

**Maskevarri Ráhppát in Finnmark
in Finnmark**

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Maskevarri Ráhppát in Finnmark, North Norway – is it an earthquake induced landform complex?

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Abstract

The Sami word ráhppát means rough bouldery/stony terrain with sharp-relief topography in Finnmark, North Norway. Ráhppáts are common features in the region of the Younger Dryas landforms, yet their origin has remained obscure. The timing of the Younger Dryas is concomitant with the maximum neotectonic fault instability in Fennoscandia, hence earthquake activity was one of the contributing factors for the Younger Dryas morphologies. Ráhppát on the Maskevarri fell, classified as a part of Tromsø-Lyngen sub-stage of the Younger Dryas, was studied by means of geomorphology and measurements of electrical-sedimentary anisotropy. Ráhppát was found to be built up of a network of stony ridges and mounds on fell terraces bordered with arch-shaped and sinusoidal ridges. These bordering ridges exhibit sedimentary (azimuthal soil electrical conductivity) anisotropy parallel-to-ridge trends and were interconnected to meltwater gullies suggesting generation through short-lived conduit infills. We did not find electrical-sedimentary evidence to support the concept of englacial thrusting and/or compression, often described for Younger Dryas moraines. Maskevarri Ráhppát is typified by ~ 500 ponds and small lakes on three different terrace elevations descending in an up-ice direction. These escarpments may have generated trough late glacial earthquake(s) contributing to subglacial deformation of Maskevarri Ráhppát.

1 Introduction

In maps and orthophotos (Norkart Geoservice AS and Geovekst), the name Ráhppát is often found given to landforms (classified as moraines or marginal moraines) constituting the Gaissa and the main (Tromsø-Lyngen) sub-stages of the Younger Dryas (YD) events (Sollid et al., 1973; Sollid and Sørbel, 1988; Olsen et al., 1996; sub-stage positions in Fig. 1). After the maximum extent of the Fennoscandian Ice Sheet (FIS) at about 25 kyrBP (Svendsen et al., 1999), deglaciation was cyclic due to the global climatic changes (Björk, 2007; Peteet, 2009). Two warming periods ~ 14,7 and

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11,5 kyrBP in the northern Atlantic region (Renssen and Isarin, 2001; Grachev and Severinghaus, 2005) significantly changed the mass-balance of FIS and eventually contributed to the rebound of the crust (Stewart et al., 2000; see Alpine rebound in Norton and Hampel, 2010). Due to lithospheric plate stresses and glacio-isostatic rebound, high-magnitude ($M_w \approx 7\text{--}8.2$) postglacial fault deformations are common features in the northern Fennoscandian plate (Arvidsson, 1996; Wu et al., 1999; Olesen et al., 2004; Lagerbäck and Sundh, 2008; Lund et al., 2009; Kukkonen et al., 2010; Fig. 1). According to the subsidence-rebound model by Stewart et al. (2000) the occurrence of PGFs includes bending of the crust that causes stress at the edge of the receding ice sheets, hence the ice-marginal terrains had been subjected to seismic impacts. The model predictions by Wu et al. (1999) suggest that the onset of fault activity started 15 000 BP, and the maximum fault instability reached 13 000–10 000 BP in Fennoscandia. With regard to the northern Fennoscandian fault zones (Roberts et al., 1997) there is good reason to suspect that these (fault) lines have reactivated within the recession of the FIS and eventually triggered high-magnitude intra-plate seismic events in the region ($M_w > 7$; Arvidsson, 1996; Wu et al., 1999; Olesen et al., 2004). Mass-flows of the offshore sediments in the Norwegian fjords provide evidence of at least three separate large-magnitude earthquakes during the period $\sim 13,5\text{--}10$ kyrBP (Bøe et al., 2004; Olesen et al., 2004). Therefore, on the basis of coincidental time-stratigraphy, one may argue that earthquakes may have also played an important role in subglacial deformation. The morphological and electrical-sedimentary studies on ráhppáts, forming extensive landform complexes in Finnmark, North Norway, may bring new insight into paleo-seismicity.

