The Orravatnsrustir palsa site in Central Iceland—Palsas in an aeolian sedimentation environment

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A B S T R A C T

The Orravatnsrustir palsa site, located north of the Hofsjökull glacier in Central Iceland, has well developed palsas located in a valley-like depression at 710–715 m a.s.l. and stands in remarkable contrast to the surrounding desert-like highland plateau. The purpose of this paper is to give an overview of the Orravatnsrustir palsa site, geographic distribution and geomorphic statistics related to size and permafrost thicknesses of the palsas, including recent changes. Icelandic palsas exhibit characteristics of both organic palsas and lithalsa (frozen mineral soil). They are subjected to intense aeolian deposition of volcanic materials. The palsas are often 40–200 cm high, with a 40–80 cm thick active layer and permafrost reaching more than 5 m depth. Measurements of the size of the palsas and the thickness of the active layer which started in 2001 indicate that their size is decreasing and the thickness of the active layer is increasing. These results are in agreement with the general warming trend which has occurred in Iceland during the last decade.

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1. Introduction

Palsas occur in many areas of the circumpolar regions and their general mode of formation has been described by many authors (e.g. Seppälä, 1988; Pissart, 2002; Luoto et al., 2004a; Zuidhoff and Kolstrup, 2005). There is no single widely accepted definition of a palsa (e.g. Pissart, 2002) other than as an ice-cored mound that rises up from wetlands in frost affected areas (Seppälä, 1988). Palsas are remarkable geomorphic features, but many palsa areas are now subjected to degradation due to climate change (e.g. Luoto et al., 2004a; Vallée and Payette, 2007). Palsa areas are uncommon but are important ecosystems in Iceland and have played a significant role in the Icelandic natural environment because of their esthetic value, rarity, and associated wildlife (Magnusson et al., 2009). Most palsas in Iceland form in areas receiving a large amount of aeolian dust input in addition to periodic tephra deposition events, which separates them from many other palsa areas of the world. The largest palsa area and best studied in Iceland is the Thjórsarver area (Fig. 1). Palsas occur sporadically in other areas, mainly in the highlands of the northern part of Iceland such as in the Blanda area, the Jökuldalshreitid heath and other areas north of the Vatnajökull glacier (Fig. 1). Climate change has affected the distribution of palsas in Iceland: They have decreased in number or disappeared from certain areas over the past 5–50 years (Bergmann, 1973; Arnalds, 2010a). The Icelandic palsas exist in an environment of rapid aeolian deposition. Further glacial retreat is likely to increase aeolian production from the Icelandic glacial margins (Arnalds, 2010b), which may affect the stability of the palsas, in addition to direct climatic effects.

One of the most prominent palsa areas in Iceland is the Orravatnsrustir palsa site and neighboring palsa patches north of the Hofsjökull glacier (Fig. 1). The area is considered among the most important natural features in Iceland and is listed on the Nature Conservation Register in Iceland (Naturverndarrad, 1996). A hydroelectric project has been suggested that would create a large reservoir with fluctuating water level east and south of the Orravatnsrustir site (VSO, 2001). If constructed, this reservoir would potentially influence the hydrology which in turn would affect the palsa dynamics in the area. The purpose of this paper is therefore to provide an overview of the Orravatnsrustir palsa site, its general geomorphic characteristics related to size and permafrost thickness, based on studies initiated in 2001. Some initial measurements of temporal changes are also provided.

