



Evidence of multiple slip events on postglacial faults in northern Fennoscandia

J. Mattila ^{a,*}, A.E.K. Ojala ^a, T. Ruskeeniemi ^a, J.-P. Palmu ^a, I. Aaltonen ^a, A. Käpyaho ^a, A. Lindberg ^a, R. Sutinen ^b

^a Geological Survey of Finland, P.O. Box 96, 02151, Espoo, Finland

^b Geological Survey of Finland, P.O. Box 77, 96101, Rovaniemi, Finland

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ABSTRACT

An analysis of high-resolution LiDAR-based digital elevation models (DEMs), trenching of Quaternary deposits, diamond drilling and a structural analysis of the bedrock were conducted in order to characterise the geological structure and to derive full slip profiles of the Venejärvi–Jauhojärvi postglacial fault complex located in northern Finland. The Venejärvi–Jauhojärvi fault complex consists of 17 surface ruptures striking in a SW–NE direction, cutting through Late Weichselian till and traceable for a total distance of 29.9 km. Based on stratigraphical and structural analysis we show that the Naamivitikko fault segment, which is part of the Venejärvi–Jauhojärvi complex, hosted up to three distinct slip events and it is therefore argued that the prevailing single-rupture hypothesis of postglacial faults should be treated with caution. Based on the measured surface rupture dimensions, it is conservatively estimated that the maximum moment magnitude of the paleoseismic event that the complex hosted, ranged between $M_w \approx 5.8$ –8.4. If uncertainties in the scaling laws equating surface rupture dimensions to moment magnitudes are accounted for, a more realistic maximum moment magnitude range between $M_w \approx 5.8$ –7.6 is given.

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1. Introduction

Postglacial faults (PGF) in northern Fennoscandia are intriguing structures, representing an end-glacial phase of much higher seismic activity and moment magnitudes than currently observed in the Fennoscandian shield. These postglacial faults are considered to have formed due the release of excess horizontal flexural stresses generated in Earth's crust during glacial period and triggered by deglaciation and glacial isostatic adjustment (e.g. Wu et al., 1999; Stewart et al., 2000; Lund et al., 2009) and as such represent a unique seismic and mechanical setting which cannot be directly associated with present day stresses or strain accumulation. Some of the postglacial faults are reported to have generated earthquakes up to moment magnitudes of $M_w \approx 7$ –8 (e.g. Arvidsson, 1996; Wu et al., 1999; Lagerbäck and Sundh, 2008; Lund et al., 2009; Lund et al., 2017; Ojala et al., 2019a) and thus portray a period of high-magnitude intraplate seismicity. As discussed by Stewart et al.

(2000), the postglacial faults in northern Fennoscandia are generally considered to be the result of single rupture events that took place at the end of, or after, the last Weichselian glaciation. The single-rupture hypothesis has been the general understanding with respect to the formation of the postglacial faults and, until recent times, no direct or indirect evidence has been given to show otherwise. Lagerbäck and Sundh (2008) discussed the possibility that the scarps associated with the Lainio–Suijavaara fault in Sweden were formed in more than one slip event, but this hypothesis has not been confirmed.

Several recent studies employing the use of high-resolution LiDAR (Light Detection And Ranging) -based digital elevation models (DEM) have shown that postglacial faults are complicated structures, consisting typically of SW–NE-trending segments located close to each other and forming larger fault systems - closely located fault systems, on the other hand, form larger fault complexes (e.g. Mikko et al., 2015; Palmu et al., 2015; Lund et al., 2017; Ojala et al., 2017; Ojala et al., 2019a). The Suassellkä fault complex, located close to the town of Kittilä in northern Finland for example, consists of a total of 37 isolated 150–7500 m long segments, which further form a total of 4 fault systems (Ojala et al.,

* Corresponding author. Rock Mechanics Consulting Finland Oy, Vantaankoskentie 14, 01670 Vantaa, Finland.

E-mail address: jussi.mattila@rmcf.fi (J. Mattila).

2019b), thus depicting a highly complex structure of the surface rupture. Analysis of LiDAR DEM data, together with detailed trenching and investigation of landslides associated with post-glacial faults have, however, shown that different PGF fault segments were activated or reactivated at different times during glacial-interglacial cycles (e.g. Sutinen et al., 2007, 2014a, 2014b; Ojala et al., 2017, 2018a,b, 2019a,b; Smith et al., 2018) and, therefore, show that the single-rupture hypothesis is most likely wrong and thus that views on the formation mechanisms of the faults should be updated.

In this paper we explore the characteristics of the Venejärvi–Jauhojärvi PGF complex in western Finnish Lapland and specifically the Naamivitikko faults segment located in the SW part of the complex (Fig. 1). Using LiDAR DEM analysis, ground-penetrating radar, trenching and drilling we describe the

structures observed both in glacial sediments and in the bedrock at the Naamivitikko site. We also use height and length data from the surface ruptures to estimate the potential moment magnitudes of the palaeoseismic events that took place in the Venejärvi–Jauhojärvi complex. Furthermore, with observations from the Naamivitikko study site, we discuss whether the postglacial faults can indeed be considered as the result of a single rupture.

2. Regional setting

The Venejärvi–Jauhojärvi PGF complex is located in northern Finland, ca. 20 km SE of the municipality of Kolari and north of the Pasmajärvi PGF Complex (Fig. 1). Ojala et al. (2019a) divided the segments of the Venejärvi–Jauhojärvi PGF complex into two fault systems, the Venejärvi PGF system, which consists of a total of 10