Maskevarri Ráhppát (Fig. 1) was selected on the basis that it has been (i) classified as a part of Tromsø-Lyngen sub-stage in Finnmark in Sollid et al. (1973), (ii) described as ice marginal moraine in the geomorphology map produced by the Nordkalott Project (1986), and (iii) classified as ablation hummocky moraine in the general scale (1 : 500 000) Quaternary map by Olsen et al. (1996). We studied whether topographic position, elevation, geomorphology and electrical-sedimentary anisotropy of ridges in

Maskevarri Ráhppát support the concepts presented for the YD moraines: (i) compressive shearing similarly to present-day polar and periglacial climate (Sollid et al., 1973; Sollid and Sørbel, 1988), (ii) englacial thrusting by polythermal glaciers such as in Svalbard (Graham and Midgley, 2000), or (iii) deformation of former supraglacial debris by readvancing ice in a similar way as those in a temperate glacial regime in SW Norway and Iceland (Lukas, 2005). The alternative hypothesis was that (iv) the Ráhppát is associated with late glacial fault instability and subglacial deformation caused by earthquake(s).

2 Morpho-sedimentary analysis

Orthophotos (Norkart Geoservice AS and Geovekst) and satellite images (Landsat TM images GoogleEarth; virtual globe www.norgei3D.no) as well as maps of geomorphology and ice flow indicators produced by the Nordkalott Project (1986) and the Geological Survey of Norway (Olsen et al., 1996) were used to interpret the landform complex associated with the terrain demarcated by the Tromsø-Lyngen sub-stage of the Younger Dryas in Finnmark, North Norway (Solid et al., 1973; Nordkalott Project, 1986; Sollid and Sørbel, 1988; Olsen et al., 1996).

The Ráhppát on Maskevarri fell, centered at 70°09' N and 27°56' E and 5–10 km north of the Finnish–Norwegian border, is a field (five kilometers long and three kilometers wide) of rough (stony/bouldery) ridges and hummocks separated by a number of ponds and lakes and bordered by arc-formed/sinusoidal ridges, extending diagonally to the Maskejohka river valley (58–74 m.a.s.l.; Fig. 2). Ráhppát is located on the SW slope at elevations from 285–240 m.a.s.l., whereas the top of the Maskevarri fell reaches 308 m.a.s.l. The region is represented by the lowermost nappes in the Caledonian mountain chain in Finnmark, so called Gaissa Nappe Complex, and the bedrock is composed of Neoproterozoic qartzites, sandstones and dolomites (Roberts et al., 1997). We also paid attention to the network of mounds and ridges, morphologically similar to Maskevarri Ráhppát, on Boaltunoaivi fell of Varanger Halvøya (Peninsula).

Boaltunoaivi is located between the Porsanger and Gaissa lines (Sollid et al., 1973; Olsen et al., 1996; location in Fig. 1).

In the field we utilized in situ azimuthal electrical conductivity (σ_a) measurements to determine sedimentary anisotropy of the sinusoidal ridges bordering the main section of the Ráhppát field on the Maskevarri fell (Fig. 3). The flow paths of pore water predominantly follow preferred anisotropic (hydraulic) structures (Taylor and Fleming, 1988; Friedman, 2005). We targeted σ_a -anisotropy surveys on an unsaturated (vadose) zone of the ridges, and within this zone the sediments are considered to be a three-phase, solid-air-water system. Minerals of Neoproterozoic quartzites (Roberts et al., 1997) constituting the solid phase were considered non-conducting and $\sigma_a = 0$ applies to air in the pore spaces, hence the dominant conductive phase was the pore-water solution conductivity (Friedman, 2005). Non-spherical particles in glaciogenic sediments typically are preferentially aligned, hence e.g. tills are anisotropic in nature and their σ_a depends on the direction in which it is measured (Friedman, 2005). The σ_a -anisotropy of glaciofluvial materials, sediment mass flow deposits or tills parallels with the depositional fabric derived either from active-ice movement, mass or meltwater flow (Sutinen et al., 2009b). In addition, structurally complex landforms, such as Rogen moraine and/or glacially streamlined flutings, possessing time-statigraphical information about the glacial episodes, can be revealed with σ_a -anisotropy surveys (Sutinen et al., 2010a, b). Therefore, the measurements of azimuthal electrical conductivity assist better the understanding of the genesis of the Ráhppát complex in Finnmark.

