Historical Resilience of Landscapes to Cultural and Natural Stresses: Grænavatn farm estate, Mývatnssveit north-east Iceland

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Abstract

Reconstructing historic landscapes responses to a range of factors contributed by natural processes and anthropogenic activities is an important part of understanding why natural systems fluctuate between stable and unstable conditions. In doing so new understanding of landscape resilience in a dynamic environment can emerge and ultimately lead to new ideas for sustainable management.

To understand the natural and cultural features interacting on the Grænavatn farm estate, this study assesses factors of historical land management, climate change and natural catastrophes and their contribution to changing vegetation cover and soil erosion over extended periods of time. To do so a range of data is considered on the effect of soil and vegetation properties sourced from soil accumulation rates, tephrochronology, ice-core records, pollen analysis, micromorphology and historical records.

The results demonstrate a complex interaction of natural processes, such as fluvial, climate and natural volcanic catastrophes influencing the stability of the landscape before *Landnám.* Changes in vegetation post-*Landnám* initiated by anthropogenic influences extended the natural process, resulting in instability with varying severity of land degradation. The landscape did show some recovery identified in the proxy data from micromorphology and pollen records pre-1477 AD. However, anthropogenic activities and deteriorating climatic conditions from 1717 AD shows a reversal in soil conditions and a subsequent increase in erosion which was beyond the ability of the natural system to recover, resulting in the severe land degradation visible today.

Introduction

1.1 Introduction

Landscapes are generally considered to be temporally and spatially adapting to complex natural processes or anthropogenic activities (Farina, 2006). A natural landscape will be exposed to a range of stresses, shocks and disturbances and may fluctuate between stable and unstable. The range of factors can be contributed by both society and nature, and include fire, flooding, climatic conditions and biomass removal (Pearce & Barbier, 2000: Wild, 2003: Walker & Salt, 2006). If the landscape's natural systems recover its original basic function and structure after stress factors being imposed on it, it may be considered to be a resilient and stable environment. However if the complex interactions of natural functions are extended the result can be instability with varying severity of land degradation (Gallopin, 2006). As described by Ólafsdóttir & Gudmunðsson (2002) key indicators of landscape responses to stress factors are changes in the most basic multi-functional of all natural systems – the vegetation and soil properties.

This dissertation will focus on the resilience of the landscape at Grænavatn farm estate – Mývatnssveit north-east Iceland. Research carried out previously substantiates the estate supported historically three farms - Oddastaðir (Adderley, *et al*, 2008), Sveigaköt (Simpson *et al*., 2004) and Grænavatn together with a réttir (sheep pen) (Aldred & Madsen, unpublished). Grænavatn is the only farm still to remain today in the estate which is currently experiencing vast areas of severe soil erosion. The interactions of natural and cultural features present on the estate and their interactions are poorly understood, making it an important area for research. The aim of this study is to assess landscape responses to natural and cultural factors on a temporal scale and understand the historical processes that contributed to the soil stability / instability and vegetation changes in a dynamic landscape.

Landscapes comprise a dynamic soil function which has been generally thought of as a static component of the terrestrial ecosystem (Lal, 1997: Sivakumar & Ndiang'ui, 2007). However it has been suggested by Richter & Markewitzn (2001) that soil is a more dynamic system and can substantially change in many properties. Soils can be considered to be a renewable resource formed to temporal scales of over 1000 years. It has been reported that 83% of the terrestrial land has been influenced by humans thus a key concern of many parts of the world is when natural erosion rates are accelerated significantly by human activity (Wild, 2003).
Continued intensification of inappropriate farming techniques are, in part causing soils to be degraded both physically and chemically resulting in poor soil structure and depleted soil fertility (UNEP & EEA, 2000: Lal, 2003). This is exemplified in the various reports of

landscape degradation in Iceland by authors such as Arnalds & Kimble (2001), Ólafsdóttir & Guðmundsson (2002), and Simpson *et al*., (2004).

Iceland is widely recognised to be the most degraded country of northern Europe with vast areas of the ecosystem devastated by soil erosion (Arnalds, 2000; Simpson *et al.,* 2004). Many previous case studies have debated on the causes of these conditions in Iceland as there is no or very limited evidence of rapid degradation before the colonisation *Landnám* (Old Norse – landtake) by the Norse Vikings 874 AD. Numerous approaches to explain the severity of land degradation and soil erosion have been attributed to the interaction of different pressures including agricultural expansion specifically animal husbandry (Simpson *et al*., 2004), climatic variations (Bergthorsson, 1985: Haraldsson & Ólafsdottír, 2003) and natural disasters especially volcanic events (Dugmore, *et al*., 2009), although most research corroborates that the initiating stress factor that set in motion the accelerated degradation trends was anthropogenic. It should be noted that *Landnám* may not directly cause the soil to degrade; it is however what the population does that determines the extent of the degradation (Lal, 1997).

The Icelandic landscape is characterised by vast areas of barren desert resulting in the majority of the island being uninhabitable (Bolender, *et al.,* 2008). Prior to *landnám* Iceland was considered to be a well-vegetated fertile island (Arnalds & Barkarson, 2003). This is further supported by Berglund (2003) who demonstrated from pollen analyses in Northwest Europe that human activities in the landscape resulted in deforestation and a loss of 50% of the original vegetation throughout Iceland (Runolfsson, 1987). Removal of vegetation cover by grazing animals and forest cutting for fuel resources has been considered by Simpson *et al.*, (2004) to have directly contributed to this environmental imbalance.

A key to understanding present land problems is to understand the original nature of the landscape and evaluate temporal patterns from factors being imposed on it. The principal reason for integrated historic and scientific research in Iceland is its uniqueness as the history of anthropogenic activity can be dated back to an exact decade l*andnám*. Moreover the significance of soil profiles for this area is the distinct tephra layers (volcanic ash) which have been preserved in the soil (Ólafsdóttir & Guðmundsson, 2002). Each individual layer can be identified by their own ‘signature’ in the form of “time-parallel marker horizons” which allows for dating and are of considerable use when reconstructing accurate spatial soil profiles (Dugmore *et al.,* 2005; 23-24).
Ultimately the tephra layer *landnám* provides a baseline of pristine landscape which can be considered of vital importance when assessing erosion signals. Thus being able to distinguish between trends and cycles in historic soils which can be used to compare

between pre-settlement and post-settlement (Simpson *et al*., 2004).

This study aims to identify relationships between land degradation and stress disturbances including fluvial, volcanic, climate and human related stress impacts from grazing pressure (Figure 1). This will be achieved by considering historical records and environmental data that includes soil accumulation rates and pollen samples collected during field work in Iceland in June/July 2009. In doing so new understanding of landscape resilience in a dynamic environment can emerge and ultimately lead to sustainable management.

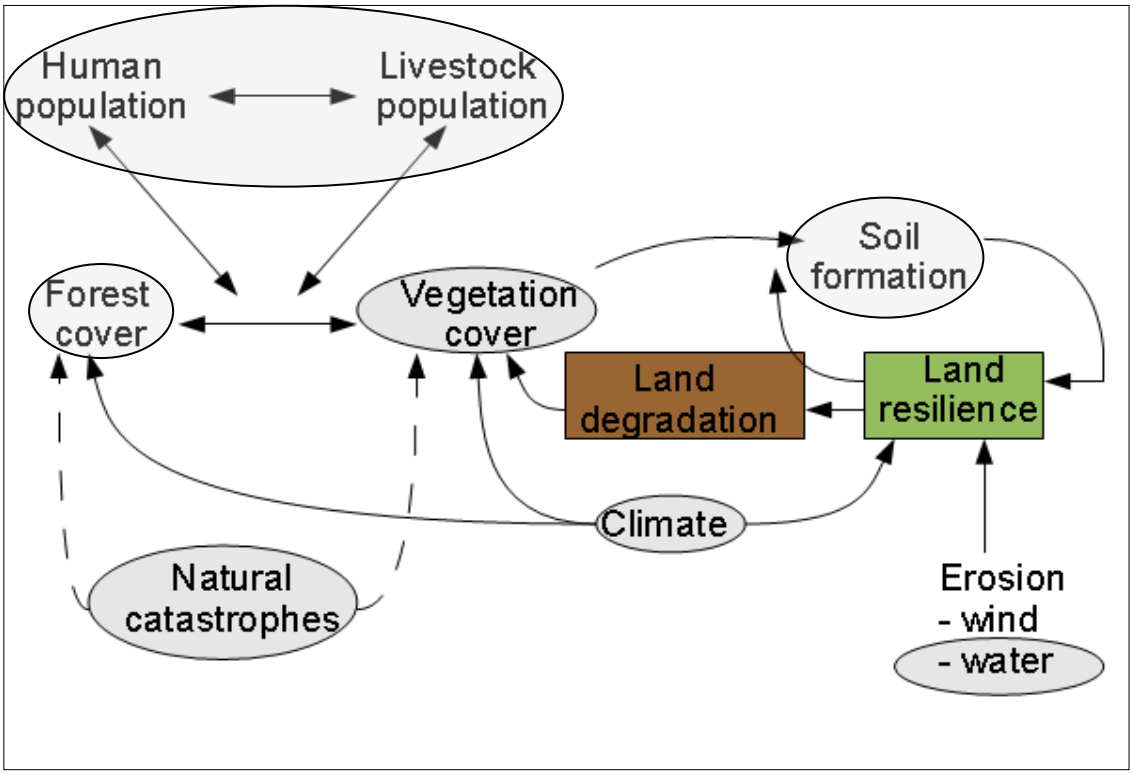


Figure 1 - An overview of natural and integrated interactions influencing land degradation (adapted from Haraldsson & Ólafsdóttir, 2003)

1.2 Iceland: Settlement and Landscape Change

Prior to the 9th Century the Island of Iceland was almost completely uninhabited. Ahronson (2002) surmised that a few Irish monks (*papar*) had previously settled on the island although no archaeological evidence has been found to substantiate this fact (Dugmore *et al*., 2005). The discovery by Scandinavian seaman of a 'pristine' landscape spread to the Norse Vikings (Adderley *et al*., 2008). Estimating the settlement date of the last major uninhabited island of the North Atlantic has been sourced from historical records sagas and annals, ie, Book of Icelanders (*Ísledingabók*), Book of Settlement (*Landnámabók*) and dated volcanic tephra layer *landnám* and indicates colonisation took place over the period 870- 930 AD. With the

opportunity to flee from economic and social problems of the emerging Norwegian states and the opportunity to expand on lands suited to farming, fishing and stock raising, *landnámsmenn* (land takers) crossed the North Atlantic in waves (Smith, 1995). Byock (1988) suggested that as many as 20,000 men and women migrated over this period with goods and domestic animals in laden boats. Documentary records should not be solely relied upon for the knowledge of settlement as the information was recorded over 300 years after the event (McGovern, *et al*., 2007). Therefore the reconstructions of historical records have been subjected to a 'fading record' problem where the quality of data decreases with increasing time. In addition the historical records are also limited by a 'cultural' filtering affecting their consistency (Swetnam *et al.,* 1999). Nevertheless, the colonisation process is relatively well established.

"Humans are short-term optimisers" (Walker & Salt, 2006: 31) and the choice of sites for the early settlers would have been near a water source and good farming land. Initial archaeological reports reported the distribution of early settlement sites of the 9th Century to be concentrated on coastal regions with a spread into Iceland's interior during the 10th Century (Smith, 1995). However, subsequent research from zooarchaeology sources have dated interior sites in the region of Lake Mývatn, north-east Iceland, ie, *Skútustaðir* (Hicks & Harrison, in-press) and *Hofstaðir* (Simpson, *et al.,* 2004) to be amongst the earliest 9th Century settlement sites.

To have a continued settlement and succession of life on Iceland, Adderley *et al.,* (2008) emphasised that the primary importance to the new communities would have been depended on the sustainability of their European-style farming practices to provide enough sustenance to nourish the population and provide fodder for livestock. Dugmore *et al*., (2007) corroborates this claim, but insists that warm climatic conditions that prevailed for several centuries after the first settlement in Iceland during the Medieval Warm Epoch aided and favoured arable activity until around 1200 AD. The preference for arable farming was largely abandoned by the 1500's due to the declining climatic conditions of the Little Ice Age (Simpson *et al.,* 2002).

Animal husbandry became the major source of subsistence and the grazing pressures have been considered to the one of the main causes of accelerated erosion rates on the 'marginal areas' of the ecosystem (Arnalds & Kimble, 2001: Arnalds Barkarson, 2003; 105). One of the reasons why a reduction of vegetation cover from grazing domestic livestock and removal of woodlands to have such a dramatic impact on the ecosystem is complex; however, it is primarily due to inherent landscapes fragility (Simpson *et al*., 2004).

Soil erosion rates have been reported to be far greater in Iceland than that observe in any other European country (Ólafsdóttir & Guðmundsson, 2002), with UNEP and EEA (2000) predicting that there could be a further increase of up to 40% higher rates of erosion across Europe by 2050 if current trends continue. This is a worrying concern for Iceland as 16.2% of 102, 721 km2 land cover has already been classified as severe or very severe erosion rates (Arnalds & Kimble, 2001). The predominant soils in Iceland – Andosols vulnerability to erosion is mostly due to the low density and soil aggregates originating from the mixture of volcanic parent material, lava flows and tephra deposits. This leads to a lack of particle cohesion which is highly susceptible to wind and water erosion (Wada *et al*, 1992: Orradóttir *et al*, 2008). Rofabards are a common erosion feature throughout the Icelandic landscape which are described by Arnalds (2000; 18) as "erosional escarpments where Andosols which are being truncated from the surface and barren desert is left behind" (Figure 2). Rofabard erosion has been found to be more common in northern-Iceland, favouring soils formed by extensive aeolian deposits.

Figure 2 - An example of a rofabard escarpment, in the study area, which is a boundary between barren desert and fertile Andosol vegetated landscape, in the distance Sellandaja.

Attempts have been made to reconstruct the Icelandic vegetation cover present at *landnám* using pollen analyses, historical data and edaphic conditions through micromorphological analysis. Notably, Arnalds & Barkarson (2003) has observed that before the island was colonised by the Norse, Iceland was previously a vegetated fertile landscape principally birch (*Betula sp*.) and willow (*Salix sp*.) woodlands. This is further supported by Berglund (2003) who demonstrated from pollen analyses in Northwest Europe that human deforestation cleared vast areas of vegetation for building materials, fuel and hayfields (Aradottir & Arnalds, 2001). Vegetation cover stabilises soil structure and provides protection from wind and water

erosion which Aradottir & Arnalds, (2001) considers being one of the most important factors when preventing soil erosion. Their research found that hardly any erosion took place in birch woodlands compared to areas where vegetation cover had been removed.

It could be surmised therefore from evidence sourced from historical records, ie, sagas and annals, relict areas, pollen and soil analysis that the ecosystem *pre-landnám* had spatially and temporally evolved resilience to natural stress factors; intermittent volcanic ash-fall events, glacial and snow melt flooding and a harsh climate, to form a stable sustainable environment (Aradottir & Arnalds, 2001).

Therefore the factors that have been considered to have caused accelerated erosion rates and "marginal areas" in the ecosystem have been attributed to the combination of human stresses from traditional farming methods more suited to their homelands and vegetation removal (Arnalds & Kimble, 2001: Arnalds & Barkarson, 2003; 105, Adderley *et al.*, 2008).