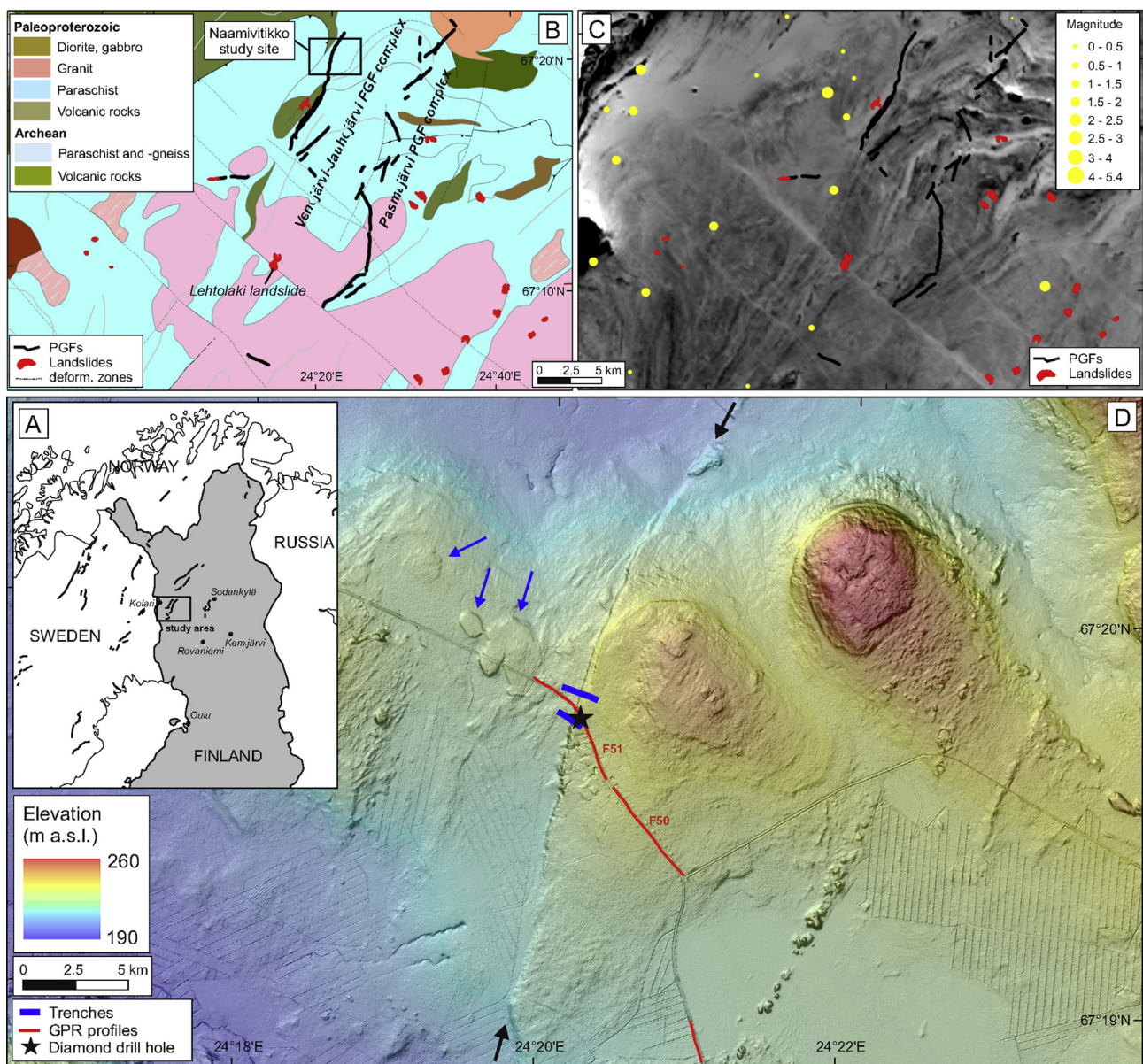


Fig. 1. Maps showing the location of a study area in relation to other PGFs in the northern Fennoscandian Shield area (A), bedrock characteristics of the Venejärvi and Jauhojärvi PGF systems (B) and airborne magnetic anomalies (white = low, black = high) with PGF scarps, landslides and instrumental earthquake observations from FENCAT (C). A lower image presents a detailed LiDAR DEM with locations of the trench, ground penetrating radar (GPR) lines and diamond-core drill holes at the Naamivitikko study site (D). Black arrows indicate the location of presently studied Naamivitikko fault segment while the blue arrows indicate the distribution of round-shaped liquefaction bowl morphologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

segments, and the Jauhojärvi PGF system, which consists of total of 7 segments (Fig. 1). The systems are separated by a gap of ca. 4.5 km between their closest segments. The whole complex consequently consists of a total of 17 segments whose surface rupture lengths vary between 0.3 and 5.2 km. The complex is characterised by a NE–SW-striking structure of clustered and discontinuous fault segments which can be traced for a distance of ca. 29.9 km. Geologically, the Venejärvi–Jauhojärvi PGF complex is located in the NW part of the western Karelia sub-province and the area is characterised by Archaean and Paleoproterozoic metasediments and –volcanic rocks and Paleoproterozoic granites (Nironen, 2017, Fig. 1). The Venejärvi PGF system is mostly located within a lithological unit of paraschist, but the southern part of the fault segment is located next to a contact between paraschist and an undefined unit of volcanic rocks (Fig. 1).

On the airborne high-resolution magnetic map (Fig. 1), the SW part of the complex does show a clear correlation with an NNE–SSW-trending magnetic anomaly, potentially indicative of a lithological contact not visible in the geological map. At the NE end of the complex, a clear bending of the structure is observed, and this aligns exactly with a similarly bending fold structure seen on the magnetic map. Another striking feature of the fault is that at its SW end, the Venejärvi fault is clearly truncated against a major NW–SE-trending fault zone. The NW–SE-trending fault is part of a larger fault system that can be traced from the Rovaniemi and Kemijärvi regions to Kolari, i.e. for a total distance of about 140 km. Similar truncation behaviour is also observed for the Pasmajärvi PGF complex and one smaller fault segment is also seen to be aligned and directly overlapping with such a NW–SE-trending magnetic anomaly (Fig. 1).

The overburden in the area is mainly composed of glacial sediments (diamicton and sand) of Weichselian and pre-Weichselian origin, which are covered by postglacial peat and gyttja in the lower lying areas (e.g. Kujansuu, 1967; Sutinen, 1992). The area was deglaciated during the Early Holocene, probably around 11,200 cal BP (Ojala et al., 2018a,b). The Venejärvi PGF system is spatially associated with the Lehtolaki landslide, located on the NW side of the fault and about 5 km SW of the Naamivitikko study site. As presented by Ojala et al. (2018a,b), the Lehtolaki landslide exhibits a complex geomorphology and dispersed lithostratigraphy with early- (10,201 cal BP), mid- (5893 cal BP), and late-Holocene (1225–1582 cal BP) ages of buried organic material in adjacent drill core sections. In addition, as presented by Ojala et al. (2019b), there are more than ten landslides within 35 km of the present study site, which are mostly located in the SE sector (Fig. 1). An interesting geomorphological feature in the vicinity of the Naamivitikko study site are the round bowl-shaped morphologies, which are sometimes located near PGFs in northern Finland and Sweden (e.g. Lagerbäck and Sundh, 2008; Sutinen et al., 2019) and are found next to the fault segment studied here. According to Sutinen et al. (2019) the complete lack of anisotropy in these bowls suggests chaotic deformation of sediments, which was probably due to palaeoseismic shaking in association with the subaerial liquefaction of sediments.

The Venejärvi–Jauhojärvi PGF complex is associated with a band of recent macroseismic earthquakes (FENCAT-catalogue, www.seismo.helsinki.fi), with the band having an approximate trend of SW–NE, i.e. aligning with the general trend of the PGF faults (Fig. 1). The SE side of the complex is essentially void of seismicity with most of the known events located on the NW side of the complex. The events on the NW side of the Venejärvi–Jauhojärvi PGF complex mostly took place in a period between 2004 and 2017 and had moment magnitudes ranging between $M_w \approx 0.9$ –1.7. None of the segments of the complex show a clear association with the events and the events are rather

diffusively located around the complex.

3. Material and methods

3.1. LiDAR DEM analysis

LiDAR-DEM data was used to obtain fault slip profiles and to determine the variability in scarp heights and lengths of surface ruptures, following the method described in Ojala et al. (2017) and Mattila et al. (2016). We first digitized lines at the hinges of the upthrown and downthrown sides of fault scarps and then extracted the height data in the DEM at the location of these lines. By dividing the upper line into points separated by 1 m distance and computing the closest point on the line at the downthrown side of the scarp, we could then compute the vertical distance between these points and extract the throw of the fault scarp at these points. By linking the points to specific locations along the scarp, we derived highly detailed vertical fault slip profiles for the scarps, which we further utilised in the analysis of the mean and maximum displacement values and the shape of the slip profiles.