We measured azimuthal electrical conductivity inductively with EM31 ja EM38 devices (Geonics Ltd., Mississauga, Canada) at three sites on the main sinusoidal ridges bordering the main section of the Ráhppát field on the Maskevarri fell (locations in Fig. 3). The sites on the ridge were selected on the basis that the anticipated pseudoreplication, estimated to be of the order of < 100 m, should be avoided by using lateral offsets > 100 m (Sutinen et al., 2009b, 2010a). At each site, the azimuthal σ_a was obtained using 10° lateral increments. For each increment a sum of hundred samples were stored in an Allegro CX logger (Juniper Systems Inc, Logan, UT USA). The skin

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depth information was roughly as follows: EM38V (vertical coil configuration) 0–1.5 m, EM31H (horizontal coil configuration) 0–3 m and EM31V 0–6 m, respectively. The measured data were visualized as polar plots (Grapher 4.0, Golden Software).

3 Results and discussion

3.1 Electrical-sedimentary anisotropy

The azimuthal σ_a -data indicated that the sediments in the cores of the ridges were oriented more or less parallel-to-ridges. The EM31V-data, referring to a depth-range of 0–6 m, indicated west-northwest maximum anisotropy (Fig. 3). In a similar manner, the EM31H-data, referring roughly to a depth-range of 0–3 m, clearly showed the west-northwest sedimentary anisotropic pattern. These observations indicate that the cores of the border ridges are depositional, and a north-westward sediment (mass) flow heading diagonally towards the Maskejohka valley (Figs. 2–4). In addition, the bordering ridges are interconnected to meltwater gullies in the valley suggesting generation through short-lived conduit infills (Sutinen et al., 2009b). Therefore, the azimuthal EM-data support other mechanisms for the Ráhppát than those proposed for the YD moraines, such as compressive shearing (Sollid et al., 1973; Sollid and Sørbel, 1988), englacial thrusting (Graham and Midgley, 2000) or the concept by Lukas (2005), according to which former supraglacial debris had been subglacially deformed under readvancing ice margin. In the case of the transverse-to-ridge sedimentary origin, the sedimentary anisotropy should be, according to streamlined features towards north-east, i.e. from a sector of 200–245°. No such orientation was found. In the case of the ridges here, the maximum sedimentary anisotropy matched the ridge-crestline trends similarly to sinusoidal moraine ridges in Finnish Lapland (Sutinen et al., 2009a). The polar plots of maximum EM38V-anisotropy (0–1.5 m) showed to be north/northeast in a sector 180–200°, eventually due to post-depositional slope reworking as particularly seen in the foreground of the Fig. 4b.

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Since the Ráhppát field is oriented diagonally with respect to glacial lineations on the Maskevarri fell (Fig. 2), it clearly post-dates the glacial lineations and no surface evidence of active ice remoulding features can be found (cf. Rogen moraine in Sutinen et al., 2010a). The position of Ráhppát on the SW slope of the Maskevarri fell does not fit into the concept of polar ice-marginal moraines, generated through englacial thrusting or compression (Sollid and Sørbel, 1988). The orientation of the YD main stage ice margin (Sollid et al., 1973) should have been roughly W–E, according to up-ice drumlin orientation from the southwest (Nordkalott Project, 1986; Olsen et al., 1996; Fig. 1). The mainland ice flow streamlining (Nordkalott Project, 1986; Olsen et al., 1996) continued as the Tanafjord and Varangerfjord ice streams (Olsen et al., 1996; Ottesen et al., 2008).

