakivialueelta lukuun on kelpuutettu myös muutama myloniitti. Myloniitit sekä yksi selvä ruhje ulottuvat kallioperään myös syvyyssuunnassa ja ovat vanhoja, ruhjeessa myös jääkauden jälkeinen aktivoituminen on todennäköistä. Muut rapakivessä esiintyvät siirrokset ovat nuoria, todennäköisesti jääkauden aikana syntyneitä, mutta niiden syvyysulottuvuus päättyy ensimmäiseen vaakarakoon, arviolta 0,3 – 1,5 metrin syvyydessä. Olkiluodon ympäristöstä ei löytynyt yhtään siirrosta, joka kiistatta olisi ollut aktiivinen jääkauden aikana tai jälkeen. Joissakin rantakallioissa tosin on pieniä lohkoja, joita routa ja rantavoimat ovat liikutelleet.

Avainsanat: siirros, rako, glasioisostasia, maankohoaminen, postglasiaalinen, Olkiluoto, Eurajoki

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1 INTRODUCTION

1.1 Background

Recognition and analysis of displacements caused by glacio-isostatic movements of the bedrock is an important part of the safety analysis of the deposition of spent nuclear fuel due to possible seismic risk. Because of land uplift of 5 - 6 mm/year seismic activity and faults caused by glacio-isostatic rebound are in the region. Horizontal movement of the crust is also controlled by the vertical rebound and can be 2 mm/year (Ojala et al. 2004).

The purpose of this study is to attempt to recognise possible glacio-isostatic movements within the Olkiluoto region. The investigation area comprised shore outcrops of islands in the vicinity of Olkiluoto. All long fractures (fractures with a trace length > 4m) were mapped and special attention was paid to the recognition of signs indicating glacio-isostatic movements. The mapping area extended from 2.5 to 5 km west and south from Olkiluoto (Fig. 1). A few islands on the north side of Olkiluoto were also studied. A total 136 outcrops were investigated and 619 fractures and faults were mapped.

This work also included reviewing some possible postglacial faults in the municipality of Kustavi, SW-Finland (Kuivamäki et al. 1998) as well as one target area in Raippaluoto, Korsholm.

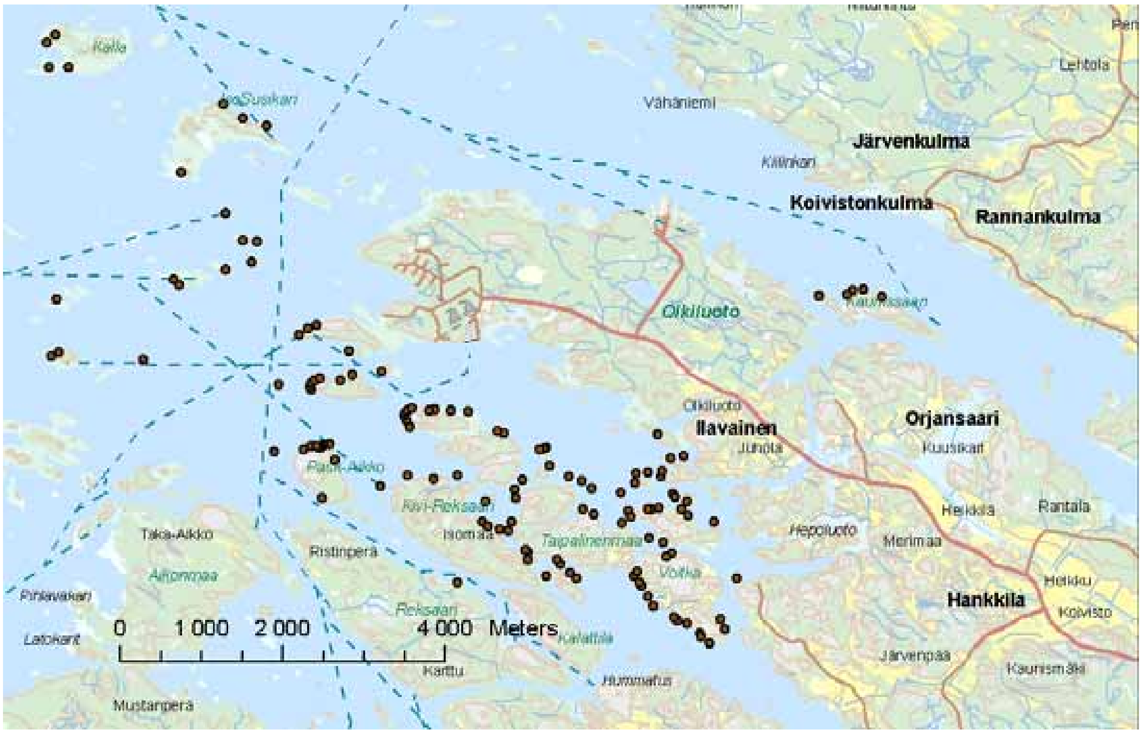

__Figure 1.__ Map of the research area and observation points marked with black squares (Base map © National Land Survey, Licence no 13/MYY/07).

The bedrock of the investigation area consists mainly of veined mica gneiss, which seldom appears as homogeneous grey mica gneiss. Plutonic rocks in the area are grey tonalites and granodiorites. Coarse-grained reddish pegmatite granites are common. The bedrock map was published in 1993 (Suominen and Torssonen 1993) and its explanation few years later (Suominen et al. 1997). The Vehmaa rapakivi stock (including the Kustavi area mentioned in this paper) has been described by Lindberg and Bergman (1992, 1993). Due to the different geological environment the local fracturing also displays different properties.