2. General characteristics

2.1. Physiography

The Orravatnsrustir palsa site is located 10–20 km north of the Hofsjökull glacier in the Hofsaftrett area in Central Iceland (Fig. 1). The area draws its name from the small Lake Orravatn located in the southern part of the area (Fig. 2). The term ‘rustir’ in Icelandic
means palsa mounds, but a more common translation of the word is ‘ruins’. Most of the area is located above 700 m a.s.l. and is characterized by gently rolling glaciated hills which are typically 10–20 m high. The palsas are located in a shallow depression, about 1–1.5 km wide and 2 km long, south of Lake Reydarvatn (Fig. 2). In the northern part of the area the palsas are commonly around 40–60 cm high and up to 2000 m² (Fig. 3A). In the southern site the palsas are larger, around 150–200 cm high and up to 2500 m² (Fig. 3B). Many small lakes and ponds occur in the area. Only one small braided stream, the Pollakvisl, flows through the palsa site into Lake Orravatn in the southern part of the area. The area is drained by two streams, one entering Lake Reydarvatn toward the north-east and a larger one, the Rustakvisl, to the north-west (Fig. 2). The amount of water draining the area by these two streams is much greater than the entering the system by the stream or as rainfall/snowmelt, indicating that the major part of the water within the system is groundwater (Adalsteinsson, 1985; Sigurdsson, 2004). Groundwater level is found at the base of most of the palsas, hence the many small ponds and lakes (Fig. 3A and B).

The Orravatnsrustir palsas and other Icelandic palsas are always vegetated. The surrounding area at Orravatnsrustir is barren desert, but barren ground dominates areas above 600 m elevation in Iceland. The site itself is vegetated, covered with mosses, grasses, sedges and lichens (VSO, 2001). Prominent species (each often 3–10% of the cover) on 200 m long transects covering both wet and dry parts of the area include Cetraria spp., Sphagnum moss, Betula nana, Bistorta vivipara, Calamagrostis stricta, Cardamine pratensis, Carex bigelovii, Carex rariflora, Carex rupestris, Descampsia alpine, Empetrum nigrum, Equisetum variegatum, Eriophorum angustifolium, Salix herbacea, Salix callicarpea, and Silene acaulis (data from Icelandic Institute for Natural History; methods described by Magnusson et al., 2009).

No meteorological observations have been carried out at the Orravatnsrustir palsa site, so no precise meteorological data are available. The closest highland weather stations are at Hveravellir, about 60 km to the south-west (elevation 640 m) and Sandbudir about 33 km to the south-east (elevation 820 m) (Fig. 1). The annual precipitation at the Orravatnsrustir site is therefore unknown, but the nearby weather stations have recorded the average annual precipitation at Sandbudir from 2004 to 2010 as around 440 mm yr⁻¹ and at Hveravellir as around 705 mm yr⁻¹ from 1966 to 2004. The monthly average precipitation from 1966 to 2004 at the Hveravellir weather station ranged between 37 (May) and 73 mm (October), with 0.9 to 264 mm recorded as the monthly minimum and maximum. Judging from the annual precipitation maps from the Icelandic Meteorological Office giving data series from 1961 to 1991 and 1971–2000, the annual precipitation at the Orravatnsrustir site is somewhat lower than in Hveravellir but similar to the Sandbudir area, ranging from 400 to 600 mm yr⁻¹ (Icelandic Met Office, 2011). Most of the precipitation falls as snow in winter, and is partly blown off the surrounding hills and palsa tops into the depressions between the palsas. Air temperature measurements have not been made in the Orravatnsrustir area, but based on the 1961–1991 average measurements from the Isopach Map provided by the Met Office the mean annual extrapolated temperature for the Orravatnsrustir area is −2 to −4 °C, with −6 to −8 °C in January and +4 to +6 °C in July (Icelandic Met Office, 2011). During the last decades a general warming with an increase of 1–2 °C in mean annual temperature has been seen from 1966 to 2010 (Fig. 4). It should be noted, however, that there were cold spells around 1970 and 1980 (Fig. 4). A similar warming trend can be seen at the Sandbudir weather station, indicating a general warming in the highlands around the Hofsjökull glacier (Icelandic Met Office, 2011).