1.3 Cultural Stress Factor – Early Farm Management

Early settlers in Iceland were mostly Norse farmers adapted to cope with 'marginal farming' conditions in north latitudes and on arrival in Iceland established their traditional 'ideal' farm management (Dugmore *et al*., 2005, Jones & Olwig, 2008). Bolender *et al*. (2008) suggested that due to limited spaces on the ships that a small amount of animals may have been introduced to Iceland consisting of cattle, sheep, pigs, goats and horses, rapidly building up populations. The requirement for grasslands was a pressing need for the newly arrived settlers as the animals had to be well-fed over the winter to ensure high fertility in the spring. This then suggests that preference sites for feeding livestock at *Landnám* would have been based on pre-existing well vegetated lands. This is evident in the pollen records pre-*Landnám* which shows the landscape to be well vegetated in wooded species such as birch (*Betula sp*.), juniper (*Juniperus sp*.) and willow (*Salix sp*) which is suited for grazing type farming. Thereafter, post-*landnám,* the introduction of farming is indicative of cultural impact on the landscape which is evident in the palynological record and the reduction of natural vegetation, i.e., birch (*Betula sp.*) and willow (*Salix sp.*) (Erlendsson, *et al.,* 2009).

Pinson (1992) and Vésteinsson, *et al.,* (2002) describe the distribution of early settlements to be highly dispersed and isolated small-scale farms estimated to be c. 540 from historical records *Landnámabök* (Sveinbjarnardóttir, 1992). The traditional small-scale farm is thought to have consisted of a homefield, the common summer rangelands (*affrétir*), shielings and common transitional herding area (*rétt*) (Simpson, *et al*., 2001: Adderley and Simpson, 2005: Thomson & Simpson, 2006: Adderley, *et al*., 2008, Aldred & Madsen - unpublished) (Figure

3).

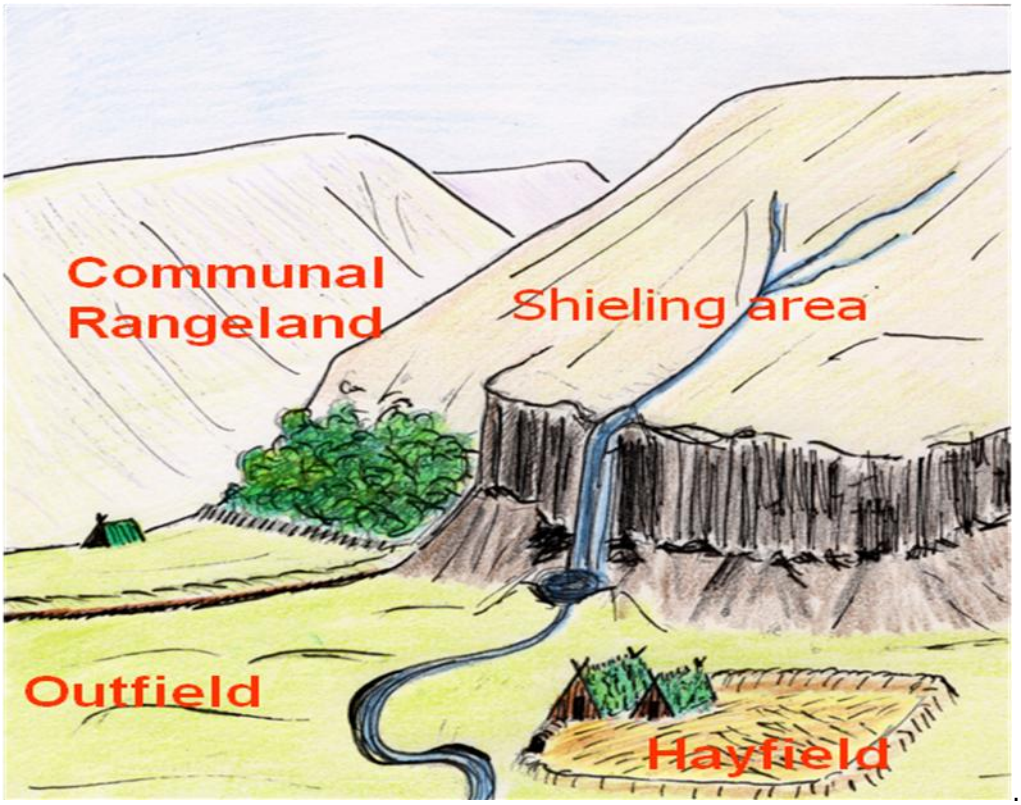


Figure 3 – Representation of traditional farming practiced by Norse settlers (After A. Thomson)

The shielings area was a private area belonging to the farmer for pastoral use. *Jónsbok* records the summer shieling area being used for milking livestock only from the middle of June until late September. This was probably to save the infield for grazing during the winter months (Berson, 2002). The homefield area adjacent to the dwelling has been considered by (Adderley, *et al.,* 2000) to be a key area for farm management. The homefield was used to provide fodder for the live-stock over winter. The byre for the animals was also located either just inside the homefield or on the outskirts and the location has been thought to have considered keeping animals away from trampling the agrarian crops (Berson, 2002).

To make the most of vegetation resources the rangelands (*affrétir*) are used as communal grazing areas predominately located in the mountainous interior of Iceland. As the vegetation turns green over different altitudes during spring and summer months the grazing animals follow (Jones & Olwig, 2008). This practice of moving grazing animals in spring from the lowlands to mountainous rangelands is a practice still used today (Pinson, 1992). The highland pasture lands are a vast open space of which are considered to be more susceptible to disturbances than the lowlands. This has been attributed to the negligible levels of vegetation cover compared to the low lying areas of the coastline and river plains (Arnalds & Barkarson, 2003). Communities worked together and during September farmers would search for grazing animals (mostly sheep) in the rangelands, *affrétir*, that belonged to the farms on the estate. The sheep were then herded into the large common enclosure (*rétt*) and the marked sheep were sorted into pens (*dilkur*) before being herded back to their respective farms. The annual gathering at the *rétt* is a major social event for the whole community and the practice is still continued today (Aldred & Madsen, unpublished).

Rural communities, the *hreppur*, would have been restricted to the resources available within their own catchments and they may have been aware of the effects grazing pressures was having on the ecosystem (Berkes & Folke, 1998). However, unable to halt the onset of land degradation farms were first recorded as being abandoned in 1785 with 776 either totally affected by erosion, glacial rivers or the sea (Sveinbjarnardóttir, 1992).

1.4 An Introduction to the study area – Grænavatn farm estate

The Grænavatn farm estate investigated in this study is located south of the third largest lake in Iceland, Lake Mývatn in the Mývatnssveit region of north-east Iceland (Figure 4). The Krafla volcanic system, which Lake Mývatn is located, is an active caldera volcano and has experienced many eruptions during the Holocene, recently (1724 – 1729) referred to the Mývatn Fires (Thordarsson & Hoskuldsson, 2002). Mývatnssveit is the furthest inland permanently settled area of Iceland and has been intensively studied for both archaeology and ecology research (Lawson, *et al.*, 2007). The ecology of Lake Mývatn is known for its rich fishing, abundant bird life and enormous numbers of midges and blackflies, hence the name Lake Mývatn: Midge Lake (Einarsson, 2004).

The Grænavatn farm estate is just one of the community units of this region referred historically to as *hreppur* - meaning both a community unit of 10 – 30 farms and the farms associated with the area. The modern community name is Skútustaðahreppur which is in reference to one of the main settlements of the area Skútustaðir (Thomson & Simpson, 2006).

The boundary of the Grænavatn farm estate is surrounded by natural features of the River Kráká on the west and the 3,800 year old barren lava fields of Grænavatnsbruni on the east. The estate is mostly covered in vegetation although there a large area of severe soil erosion to the south of the rangelands resulting in barren desert (Figure 2). The only farm to have succeeded in this estate to present day is Grænavatn located just to the south of Lake Mývatn. Two further farms are located in the boundaries Sveigaköt and Oddastaðir which have been abandoned; there are also the remains of an abandoned rétt close to the River Kráká. Previous research suggests that the characteristics of the farms are consistent with independent farmsteads (Thomson & Simpson, 2006: Adderley *et al.,* 2008: Bolender, *et al*., 2008: Aldred & Madsen, unpublished).

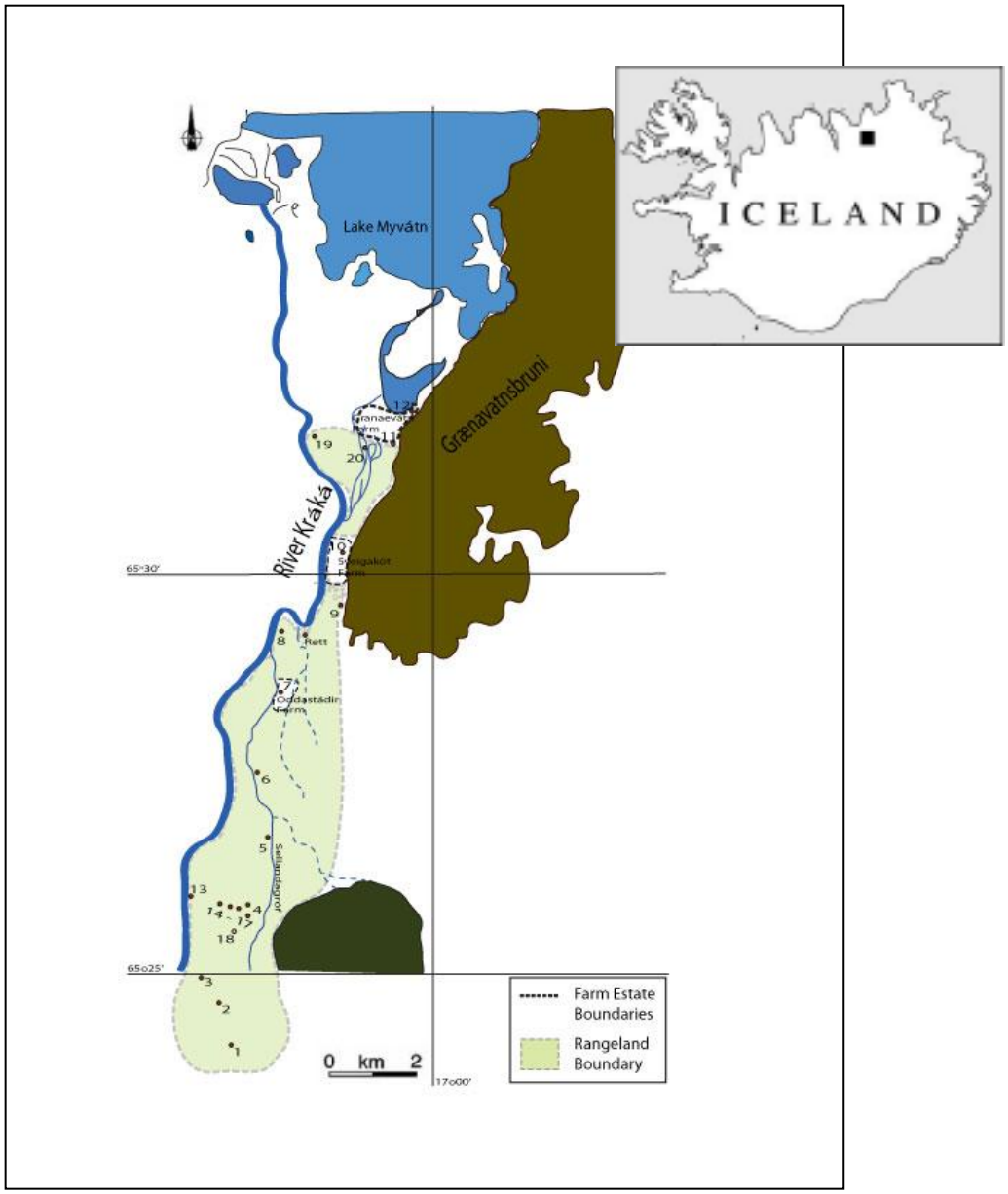


Figure 4 – Location map of the Grænavatn Estate

Grænavatn Farm

The historical record of Jarðabók references that this farm was the location of a medieval church however for as long as people can remember in 1703 the church had been abandoned. This suggests that Grænavatn farm was an important site as churches were unlikely to have been located on 'subordinate' property (Bolender, *et al*., 2008). Today this is the only working successful farm on the estate (Figure 5).

Figure 5 – The only remaining working successful farm – Grænavatn farm

Sveigaköt Farm

The meaning of Sveigaköt is "cottage of the swathes (of grassland)" and is probably indicative that the area was well vegetated and the land surface was stable (Thomson & Simpson, 2007; 156). This is compared to the site today which is now extensively eroded with little vegetation (Figure 6). Previous excavations carried out at Sveigaköt (Thomson & Simpson, 2006) have been dated from tephrochronology and radio-carbon dating and the site was settled shortly after *Landnám*. The farm consisted of a small Viking-age long house and pit house and was entirely abandoned by the late 12th century A.D.

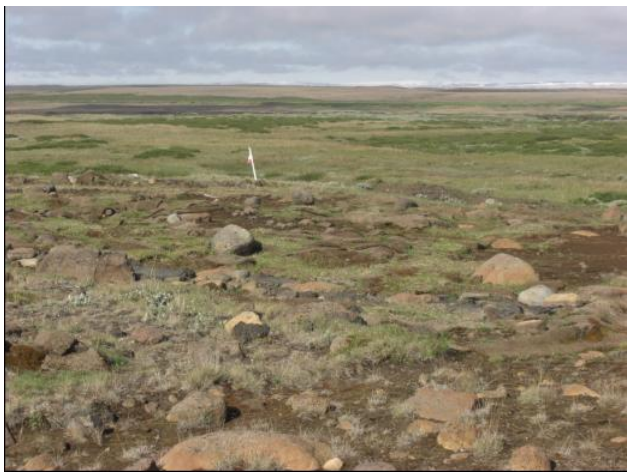


Figure 6 – The remains of Sveigaköt Farm

Oddastaðir Farm

Oddastaðir is another ancient abandoned farm which has experienced successive periods of occupation. Previous excavations by Adderley *et al. (*2008) have suggested that this was a peripheral farm with a small cottage which experienced two period of occupation, the initial period of occupation by 950 A.D. and is thought to be abandoned by 1300 A.D. The site excavations suggest another occupation for a short time during the 15th century. Historical records Jarðabók references that the site may have subsequently been used as a shieling area (Figure 7).

Figure 7 - Abandoned remains of Oddastaðir Farm building

Rétt

The abandoned *rétt* – *Strengjarétt* is located close to the River Kráká and today is totally devoid of vegetation. The *rétt* was used as sorting pens when the sheep were driven from the communal *affrétir* grazing grounds to the individual farms winter shielings. This site has been subject of research by Aldred & Madsen (unpublished) and has surmised that the *rétt* - *Strengjarétt* was most probably abandoned due to the accumulation of sand inside it.

The layout of the rétt consists of 3 sides containing 3 *dilkur* (sheep pen) per side and entrance gate located on the south wall. The building was completed with stone and each wall is approximately 1m thick and 1.5 m tall. The *dilkur* are of varying sizes and it is thought according to ethnographic sources that size was in relevance to the importance of the farm status (Figure 8 and 9) (Aldred & Madsen, unpublished).