1.2 Methods

During the investigation, each long fracture was mapped and the following attributes were measured: dip, dip direction, length, aperture, Jr number and profile, the alteration of fracture surface (Ja number), undulation, fissure filling and rock type of the outcrop. Fractures shorter than 4 m were excluded from the investigation. If a fracture was considered a fault its dip, strike and fault type (sense of movement) was also estimated. In addition, each studied fracture was photographed. Observation points were specified with GPS and a geological compass was used to measure directions.

In the estimation whether any glacio-isostatic movement has occurred in an observed fracture or fault, the offset of glacial marks such as striations and grooves were considered important, and, as already pointed out by Edelman (1949), polished vertical surfaces were also considered as an indication of pre-glacial movements. It is pointed out that these methods do not discriminate between aseismic and seismic movements and, as a consequence, no conclusion can be drawn whether the observed movements are associated with post-glacial earthquakes or not.

Attribute and coordinate data was collected in an excel file which is, together with the photographs, attached to this report in digital format.

2 FAULT OBSERVATIONS

2.1 Olkiluoto area

During this research a total of 30 faults were detected. This number includes a few mylonites and small fracture zones. They are listed in table 1. For further discussion the group has been divided into two, because of the different nature of faults in rapakivi granite. Faults in the Olkiluoto area are shown in figure 2.

Manterenpää (fault 5.2): a steep (dip 77) normal fault with a scarp from 1 to 4 m high. The fault appears as 1metre wide fracture zone. The vertical surface has been polished and the edges rounded by ice. There is no evidence of post-glacial reactivation.

Liaskari (fault 63.1): a ten metre long fracture with an aperture of 10 - 20 mm. The west side of this very undulating fault is 2 – 4 cm higher than the east side (Fig. 3). Between the fault surfaces the rock is mylonitized and eroded. Both ends of the fracture are visible and the height difference decreases to zero at the ends. Only very slight polishing can be found at the edges of the fault. The possibility of a post-glacial component cannot be completely excluded.

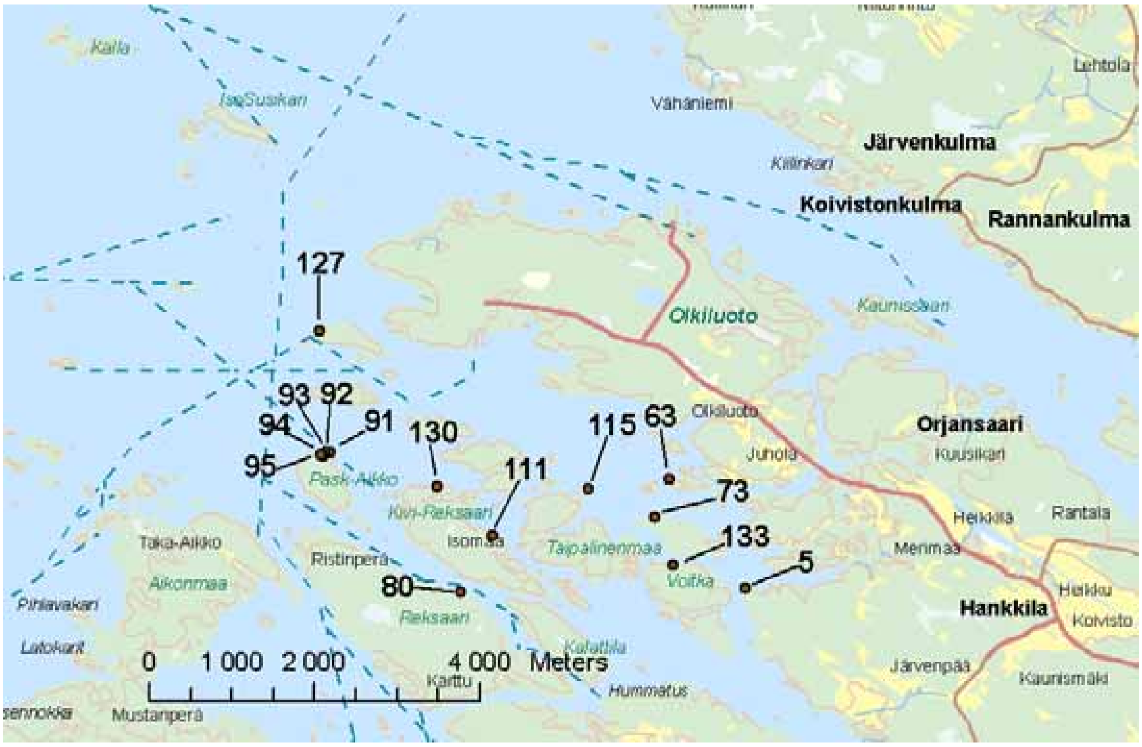

__Figure 2.__ Map of the faults in the surroundings of Olkiluoto. Observation numbers are shown (Base map © National Land Survey, Licence no 13/MYY/07).

Pukkiluoto (fault 73.1): a quite sharp, 18 cm high scarp, striking 160°. This fault has the character of an old fracture; the aperture is great (80 – 100 mm) and on the bottom there is a fractured, but compact rock. The proximal side (the side of glaciation centre) of the outcrop (and the fault) is higher, but the rough striations do not continue across the fault (Fig. 4). On the distal side (the side further away from the glaciation centre) the nearest 0.5 – 1 m of rock surface is only slightly polished by ice. The fine striations there also have a different direction to the main ones. Both pieces of evidence prove that the ice has moved over the scarp, not an even surface, and that the surface near the fault on the distal side has not received the whole pressure of flowing ice. So it is possible to conclude that this fault already existed in the glacial period.

Reksaari (fault 80.2): a shore outcrop that contains blocks of some tens of cubic metres. One of these blocks has been moved (possibly by marine ice in winter) along existing fracture and a displacement of 0.5 – 4 cm occurs. This kind of block movement is a common phenomenon, but usually the blocks are smaller, only few cubic metres.