The Orravatnsrustir palsa site is part of the Hofsfjöll communal sheep grazing area which is used during the summer. Grazing of vegetated patches in the highlands is detrimental to these ecosystems, and the Orravatnsrustir site was badly damaged by horse grazing in the early 1990s. Grazing by sheep and horses continues to be a threat to this fragile highland ecosystem.
2.2. Soils

Icelandic soils are mostly Andosols, soils that form in volcanic deposits (Arnalds, 2004). The highland desert soils are sandy and have very low organic content (<1% C), while the soils under highland vegetation (the bogs) are mostly Gleyic Andosols. These have considerable organic content (often 3–12% C), but usually not high enough to be considered peat soils (Histosols), which are normally defined as >12% C but >25% C where the soils have Andosol properties (IUSS Working Group WRB, 2006). The reason for the relatively low organic content compared to Arctic wetlands is the constant flux of aeolian sediments due to sandstorms, together with occasional tephra deposition during volcanic eruptions (Arnalds, 2010b). It should be noted that Andosols have unique soil properties that influence physical processes in the soil (Nanzyo et al., 1993; Kimble et al., 2000), with very high water retention properties and rapid hydraulic conductivities, though in Iceland these are often disrupted by coarse tephra layers.

2.3. Tephra layers in the Orravatnsrustir palsa area

There have been several major volcanic eruptions in Iceland during the Holocene and an extensive tephrochronological record has been assembled, including several well known dated tephra layers (e.g. Thorarinsson, 1944, 1967; Larsen and Thorarinsson, 1977). Between tephra deposition events there has been a steady deposition of aeolian sediments (>250 g m⁻² yr⁻¹ at the Orravatnsrustir site; Arnalds, 2010b) burying the tephra layers and creating thick profiles with distinct tephra layers. The most extensive tephra fallout in northern Iceland, which includes the Orravatnsrustir palsa site, originates from the Hekla volcanic system in south-west Iceland (Fig. 1). Four of these tephras are widespread and important time markers in post-glacial soils. They are light-colored rhyolitic tephra layers called H₅, H₄, H₃ and H₁, dated to 7000 BP, 4500 BP, 2900 BP and 1104 AD, respectively (Larsen and Thorarinsson, 1977). The best known dark-colored basaltic tephra layers in the area are those from the Hekla eruptions in 1300 AD and 1766 AD.

3. Methods

Two representative soil/tephra profiles were measured in the Orravatnsrustir palsa area (Fig. 2) and samples were obtained from representative soil horizons. One profile was dug at the edge of a large palsa on the southern part of the area. The second was located in a non-frozen site for comparison, in the bank of the stream flowing north-west of the area (Figs. 2 and 5). The two profiles showed tephra layers of both rhyolitic and basaltic composition. Soil samples were analyzed for soil pH (1:1 water: soil ratio) and carbon and nitrogen (dry combustion). Oxalate extractions (Blakemore et al., 1987) were made and the Al, Fe and Si extracted were used to quantify allophane and ferrihydrate clay contents of the soils (Parfitt and Childs, 1988; Parfitt, 1990). Textural class (USDA textural classes, see Gee and Bauder, 1986) was estimated by hand in the field (hand texturing), which gives a more reliable estimate because of problems in
determining size fractions of Andosols with conventional methods (Maeda et al., 1977).

Observations have been carried out from 2001 to monitor changes which occur on the palsa site. Representative palsas of different sizes and shapes were selected from both the northern and southern parts of the area. The monitoring included both diameter and area measurements of selected palsas using both differential GPS and a total-station. The sizes of seven palsas in the northern part of the area and of three in the southern side were measured, making a total of 8 palsas of different sizes and shapes (Fig. 2).

Measurements of the active layer depth were carried out along the size measurements at the end of the melt. A 2 m long stainless steel rod was pushed through the upper soil layers (the active layer) down to the frozen surface along fixed transects across selected palsas at a 2–5 m interval. Three palsas were measured in the northern part of the area (palsas 2, 3 and 7) and one in the southern part of the area (palsa 8) (Fig. 2). The size measurements started in 2001 for palsa 2, in 2004 for palsa 8, in 2007 for palsas 5 and 7 and in 2009 for palsa 3. All measurements were carried out in late August and early September 2001, 2004, 2007, 2009 and 2010.

From July 2006 to August 2007 soil temperature measurements were made at the Orravatnsrustir site. The data loggers were placed at a 10 cm depth on a small palsa in the northern part of the area.