Figure 8 - *Strengjarétt* from the distance with the River Kráká visible in the background

Figure 9 - Inside *Strengjarétt* east-side *dilkur* which has been filled with sand accumulation

1.5 Research Questions

The main aim of this dissertation is to evaluate and explain landscape change from the 9th Century onwards on the Grænavatn Estate. In order to gain an understanding of different stress factors contributing to landscape change the following objectives will assess which factor(s) may have contributed to the land degradation currently being experienced.

a) Vegetation change and the factors contributing to that change.

b) Soils change and the factors contributing to that change.

Methodology

2.1 Introduction

In focusing on the historic resilience of the landscape within the Grænavatn farm estate, stress factors considered are, climate, fluvial, volcanic and grazing pressure. This chapter sets out the methodologies used to assess landscape resilience in relation to stress factors, including ice-core records, pollen analysis, soil accumulation and micromorphology as means to reconstruct historical events.

2.2 'Desk-based' sources

Sources in this section are based on cultural data recorded in *Jarðabók*, remote sensing map construction and climatic proxy records developing an overview of the Grænavatn farm estate to identify patterns in land degradation.

2.2.1 Cultural Data

Written records became more abundant during the 18th Century *Jarðabók* was a historical census recording information of all Icelandic farms during the time period 1703 – 1714 AD (Sveinbjarnardóttir, 1992). Livestock numbers are taken from this source and further supported from zooarchaeological research. *Jarðabók* is written in Old Icelandic Norse therefore the documentary evidence is sourced from previous research in the area (Simpson, *et al.,* 2004: Thomson & Simpson, 2006: Thomson & Simpson, 2007, Aldred & Madsen, unpublished: Green, unpublished). This information will be used to explain any relationship between livestock populations and grazing areas.

2.2.2 Remote Sensing and Maps

Remote sensing of the study area includes data sourced from field surveys and aerial photos. A map of Húsavík - Mývatn at 1:100 000 scale was scanned, sample sites were geographically referenced and plotted using Adobe Illustrator software. The resulting base image was generated for the purposes of overlaying a time series of maps. This temporal reconstruction allowed for the examination of changes in soil cover for the time periods, *Landnám,* H1158/1104, H1300, 1477 AD and 1717 AD.

2.2.3 Climatic Proxy Records

To assess the impacts of climate on the landscape proxy data from the GISP2 (Greenland Ice Sheet Project 2) was used. GISP2 is situated on the Greenland Ice Sheet covering an area of 1.8 million km^2. Ice-core drilling from 1989 to 1993 extracted a record 3053.44 m deep core, making it the deepest ice-core ever recovered and thus showing the longest time-span of proxy data (Stuiver & Grootes, 2000).

Data collected was analysed mostly by the University of Washington's Quaternary Isotope Laboratory and has been made available to the public on the official NOAA Paleoclimatology - GISP2 website (Alley, *et al*., 1995: The Greenland Summit Ice Cores, NOAA.gov).

Considered an important measurement for studying past climates, preserved in ice-cores are varying levels of oxygen 18 to oxygen 16 ($^{18}O/^{16}O$). This measurement is converted into the variable $\delta^{18}O$ influenced by the evaporation and condensation of the isotopes in the oceans. The concentration of ^{18}O in precipitation decreases with temperature as the heavier isotope condenses easier than the lighter ^{16}O isotope therefore the concentration can be used to determine climate changes; 'a palaeothermometer' of how cold the air was when the snow fell (Vardiman, 1997). Following this logic, during an ice age there is less of the heavy oxygen molecule as precipitation occurs nearer the equator. Therefore water vapour falling as snow at the poles is higher in the light oxygen molecules. This information can also show the amount of the Earth covered in ice. (Dugmore, *et al*., 2007).

The data provided from NOAA was correlated with volcanic activity identified in tephrochronology. The time periods selected for further analysis are; Landnám – this is the baseline to compare further land degradation; 1477 – this time period has been associated with the abandonment of arable farming and 1717 – farm abandonment was first recorded throughout Iceland. The proxy data sourced from GISP2 ice-core will explore climatic influence into environmental and cultural development.

2.3 Field-work

The field data was collected at the end of June / July 2009. In view of the nature of the terrain, a topographical transect based approach formed the basis for the sampling framework. The main sample transect ran from the southern boundary of the estate to the north, using the track 'road' as the transect line and two additional transect lines were located off the main transect cutting across the topographical gradient from east to west. Eleven soil pits excavated at approximately 2 km intervals along the main transect line, with four soil pits

excavated on cross-transect 1 and four on cross-transect 2 (Figure 4). At each profile location soils were exposed to the top of Hekla (H3) 2500 BP as a marker or the water table where there was no possibility of digging any further.

Data recorded at each site included Global Positioning System (GPS) co-ordinated, altitude (taken from handheld GPS receiver) and vegetation cover. Descriptions of each soil profiles were recorded, using Munsell colour and soil texture. In each profile visible tephra horizons were recorded and sediment thickness between tephra layers were carefully measured to an accuracy of 5mm to allow estimates of soil accumulation rates.

To allow assessment of the nature of soil accumulation in profiles, three undisturbed block samples were taken in 8 by 6 by 4 cm Kubiena tins, for thin section manufacture two samples came from Profile 4 and one sample from Profile 5. Profile 4 - sample 1 was taken pre-1477 at 121 cm; Profile 4 - sample 2 was taken post-1477 at 76.5 cm; Profile 5 - sample 3 was taken between *landnám* and H1104/1158 at 72 cm (Graenv 4-1; 4-4; 5).

A 210 cm pollen core was also collected from the study area at a '*sellönd*', shieling area N 65°25.899', W 017°07.028', Altitude 1270 ft. The sample was obtained using a ½ m Russian corer. Data recorded at the site was GPS co-ordinated, altitude (taken from handheld GPS receiver). Each sample core had a 10 cm overlap and was removed in five sections from the site in a protected plastic guttering and wrapped in polythene they were then stored at University of Stirling cold store for subsequent analysis.

2.4 Analyses

Analyses included soil accumulation rates, loss on ignition, pollen analysis and micromorphology allowing the development of temporal and spatial patterns of landscape.

2.4.1 Soil Accumulation Rates

Soil accumulation rates were calculated from the soil pits excavated on the transect lines. The depth of the soil pit was dependent on the conditions at each site such as the water table; however most sites were excavated until Hekla-3 tephra was exposed. For the purposes of this study accumulation values were calculated between tephra horizons identified in the field from *Landnám* 871 + 2 A.D. These accumulation values were compared with regional mean soil accumulation rates for Mývatnssveit presented by Ólafsdóttir and Gudmundsson (2002). The data were then plotted onto a graph and the landscape reconstructions of eroded areas were identified from prominent tephra deposits, *Landnám*,

H1105/1158, 1300, 1477, 1717 A.D.

2.4.2 Soil Thin Section Micromorphology

The Kubiena tins were returned in protective polythene to University of Stirling Thin Section Micromorphology Laboratory. Thin sections were prepared to allow assessment of soil accumulation processes by standard procedures which include water removal by acetone replacement, impregnating the soil samples under vacuum with polyester crystic resin and then bonding the resin block to a slide, cutting off excess, grinding to desired thickness, polishing to 30 micron thickness and finally coverslipping (Adderley, *et al.,* 2002*,* 2006).

Following preparation thin section was studied using an Olympus BX-50 polarizing microscope. A range of magnifications (x10 – x 400) and light sources including plane polarized illumination (PPL), oblique incident illumination (OIL) and cross polarized light (CPL) were produced from two non-polarized beams from a 150 W halogen bulb (Adderley, *et al.,* 2002).

Descriptions were according to Bullock *et al*., (1985) *Handbook for Soil Thin Section Description*, allowing a standardised description of a range of features. The main soil characteristics identified were mineral and organic materials, pedofeatures, microstructure, material arrangement, groundmass ь fabric and any related distribution. To allow thin section comparisons the results were recorded in a standard quantitative summary table

Using a three-chip video camera a series of 5 images were captured and imported into AnalySIS software (Soft Imaging System, Munster). This would allow temporal assessment of erosion factors at Profile 4 and Profile 5.

2.4.3 Loss on Ignition

The pollen sample core was removed from the site and stored in Stirling University refrigerator. Samples of the profile were tested for total organic context to establish the tephra layers for subsequent pollen samples. This was conducted using the procedure of Loss on Ignition (LOI). Porcelain crucibles were cleaned and placed in a furnace for 105°C for 1 hour. They were removed from the furnace, cooled and weighed empty. Samples of the pollen were taken at 1cm^3 then added to crucibles to be weighed again. A set of 50 samples were taken at one time and were placed in the furnace at 105°C overnight to burn off the organic matter in the sample.

The samples were removed from the furnace and were placed in a dessicator to allow the

crucibles to cool without being contaminated with moisture. After the crucibles were cooled each sample was weighed and at each weighing the data was recorded. The percentage of organic matter was calculated from the loss on ignition formula:

$$\% \text{ LOI} = \frac{\text{Crucible (unburnt soil)} - \text{Crucible (burnt soil)}}{\text{Crucible (unburnt soil)} - \text{Empty crucible}} * 100$$

The data was then plotted on a graph using excel to ascertain where there was low organic matter as this is an indication of where tephra layers are located in the core.

2.4.4 Pollen Analysis

From the results of Loss on Ignition identified areas of high organic matter and samples were removed from 3 cores. Section 1 two samples were taken at 7 cm and 11cm. In section 2 three samples were taken at 54 cm 37 cm and 44 cm. In section 3 eight samples were taken at 47 cm, 48 cm, 53 cm, 63 cm, 66 cm, 76 cm, 82 cm and 83 cm. The reason for more samples being removed from section 3 is due to two tephra layers from *Landnám* and H1300 being identified.

The samples were prepared by University of Stirling and an exotic pollen marker of Lycopdiam was added (Moore *et al.,* 1991). Samples were prepared by Helen Ewen of the University of Stirling. Each slide was counted at x 400 magnification and a minimum of 300 terrestrial pollen taxa were counted for each sample. Moore *et al*., (1991) was referenced for the identification of pollen. The total terrestrial pollen taxon was presented as percentages and the pollen diagram was drawn using Tilia and Tilia Graph software.

Results

3.1 Introduction

The following results are pertinent when considering the interrelation between natural and cultural factors identified in Figure 1 on the landscape. An integrated approach is based on a spatial framework derived from remote sensing to further investigate cause and affect relationships. This allows assessment of soil and vegetation responses to either a single stress or multiple stress factors from, climate change geomorphic processes, topography and anthropogenic activities.

3.2 Cultural Data (*Jarðabók*)

Data of livestock numbers and management of early farms are available from the Icelandic historical census Jarðabók carried out in August 1712 for all farms in the Mývatnssveit region and substantiated with zooarchaeological research (Thomson & Simpson, 2007). Livestock numbers are available for Grænavatn only as Oddastaðir and Sveigaköt were already abandoned by the time the census was conducted. However, zooarchaeological research at Sveigaköt has surmised livestock numbers, therefore a limited amount of information is available regarding farm management at this site (Adderley, *et al*., 2008: Green, unpublished).

Consideration must also be taken when using this information as ‘factual’ data as the information was collected for tax purposes. Therefore the quality of data is based on the farmer’s accuracy which may be imprecise with lower numbers of livestock recorded to avoid higher tax implications. The data can however be used to explore the management of livestock and assess zones of grazing pressures on the Grænavatn Estate (Table 1).

Table 1: Estimated Livestock Numbers and Management Information of known farms on the Grænavatn farm estate (adapted Thomson & Simpson, 2007; 157: Green, unpublished)

Livestock Type	No. of Animals: Grænevatn Farm	No. of Animals: Sveigaköt Farm	Management Information	Grazing Area: Summer Months	Grazing Area: Winter Months
Dairy Cattle	4	12	Kept for milk production	shieling	byre
Calves	2	10	Culled in May	shieling	-----
Ewes	40	13	Some milk production	*affrétir*	outfield
Lambs	16	9	11 retained for autumn cull	*affrétir*	------
Immature sheep	30	10	5 retained for spring cull	*affrétir*	------
Wethers/rams	12	4	Kept for wool production	*affrétir*	outfield
Horses	3	1	Kept for transport purposes	outfield	*affrétir*

3.3 Ice-Core Data

Since 1846 meteorological conditions have been scientifically monitored and recorded in Iceland (Bradley & Jones, 1995). However to have a better understanding of the influence of climate change on the landscape before then proxy data has been sourced from ice-cores. Ice-cores are an archive of palaeoenvironmental conditions and isotopes trapped in the ice are often controlled by climatic conditions. Oxygen isotope consisting of the heavier $\delta^{18}O$ and lighter $\delta^{16}O$ are trapped in the ice and the concentrations provide a proxy temporal record of temperature variations. $\delta^{18}O$ isotopes within the GISP2 (Greenland) ice-core are an indicator of temperatures in the northern hemisphere and low concentration levels of $\delta^{18}O$ are an indication of a warm atmosphere whereas higher values indicate a colder climate (NOAA.gov).

Figure 10 shows the variation of $\delta^{18}O$ data ten years before and after the 1717 AD volcanic eruption. This data shows that there was rapid variability with two periods of increased temperatures observed before and after the 1717AD eruption. The trend-line became a more ‘jagged’ decline for 5 years after the eruption.

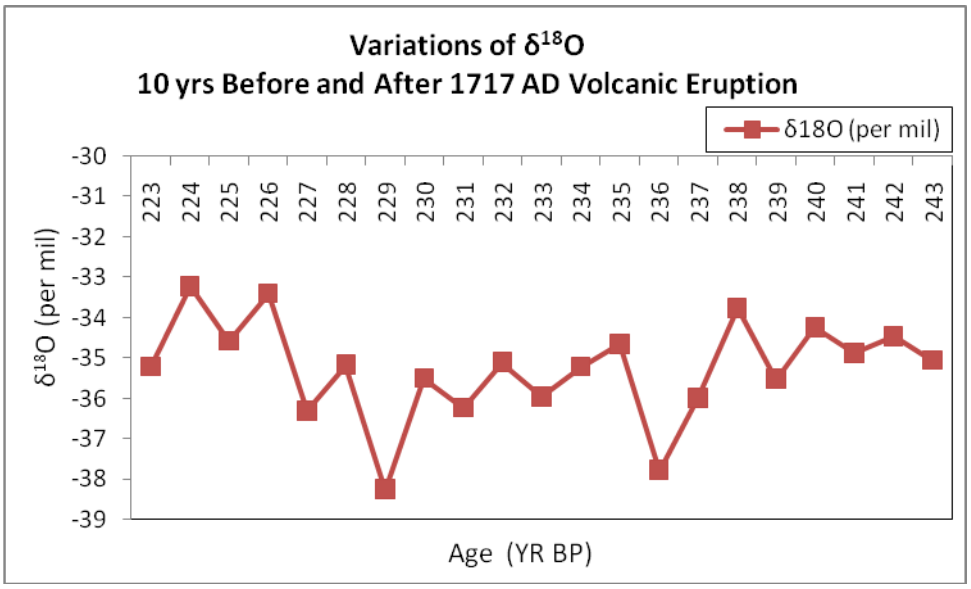


Figure 10 - 1-year variations in $\delta^{18}O$ from the GISP2 ice-core – 10 years before and after the 1717 AD volcanic eruption

Climatic conditions before and after 1477 AD volcanic eruption the record became more changeable with extreme years particularly before the eruption. Figure 11 shows that prior to volcanic eruption there was an increase in temperature followed by colder climatic conditions which remained for seven years over the volcanic eruption. Then there an increase in climatic conditions for two years then stabilised to conditions prior to the warm period.