Pask-Aikko (faults 91.1, 92.1, 93.1, 94.1, 94.2, 94.6, 95.1 and 95.4): several faults and fractures with almost uniform strike, 160^{o} – 180^{o}, and near vertical dip. Many faults have also a scarp from 30 to 120 cm high (Figs. 5 and 6) and the sense of movement is ambiguous. Fault 91.1 (Fig 4) has a high proximal side and a lower distal one. The vertical fault surfaces are also polished by ice. They are 5 – 30 cm apart and between them the rock is very fractured and eroded to the depth of 0.5 –1.5 metres. It seems clear, that the scarp already existed during glaciation and no signs of later activation are available. In figure 5 the scarp is higher on the distal side and the vertical plane is polished and the upper corner rounded by ice, which are clear indications that also this fault already existed in the glacial period. The other faults on the north shore of Pask-Aikko have similar features to those described.

Kivi-Reksaari (fault 111.1 and shear zone 130.1): here is the highest scarp of the whole research area and it is approximately 3 – 6 m high with a length of 22 m (Fig. 7). About 1.5 – 2 m of this scarp is below sea level. There is no indication of post-glacial reactivation. The scarp itself is slightly polished by ice. At least a 35 m long, old shear zone (130.1), about 1 – 2 metres in breadth follows the north shore of the island Kivi-Reksaari. The rock is mostly highly fractured and in places mylonitized. The form of the bedrock surface shows that it has been ground to smoothness by ice, so any later movement is improbable.

Tormkari (fault 115.1): this small islet has 12 m long fault (Fig. 8). The proximal side is the higher one and the maximal vertical height difference at the northern end is 17 cm. This height difference decreases to zero at the southern end, just before the fault disappears under the soil cover. Horizontal displacement cannot be proved because of the lichen covering the rock. Striations are weak on both sides. The edge of fault is slightly polished, which is not enough to prove a glacial or pre-glacial nature. This one is not possible to determine whether it is pre-glacial or post-glacial fault. Similar to the Liaskari fault (63.1).

Kuusisenmaa (fault 127.1): a steep (79 degrees) 30 metre long fault filled with soil. The bedrock is all around polished by ice, with no apparent movement after glaciation.

Voitka (fault 133.1): a 25 m long, old fault and fracture zone with ice-polished surfaces and quite deeply eroded fractured rock between the fault surfaces (Fig. 9) near the shore, but further off, on the bedrock top, the aperture is only 5 cm. This fault is very similar to number 5.1 (Manterenpää) and also the strikes are near each other (05 – 19 degrees). They are old pre-glacial faults without any signs of post-glacial reactivation.

Table 1. *All observed faults. Rock types: MGN = mica gneiss, VMG = veined mica gneiss, RPK = rapakivi, DB = diabase, GRDR = granodiorite, TON = tonalite, MTON = migmatitic tonalite, GR = granite, PGR = pegmatitic granite, nm = non measurable. Fault 1.2 from Raippaluoto is not plotted on diagrams in Chapter 3.*

ID	DIP	DIRECTION	LENGTH	APERTURE	ROCK TYPE
			m	mm	
1.2	84	89	6	5	MGN
5.2	77	109	40	1000	MGN
18.1	82	165	22	10	RPK
18.2	85	155	9,1	5	RPK
18.3	82	170	17	20	RPK
18.4	76	163	5	40	RPK
18.5	86	301	6,3	20	RPK
18.6	73	165	4,5	20	RPK
19.1	86	227	13	3	RPK
63.1	89	68	10	10	VMG, DB
73.1	75	255	6,6	100	VMG
80.2	71	147	5,5	8	VMG
91.1	81	82	24	300	GRDR
92.1	87	72	24	100	PGR, TON
93.1	87	268	22	8	GR, PGR
94.1	81	87	15,5	15	MTON
94.2	89	263	14	20	MTON
94.6	86	267	22	20	MTON
95.1	84	269	20	50	PGR,GRDR
95.4	84	268	30	200	PGR,GRDR
111.1	80	270	22	0	TON
115.1	65	85	12	10	VMG
127.1	79	180	30	50	TON, PGR
130.1	60	165	35	3	MGN, PGR
133.1	50	95	25	50	VMG
135.1A	80	177	nm	0	RPK
135.1B	70	67	nm	0	RPK
135.2	77	75	55	5	RPK
136.1	88	98	7	60	RPK
136.2	88	286	13	5	RPK
136.4	85	67	10	0	RPK

Figure 3. *A fault on Liaskari island, Eurajoki (IAL-2006- 63.1; x = 6790.146; y = 1526.493). The height difference is 2 - 4 cm, W-side (left) is higher, strike 158^o and ice has come from 297^o. The tag is 15 cm long.*

Figure 4. *A fault on Pukkiluoto island, Rauma (IAL-2006- 73.1; x = 6789,690; y = 1526,314). Scarp is 18 cm, strike 160^o and ice has come from 300^o.*

Figure 5. *A fault on Pask-Aikko island (IAL-2006- 91.1; x = 6790,482; y = 1522,390). Ice movement from right (290^o) to left.*

Figure 6. *A fault on Pask-Aikko island (IAL-2006-93.1; x = 6790,437; y = 1522,293). The scarp height varies 30 – 110 cm. The tag is 15 cm long.*