3.2. Ground-penetrating radar and trenching

The field survey of the Naamivitikko site was initiated by sediment thickness and fault ramp profiling using ground penetrating radar (GPR) (Fig. 2). We used a GSSI SIR® 3000 single-channel GPR data acquisition system with a 100-MHz antenna. The properties of the sediment deposits were calculated using Geoductor software with a dielectric value of 6 without any recalculation.

The selection of trenching location across the Naamivitikko PGF was based on GPR results and LiDAR DEM information. We selected the Naamivitikko location for trenching as the high-resolution LiDAR DEM showed a distinct scarp in the quaternary sediments and, based on GPR data, the total thickness of loose sediments was thin enough to reach the weathered bedrock (Fig. 2). Two trenches were excavated at the Naamivitikko site, but as the trenches turned out to be sedimentologically similar to each other, in our analysis we focus on the southern trench. The southern trench was ca. 30 m long, 4 m wide and 9 m deep and was excavated perpendicular to the scarp observed in the LiDAR-DEM. The near-vertical walls of the trench were sedimentologically logged and documented with photographs to create a map of the sedimentological details. The sedimentological observations of the trench included sediment colour, texture and grain size (i.e. lithostratigraphy), as well as the structures and compactness of the sedimentary layers. The soft, weathered bedrock was excavated on the footwall side, allowing detailed investigations of the fault scarp. During the excavation we did not however reach the bedrock at the footwall side of the fault and no observations of the bedrock on the footwall side could be made.

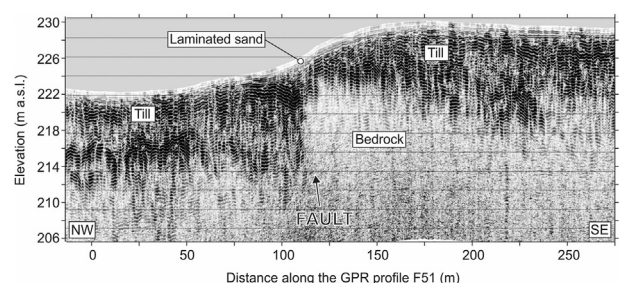


Fig. 2. GPR Profile of the southern trench at the Naamivitikko site (Venejärvi PGF system) with interpreted sediment units, bedrock and the location of the fault scarp.

3.3. Drilling

One 88.6 m long diamond cored drill hole (core diameter 41 mm) was drilled through the Naamivitikko fault with a plunge of 60° and azimuth of 280° at the location of the southern trench (Fig. 1). Bedrock lithologies were mapped along the core and fracture frequency analysis was carried out. The results of the core logging allowed us to interpret the 3D orientation of the fault zone.

4. Results

4.1. LiDAR-DEM analysis

Based on the LiDAR-DEM, the surface rupture of the Venejärvi-Jauhojärvi complex is highly segmented, consisting of 17 segments (Fig. 1). The slip profiles of the complex acquired from the LiDAR DEM are shown in Fig. 3. The cumulative length of the segments in the complex is 29.9 km, the mean vertical displacement 2.6 m and the maximum displacement 11.1 m. The mean displacements of the individual segments vary from 0.1 to 4.1 m and the maximum displacements from 0.4 to 11.1 m. Surface rupture lengths of individual segments vary from ca. 350–5200 m. The largest vertical displacements in the complex are observed in the SW part and the displacements have a tapered distribution towards NW, which may indicate that the cumulative rupture direction was towards the NE (e.g. Manighetti et al., 2001; Davis et al., 2005). Similar asymmetrical slip profiles were also observed for the Isovaara–Riikonkumpu PGF complex by Ojala et al. (2017) and for the Suasselkä PGF complex by Ojala et al. (2019c), which also suggested that the cumulative rupture propagation direction of these fault complexes could have been from SW to NE. There are distinct gaps between the systems along the strike of the complex which may further indicate that the systems ruptured independently or that earthquakes jumped from one system to another due to triggering caused by stress transfer. Observations from historical surface ruptures indicate that earthquakes do not typically jump from one segment to another if the distance between the segments is more than 3–5 km, and such distances are sufficient to stop earthquakes from propagating (e.g. Wesnousky, 2006, 2008). This would support the idea that the systems in this study may have ruptured independently.

4.2. Quaternary sediment thickness and stratigraphy

The lithostratigraphic profile from the south-facing i wall of the southernmost trench is shown in Fig. 4. During the excavation, we were unable to reach the bedrock on the footwall side of the fault, but a distinct hanging wall faulted block was observed in the trench (Fig. 4A), with a dip and dip direction of 65°/094° and with a minimum vertical displacement of at least 6 m. Across the fault, weathered granite was thrust on top of Quaternary sediments (Fig. 4A) which indicates a reverse dip slip component of the fault. In the trench, hanging wall block consisted of a deeply weathered and highly fractured middle – to coarse-grained leucocratic locally K-feldspar porphyritic granite with some gneissic mica-rich bands (Unit 1, Fig. 5), which differs from the parascists marked on the geological map, and we thus infer that the available bedrock geological map is not detailed enough at the location of the study site.

On the footwall side, the granite truncates against a lower till unit (Unit 2) and a laminated sand unit (Unit 3), which further truncates against and is eroded by a massive, unstructured pocket of gravel and overlain by a small unit of laminated till, which also overlays the pocket of gravel. The hanging wall side of the granite is overlain by two units of till (Units 2 and 4/5). The topmost till unit (Unit 4) is ca. 0.5 m thick on the hanging wall side but grades into a thicker unit of laminated gravelly sand (Unit 5) on the footwall side, composed of the same material as in unit 4 but redeposited upon the footwall side. At the contact of the fault and the sedimentary units, a narrow band of brecciated and sheared granite and a narrow layer of sandy silt is observed (Figs. 4B and 5). The sandy silt (Unit 6) further forms injection structures into the lower till (Unit 2) and into the laminated sand (Unit 3) (Figs. 5 and 4C), and in the lower till sandy silt also exhibits a larger lens of injected material, which extends up to a couple of metres away from the fault plane (Fig. 4D). These injection structures are indicative of rapid liquefaction thus proving that the observed offset is associated with an earthquake rather than an aseismic event. As the sandy silt unit (Unit 6) is injected into both the lower till and the laminated sand units (Fig. 4C) this clearly indicates that at least one seismic event took place after the deposition of sedimentary units 2 and 3. The uppermost laminated sand (Unit 5) is also slightly folded close to the fault plane, providing evidence of a slip event, which is younger in age than unit 5.