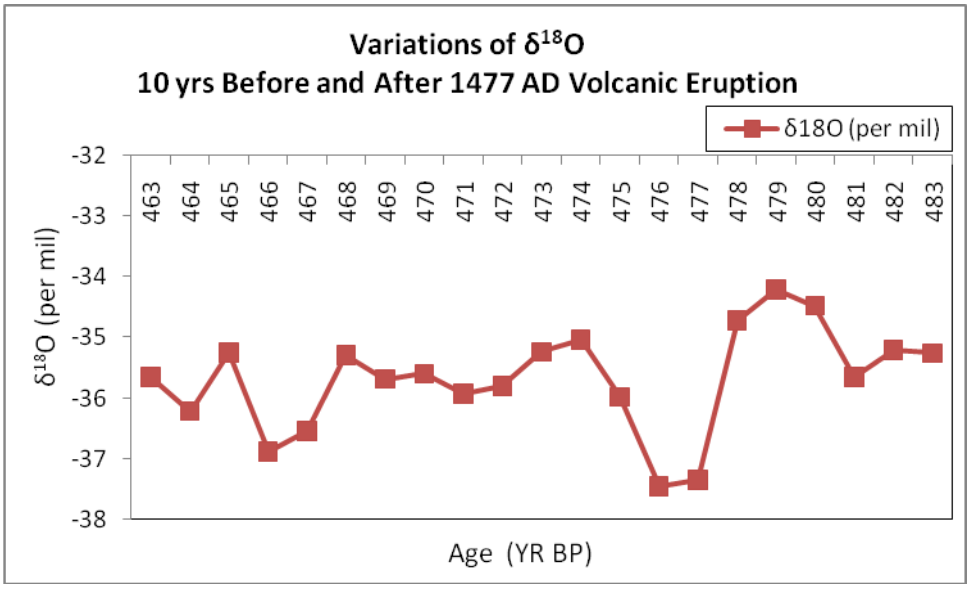


Figure 11 - 1-year variations in $\delta^{18}O$ from the GISP2 ice-core – 10 years before and after the 1477 AD volcanic eruption

Climatic conditions remained fairly stable over the *Landnám* twenty year period apart from cold peaks experienced 1080, 1076 and 1077 yrs BP, which covers the *Landnám* volcanic episode 871 $\pm$ 2 AD (Figure 12).

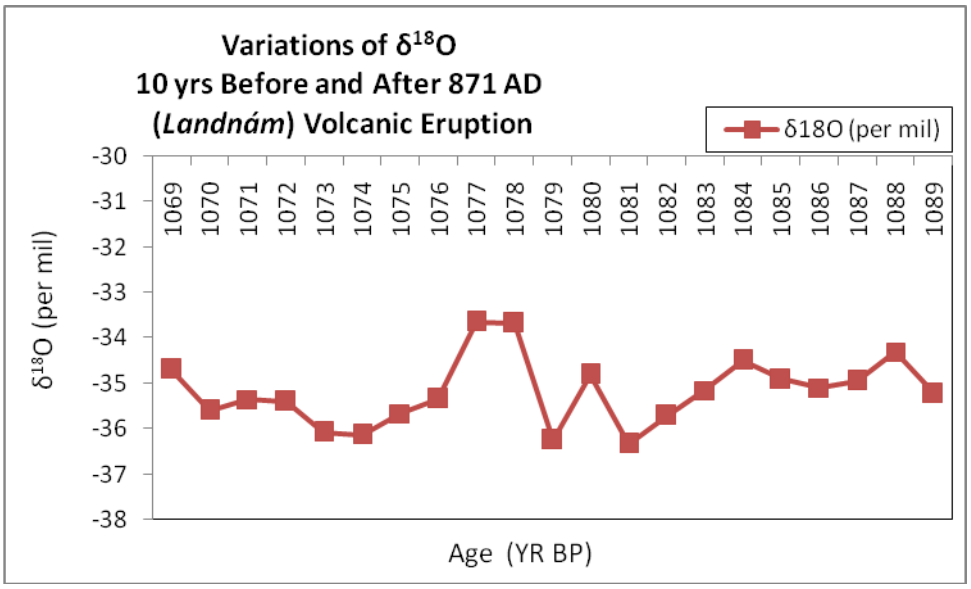


Figure 12 - 1-year variations in $\delta^{18}O$ from the GISP2 ice-core – 10 years before and after the *Landnám* volcanic eruption

3.4 Tephrochronology

The stratigraphic profiles from 16 soil pits excavated at the study site show that the area has frequently been covered by volcanic fallout (Figure 13). Across the site nine different tephra layers were visually identified and recorded (Table 2). No profile contains all regional tephra, although profiles 6 and 13 close to the bank of the River Kráká have most complete regional tephra records.

The distribution of tephra preserved in the soil is important as they can be used to identify spatial and temporal rates of change (Dugmore *et al*., 2009). Therefore finding and identifying *Landnám* AD 871 ± 2 tephra is of particular interest for this study as this was deposited at the time of the Norse settlement and has widely been accepted as a chronological baseline for considering the developments of anthropogenic activities on a pristine landscape (Smith, 1995). However it should be noted that spatial reconstruction of the tephra deposits are limited to the areas of volcanic fallout which is dependent on the strength and direction of the wind at the time of eruption (Gerard, 1992).

For example, *Landnám* tephra deposits originated from the largest volcano in Iceland Veiðivötn Volcano located south-west of the island. Eruptions are characteristic of large volumes of volcanic ejecta and debris that are short-lived over days/weeks. This releases a greater amount of discharge to be deposited over the landscape in thicker more visible layers. Hekla H1104/1158 and H1300 AD in comparison has volcanic eruptions which consistently follow the same three patterns of explosive and fountaining phases and a moderate level of tephra fallout discharge (Thordarson & Larsen, 2007).

Unknown tephra deposits were also recorded in the tephra stratigraphy, these layers were most likely aeolian deposits and statistical adjustments were taken into account when calculating soil accumulation rates (Simpson *et al*., 2004). The complete soil profiles for each of the study sites can be found in the appendix.

Table 2 : List of tephra layers and profiles identified at the Grænavatn Estate (adapted Boygle, 1999; 138: Ólafsdóttir & Guðmundsson, 2002; 162)

Tephra	Origin and age	Description	Site(s) where tephra visible
1717	Veiðivötn AD 1717	Black sandy tephra	2, 3, 5, 6, 8, 13
1477 'a'	Veiðivötn AD 1477	Dark grey fine-grained tephra	2, 3, 4, 5, 6, 8, 10, 11, 13, 14, 17, 20
1300 AD	Hekla AD 1300	Blackish-grey tephra	6, 8
H1	Hekla AD 1158 / 1104	White fine-grained tephra	5, 6, 8, 19, 20
Landnám	Veiðivötn AD 874	Two fine-grained tephra bands, olive-green and white, from two distinct eruptions	3, 5, 6, 13
b/c	n/a – estimated AD 700 and AD 600	Two black fine-grained tephra layers – origin is not certain	13
H Tephra 2500 BP	Hverfjall 2500 BP*	Coarse black tephra layer	2, 6, 8, 13
H3	Hekla 2800 BP*	Double layer – black fine-grained upper part and white fine-grained lower part	2, 3, 6, 8, 13
H4	Hekla 4000 BP*	White fine-grained tephra layer.	13

* ^{14}C age

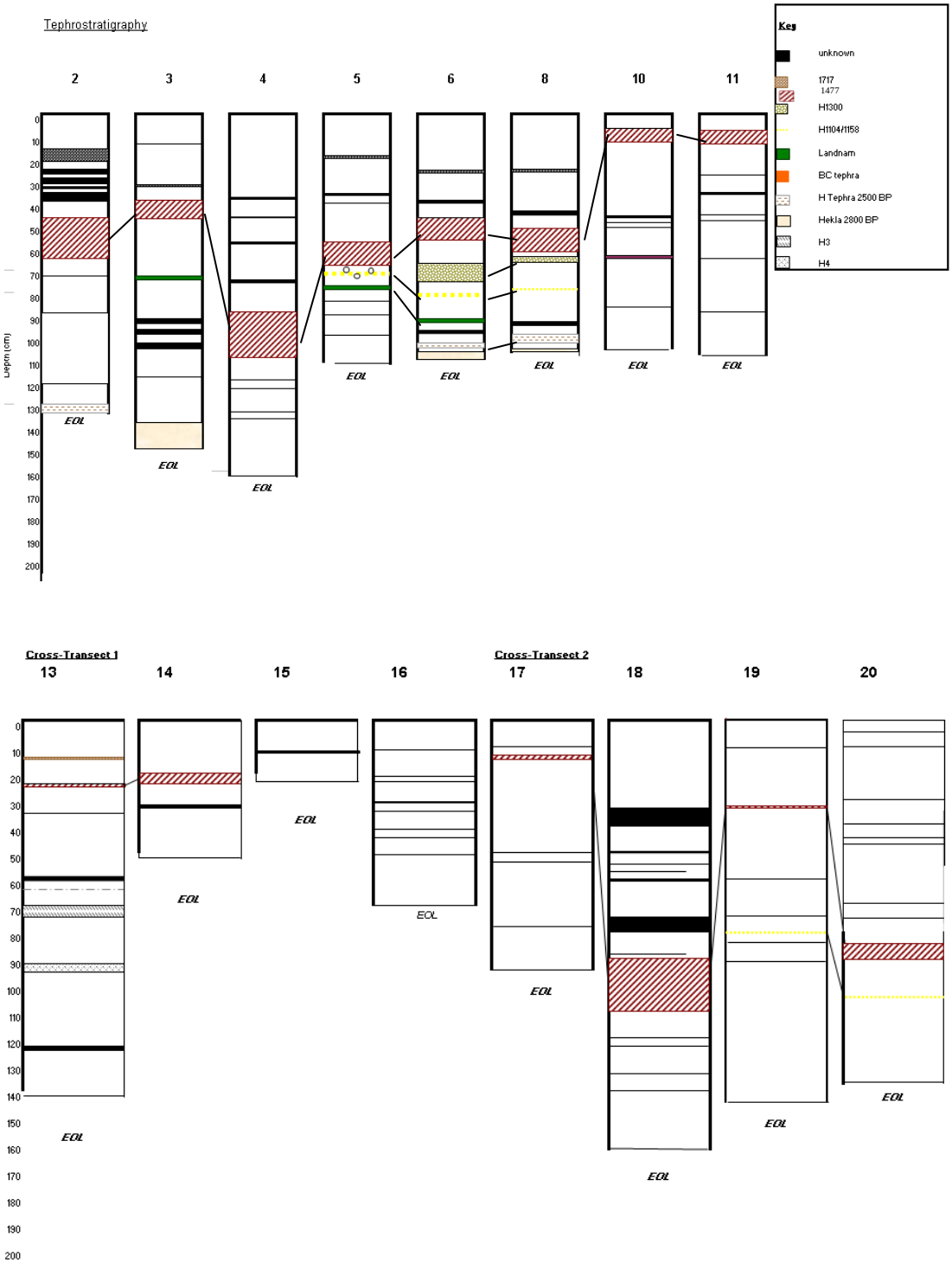


Figure 13 – Tephro-stratigraphy of soil profiles from the study site – Grænavatn Estate, 9 different tephras visually identified – unknown tephra layers were also added to stratigraphy EOL : end of log

3.5 Loss on Ignition

Loss on ignition carried out on a peat sample removed from the '*sellönd*' area indicates the distribution of organic matter varies throughout the profile (Figure 14). A decrease in organic content is in most cases an indication of tephra layers, 45 – 12% LOI for 1717 AD , 68 – 72% LOI 1477 AD , 56 – 62% LOI for 1300 AD and 56 – 49% LOI for *Landnám* 871 + 2. This information was used as a guide when preparing sample sections for pollen analysis.

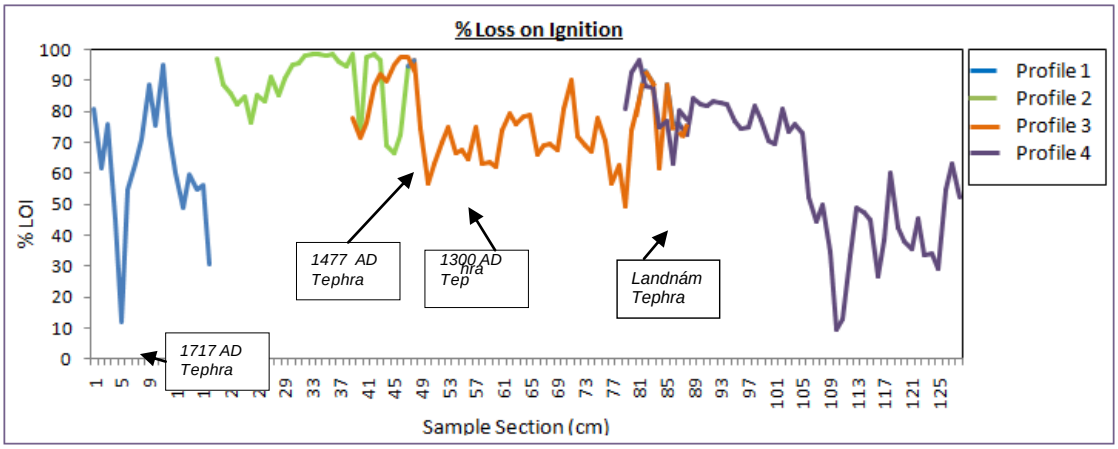


Figure 14 - Percentage loss on ignition for peat profile and age model

3.6 Pollen Analysis

The sample extracted from the *affrétir* location was used for pollen analysis. The sample was divided into 13 subsamples in accordance with tephra layers identified from loss on ignition results; *Landnám*, H1300 AD and 1477 AD.

Prior to *Landnám* pollen analysis (Figure 15) shows that the shrub taxa dominated the sequence, birch (*Betula)*, and willow (*Salix)* and juniper (*Juniperus)*. Herbs recorded were dominated by *Cyperaceae* with a small amount of grasses (*Poaceae*) and Thalictrum present. Post-*Landnám* there was a significant change in the composition of pollen data found in the sequences. The major changes were the decrease in both *Betula* and *Juniperus* with a correlating increase of grasses (Poaceae) and herbs (Cyperaceae).

The recorded amount of *Betula* and *Juniperus* virtually disappears from the data set around H1300 AD with a significant increase of Poaceae. This trend continues until after 1477 AD when there is a recovery of *Betula* and *Juniperus*. Willow quantities remained constant throughout the data set. Several other taxa were presents including the shrub *Empetrum nigrum* and the herb *Ranunculus*.