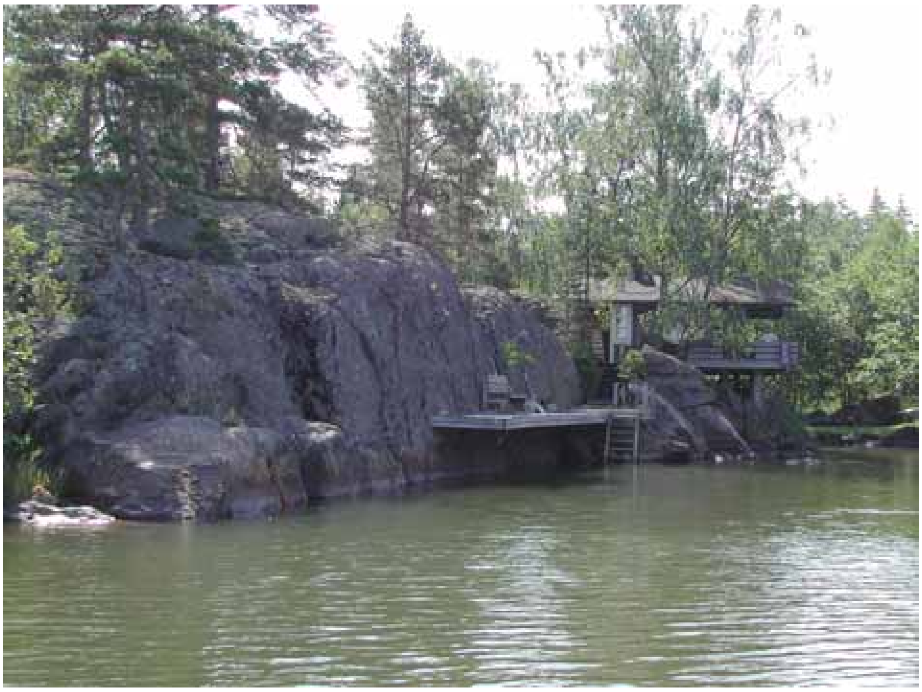

Figure 7. *About 1.5 – 2 m of this scarp is below sea level. The whole height is approximately 3 – 6 m. Kivi-Reksaari, Rauma (IAL-2006-111.1; x = 6789,471; y = 1524,347). Strike 360°.*

Figure 8. *The outcrop and fault on Tormkari islet, Rauma. (IAL-2006-115.1; x = 6790,036; y = 1525,500, strike 170°).*

Figure 9. *The fault on the north shore of Voitka island, Rauma. (IAL-2006-133.1; x = 6789.104; y = 1526.538, strike 170^{o}).*

2.2 Kustavi and Korsholm

2.2.1 Kustavi

This work deals with the control of some postglacial faults from Kustavi, SW-Finland. They have been mentioned in earlier papers (Kuivamäki et al. 1998), but are based only on personal communication. In addition one recent observation from Raippaluoto island, in the municipality of Korsholm, was included in the research because of its suspected post-glacial character (Jukka Ojalainen, Personal communication).

The reported postglacial faults of Kustavi are situated in the rapakivi area, while Raippaluoto lies within a completely different metamorphic area with mica gneisses and inhomogeneous infracrustal rocks. Also the jointing is quite different, where rapakivi is characterised by three clear joint directions, one of which is nearly horizontal. The studied faults from Kustavi are shown in figure 10.

The first target fault was photographed by Aarne Veriö (in Kuivamäki et al. 1998). According to the photograph, it is a sharp vertical fault (Fig. 11), but other attributes were not known. This fault was not found, due to a lack of spatial information. Instead some other, small faults were found and mapped from the shore outcrops in the Kustavi area (Figs. 12 and 13).

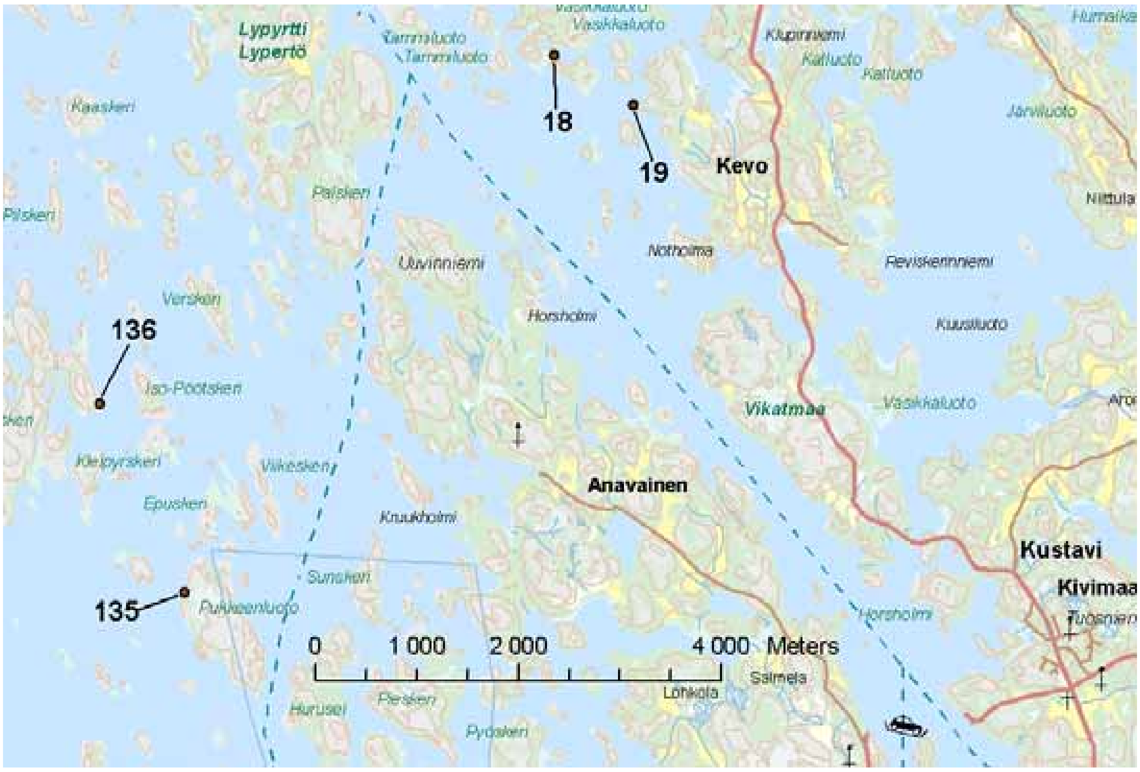

Figure 10. *Map of the studied faults in Kustavi. Observation numbers are shown (Base map © National Land Survey, Licence no 13/MYY/07).*