3.2 Morphology and paleoseismicity

Ráhppát is typified by ~ 500 small lakes, ponds and puddles (Figs. 2–4) that are arranged at three different elevation levels (terraces) on the SW-slope of the Maskevarri fell. The data indicate that the terraces are separated with escarpments ranging from 285–280 m a.s.l. in the upper part of the Maskevarri fell, to 270–260 m in the mid-level and < 260 m a.s.l. at the lower part of the field. The differences between the water levels of the lakes on the adjacent terraces may be of the order of 5–10 m (Fig. 4). The sinuoidal “bordering ridges” with 5–10 m in height form the junction between the terraces. We suggest that the “hanging” ponds indicate disruption of bedrock, the escarpments being created through earthquakes (see Lagerbäck and Sundh, 2008). If these ponds were part of the formation of the main YD sub-stage (Tromsø-Lyngen), they should be much more abundant all over Finnmark than they are.

Surface roughness (stones/boulders) of the Maskevarri Ráhppát is ubiquitous (Figs. 3 and 5). Stones and boulders, up to 30 m³ in size, can be found both on the top and bottom of the ridges and mounds. In the southern section of the Maskevarri Ráhppát the boulder fields appears to be lag formed (Fig. 5c), yet only the gullies near the

Maskejohka valley are truly meltwater (erosion) forms. The lags and gullies indicate wet base conditions at the time of Ráhppát formation.

Morphologically similar to Maskevarri Ráhppát, a network of moraine ridges and mounds (2.2 km × 1.6 km in size) is present at Boaltunoaivi fell (centered at 70°17' N and 29°01' E). The field is on the SE slope of the Boaltunoaivi fell ranges from 315 to 240 ma.s.l. in elevation (location in Fig. 1). The geographical position of this field between the Porsanger and Gaissa lines, 80 km apart, (Sollid et al., 1973; Olsen et al., 1996) suggests that morphologically similar chaotic landforms may have been created during different times within the deglaciation of the FIS. This time lag between the Porsanger sub-stage and the main sub-stage, about two thousand years, is coincidental with the increased fault instability in northern Fennoscandia (Wu et al., 1999; Lund et al., 2009). Therefore, Maskevarri Ráhppát and Boaltunoaivi field, similar in geomorphology, may have similar genesis, yet different time-stratigraphic position.

Late Weichselian ice-sheet mass-balance fluctuations, due to the fast melting rate and retreat of the FIS margin (Svendsen et al., 1999), eventually released isostatic crustal rebound and triggered large scale seismic events ($M_w > 7$; Arvidsson, 1996; Wu et al., 1999; Olesen et al., 2004). Limited information, however, is available on the subglacial deformations associated with the paleoseismicity (Sutinen et al., 2009a, b). In the Norwegian fjords at least three separate large-magnitude YD-earthquakes have resulted in mass-flows of the offshore sediments concurrently with glacial events within northern and northwestern Norway (Olsen et al., 1996; Vorren and Plassen, 2002; Bøe et al., 2004; Olesen et al., 2004). Paleoseismicity may have played an important role in subglacial deformation (Sutinen et al., 2009a, b), yet the seismic origin of the ráhppát terraces needs to be verified in further studies. The morphological evidence through the airborne LiDAR would be particularly important in the future (Sutinen et al., 2013, 2014). The nearest known postglacial fault Stuorragurra ($M_w \approx 7.4-7.7$; Dehls et al., 2000) in Finnmark, Norway, is about 130 km southwest of Ráhppát on Maskevarri fell, yet new information about local seismic structures can be revealed whenever LiDAR data are available.