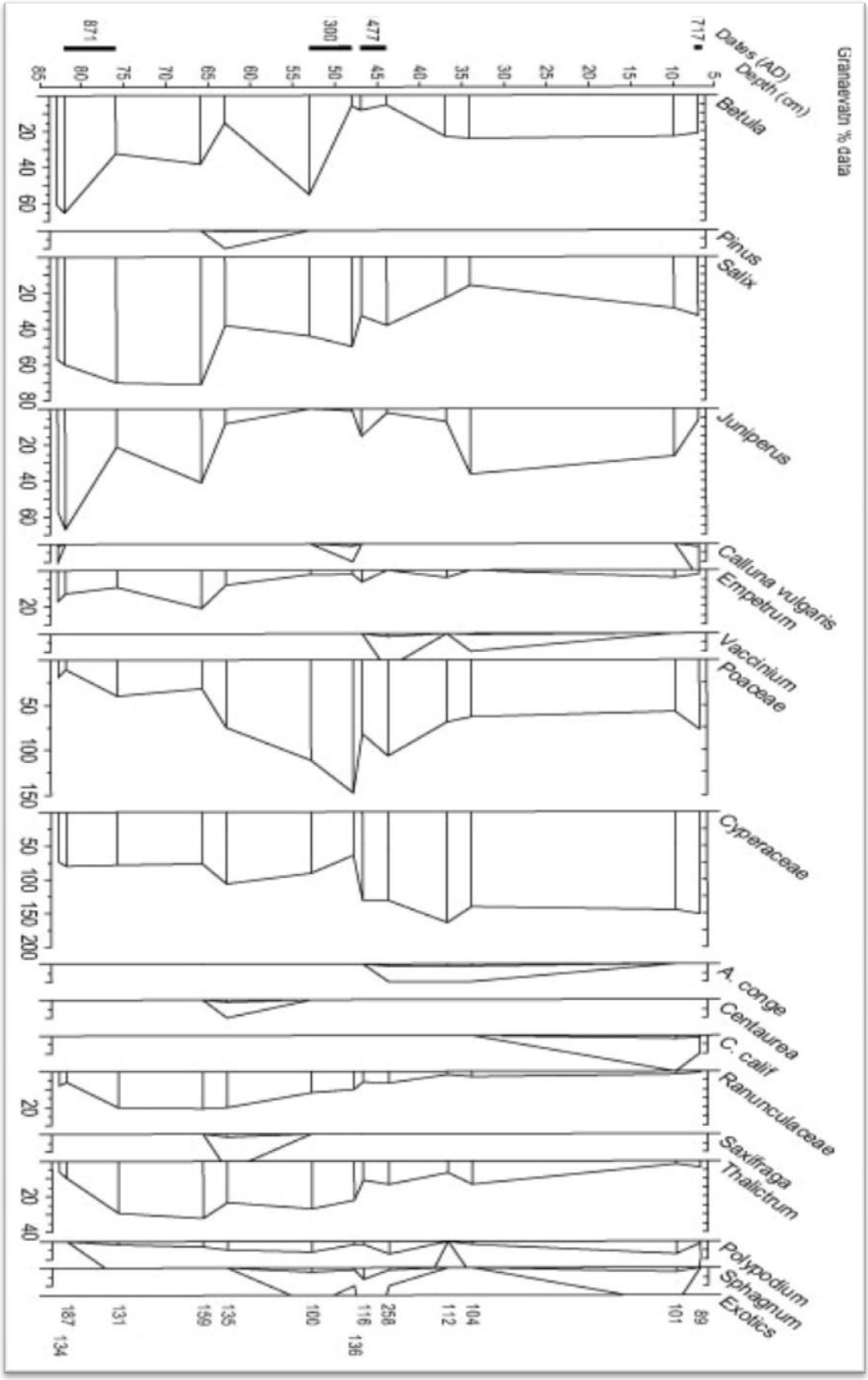


Figure 15 – Pollen percentage data from Grænavatn

3.7 Soil Description and Soil Accumulation Rates

3.7.1 Soil Description

Soils in the Grænavatn Estate are predominately free-draining Andosols, consisting varying levels of silts and sands, with the exception of a section of peat located south of Oddastaðir Farm. The depth of the profiles varied across the site, generally sites predominately Andosols were excavated to a depth >100 cm. The sites containing peat due to the water table were excavated to a depth < 100 cm.

Profile 4, 5, 10 and 11 have distinct fluvial deposits below 1477 AD tephra layer. Profile 4 consists of fluvial patters of micro-banding sequences; profile 5 has low energy and then high energy fluvial patterns; profile 10 has a well bedded fluvial black sands; profile 11 has aeolian deposits interbedded with fluvial deposits. Evidence of changing fluvial activity from the River Sellandagróf is evident in aerial photos (Google Maps) (Figure 16).

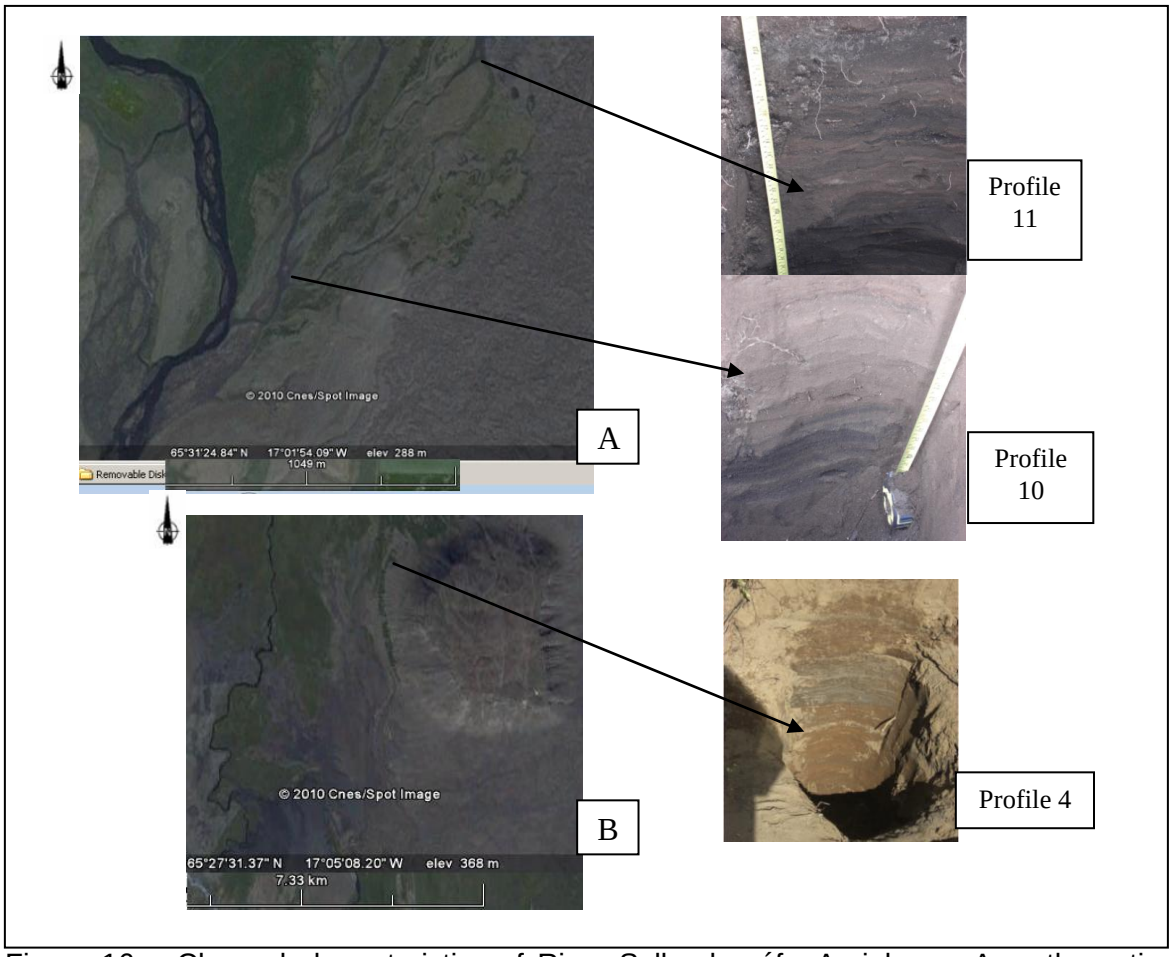


Figure 16 – Channel characteristics of River Sellandagróf. Aerial map A north section of estate, Profile 11 very coarse sands found at base of pit – almost channel material), Profile 10 well bedded sand medium fluvial sands at base of pit; Aerial map B south section of estate, Profile 4 fluvial patterns of micro-banding sequences; all fluvial material found below 1477 AD tephra layer. (Aerial photos - Google Maps)

Bare ground covers the full east-side of the *affrétir*, site 8 and rétt and also the furthest south site 1. Comparing Ólafsdóttir and Gudmunðsson (2002) regional data the distribution of bare ground and altitude is 4% at 200 – 300 m, 8% at 300 – 400 m and 16% at 400 – 500 m. The current proportion of bare ground on the estate in relation to altitude, Figure 15 shows at altitudes between 300 – 400 m and 400 – 500 m bare ground is well above this regional average. Between altitudes 200 – 300 m the proportion of bare ground is below the regional average (Figure 17).

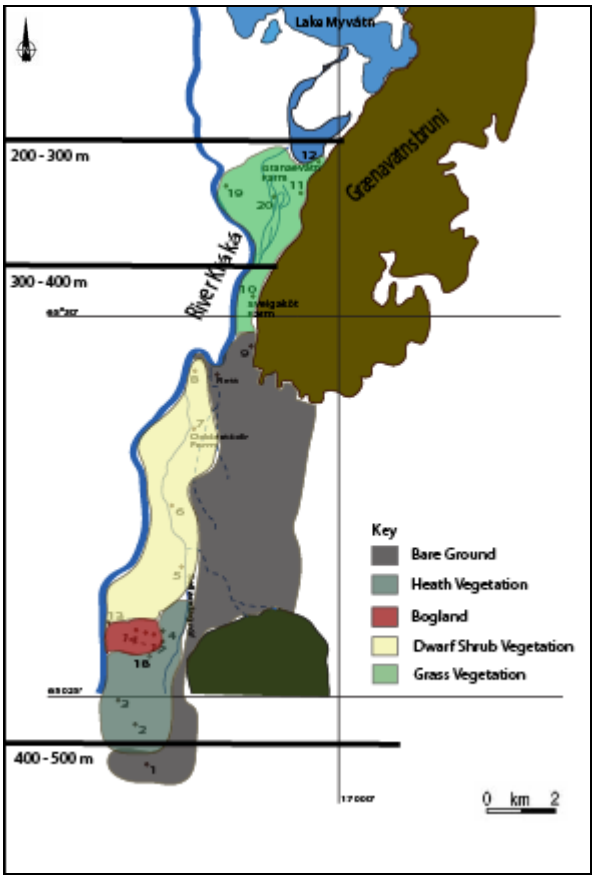


Figure 17 – The distribution of bare ground between altitudinal zones

3.7.2 Soil Accumulation Rates (SAR)

Patterns of soil accumulation rate (SAR) shows temporal and spatial variations in the volume of soil being eroded and deposited. Increasing rates of SAR can be an indication of land degradation which is important when reconstructing landscapes, ie, higher levels of SAR can be an indication of the extent of land degradation going on. The following figures (Figure 18 and Figure 19) show the overall patterns of soil accumulation rates for the Grænavatn Estate. The time periods chosen AD 871 – AD 1477 and AD 1477 – present day (AD 2009) was based on present tephra layers identified in the study site and can be compared with regional accumulation rates, given as the horizontal bar (Ólafsdóttir & Guðmundsson, 2002).