A geoelectrical survey was made on several palsas in the area to estimate the distribution and the thickness of the ice in the palsas and to estimate the depth of the active layer. Several electrical resistivity tomography surveys using 1 m to 2 m spacing were performed (Kneisel et al., 2007; Kneisel, 2010).

A comparison was made between aerial photographs taken in 1960 and 1998. The 1960 photo is a black and white contact print taken by the US Air Force in August 1960 (USAF VM M-436 1375MCS, Roll 97 no. 10109;) with an approximate scale of 1:40000. The 1998 photo is a color photograph taken by Loftmyndir ehf., with a scale of about 1:5000. The diameter measured in 2004 was superimposed on the 1998 photograph, together with the palsa outlines in 1960. These photographs were also used to determine if some palsas from 1960 had
disappeared or if new ones had appeared on the 1998 photos and were therefore not visible on the 1960 photos. Nine randomly selected pairs, each covering an area of 200 × 600 m, were prepared and evidence of changes was observed visually.

4. Results

4.1. Soils and tephra layers

The soils at the Orravatnsrustir palsa site are classified as Vitric Gleyic Andosols (unfrozen surfaces) and Vitric/Andic Cryosols (palsas) according to the World Reference Base classification system (IUSS Working Group WRB, 2006). They are silty and coarse textured, mostly sandy-loam to loam with low (5–10%) clay content (allophane and ferrihydrite) (Table 1), and with no coarse fragments (>2 mm). The soils have 1–6% C in surface horizons. The C/N ratio is near 10. The soils exhibit frequent abrupt textural changes because of alternating deposition phases between tephra layers and aeolian sediments (Table 1).

The palsa profile (Fig. 5) contains at least two thin continuous dark-colored basaltic tephra layers in addition to several lenses or traces of dark basaltic tephra. The continuous and unbroken layers probably represent the ash fallout from the Hekla eruptions in 1766 AD and 1300 AD. A trace of a rhyolitic tephra was found beneath the lower basaltic layer, and corresponds to the tephra layer H1. The palsa profile also contains a thick horizon of rhyolitic tephra interbedded in the frozen palsa core. This tephra layer was identified as the H4 layer with a visible darker upper part which is characteristic of the H4 tephra layer (Larsen and Thorarinsson, 1977).

4.2. Size of the palsas and depth to active layer

Area measurements carried out between 2001 and 2010 from late August to the middle part of September are presented in Fig. 6. The sizes are given as a proportion (in %) relative to the size at the beginning of the measurements. A clear decreasing trend in the size of the palsas can be seen, up to 15–20% from 2001 to 2010 over the entire area. Most of the larger palsas (from a few hundred m² to >5000 m²) existing in 1960 still exist today, mostly with the same or similarly shaped boundaries. Most of these palsas show evidence of shrinkage in size, but there is also evidence of growth for some of the large palsas, though shrinkage is more common. The size of 5 palsas ranged from 253 to 3553 m² in area in 1960, but the area has decreased from 11 to 31% from their original size between 1960 and the 2004 aerial measurement (GPS), as shown on the 1998 photograph in Fig. 6. One of these palsas has now been broken into two, labeled 1 and 2. The more recent aerial photograph (1998) shows palsas (e.g. 4, 5 and 6) which did not exist in the 1960 photo. We counted clear evidence of 2–4 new such palsas within each of the nine 200 × 600 photo printouts, ranging from <100 m² in area to about 500 m². Similarly, there was also clear evidence of palsas that have disappeared during the period between the 1960 and 1998 dates. We counted a similar number of palsas (2–4