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4 Conclusions

The geomorphology of Maskevarri Ráhppát with ~ 500 small lakes, ponds and puddles on three terraces differ from the onshore and offshore YD-moraines in the Norwegian fjords often exhibiting glacial tectonic overridden Allerød deposits as well as pushing features on their proximal sides, hence showing a glacial readvance during the main YD phase. Even though positioned on the line of the main (Tromsø-Lyngen) sub-stage the Maskevarri Ráhppát has no remoulding features to support the ice readvance during the cold reversal. The electrical-sedimentary anisotropy in the core of the bordering ridges, parallel-to-ridge trends and towards west-northwest, is more or less orthogonal with respect to northeastward ice flow towards the Tana fjord. Therefore, the mechanisms such as compressive shearing, englacial thrusting or deformation of former supraglacial debris by readvancing ice, as proposed for the genesis of the YD moraines, do not apply to Maskevarri Ráhppát. The time lag between the Porsanger sub-stage and the main sub-stage, about two thousand years, is coincidental with the increased neotectonic instability in northern Fennoscandia. Therefore, Maskevarri Ráhppát and Boaltunoaivi fields, similar in geomorphology, appear to have similar genesis, yet different time-stratigraphic position. Earthquakes induced by the glacio-isostatic rebound potentially deformed subglacial bed and created ráhppát landforms.

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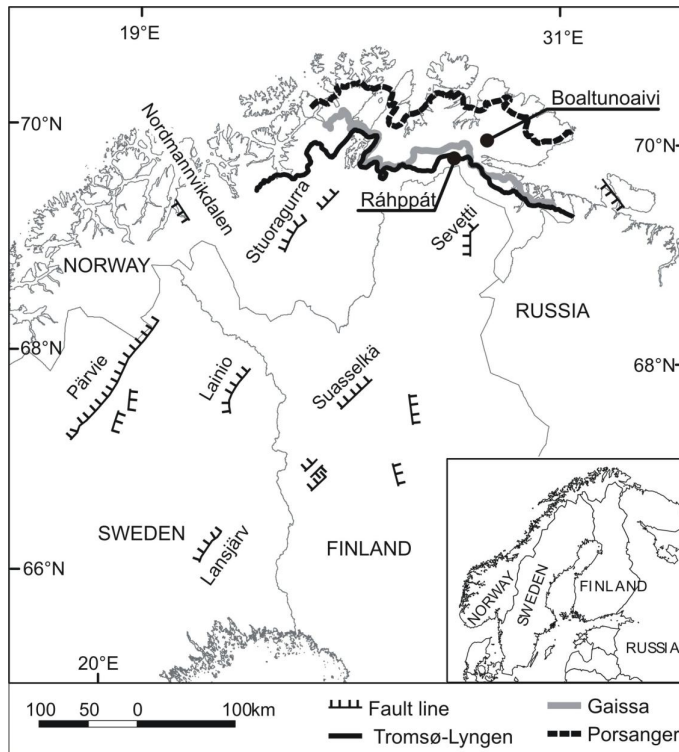


Fig. 1. Location map showing major ice-marginal moraines in Finnmark, North Norway (after Sollid et al., 1973; Olsen et al., 1996). Maskevarri Ráhppát study site and morphologically similar moraine field on Boaltunoaivi fell indicated. The Tromsø-Lyngen moraines were formed ~ 12.5–12 kyrBP and the Skarpnes event, possibly correlative to the Porsanger sub-stage, ~ 14.3–14.1 kyrBP (Sollid et al., 1973; Vorren and Plassen, 2002). Locations of the northern Fennoscandian postglacial fault lines according to Tanner (1930), Kujansuu (1964), Lundqvist and Lagerbäck (1976), Lagerbäck (1979, 2008), Dehls et al. (2000) and Sutinen et al. (2009).