Figure 11. *A sharp fault somewhere in Kustavi. Photo: Aarne Veriö.*

Observation point Vasikkaluoto (Faults18.1 – 18.6) is a flat outcrop (about 40 x 30 sq. m) where there are several quite rough fractures (undulation 5 – 6 cm, which is more than in typical rapakivi outcrops). On closer inspection, it can be seen that the fractures are filled with loose soil and have an aperture from 3 to 40 mm (Fig. 12) and the different blocks have a few millimetre or centimetre step (height difference). On this wide outcrop all the steps are lower in the direction of ice movement. It seems possible that the ice sheet has pushed the blocks along a near-horizontal plane and, at the same time, apart from each other. In the immediate terrain there are examples of near-horizontal fractures and great (e.g. 3 x 4 x 5 m) blocks, which have moved along them.
The same kind of small structure was found on the shore of Sammalperänniemi (Fault 19.1, Fig. 13). There is only one fault and its strike differs by just 10^{o} from the striations. These kinds of faults are glacial, not postglacial. They have no relation to the post-glacial land uplift.

Figure 12. *A vertical fault with aperture 20 mm has been caused by the ice sheet pushing the blocks of bedrock. Vasikkaluoto, Kustavi (IAL-2006-18.6; x = 6721,231; y = 1514,603).*

Postglacial faults in Pukkeenluoto (135.1 and 135.2) and Lanskeri (136.1 – 136.4) have been reported by Kujansuu (in Kuivamäki et al. 1998). On the NW shore of Pukkeenluoto island there is a 55 m long sharp fault (Fig. 14) and several fractures, mylonites and even scarps striking almost parallel (150^{o} – $160^{o)}$, which differs only slightly from the regional, very strong lineaments (ca. 140^{o} – 150^{o}). The main fault is composed of two fractures, which are 15 cm apart and contain very fractured rock between them. The fracture surfaces, as well as the edges are sharp and do not contain any striations or polishing caused by ice.

Figure 13. *Vertical displacement is a result of horizontal (dextral) movement. Relatively thin blocks have been pushed along an inclined (near-horizontal) fracture surface by the ice sheet. Sammalperänniemi, Kustavi (IAL-2006-19.1; x = 6720,737; y = 1515,374).*

On the island of Lanskeri two faults (136.1 and 136.2), one open fracture/fault (163.3) and one mylonite (136.4) have been mapped. From these only the quartz-filled mylonite (136.4 in Fig. 15) have the same strike (157^{o}) as the fault described from Pukkeenluoto. The others strike almost N – S. One of them is a typical large block, which has slipped along the first horizontal fracture at a depth of 1.0 – 1.2 metres (Fig. 15). Just this and the open fracture 136.3 have the same strike as the fault, which was sketched on a map by Kujansuu (Kuivamäki et al. 1998). It is possible that, for example, with aerial photo interpretation this kind of fractures may give the impression of a postglacial fault. The fourth fault (136.2) from Lanskeri is located onshore and is a typical dextral fault without any evidence of its age.