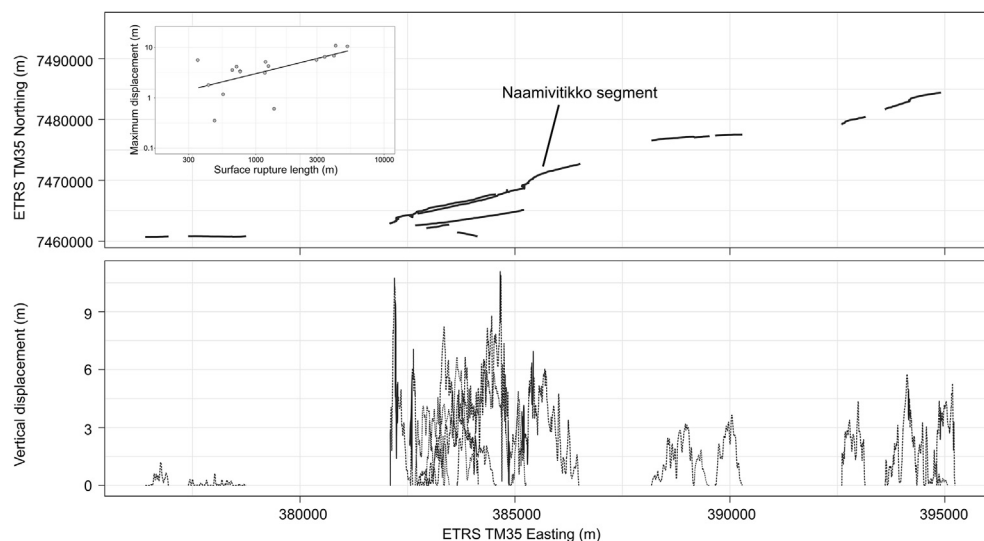


Fig. 3. Geometry and vertical displacement profiles of individual fault segments in the Venejärvi-Jauhojärvi PGF complex, together with the maximum displacement vs. surface rupture length plot (inset figure). The length and displacement data are given in supplementary file S1.

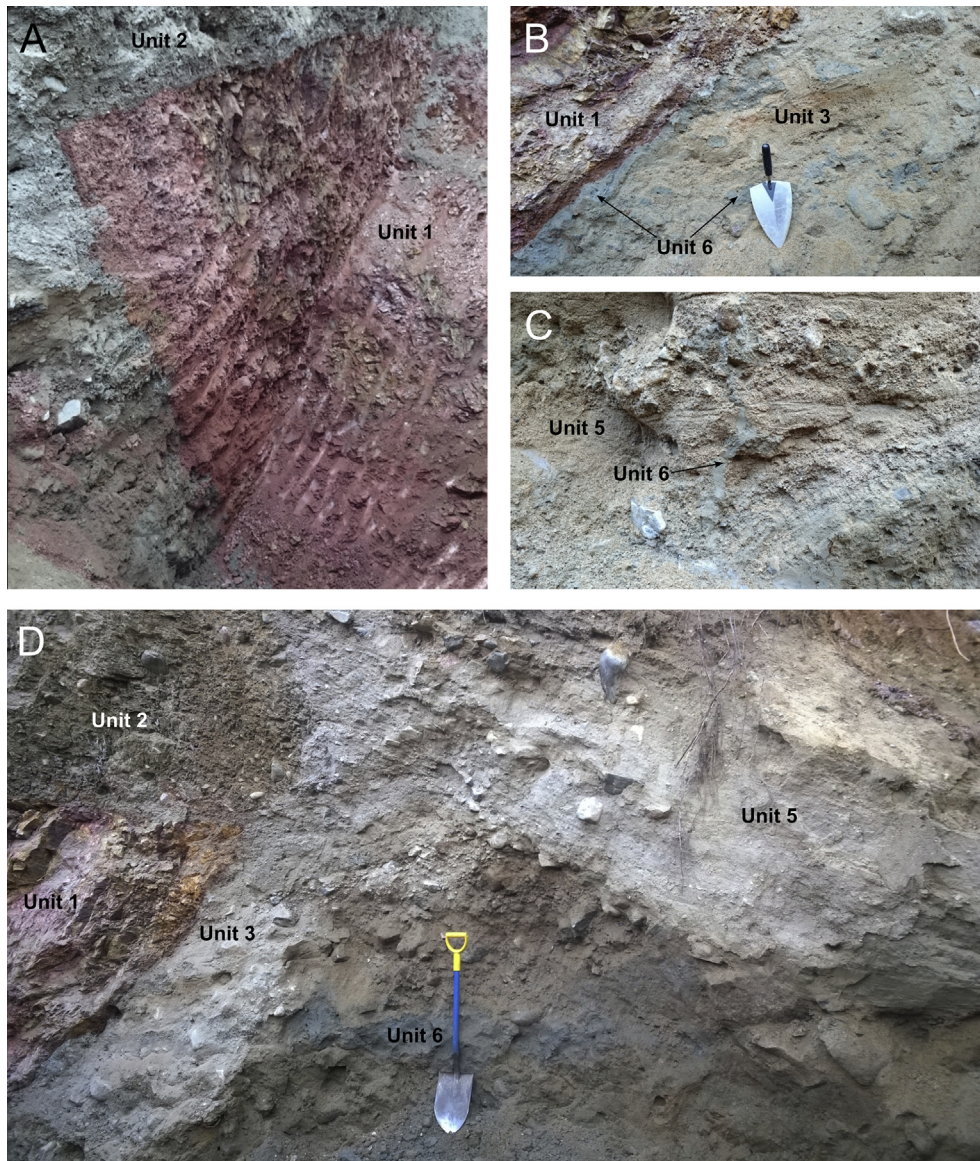


Fig. 4. Detailed images of the Naamivitikko trench. A) a view of the hanging wall bedrock block on the NE side of the trench, B) injection structures as observed in the trench, silt veins intruding into the laminated gravelly sand unit (unit 3), C) a close-up of the fault plane, showing a seam of brecciated granite and silt injected into the laminated sand unit (Unit 4), and D) A view of the SW wall of the trench showing the relation of units 1, 2, 3, 5 and 6. The length of the shovel in D) is ca. 1 m. Use Fig. 5 for reference to the units.

We interpret the structures in the trench in the following way (Fig. 6). The lowermost till (Unit 2) represents the unit originally deposited on top of the bedrock (Stage 1). During the first slip event, Unit 2 together with the overlying Unit 3 (laminated gravelly sand) and the underlying granite were offset (Stage 2). After Stage 2, sediment collapse, erosion and redeposition in a littoral or fluvial environment took place. This resulted in the thinning of the till unit (Unit 2) in hanging wall and lead to the stacking of material on the footwall side (Stage 3). This was followed by the deposition of the upper till unit (Unit 4) on top of the whole sequence and erosion of the laminated gravelly sand (Stage 4). The second slip event then occurred resulting in the faulting of till units and their subsequent collapse onto the footwall side as well as in the formation of a massive gravel unit (Stage 5). After the slip event, shoreline processes of erosion and redeposition occurred again, probably in a proglacial ice lake environment (Stage 6). The ancient shore ridges of the local ice lake can still be detected in the area at an altitude of 235–245 m

a.s.l. As a consequence, the topmost till unit (Unit 4) was significantly washed away and redeposited along the scarp and the footwall side as a laminated gravelly sand unit (Unit 5). The occurrence of a block of laminated till on top of Unit 3, which further seems to cross-cut the top of Unit 4 and slightly folds Unit 5, suggests that a third slip event has also taken place (Stage 7). The amount of displacement on this third event was, however, quite modest as there are no clear offsets, only a slight folding of the laminar layers in unit 5. With respect to the age of the injected silt, as it crosscuts the laminar features of unit 5, the age of the laminar unit sets the minimum age of the injection. With the stratigraphic information available however, we cannot exclude that separate injection events could not have also happened during the earlier slip events. The sedimentological and structural observations from the trench thus suggest that up to three slip events have taken place during the evolution of the fault and that they date to different times of the Weichselian glaciation and deglaciation.