Table 1

Soil properties for two profiles at the Orravatnsrustir palsa site. Texture is based on hand texturing.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Texture</th>
<th>pH</th>
<th>C (%)</th>
<th>N (%)</th>
<th>C/N</th>
<th>Allophane</th>
<th>Ferrihydrite</th>
<th>Total clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedon 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Sandy loam</td>
<td>7.3</td>
<td>1.2</td>
<td>0.11</td>
<td>10.8</td>
<td>6.5</td>
<td>2.5</td>
<td>9.0</td>
</tr>
<tr>
<td>50</td>
<td>Loam</td>
<td>6.5</td>
<td>0.7</td>
<td>0.07</td>
<td>9.8</td>
<td>6.7</td>
<td>2.0</td>
<td>8.8</td>
</tr>
<tr>
<td>100</td>
<td>Loam</td>
<td>6.0</td>
<td>0.7</td>
<td>0.07</td>
<td>8.9</td>
<td>10.4</td>
<td>2.5</td>
<td>12.9</td>
</tr>
<tr>
<td>140</td>
<td>Silt loam</td>
<td>6.6</td>
<td>1.0</td>
<td>0.10</td>
<td>10.5</td>
<td>2.3</td>
<td>0.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Pedon 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Silt loam</td>
<td>7.5</td>
<td>2.8</td>
<td>0.24</td>
<td>11.8</td>
<td>5.3</td>
<td>1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>70</td>
<td>Sandy loam</td>
<td>7.0</td>
<td>2.3</td>
<td>0.15</td>
<td>16.0</td>
<td>5.4</td>
<td>1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>130</td>
<td>Sandy loam</td>
<td>6.6</td>
<td>2.1</td>
<td>0.11</td>
<td>18.7</td>
<td>6.2</td>
<td>3.3</td>
<td>9.5</td>
</tr>
<tr>
<td>170</td>
<td>Sandy loam</td>
<td>6.6</td>
<td>1.9</td>
<td>0.11</td>
<td>17.2</td>
<td>6.7</td>
<td>2.2</td>
<td>8.9</td>
</tr>
<tr>
<td>300</td>
<td>Loamy sand</td>
<td>7.3</td>
<td>0.9</td>
<td>0.06</td>
<td>15.8</td>
<td>4.2</td>
<td>1.3</td>
<td>5.5</td>
</tr>
</tbody>
</table>

a. Middle of sampling interval.
b. USDA textural classes.
on each photo pair) that had disappeared within the same area, again from $<100\,m^2$ to $>500\,m^2$. Otherwise, there was a large degree of uncertainty about many palsas that did not show up well on the older photo, so information on size and changes was inconclusive. In general, changes are better observed with the smaller palsas than the larger.

The thickness of the active layer has decreased considerably since the measurements started in 2001. Fig. 7 shows the results from the measurements carried out in late August and early September in 2001, 2004, 2007, 2009 and 2010. As shown in the figure the thickness has increased from around 43 cm in 2001 up to 63 cm in 2010 in palsa 2. The other palsas on the northern side show similar thickening of the active layer. A similar trend can also be seen at the southern site, where the thickness increased from 69 to 81 cm in palsa 8 (Fig. 7).

The 2D electrical imaging shows an active layer thickness of 35 to 75 cm, which compares well with the direct measurements of between 40 and 50 cm using a steel rod (Kneisel et al., 2007).

5. Discussion

5.1. Depth to active layer

The depth to the active layer in late summer has decreased on average and at an increased rate from 2009 to 2010 (Fig. 7). Hirakawa’s (1986) observations of the thickness of the active layer indicated about 45 cm thickness in July and 65 cm in September, which is similar to the depths measured in this study. The exact locations of his measurements are not given, nor whether his values are averages, as there is a great difference in the thickness of the active layer from the lower palsas on the northern site to the higher one on the southern site in our study. The obtained results compare very well and the geophysical model interpretation indicates that permafrost depth varies between 5 and 7.5 m (Kneisel, 2010).

5.2. Environmental conditions

The formation of palsas is generally related to climatic, hydrological and thermal conditions, which are influenced by insulation of the surface cover, topography, soils and characteristics of the vegetation (e.g. Seppälä, 1988; Zuidhoff and Kolstrup, 2000; Pissart, 2002). The general environment of the Orravatnsrustir site has characteristics favorable for palsa formation. There is an ample water supply for cryosuction, rapid hydraulic conductivity of the silty volcanic soil materials with loamy texture, and robust wetland/peatland vegetation in the depressions which have variable thermal conductivity between frozen and unfrozen soils (see Seppälä, 1988; Kujala et al., 2008). In Iceland, there is an important additional environmental factor to consider: the steady deposition of aeolian sediments on the top, slowly raising the surface, often at a rate exceeding 0.5 mm yr$^{-1}$ within or close to desert conditions.