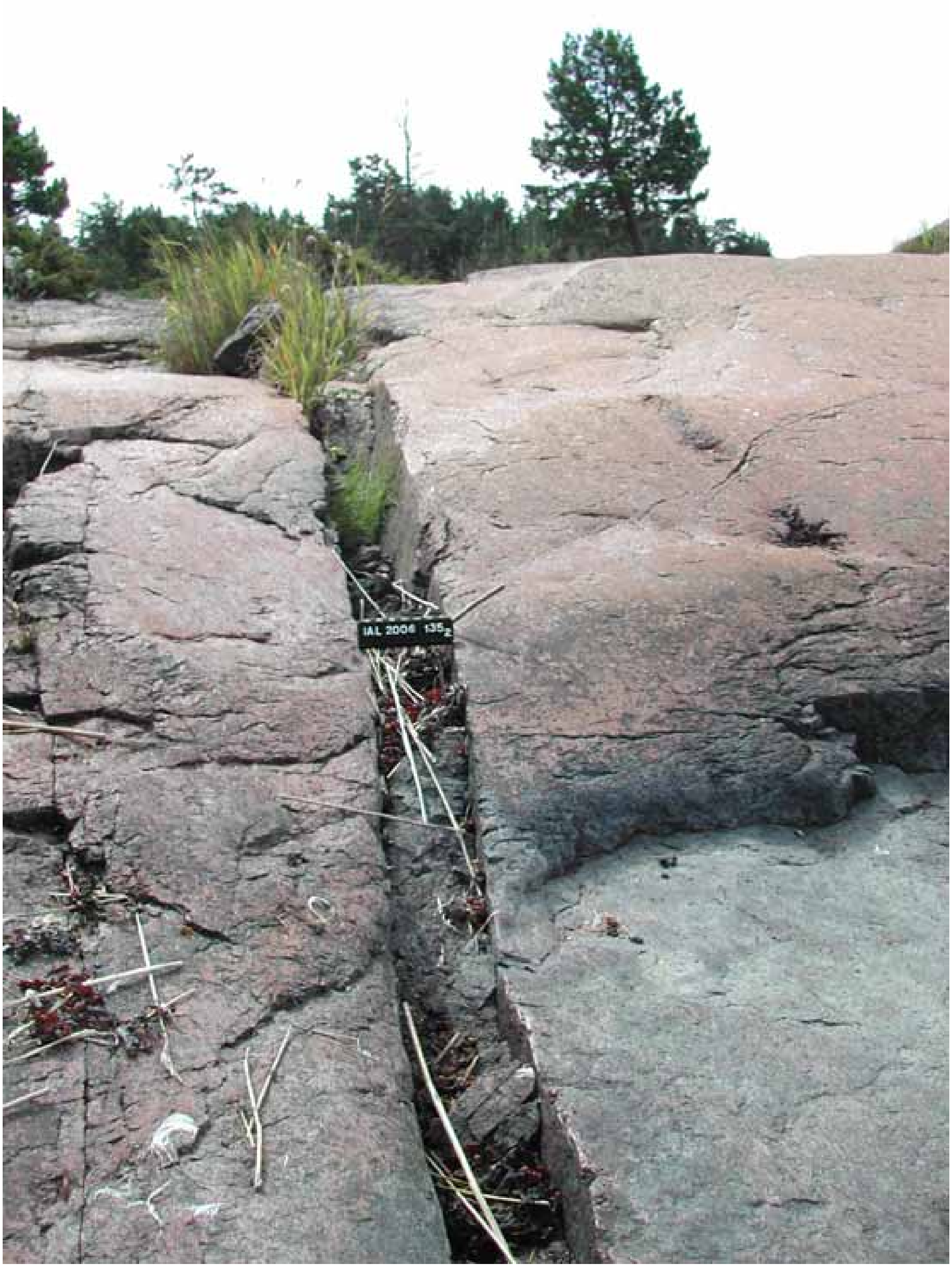

Figure 14. *The most spectacular part of the fault on Pukkeenluoto island, Kustavi (IAL-2006-135.2; x = 6715,924; y = 1510,956).*

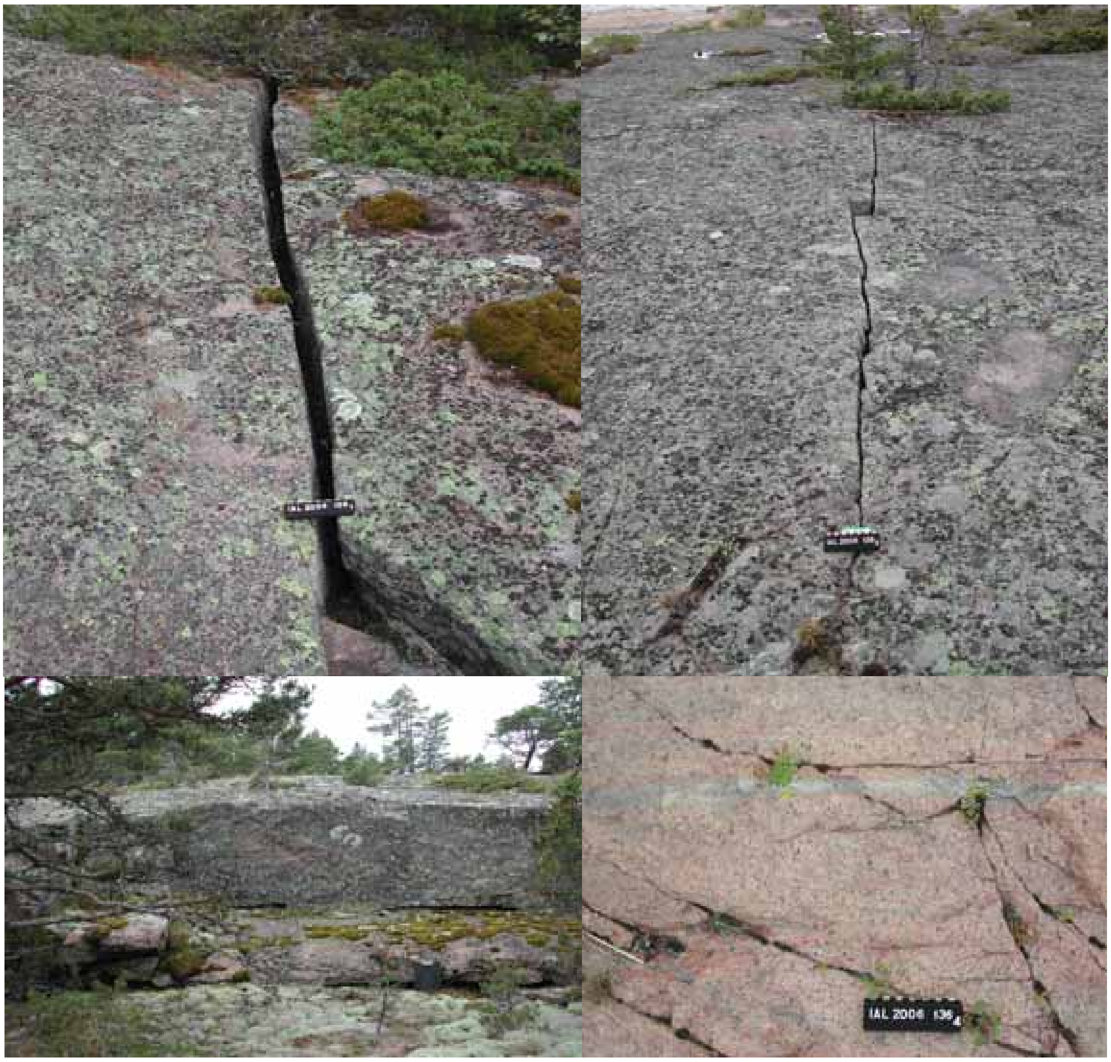

Figure 15. *Faults of Lanskeri. IAL-2006-136.1 (top left), IAL-2006-136.3 (top right) and the explanation to them: horizontal open fracture (down left). Quartz-filled mylonite (IAL-2006-136.4, down right. x = 6717.786; y = 1510.111).*

2.2.2 Korsholm

A possible postglacial fault (1.2) on an outcrop on Raippaluoto Island, which is situated near the centre of the postglacial land uplift, was researched in this study. The rate of land uplift of the Quarken area is still 9 mm/yr. So it would be the most favourable area for glacio-isostatic faulting. However, during the intensive bedrock and Quaternary deposit mapping in 2003 – 2005 no other suspicious targets were found.