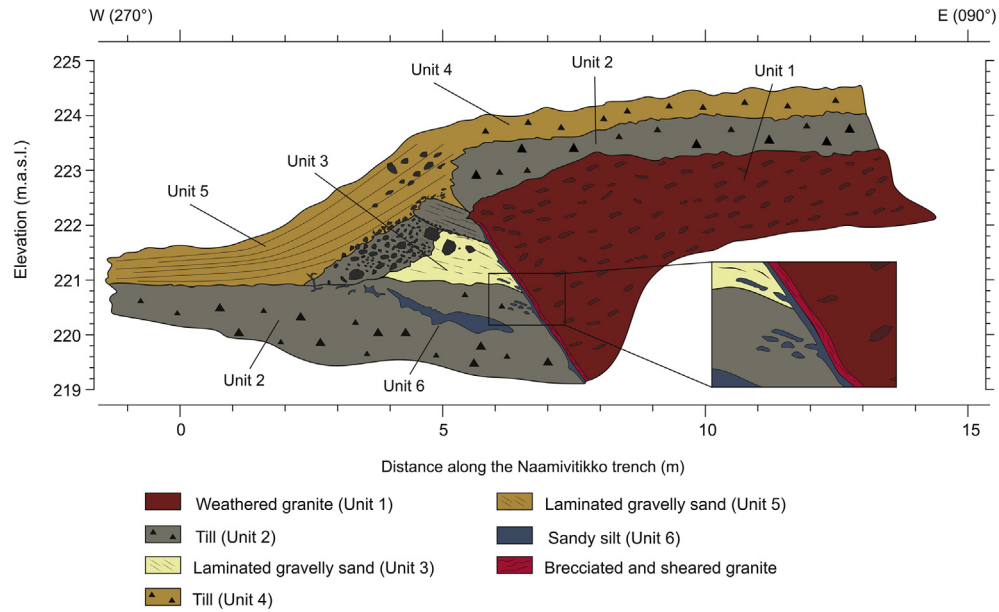


Fig. 5. Profile of the south-facing wall of the southern trench at the Naamivitikko site (Venejärvi PGF system) with sediment units and structural characteristics.

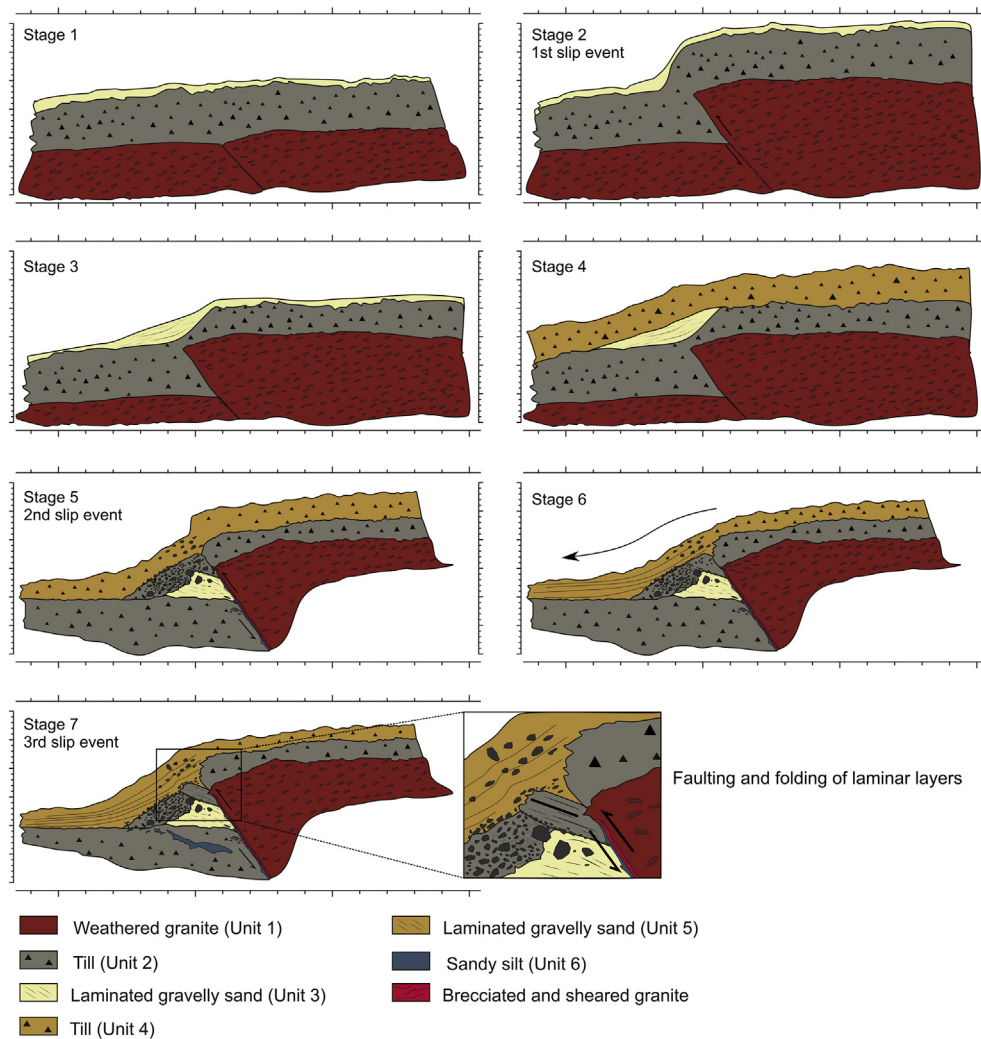


Fig. 6. Interpreted model of the deposition and movement of different lithostratigraphical units during slip events of the Naamivitikko PGF segment (see Fig. 3 for scale and a description of the lithostratigraphical units).