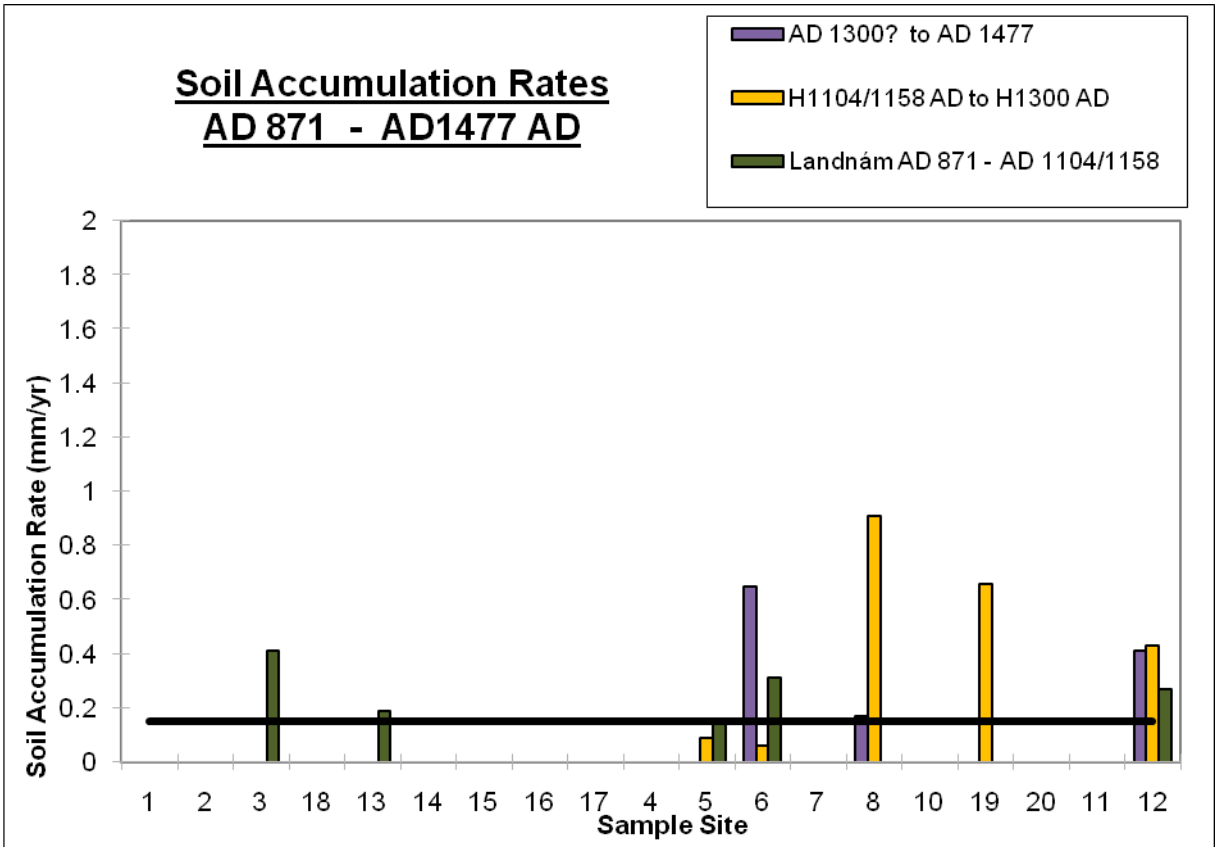


Figure 18 – Soil Accumulation Rates for the period Landnám to 1477 AD

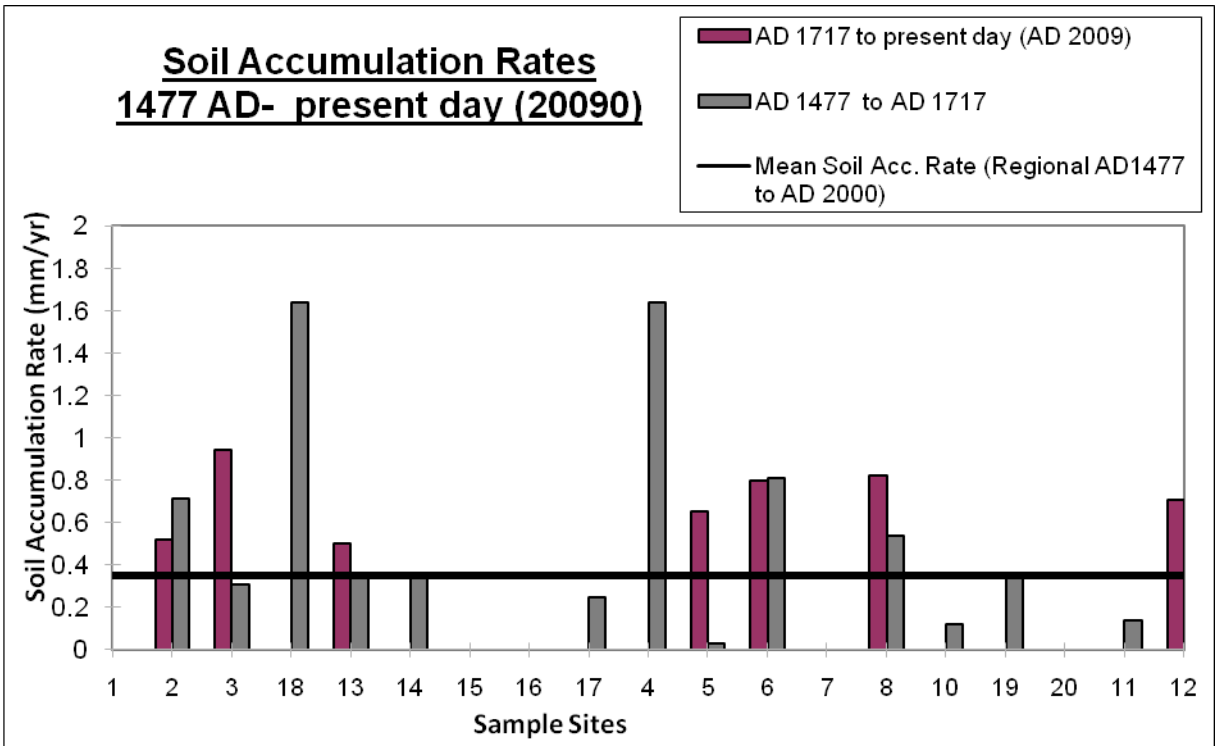
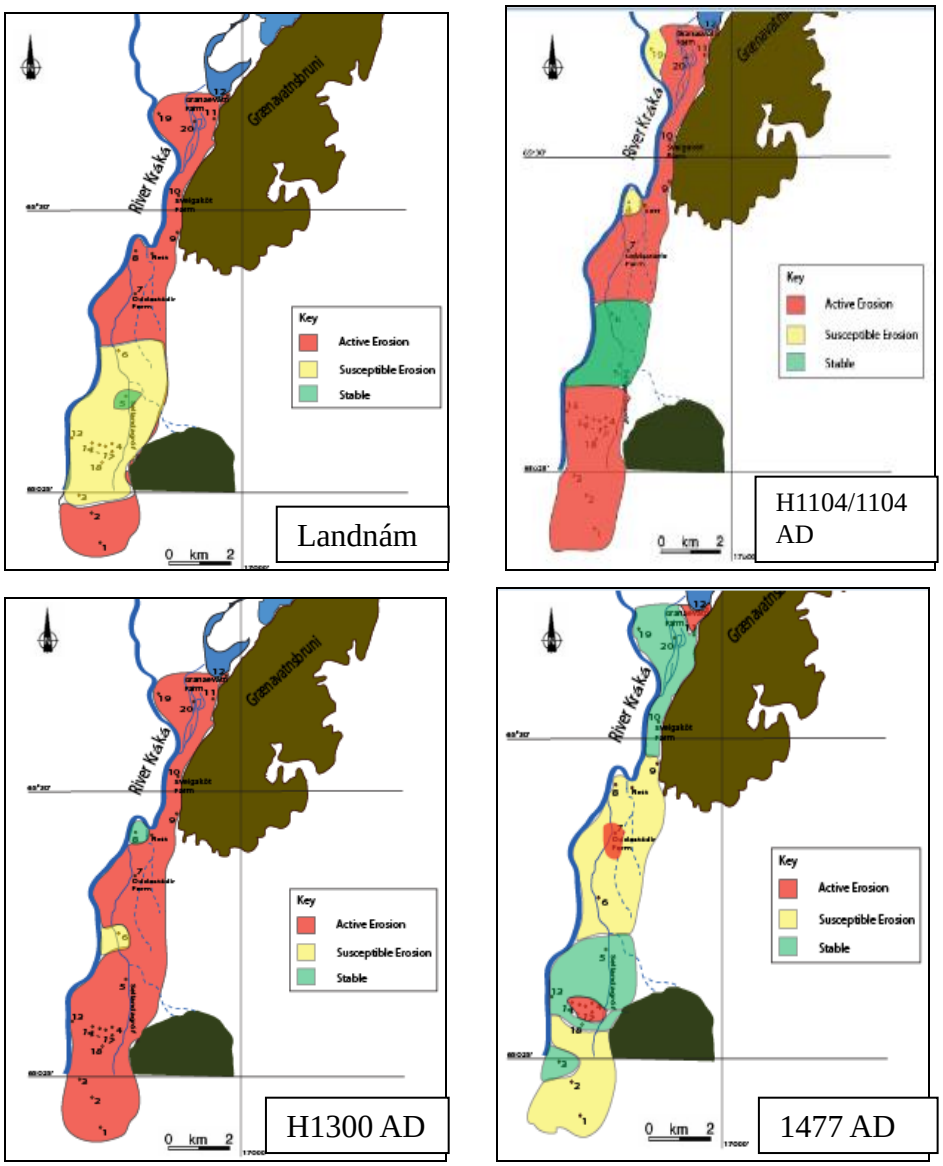


Figure 19 – Soil Accumulation Rates for the period 1477 AD to present day (2009)

Soil Accumulation Rates demonstrates that soil formation can spatially and temporally change over time. By evaluating these changes an overall representation of the Granaevátn Estate can be proposed (Figure 20). Three criteria, adapted from Popps, *et al*., (2000), were adopted to visually represent soil conditions over the following periods, Landnám, H1104/1158, H1300, 1477 AD and 1717 AD. The criteria were; 'stable' represents soil conditions immune to stress factors and SAR is below regional results; 'susceptible erosion' represents soil conditions with rates higher than regional results; 'active erosion' is when tephra layers are absent from the soil profile and may be influenced by accelerated degradation from water or wind erosion.



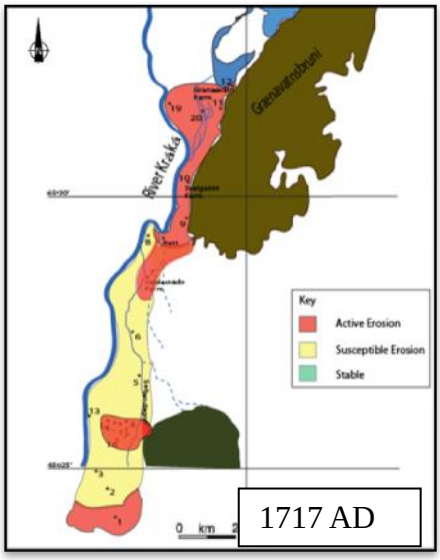


Figure 20 – Temporal soil movement across Grænavatn farm estate

3.8 Soil Thin Section Micromorphology

Thin sections were extracted from two sites of the estate to assess in finer detail the interations of aeolian and fluvial influences on the soils (Figure 4). The main soil characteristics are presented in Table 2, with a more detailed explanation being described to allow for further interpretation of the sampled soils.

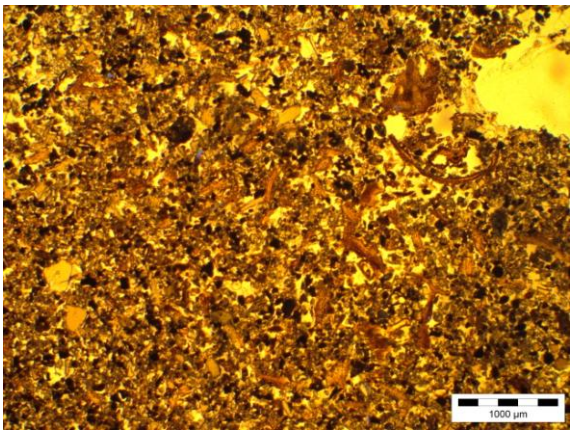
Sample 4.1 (pre-1477 AD) consists of two micro-horizons. Both horizons feature an intermix of both fluvial and aeolian material associated with moderately sorted silt organic mix. Horizon 1 has significantly higher organic material (~ 50%), with associated iron accumulation, and the presence of excremental pedofeatures (mamillate) indicating biological activity (Figure 21 A). The fine organic material consists predominately of amorphouse (brown) frequent/common and a trace of amorphouse (black). Horizon 2 is a discret micro horizon and was observed to have significantly less organic material but shows well sorted black single grain coarse mineral material which may be acccumulated from run-off from the nearby hill.

Sample 4.4 (post-1477 AD) consists of three horizons which have distinct contrasts between fluvial and aeolian material throughout the section. Horizon 1 is the smallest observed in this section and is characteristic of pale brown and black aeolian coarse material. The grains were possibly captured by light vegetation cover, however there is no organic material is present in this section. The shapes of the coarse material is blocky and well sorted. The related distribution has been defined as enaulic which consists of larger fabric units with smaller aggregates partially filling the interstital spaces. There is also evidence of freeze-

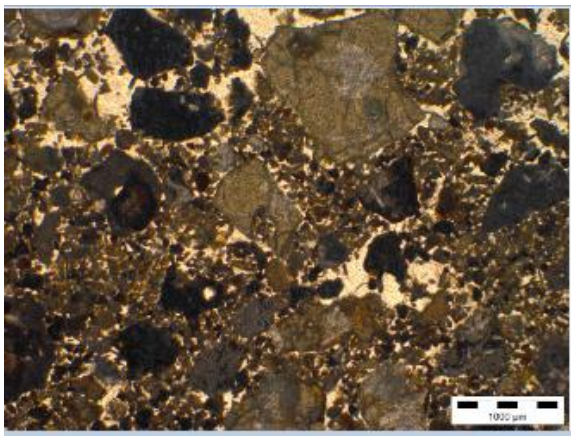
thaw action in this horizon (Figure 21 B). Horizon 2 is divided over three different sections througout the profile. The microstructure of this section is interwoven micro-aggregates with a higher frequency of black with few brown and pale brown grains which are moderately well sorted. The related distribution of Horizon 2 & 3 is porphyric and has also been identified stipple groundmass ь fabric. Horizon 2 is characteristic of a mixture of fluvial and aeolian mixed aggregates which may be been due to seasonal low water flow and the vegetation trapping the silty material (Figure 21 C). Horizon 3 has no coarse materail present in this section and has few traces of fine organic material amorphous(black) and is more common with amorphous (brown). There is a rare frequency of silt coatings and the micro-structure is classed as lenticular. This fine material is characteristic of aeolian deposits (Figure 21 D & E).

Sample 5 (H1104/1158 AD to 1477 AD) consists of similar features to Sample 4.1. There are two horizons present, Horizon 1 was observed to have frequent to common moderately sorted black coarse mineral material. There is evidence of iron accumulation mottling through the soil section with few traces of fine organic material (amorphous – brown) and traces of crystalline (reddish) and depletion pedofeatures. This sample was taken at Profile 5 and should be considered the coarser materail may be due to the location relative to the river. Horizon 2 is well sorted coarse mineral materail and is observed to be slightly more layered which is charateristic of aeolian layering.

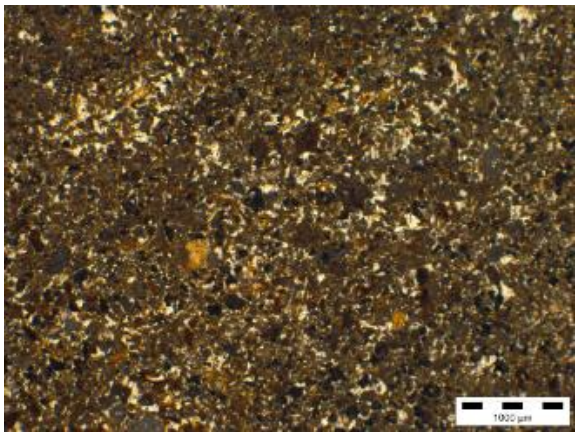
A) Graenv 4.1; 1.



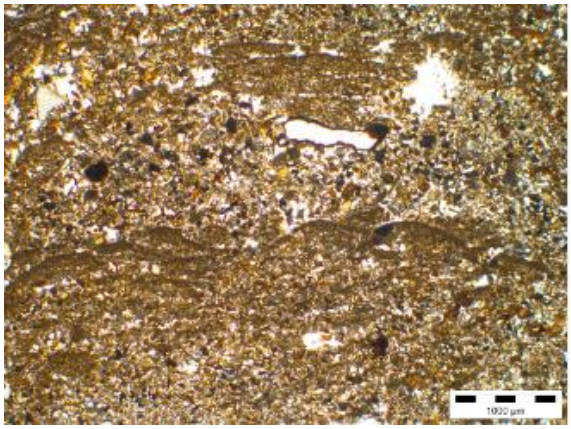
B) Graenv 4.4; 1.



C) Graenv 4.4; 2



D) Graenv 4.4; 3a



E) Graenv 4.4; 3b

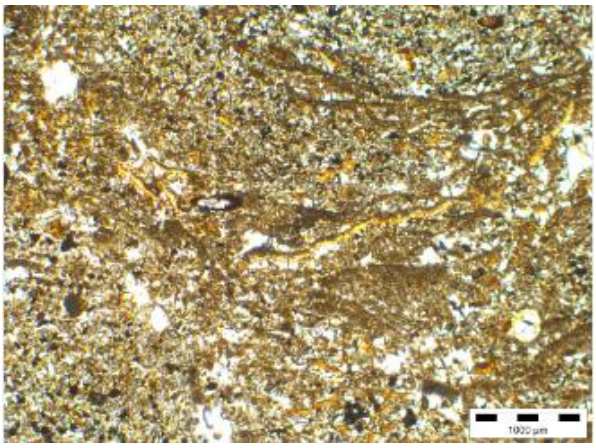


Figure 21 – Grænavatn Estate Micromorphology Photos

A)	Graenv 4.1 1/1	Intermixed aeolian and fluvial material with an increase in organic matter (plane polarised light)
B)	Graenv 4.4 1/1	Increased coarse aeolian material (plane polarised light)
C)	Graenv 4.4 2/1	Mixed erosional material (plane polarised light)
D)	Graenv 4.4 3/1	Fine aeolian material with freeze-thaw process (plane polarised light)
E)	Graenv 4.4 3/1	Fine aeolian material with fragments of organic material (plane polarised light)