The glacial striations on this outcrop are from several directions and mostly quite weak and it is not easy to say whether they continue across the observed fracture. The main direction of striations is 333° and the strike of the fracture 073°. The proximal side of the facture is the higher one with a maximum height difference of 12 cm. The vertical surface of the fracture is also slightly smooth-worn or polished (Fig. 16). Therefore it is not considered a post-glacial fault.

Figure 16. *The fault of Raippaluoto (2006-IAL-1.2; x = 7011,011; y = 1521,447). Two directions of striations are marked, the main direction with a thicker arrow. Note that in the right margin of photo the vertical displacement is zero.*

3 FRACTURE DATA

From every fracture 12 –15 parameters were measured (Chapter 1.2, Methods). This table is appended to report in digital form (on DVD).

The dip/dip direction analyses of fracture data were made with Rocscience Dips – software using the lower hemisphere equal angle projection. Before plotting the data all measured directions were corrected with the local variation, +5 degrees.

Results of all fractures (Fig. 17) show that most of them are near-vertical and very often striking N – S. When fractures longer than 10 metres are selected, this phenomena is still stronger (Fig. 18). Faults around Olkiluoto also belong to this group (Fig. 19a), but faults from the Kustavi rapakivi area are mostly WSW – ENE striking (Fig. 19b. In both cases the number of observations is small.

The fracture length distribution is shown in Figure 20. Fractures shorter than 4 metres were not included in this study. Soil cover often limited the visible length of the fractures or the end of a fracture disappeared beneath the water. Both ends were shown in 47 % of the fractures.