4.3. Drill core logs

One drill hole was drilled at the Naamivitikko trenching site with a total length of 88 m and a dip of 60° with an azimuth of 280°. Fracture frequencies for the drill core are presented in Fig. 7A. The lithology in the drillcore consists mainly of mica gneiss and granite (Fig. 8). The core was strongly fractured, especially in the upper part and the fracture frequencies were therefore estimated visually for the upper 40 m of the hole and counted for the remaining hole. We consider the core sections of elevated fracture frequencies as potential locations for the fault zone intersections. Based on that assumption, the most likely location for fault zone intersection is in the upper part of the drill hole, approximately at the depth (along the hole length) of 15–40 m or 77–80 m, where a clear increase in fracture frequency is observed. Due to the highly fractured nature of the drill core in these sections, we were not able to determine the exact location of the fault in the core, which would be required for the exact determination of the fault zone orientation. Nevertheless, we interpret that the intervals of elevated fracture frequencies are indicative of the fault damage zone extent, thus giving upper and lower estimates for fault zone boundaries. We further analysed the potential location of the fault damage zone by applying cumulative fracture count diagrams (Choi et al., 2016, Fig. 7B). The cumulative

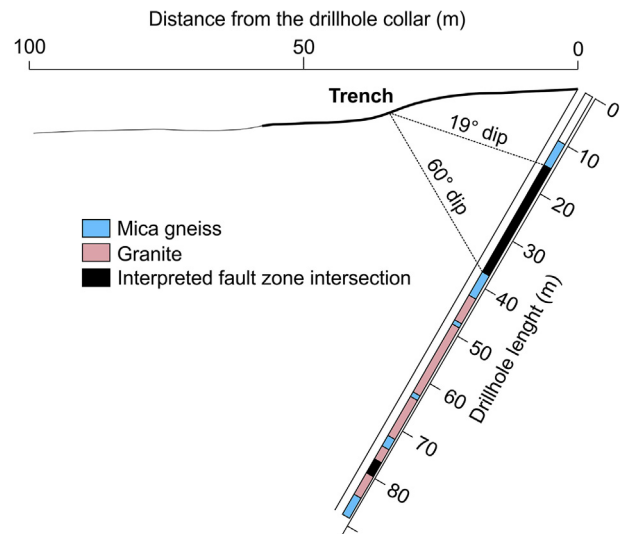


Fig. 8. Log of bedrock lithology profile for the drill hole R1 at the Naamivitikko site. An estimation of the dip of the Naamivitikko fault based on fracture frequencies (Figure/A) is given with dashed black lines.

fracture count is computed for along-hole-length and damage zones (intervals of higher fracture frequency on average) show up as intervals of gentler slopes, indicative of faster accumulation of the number of fractures. Areas of lower fracture frequency, on the other hand, have steeper slopes. The data supports the interpretation that for the Naamivitikko PGF, the damage zone is intersected by the drill hole at the depth of 15–37 m, which shows up in Fig. 7B as an interval of gentler slope gradient (faster fracture accumulation) compared to the rest of the hole. The higher fracture frequency area at the depth of ca. 75–80 m is also seen as an area of faster fracture accumulation and is considered as another potential fault zone intersection location or is representative of another fault.

Other than the two sections of elevated fracture frequencies, we did not find any other clear signs indicative of faulting, such as fault gouges or increased number of slickensides, which could potentially be used to interpret the fault zone orientation at depth. Therefore, we can only approximate the fault orientations based on fracture frequencies and the estimated boundaries of the fault damage zone. The increase in fracture frequency in the upper part of the drill hole suggest that the fault may have a dip ranging ca. 19–60°, whereas if the deeper section of higher fracture frequencies is considered, the fault would dip towards west (Fig. 8), which we consider to be highly unlikely as the fault is observed to dip east in the trench. A dip of 60° is closer to what was observed in the trench and we consider that 60–65° is the best estimation for the orientation of the zone at least in the shallow parts of the bedrock. Lower angles are also possible based on the fracture frequency data, but here we rely more on the direct observations. The observations further suggest that the damage zone may be asymmetrical, with higher fracture frequencies on the hanging wall side of the fault.

5. Discussion

5.1. The hypothesis of single rupture event

As discussed by e.g. Stewart et al., (2000), the postglacial faults in northern Fennoscandia are generally considered to be the result of single post- or endglacial events and this has remained the prevailing understanding with respect to rupture mechanics of

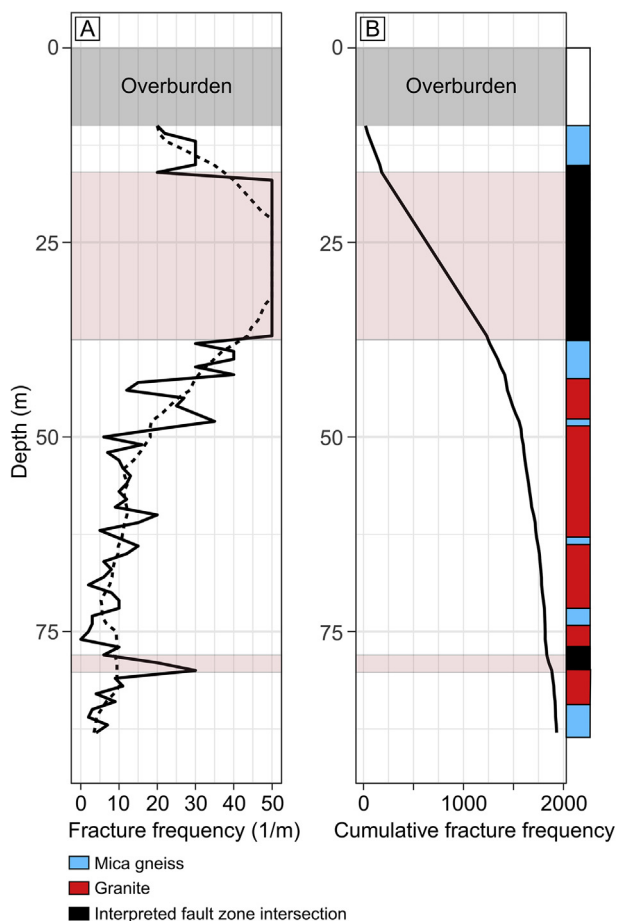


Fig. 7. A) Fracture frequency (fractures per metre) along drill hole U4142014R1 from the Naamivitikko site indicated with the black continuous line and a moving average of the fracture frequencies shown with the dashed black line (moving average with an 11 m window). B) Cumulative fracture count. The location of the overburden is shown in grey and the interpreted location of the fault damage zone in light red. Lithological log is shown on the right-hand side of the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

postglacial faults. Lagerbäck and Sundh (2008) speculated that the scarps associated with the Lainio–Suijavaara fault in Sweden may have been formed in more than one slip event. More recently however, Smith et al. (2018), showed that different segments of the Merasjärvi PGF, located in northern Sweden, ruptured at different times during the postglacial period. Smith et al. (2018) based their analysis on geomorphological evidence from LiDAR data but could not determine in detail the ages of the slip events. Their observations were based on offsets of fluvial terraces of different ages intersecting the Merasjärvi fault scarp at different locations.