Fig. 6. Size measurements of selected palsas at the Orravatnsrustir palsa site. The size of each palsa is marked as 100% at the beginning of the measurements in 2001 (palsa 7) and 2004 (other palsas).

Fig. 7. Depth measurements of the active layer of selected palsas in the Orravatnsrustir palsa site. The size measurements started in 2001 for palsa 2, in 2004 for palsa 8, in 2007 for palsas 5 and 7 and in 2009 for palsa 3. The measurements were carried out in late August and early September 2001, 2004, 2007, 2009 and 2010.
areas (>250 g m⁻² yr⁻¹; Arnalds, 2010b), together with periodic tephra fallout events. The silty aeolian materials influence the surface layer by lowering the organic content.

Snow accumulates in the depressions, with less snow cover on top of the palsas compared to the surrounding land, providing differential insulation until late spring in many years. This lack of snow may well intensify the formation and maintenance of the palsas and is often noted as an important factor for palsa development elsewhere (e.g. Coultish and Lewkowicz, 2003). However, the winter and spring climates vary considerably with limited snow accumulating in some years due to frequent snow-melt events in late winter. This variability undoubtedly influences the ice-segregation dynamics of the area, creating more ice in years of little snow, as has been shown in other research (e.g. Seppälä, 1995; Westin and Zuidhoff, 2001).

The cool, oceanic summer temperatures (+4 to +6 °C in July) may play an important role in maintaining the palsas, which is in accordance with the summer temperature arguments provided by Seppälä (1988) and Pissart (2002). Luoto et al. (2004b) concluded from modeling that optimal conditions for palsa formation occur in areas with low precipitation (<450 mm) and a −3 to −5 °C mean annual air temperature.

The Orravatnsrustir area receives more precipitation, as does the largest Icelandic palsa area south of the Hofsjökull glacier (Thjorsarver), indicating the importance of the lack of snow cover and low summer temperatures for these palsa areas. Furthermore, Thorhallsdottir (1996) emphasized the hydrological conditions (high water table) and temperature (unfrozen conditions) in early winter over the summer temperatures as factors contributing to palsa growth in the Thjorsarver palsa area.

5.3. Palsa cycles

The cyclic behavior of palsas, with alternating growth and decay, has been emphasized in general (e.g. Seppälä, 1986, 1988; Zuidhoff and Kolstrup, 2000). This is seen in Iceland; Thorhallsdottir (1996) and Kristinsson and Sigurdardottir (2002) emphasized the dynamic nature of the palsas in the Thjorsarver region south of the Hofsjökull glacier (Fig. 1). At the Orravatnsrustir site there are clear signs of formation of new palsas since 1960, but palsas have also disappeared. There is evidence of decayed palsas at various stages at the site. However, the larger palsas we studied seem stable and old, though most have decreased in area from 1960 to 1998, a trend that has continued after the 1998 photo was taken (see Section 5.4). The insulative properties of dry surface layers on top of palsa mounds, which are greater than for wet layers, are important for palsa dynamics in general (see Matthews et al., 1997; Zuidhoff and Kolstrup, 2000; Kujala et al., 2008). In contrast, Thorhallsdottir (1996) and Kristinsson and Sigurdardottir (2002) noted that in the Thjorsarver in Iceland the soil becomes dryer as the ground rises with the formation of the palsas. Draining of the soil surface causes vegetation changes that subsequently reduce insulation; hence the wet climate leads to melting of the palsa core and ultimately a pond is formed. It should be noted that the surface layer in the Thjorsarver and at the Orravatnsrustir site is not peaty as such (organic materials) with only 1–5% C content. Crack formation is also likely to play a role in the decay process (see Friedman et al., 1971; Zuidhoff and Kolstrup, 2000). This we noted in places at the Orravatnsrustir site.