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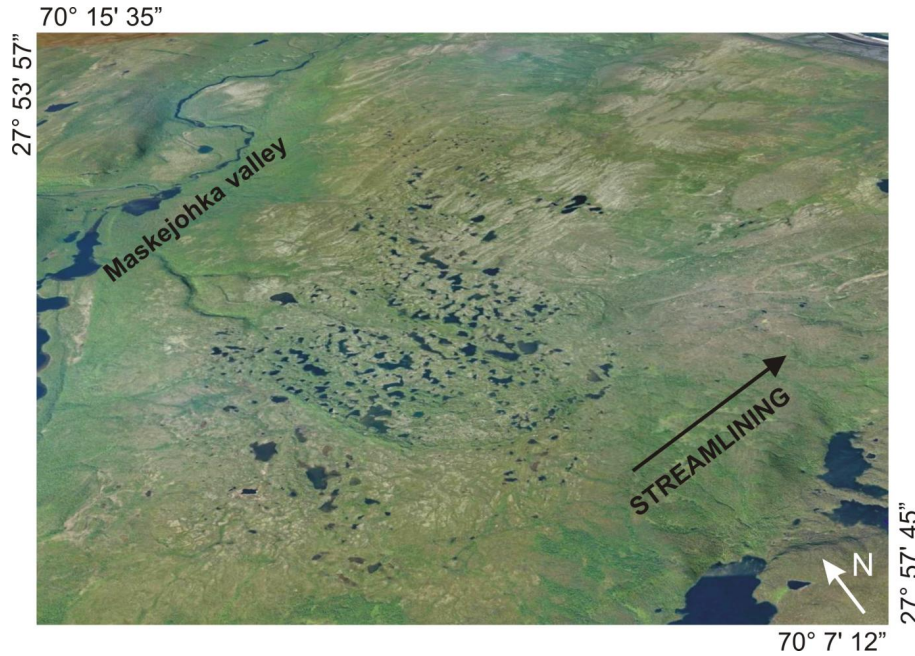


Fig. 2. A 3-D image of the Maskevarri Ráhppát, Finnmark, North Norway (Norkart Geoservice AS and Geovekst). The streamlining towards Tanafjord shown by black arrow.

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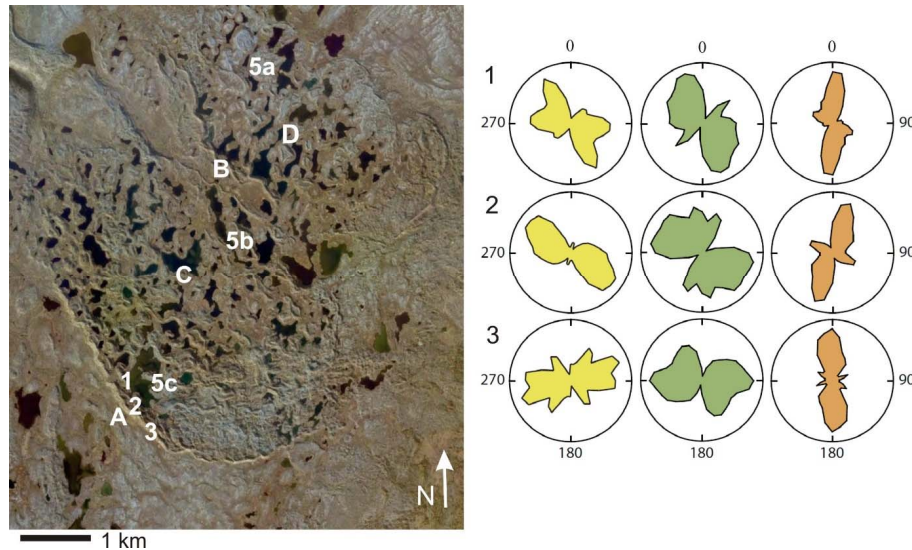


Fig. 3. Locations of the electrical-sedimentary measuring sites (1–3) on Maskevarri Ráhppát, Finnmark, North Norway (Norkart Geoservice AS and Geovekst) and device-specific azimuthal electrical conductivity presented for Geonics EM31V (0–6 m), EM31H (0–3 m), and EM38V (0–1.5 m) coil configurations. Numbers A–D refer to photographs shown in Fig. 4 and 5a–c to air photos shown in Fig. 5.