Ojala et al. (2019c) further showed that adjacent fault segments at the Suasselkä PGF complex in Northern Finland were active at different times and observed also indications that one fault segment had slipped both in pre-Weichselian and postglacial stages. Such an episodic pattern of slip events is further supported by the ages obtained from landslides spatially associated with the postglacial faults, indicating potential multiple periods of seismicity during the Holocene (Ojala et al., 2018a, 2018b, 2017). With our observations from the Naamivitikko fault we provide new evidence for this discussion as the Naamivitikko PGF segment shows that the observed fault scarp is the result of three distinct slip events. We cannot however distinguish either the absolute ages of these slip events or the exact amount of displacement that took place during these separate events, although we note that the last slip event seems to have been quite modest in respect to slip amount. We consider that there is now sufficient evidence from Sweden and Finland to state that the postglacial fault scarps were not the result of single rupture event but rather that isolated faults may have slipped multiple times – up to two or three times – and different fault segments within the fault complexes may have ruptured at different times, even during the pre-Weichselian stage. We cannot however argue that this would apply to all postglacial faults in Fennoscandia, though the evidence herein does point to the fact that the single rupture hypothesis should not be considered as a general rule for the formation of postglacial faults. We therefore agree with the statement by Smith et al. (2018), who plead for caution in assuming that all the observed postglacial fault scarps are the product of single ruptures. This should also be accounted for in long-term seismic hazard assessments, where postglacial earthquakes are used as a component of the seismic catalogue.

5.2. Estimation of the potential moment magnitudes

In the case of paleoseismic events, direct estimation of moment magnitudes of the rupture event is impossible and estimation of paleomagnitudes requires the use of indirect evidence. One approach in estimation of paleoseismic moment magnitudes is the use of scaling laws which give regression equations relating moment magnitudes to maximum surface displacement (MaxSD) values, mean surface displacement (MeanSD) values and surface rupture lengths (SRL) of single-rupture events. The scaling laws are based on observations from past instrumentally monitored events, where data on moment magnitudes and the observed surface ruptures is available. In the estimation of the moment magnitudes for the Venejärvi–Jauhojärvi complex, we applied scaling laws defined for reverse faults from stable continental regions (Leonard, 2010; Moss and Ross, 2011; Wells and Coppersmith, 1994) and by using these scaling equations, we estimated the potential moment magnitude ranges that the different parts of the Venejärvi–Jauhojärvi complex may have hosted.

With the use of multiple scaling equations, we consider that we can account for the uncertainty space associated with the estimations although we cannot directly state which parts of the complex potentially ruptured at different times. Given this problematic point, in our assessment we further computed the moment

magnitude ranges at the segment-, system- and complex-scale in order to account for this, assuming that each of these scales can be considered as a potential rupturing unit. The results of the moment magnitude estimations of these three different approaches are further outlined below. We further note that using the scaling equations for multiple-rupture events, such as here, yields conservative upper bound estimates for maximum moment magnitudes and the results given here should be thus treated with this in mind. For more realistic moment magnitude estimations, displacements associated with each rupture events should be acquired and the moment magnitude estimates should be based on these displacement values. In our study, although we could identify several slip events, we could not interpret what was the amount of displacement in each case. As a consequence, we have to limit our assessment of maximum moment magnitudes to the conservative upper bound case. The scaling equations used to estimate the moment magnitudes (M_w) with associated references and the lengths and vertical displacements of individual segments, systems and complexes, as well as the moment magnitudes computed from these, are provided in the supplementary file (S1).

5.2.1. Segment-based approach

We computed the moment magnitude estimations based on surface rupture lengths, mean and maximum vertical displacements and mean and maximum displacements based on the estimated dip of 60°. If it is considered that the segments ruptured individually, the length-based moment magnitude estimations range from $M_w \approx 3.7$ –5.9, while the estimates based on mean and maximum cumulative displacement yield values ranging from $M_w \approx 3.2$ –8.7 and $M_w \approx 5.4$ –8.3, respectively (Fig. 9). If the estimated dips of the faults are accounted for – assuming that these are valid for the whole complex – the mean displacement for the dip of 60° gives moment magnitude estimations of $M_w \approx 3.4$ –8.7. For maximum displacement values with dips of 60°, the moment magnitudes range between $M_w \approx 5.5$ –8.4.

5.2.2. System-based approach

Considering that the systems ruptured as isolated events, the moment magnitude estimations based on surface rupture lengths give values ranging from $M_w \approx 5.8$ –6.7 (Fig. 9). The mean displacement values give a moment magnitude range of $M_w \approx 6.7$ –8.2 while the maximum displacement values give moment magnitude ranges of $M_w \approx 6.7$ –8.3. When the estimated dip is taken into account, the mean displacement values give moment magnitude ranges between $M_w \approx 6.7$ –8.4 while the maximum displacement values yield a range of $M_w \approx 6.9$ –8.4.

5.2.3. Complex-based approach

With the conservative approach that the whole Venejärvi–Jauhojärvi complex ruptured within an isolated single earthquake, the moment magnitude estimations based on the surface rupture length range from $M_w \approx 6.6$ –6.9, and the moment magnitude estimations, which are based on the mean and maximum vertical displacement values, range from $M_w \approx 6.7$ –8.1 and $M_w \approx 7.0$ –8.3, respectively (Fig. 9). When the estimated dip value is accounted for, the mean displacement values give moment magnitudes in the range of $M_w \approx 6.7$ –8.3 with maximum displacement values moment magnitudes in the range of $M_w \approx 7.0$ –8.4.

5.2.4. Summary of moment magnitude estimations

Our results show that there is a clear discrepancy between the moment magnitude estimates based on segment, system and complex-based data. Additionally, the moment magnitudes based on surface rupture lengths – are generally lower than the

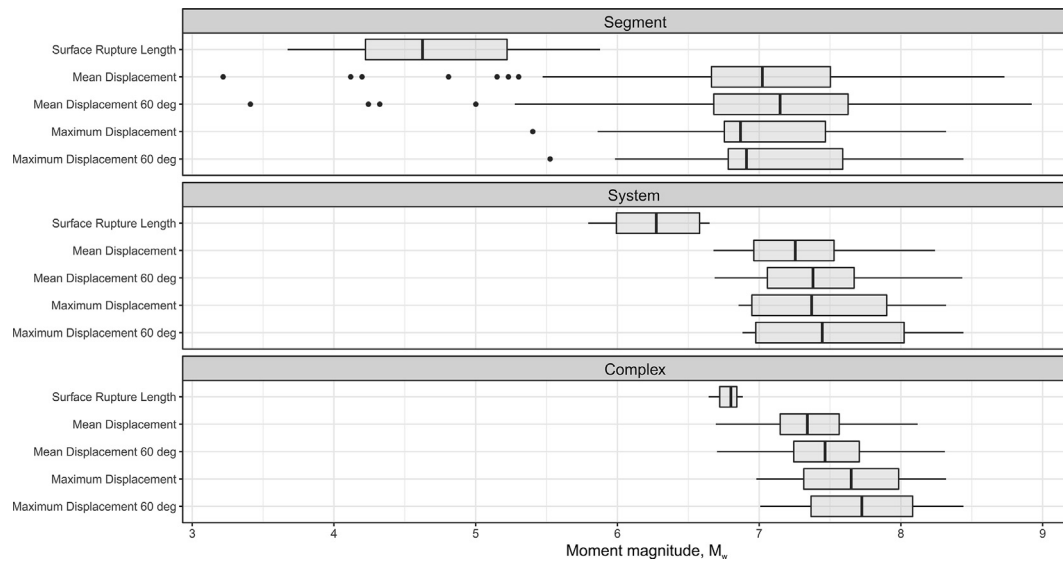


Fig. 9. Ranges of moment magnitude (M_w) estimates for the PGF segments, systems, and for the entire Venejärvi-Jauhojärvi PGF complex based on the length of the surface rupture (MSRL) and the surface rupture displacement values (MeanSD, MaxSD), accounting also for the estimated dip value of the faults. The estimates are given as boxplots where the grey boxes account for the quartiles of 0.25–0.75 and the whiskers data that are within the 1.5 interquartile range. Any values outside this range are marked as dots and are considered as potential outliers.