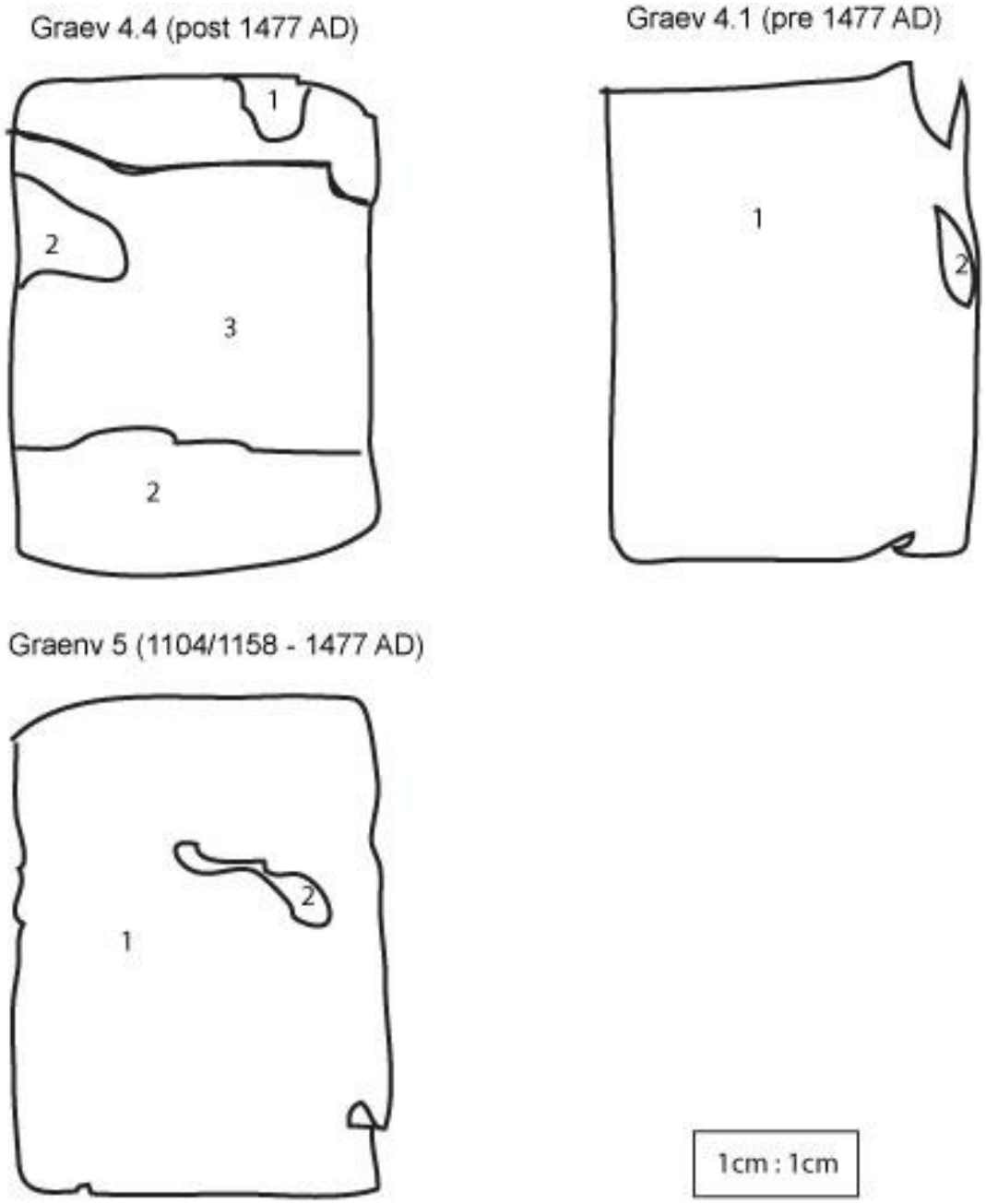


Figure 22 : Soil Thin Section Microhorizon Boundaries

Table 2: Summary Thin Section Micromorphology Descriptions for Grænavatn Estate

Thin Section Sample	Micro Horizon	Coarse Mineral Material: Brown	Pale Brown	Grey	Black	Igneous rock	Phytoliths	Diatoms	Fine Mineral Material	Coarse Organic Material: Charcoal	Parenchymatic	Fungal Sclerotia	Fine Organic Material: Cell residue	Amoprhous (black)	Amorphous (brown)	Pedofeatures: Silt coatings	Amorphous crypto-	Crystalline (reddish brown)	Depletion	Excremental (mamillate)	Excremental (spheroidal)	Microstructure	Coarse Material Arrangement	Groundmass ь Fabric	Related Distribution
Graenv – 5	1		•		•••				Organo mineral Brown					•				•	•			Intergrain micro-aggregate	Moderately sorted	Stipple	Porphyric
1104/1158 AD	2		••		••				———													Single grain	Well sorted	———	Enaulic
Graenv – 4.1	1		•		••				Organo mineral Brown	•	•			•	•••					•		Intergrain micro-aggregate	Moderately sorted	Stipple	Porphyric
Pre-1477 AD	2		•		••				———													Single grain	Well sorted	———	Enaulic
Graenv - 4.4	1		••		••																	Single grain	Well sorted	———	Enaulic
Post-1477 AD	2	•	•		•••				Organo mineral Brown						•							Intergrain micro-aggregate	Moderately well sorted	Stipple	Porphyric
	3								Organo mineral Dark Brown					•	••	•						Lenticular	———	Stipple	Porphyric

Frequency class refers to the appropriate area of section (Bullock *et al*., 1985) *t* Trace • Very few •• few ••• Frequent/common •••• Dominant/very dominant

Frequency class for textural pedofeatures (Bullock *et al.,* 1985) *t* Trace • Rare •• occasional ••• Many

Discussion

4.1 Vegetation change and the factors contributing to that change.

It is well documented that there was vegetation changes around the time of Norse settlement (Arnalds & Barkarson, 2003). This is further supported from historical references - *Islendingabók* - which indicates that the country was "covered with forest between mountain and sea-shore" at the time of settlement (Sveinbjarnardottir, 1992; 12). It is the attempt of this study to reconstruct the vegetation cover from pollen analysis for the Grænavatn farm estate. This was conducted on a peat section from the *affrétir* which was sampled pre and post *Landnám*. This allowed for a comparison of the environment before and after settlement and assess if there were any vegetation changes which could explain land degradation at the Grænavatn Estate. The pollen core was divided into thirteen sections using identified tephra layers as an indication of age-depth (Figure 14, Table 2 & Appendix 2).

Palynological analysis pre-*Landnám* (Figure 15) suggests that the area that became farm Grænavatn estate was a stable environment with a strong representation of the tree taxon, birch and a few shrub taxa, willow and juniper, dominating the vegetation record. The vegetation record did remain static pre-*Landnám* with very little variation in pollen percentages. However the stability in the pollen percentages changes post-*landnám* and there is a clear indication of cultural impacts with both birch and juniper over a few hundred years after *Landnám* and being reduced to a small percentage of their original coverage.

A rapid decline in birch pollen is evident in almost all pollen studies in Iceland (Lawson, *et al*., 2007). The pollen record from the study site indicates stable birch woodland before *Landnám*. What is an intriguing aspect of the Grænavatn farm estate after settlement instead of a rapid decline there is a gradual fall in birch woodland over a few hundred years. This is supported also by research on fuel utilisation at the Norse/early medieval farms sites in Iceland. Research by Vesteinsson & Simpson (2004) suggests that the local fuel resources was considered as one of the most important factors in the quality of life for early settlers by providing light and warmth. Fuel ash residues studies at Hofstaðir, a high-status farm of 20 km north-west of Sveigaköt, and Sveigaköt farm sites indicates that birch and willow was the primary fuel source which contributed to the decline in woodland vegetation cover from the 10th Century (Simpson, *et al.,* 2003).

Pollen analysis at the *affrétir* site supports the hypothesis that birch woodland cover was reduced for the utilisation of fuel. However, the impact from grazing domestic livestock has been considered to the one of the main causes of land degradation (Arnalds & Kimble, 2001: Arnalds Barkarson, 2003). Thomson & Simpson (2007) modelling of historic grazing pressures '*Búmode*l' has composed historic thresholds for the landscape at Sveigaköt Farm and changes in the landscape from grazing pressures. The research suggests that the available vegetation biomass was sufficient for the number of grazing livestock identified from historical literature (Table 1). However, added stress on the vegetation may have been contributed by two reasons at Sveigaköt Farm and may be extended over the whole farm estate. The overall biomass at Sveigaköt Farm was considered to be sufficient for the needs of the livestock numbers except in extreme cold climate conditions. The reason why the cold would have such an impact on biomass availability is due to no productivity over winter months. Climatic data has been limited to twenty years for each time-period in this study, however, Figure 10 – 12 do suggest that there has been extreme cold spell which would limit biomass growth. It could also be assumed from the historical land management (Table 10) that grazing pressures were concentrated over the winter months to farm outfields which does support the active erosion areas identified in Figure 20 to predominately occur within farm sites.

Also, secondly, the Grænavatn farm estate *affrétir* is constrained by the River Kráká and the barren lava field (Figure 4) therefore limiting the grazing pressures to within these boundaries which is reduced further from tephra fall deposits or flooding. This is also supported from evidence temporal soil movement across Granaevátn farm estate (Figure 20) as five of the periods suggesting that active soil erosion is concentrated in the north of the estate resulting in overgrazing thereby further reducing wood and shrub vegetation.

The use of wood and shrub for fuel and utilised by grazing animals explains the reduction of birch and juniper post-settlement. However what is difficult to explain is why there was not the same reduction seen in willow. It could be that willow was growing in locations inaccessible, for example ditches to be considered for felling or animal grazing (Erlendsson, *et al.*, 2009). Or as a small percentage of birch and juniper also remained throughout the profile there may have been some management to preserve the vegetation cover (Aradottir & Arnalds, 2001). Deteriorating climatic conditions may have also contributed to changes in vegetation cover during the mid 12th century with the onset of the 'Little Ice Age'. However, the lack of dating renders it difficult to correlate this time period with the pollen profile.

As with other pollen sites in Iceland, Poaceae and Cyperaceae flourished with the clearance of birch and juniper. Observation of Cyperaceae dominating the pollen percentages from 1300 AD to 1717 AD suggests that there was a decline in soil drainage and can be associated with reduced evapotranspiration as tree cover declines as this species is often associated with poor wet soils. The farmers must have observed a decline in productivity across the site and a reduction of grazing lands (Lawson *et al.,* 2007).

After 1477 AD a recovery of birch and juniper species is observed in the pollen profile. There may be a mixture of reasons, for example, this may be an indication of reduced grazing pressure. It has been suggested that there was a decrease in population at the start of the 15th Century due to an epidemic. It could therefore be surmised that there was less people to tend to the grazing animals that were vulnerable to the historical eruptions that caused the death of livestock from various causes for example, fluorosis (Sveinbjarnardóttir, 1992: Lawson, *et al.*, 2007).

4.2 Soils change and the factors contributing to that change.

Previous research at the Grænavatn Estate indicates that the site was settled shortly after *Landnám* and the estate was utilised for both summer and winter grazing areas for at least three known farms and herding station (Figure 5 – 9). Therefore it could be assumed that the area was the 'best land available' of a well vegetated and stable environment to have been selected as a settlement site so early (Adderley, *et al*., 2008: Simpson *et al*., 2004). However, two farms are known to have been abandoned, Sveigaköt by the 12th Century and Oddastaðir by the 15th Century, and the present landscape was observed to be sparsely vegetated and degraded with vast areas of barren desert (Figure 2, 8 & 9). The object of the study is to evaluate if the land degradation was a result of grazing pressure from poor land stewardship or as a result of other environmental conditions. Based on soil accumulation rates (SAR), tephrochronology, remote sensing and micromorphology it is possible to review the estate over three post-settlement phases and then assess these periods with different cultural factors on the Grænavatn Estate.

It is clear from analysing results between the period *Landnám* Tephra (871 AD) – 'a' Tephra 1477 AD soil accumulation rates (Figure 18) and depositional structure of tephra layers (Figure 13) that there are significant variances both spatially and temporally across the Grænavatn Estate. This temporal phase consists of three distinct tephra layers from two different volcanoes, Veiðivötn and Hekla, of which the tephra fall deposits are heterogeneously present over the Grænavatn Estate. *Landnám* and H1104/1158 AD tephra

were observed in four of the twenty sites sampled and H1300 AD was found in only two sites. The reasons for varying levels of tephra fall deposits observed across the site may be due to a mixture of reasons such as the dispersal patterns, which are highly controlled by eruption magnitude and prevailing wind (Dugmore, *et al*., 2009). Ultimately though, once tephra is deposited on the landscape it is then exposed to a range of natural and anthropogenic disturbances such as land management, climate and fluvial activity.

Dated tephra deposits can be used as a stratigraphic marker to calculate soil accumulation rates across the estate (Figure 13). Regional mean soil accumulation rates calculated between *Landnám* and 1477 AD are 0.15 mm/yr (Ólafsdóttir & Gudmunðsson, 2002). Soil accumulation rates observed between *Landnám* and H1104/1158 AD are between 0.16 mm/yr and 0.46 mm/yr, with a mean 0.27 mm/yr, which is greater than the regional mean annual accumulation for 300 – 400 m elevation. However, there does not appear to be any correlation between soil degradation and altitude zones (Figure 17). No statistical adjustments were required in calculating the mean soil accumulation rates for this phase, suggesting that nature of soil accumulation was localised.

Fluvial systems are a dynamic entity which varies spatially and temporally in response to land-use impacts, climate changes and hillslope erosion (Dotterwich, 2008). Only a little historical information exists from Jarðabök regarding the impact of the fluvial systems on the Grænavatn Estate – “the homefield is being ruined by Sellandagróf river that breaks the land and this is increasing. The Kráká River also ruins the meadow and it has to be damned every spring which is hard” (Green, unpublished). Nevertheless, evidence gathered from the site, aerial photos and micromorphology gives some indication of the impact from the fluvial systems during this time period on the landscape.

The River Kráká is thought to have been the natural boundary of the west-side of the Grænavatn Estate. The Sellandagröf is a smaller river which presently flows into the River Kráká south of the *rétt* site. However, from aerial photos (Figure 16) the Sellandagröf shows a complex network of river channels and given the sensitivity of river channels to modest climate changes demonstrates major episodes of fluvial adjustments (Knighton, 1998).

At four of the investigated sites fluvial activity was observed (Figure 16). These sites were characterised with fluvial patterns and it is interesting to note that all the activity occurred pre-1477 AD. Profile 4 shows signs of coarse banding and fluvial patterns of micro-banding sequences of gravel and sands. The profile was excavated to a gravel bed and no other tephra layer apart from 1477 AD was observed therefore limiting the date. Profile 5 is characteristic of fluvial low energy and then high energy which is evident before *Landnám*

then the river system appears to stabilise. Root nodules were found in the profile along H1104/1158 AD tephra layer, this is evidence of movement of water bringing iron which encases the roots and preserves in the soil. Profiles 10 and 11 have approximately 90% aeolian fine sand interbedded with 10% coarse black medium sands. Profile 11 also has very coarse to coarse sands found at the bottom of the profile which is almost channel material.

In addition, from thin section samples Graenv 5 (H1104/1158) and Graenv 4.1 (pre-1477) (Table 3) it is possible to identify the fine interactions influencing the landscape. Both of these samples were characteristic of a mix of fluvial and aeolian material accumulation. Graevn 5 – the frequency of slightly more aeolian moderately sorted layering was present in Horizon 1 compared to Horizon 2 which was well sorted coarser black material present which may be evidence of run-off from the nearby hill (Figure 21 A). There was also evidence of iron movement leaching through the soil which may indicate a 'wetter' environment. However consideration must also be taken into account the location of the sample site which is near the River Sellandagröf and therefore may be due to the location of the site rather than climatic conditions.

Graenv 4.1, sampled pre-1477 AD thin section Horizon 2 indicates similar conditions as Graenv 5 Horizon 2. Horizon 1 there was observed an increase of organic matter present in this horizon ~50%. The evidence of iron accumulation and biological activity gives evidence that this was a more stable environment. There were no observations of horizons or freeze-thaw features in this sample therefore a more stable environment.