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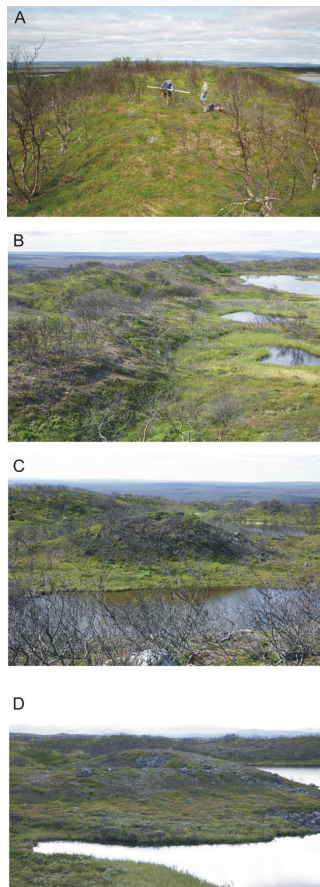


Fig. 4. (A) The south-western border ridge ($70^{\circ}08'54''$ N and $27^{\circ}54'52''$) on Maskevarri Ráhppát, Finnmark, North Norway. Note the elevation difference between the hummocky field (right) and gentle undulating tundra (left) is about 12 m. (B) The north-eastern border ridge ($70^{\circ}09'37''$ N and $27^{\circ}56'25''$) on Ráhppát. Note the elevation difference between the hummocky fields on both sides of the ridge is about 10 m. (C) An example of hummocky moraine terrain on middle part of the Ráhppát ($70^{\circ}09'14''$ N and $27^{\circ}55'32''$) ranging in elevation from 260 to 270 m a.s.l. (D) An example of hummocky moraine terrain on upper terrace of the Ráhppát ($70^{\circ}09'41''$ N and $27^{\circ}57'09''$) ranging in elevation from 280 to 285 m a.s.l. Note the leafless birch trees/bushes due to damages of autumnal moth (*Epirrita autumnata*). Photos by R. Sutinen, 2009.

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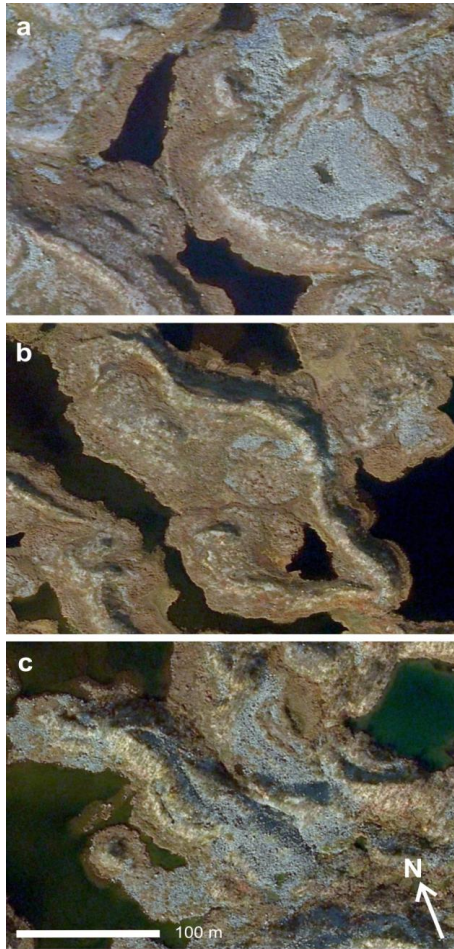


Fig. 5. Air photos (Norkart Geoservice AS and Geovekst) showing examples of surface stoniness of the Maskevarri Ráhppát, Finnmark, North Norway, Locations indicated in Fig. 3.

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