displacement-based estimates. This discrepancy occurs at all scales but is largest at the segment scale. We interpret these discrepancies to indicate that the rupture events that took place were most likely either at the system or complex level, as for these scales the moment magnitude estimates between displacement and length data have the best correspondence with each other, with the complex level estimates giving the largest compatibility between length- and displacement-based moment magnitude estimates. Such a discrepancy was already noted by Ojala et al. (2017, 2019c) in their study of the Isovaara–Riikonkumpu and Suasselkä PGF complexes. Another option is, as shown here, that the observed displacement values are the result of several slip events, yielding higher displacement-length ratios and, consequently, differences in the moment magnitude estimates based on displacement and length data. The surface rupture lengths should nevertheless scale with the displacements (i.e. surface rupture lengths increase with increasing displacement, see Fig. 3 inset) and therefore we cannot conclusively argue for this option as the reason for the discrepancy.

With the available data, we cannot state that certain segments or groups of segments would not have ruptured in isolated earthquakes, but for the reasons explained above, we use a conservative approach and estimate the maximum moment magnitudes using data from the system- and complex-levels. This approach gives maximum moment magnitude estimates in the range of $M_w \approx 5.8$ –8.4. It should however be noted that the estimates based on the scaling equations of Moss and Ross (2011) yield much higher values than those of Leonard (2010) and Wells and Coppersmith (1994) and may potentially represent unrealistically high values. If the estimates based on Moss and Ross (2011) are excluded, then the potential range of moment magnitudes that the faults may have hosted ranges between $M_w \approx 5.8$ –7.6, accounting for the system and complex-level data. This does not however give us a basis to argue, other than the discrepancy between the estimates based on Leonard (2010) and Wells and Coppersmith (1994), for whether the estimations based on Moss and Ross (2011) are truly extreme and therefore to consider that $M_w \approx 8.4$ represents a conservative maximum moment magnitude for the whole complex. The conservatism is further increased by the fact that here we assume that structures were formed in a single-rupture event, which we

have shown not to be the case.

By using empirical correlations between the landslide volume–area data and earthquake moment magnitude (Malamud et al., 2004), Ojala et al. (2019b) estimated potential maximum moment magnitudes for postglacial earthquakes in northern Finland. They also showed that most landslides are located within a radius of 35 km from the closest PGF segment and that the sizes of the landslides in northern Finland generally decrease as a function of distance from the closest PGF segment, supporting the information provided by Keefer (1984, 2002). Given that many landslides reported by Ojala et al. (2019b) are located within a 35 km radius from the presently studied sites, they are probably of seismic origin and can be used in the discussion of palaeoearthquakes in the area of the Naamivitikko PGF segment and the entire Venejärvi–Jauhojärvi PGF complex. Based on the landslide area data, Ojala et al. (2019b) calculated that a postglacial earthquake or potentially several earthquakes with a maximum moment magnitudes $M_w \approx 5.7$ –7.6 have taken place in the studied area. This conclusion correlates well with the range of moment magnitudes calculated based on PGF scarp length and offset parameters discussed above, and also showing that the moment magnitude estimates based on the scaling equations of Moss and Ross (2011) may be too extreme.

Our moment magnitude estimates of the presently studied postglacial fault ramps are also in agreement with the moment magnitude estimates presented for other PGFs in Fennoscandia which range between $M_w \approx 6.5$ –8.0. The Pärvie PGF in northern Sweden potentially hosted an earthquake with a moment magnitude range of up to $M_w \approx 7.6$ –8.0 (Lundqvist and Lagerbäck, 1976; Arvidsson, 1996; Lindblom et al., 2015), the Stuoragurra fault in Norway an earthquake with a moment magnitude of $M_w \approx 7.3$ (Olesen, 1988), the Lainio–Suijavaara PGF in Sweden $M_w \approx 7.1$ (Lagerbäck, 1979), the Lansjärv PGF in Sweden $M_w \approx 7.1$ (Lagerbäck, 1979) and the potential Vättern PGF in Sweden $M_w \approx 7.5$ (Jakobsson et al., 2014), the Isovaara–Riikonkumpu PGF in Finland in the range of $M_w \approx 6.9$ –7.5 (Ojala et al., 2017) and the Suasselkä PGF moment magnitudes in the range $M_w \approx 5.5$ –8.1 (Olesen et al., 2004; Ojala et al., 2019c). An earlier estimate for the moment magnitude of the Venejärvi–Jauhojärvi complex was

$M_w \approx 6.5$ (Olesen et al., 2004), but our results suggest that the complex may have hosted much higher moment magnitudes.

6. Conclusions

We analysed LiDAR DEM data along the 29.9 km long Venäjärvi–Jauhojärvi postglacial fault complex, located in northern Finland. Our aim was to assess the full slip profile of the fault and the maximum moment magnitude of the earthquake that the complex hosted during the postglacial period. We also employed a stratigraphical analysis of the Quaternary sediments at the location of the fault and a structural analysis of the bedrock at the Naamivitikko trenching site in the assessment of the geometry and slip events of the Naamivitikko fault. Based on the stratigraphical and structural analyses we show that the Naamivitikko fault hosted up to three distinct slip events and we therefore argue, in line with Smith et al. (2018), that the prevailing single-rupture hypothesis of postglacial faults should be treated with caution and that multiple-slip scenario should be accommodated into long-term seismic hazard assessments, where postglacial earthquakes are used as a component of the seismic catalogue.

The Venäjärvi–Jauhojärvi PGF complex consists of a total of two PGF systems and 17 isolated 0.3–5.2 km long surface ruptures. The maximum and mean vertical slip heights for the Venäjärvi–Jauhojärvi PGF complex as extracted from high-resolution slip profiles are 2.9 and 11.1 m, respectively. Assuming conservatively that the 29.9 km long fault complex ruptured in one event, the potential maximum moment magnitude of the paleoseismic event that took place in the complex is in the range between $M_w \approx 5.8$ –8.4, which we considered a rather conservative estimate due to uncertainties in the scaling laws equation surface rupture dimensions to moment magnitudes and which is not supported by landslide-based moment magnitude analysis (Ojala et al., 2019b). If the uncertainties are accounted for, we consider that the realistic maximum moment magnitudes that the complex may have hosted are more likely to be in the range of $M_w \approx 5.8$ –7.6.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2019.05.022>.

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