We have noted the formation and disappearance of palsa features in both the North-east (Vesturoaef) and North-west (Audkuluhleidi) in recent years, also documented earlier by Bergmann (1973). Furthermore, the palsas studied in 1970 by Friedman et al. (1971) in the western highlands no longer exist. This indicates that palsa areas in Iceland are very responsive to climate fluctuations as are most palsa areas in the world (Seppälä, 1988; Zuidhoff and Kolstrup, 2000).

5.4. Age

Many of the larger palsas at the Orravatnsrustir site can possibly be quite old without undergoing alternating formation and decay. Old tephra layers (1000–4500 years old) are more or less intact in places and do not show clear signs of cryoturbation. This may suggest that the cool summer temperatures of the oceanic climate are instrumental in maintaining the palsas relatively intact over a long time. Yet, the palsas show a 10–20% decrease in areal extent over the relatively short time from 2001 (Fig. 6) and a general decreasing trend from 1960. It is too early, however, to conclude whether climate change is the cause of this rapid trend or if this is still within the natural fluctuations expected in the area.

The finding of the H₄ tephra in the frozen core suggests that ice formation did not start until after 4500 BP. This is in agreement with previous observations of Hirakawa (1986) and his conclusions that the development of permafrost in the area started around 4000 to 3000 years BP. He used both tephrochronology and radiocarbon dating to conclude, based on the age of the peat, that the development of the palsa began 3000–4000 BP, which coincides with a general cooling trend in Iceland the last 2500–3000 years (Gudmundsson, 1997). Our profiles indicate similar results, with frozen soil reasonably intact from freeze–thaw cycles older than H₁ (Fig. 5), which is dated to 1104 AD.

The effect of the thick Hekla tephra layers H₄ (about 4000 years BP) and H₃ (about 2800 years BP) (e.g. Thorarinsson, 1967) on the formation of the palsas is important. The tephra provides an insulating layer (commercially used for insulation) and is known to cause permafrost aggradation in Iceland (Kellerer-Pirklbauer et al., 2007). The tephra may have helped trigger palsa formation at that time by preventing summer heat from entering the soil.

6. Conclusions

The Orravatnsrustir palsas do not have a peat layer as such on top due to the steady aeolian deposition lowering the organic content. This is interesting in the light of the fact that many definitions for palsas use the term peat, such as the widely used definition provided by Pissart (2002). The Icelandic palsas also have characteristics of the non-peaty lithalsas, and some of the Orravatnsrustir palsas resemble lithalsa plateaus (see Pissart, 2002). Cool summers, such as occur in the Icelandic highlands, are believed to be important for the formation of lithalsas as they prevent summer thawing of the ice core (see Pissart, 2002). Furthermore, a surface peat layer is stated as a prerequisite for palsa formation (e.g. Zuidhoff and Kolstrup, 2005), which is not the case in Iceland. However, the surface root mat of the wetland vegetation patches in the Icelandic highlands seems to have thermal and hydraulic properties similar to those of peat in the Arctic.

The geometry of the palsas, including the height, falls well within the often quoted definition by Washburn (1983), cited by Pissart (2002), and the depth of the active layer is in good agreement with dimensions discussed by Pissart (2002) for lithalsas.

The age of some of the frozen layers dates back to 3000–4000 years, when climatic conditions were different from the present day, with frozen layers down to over 5 m depth. We hypothesize that this palsa area is vulnerable to disturbance, and that the vulnerability is amplified by present-day climatic changes.

The size measurements of the palsas and the thickness measurements of the active layer which have been carried out during the last decade show a general decreasing trend in size and increasing thickness of the active layer. This is in agreement with the meteorological data showing a general warming trend in the highlands during the last decade. A general trend of shrinking size of the larger palsas in the area can also be seen by comparing aerial photographs from 1960 and 1998 to the present day measurements. Most of these palsas show
evidence of shrinkage in size, but there is also evidence of growth for some of the large palsas, though in general shrinkage is more common.

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References