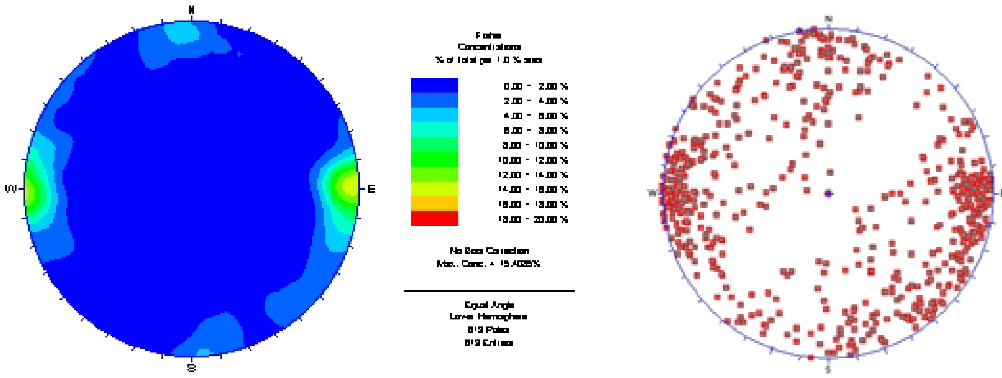

Figure 17. *Orientation of all fractures (dip/dip direction, n = 619).*

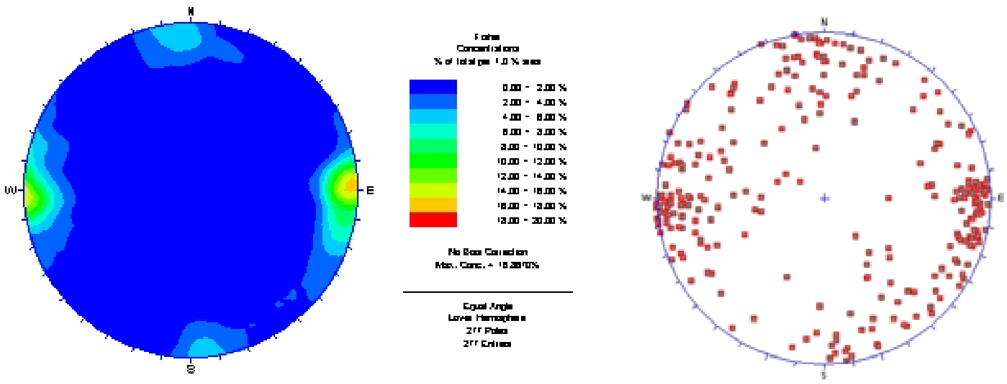

Figure 18. *Orientation of fractures over 10 m in length (n = 277)*

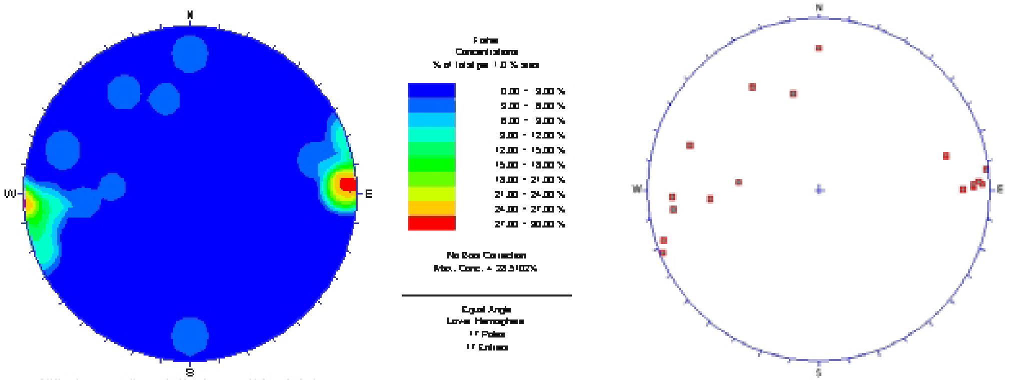

***Figure 19a.** Orientation of faults around Olkiluoto Island (n = 17)*

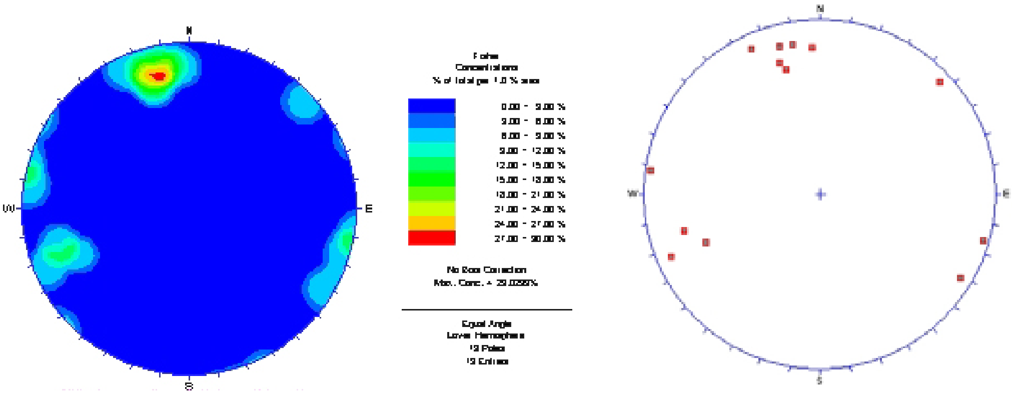

***Figure 19b.** Orientation of faults in rapakivi area in Kustavi (n = 13).*

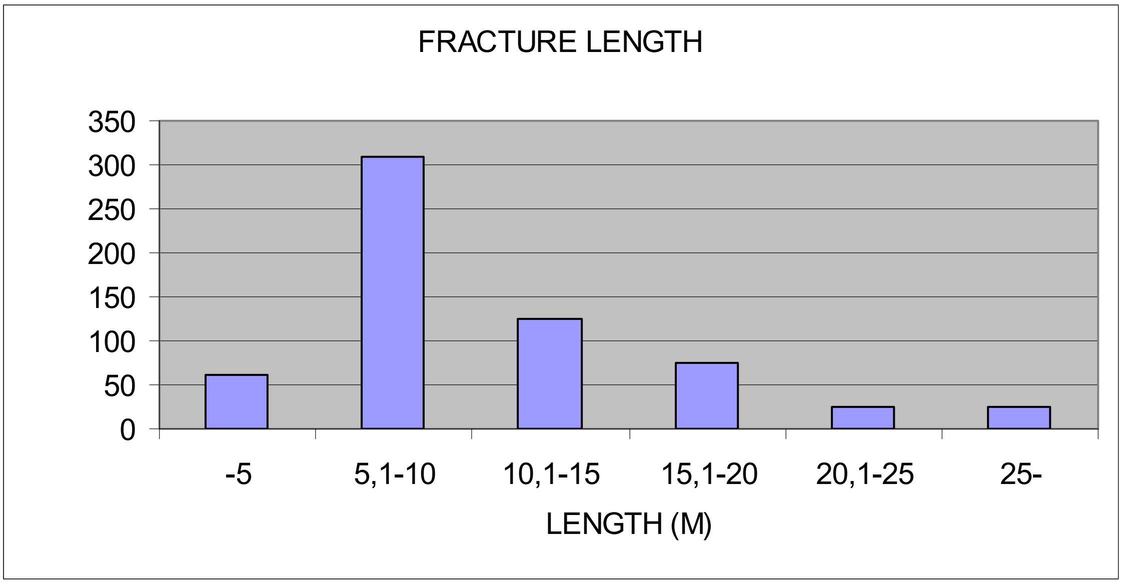

***Figure 20.** Fracture length distribution (n = 617).*

4 SUMMARY

The purpose of this study was to identify possible glacio-isostatic movements from fractures and faults around Olkiluoto Island. In addition three earlier reported places in Kustavi and one in Korsholm were included in order to check the validity of their post-glacial character.

Only few post-glacial faults are reported in the existing literature, and the most carefully inspected of them are situating in soil formations in Lapland. This study was directed to shore outcrops, where the sea has swept the loose soil cover away.

From the 619 fractures mapped 30 were considered as faults (including some mylonites). One fault in rapakivi area in Kustavi had so sharp features that it has been suggested to have resulted from glacio-isostatic movements in the bedrock. Many outcrops have massive blocks, from several to tens of cubic metres, which clearly are in their original place but loosened from the rest of the outcrop. Especially in the rapakivi areas, where outcrops are flat and wide and where the horizontal fracturing is well developed, it is difficult to distinguish these blocks from a real glacio-isostatic movements. The influence of the pressure of winter ice as well as the water freezing in bedrock joints are easily underestimated.

Evidence of glacio-isostatic movements within the Olkiluoto region and in Korsholm was not observed during this study, but in some cases the post-glacial component of displacement was not possible to exclude. The second or spin-off result is the fracture data from over 600 measured fractures, which shows a strong maximum of N – S striking fractures and faults in the area.

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