The above results suggest the fluctuations observed with the River Sellandagröf are evidence of seasonal fluctuations. It could therefore be surmised that the rapid reduction in vegetation cover experienced at *Landnám* exposed the soils to increasing erosivity which was more sensitive of surface erosion.

These observations suggest that this period was a more stable environment. Wetter conditions may have been experienced during H1104/1158 although the amount of fluvial material suggests that this may have been due to influences from the River Sellandagröf with a slight amount of wind erosion. The conditions pre-1477 AD were in a more stable environment with an increase in organic material present. When evaluating the climatic conditions (Figure 11) is characterised by an increase in temperatures before the 1477 AD eruption and stabilised climatic conditions for at least 5 years. In general this evidence from climatic conditions, pollen percentages, micromorphology and remote sensing indicate that the landscape was becoming more stable.

Remote sensing data, however, indicates that at *Landnám* there was only one section of the estate considered to be stable conditions, found in the south of the estate located close to the River Sellandagróf and away from cultural features. The north of the estate including the farm sites was experiencing active erosional processes (Figure 19). This is compared to the south of the estate associated with summer *affrétir* grazing the soil conditions were only partially susceptible to erosion processes.

The stable condition observed at *Landnám* has expanded to include profile 6 during remote sensing phase H1104/1158 AD which is both located on the Sellandagröf River. Also profile 8 and profile 9 situated along the River Kráká, although higher than regional soil accumulation rates were observed to be showing signs of improvement in soil conditions. These observations may indicate that these sections of the river were stabilising and landscape conditions were recovering from erosional factors being imposed during *Landnám,* ie removal of vegetation (Figure 20) and grazing pressures. However other parts of the estate were deteriorating and the development of isolated erosional areas may have been forming in response to overgrazing. The deterioration of the landscape continued to H1300 AD, confirming that stress factors being imposed on the soil were continuing to cause an unstable environment which was not able to revert to its original basic structure.

Soils over the period, 'a' tephra (1477 AD) – 1717 AD tephra, has the highest number of SAR's recorded, ie, thirteen out of twenty sites (Figure 19). The soil characteristics are a mixture of soil, silts and sands with a variation of 10YR Munsell colours (browns). Accumulation rates range from 0.03 mm/year to 1.64 mm/year and an average of 0.56 mm/year. This is substantially higher than the regional accumulation rate which has increased to 0.35 mm/year for this time period. Statistical adjustment was also required on six of the profile to take into account unknown tephra layers which may suggest higher aeolian activity.

Thin section post-1477 AD (Table 3) Graenv 4.4, 3 horizons were present with mixed borne wind and water erosion. Horizon 1 is aeolian material possible captured by light vegetation cover (Figure 21C). It was observed freeze-thaw features in the horizon (Figure 21D) and is of similar characteristic of Horizon 2 of Graenv 4.1 and Graenv 5. This observation is characteristic of rofabard erosional features on the landscape. The isolated spots of bare soil are blown onto vegetation. The bare soil is unable to recover and vegetation growth is limited by intense freeze-thaw cycles which if become numerous cause the development of rofabard features (Arnalds, 2000). Horizon 2 is a mix of both wind and water borne erosion, the water erosion has possible been deposited as a result of low flow water. Horizon 3 is

predominately input from stream borne material.

In general the distribution of horizons post-1477 from thin section micromorphology indicates that the landscape was less stable with erosion sourced from both wind and water. The soil accumulation then points to a wetter environment dominated by a stable environment with significant amount of material deposited from a stream. Less stable conditions prevailed before dominating the soil accumulation in a less than stable landscape. This is substantiated by remote sensing which indicates increased disturbance and a deterioration of soil conditions.

On reflection this period shows the most stability in landscape conditions which is further supported in the pollen analysis with the recovery of tree (birch) and herbs (willow and juniper) taxa. These observations may reflect that the dynamics of the landscape was recovering from previous stress factors such as reduced grazing pressures being imposed on it.

Active erosion however was identified at both Grænavatn and Oddastaðir Farm sites and also across two of the peat sites profile 15 and 16. Looking specifically at Oddastaðir Farm the deterioration of soil conditions may have been in response to short occupation during the 15th Century and the increased grazing pressure being imposed from it.

Soil accumulation over the past 300 years ca. are characterised by soils that consist mainly of fine sand silt and fine sand, apart from profile 13 which consists of fine organic silt. Black sandy tephra from 1717 AD was found in eight out of the twenty profiles (Table 2). The locations of sites were found to be located to the south of the estate mainly along the River Kráká, apart from Profile 5 which is located on the River Sellandagröf (Figure 20). Soil accumulation rates increase over this period ranges from 0.5 mm/year to 0.94 mm/year and has a mean of 0.7 mm/year. This is a substantial increase from 0.56 mm/year mean from the previous time period (1477 AD to 1717AD) and soil accumulation rates over this period are double the regional mean rate of 0.35 mm/year. Statistical adjustment was only required at Profile 3, there was no further evidence of tephra layering from aeolian erosion.

The pronounced deterioration in climate conditions (Figure 10) may have been causing vegetation degradation at different altitudes as active erosion was observed at the southern edge of the estate within the range of 400 – 500 m, although there was no distinction between the other altitude ranges 400 – 300 m or 300 m – 200 m (Figure 17 & 20).

The *affrétir* grazing areas was most utilised for sheep grazing during the summer months

(Table 1) and during September the communities worked together to herd the sheep from the affrétir to the large common *rétt* enclosure. Although it is not known the date that the *rétt* site was established there is evidence of the impact to the soil conditions leading up to the site from remote sensing 1717 AD (Figure 20) (Aldred & Madsen, in press). Indeed these results indicate that a change in management practices and a concentration of sheep herding and grazing at one site may have contributed to irreversible soil erosion which has resulted in the barren desert that is observed today (Figure 8 & 9).

Conclusion

It is clear from evidence presented in this study that the soil conditions on the Grænavatn Estate has been more dynamic than had previously been thought. Temporal remote sensing maps show variations of soil conditions based on tephrochronology and soil accumulation rates. Further analysis from micromorphology, pollen analysis, cultural data and climatic conditions was used to review a wide range of natural processes and anthropogenic influences interacting with the landscape.

Prior to *Landnám,* within the areas that became Grænavatn farm estate, pollen records characterises an established vegetated site. Comparing the soil accumulation rates of the estate to regional data indicates that the farm estate is marginally above the mean range. This suggests that the area was broadly a stable environment. Therefore, it can be surmised that the landscapes soil and vegetation systems were resilient and able to recover the natural stress factors, climate, volcanic activity and fluvial, that were imposed on it over time. This is supported for example by the evidence of recovery from fluvial impact on estate which did substantial contribution to the fluctuations between stability / instability, however it appears that the affected areas recovered and stabilised over time.

In marked contrast, post-*Landnám* there was a gradual decline in vegetation and an increase in soil accumulation rates. Changes in farm management practices and the introduction of the *rétt,* further contributed from 1717 AD accelerated erosion and complete desertification observed present day. Therefore it is plausible that landscape was unable to withstand the additional stress factor imposed by anthropogenic activities. Ultimately, the natural systems were gradually extended beyond the ability to recover which resulted in instability of the landscape and irreversible soil erosion.

Ultimately, it is clear that investigating natural and integrated interactions influencing the landscape are complex. However, it is the conclusion of this study that grazing pressures has had the most influence on the removal of vegetation cover which ultimately exposed the soils to increasing erosivity and were more sensitive to subordinate contribution from climate, volcanic activity and fluvial impacts.

It is the recommendation of this study that the Grænavatn farm estate would benefit of a more comprehensive investigation of temporal soil conditions across a wider range of sites, especially on the east River Kráká boundary and the along the River Sellandagröf. This would perhaps reveal a further insight into the contribution of subordinate factors, such as revealing the impact from periodic flooding or extensive tephra deposits. It is also

recommended to expand on the pollen profile and identifying historic vegetation changes which may lead to a wider understanding of the interactions of natural stress factors influencing the landscape. This data could then contribute to existing Búmodel by considering natural stress factors on the environment as well as anthropogenic and climatic.

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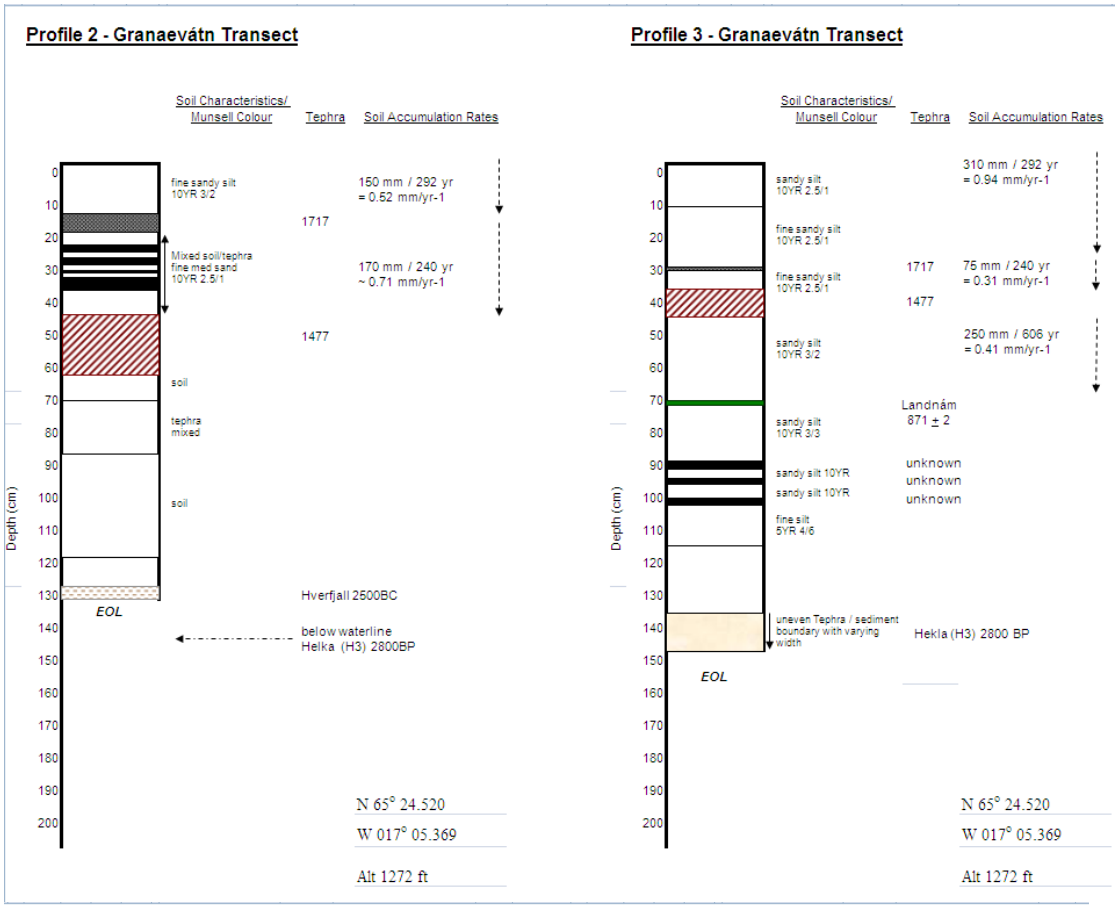
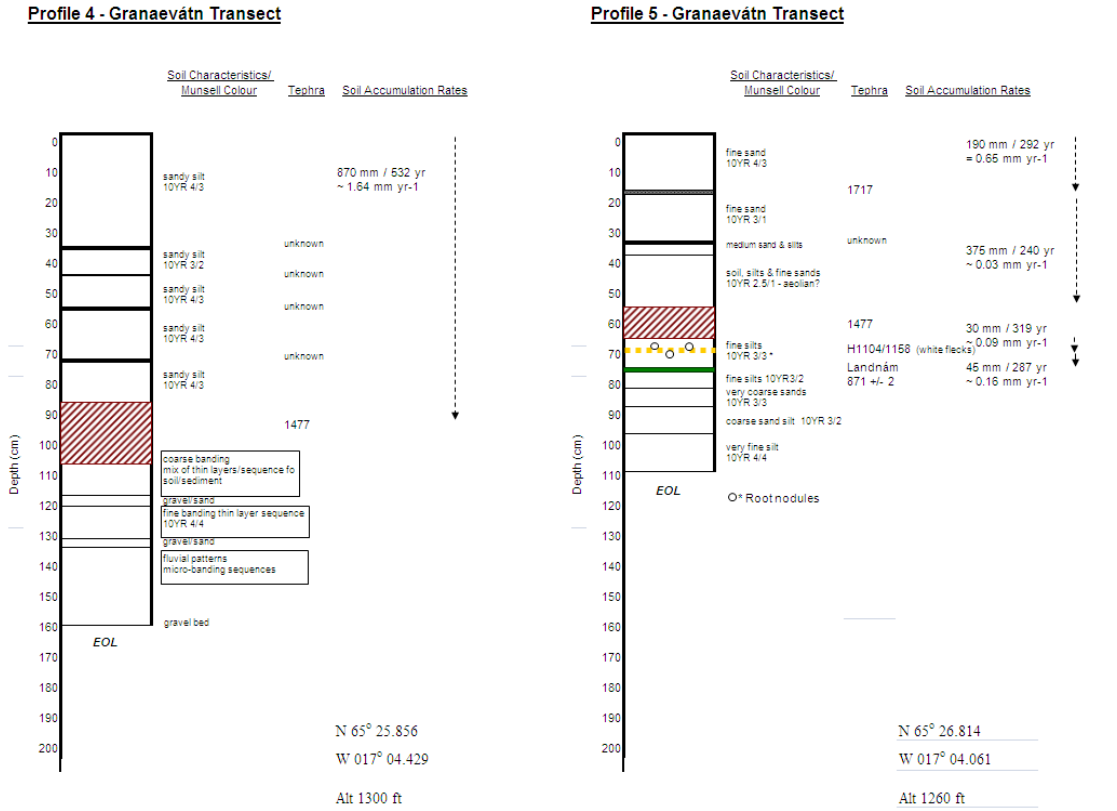
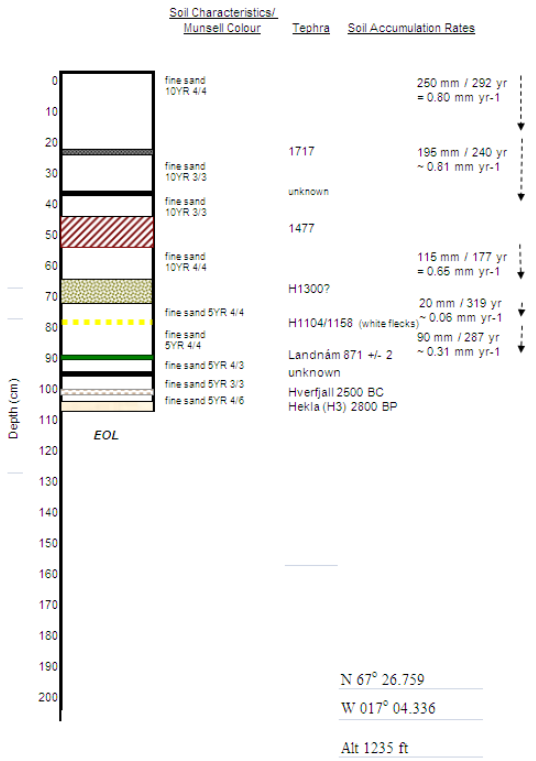
Appendix 1 – Soil Profiles from Granaeváthn farm estate

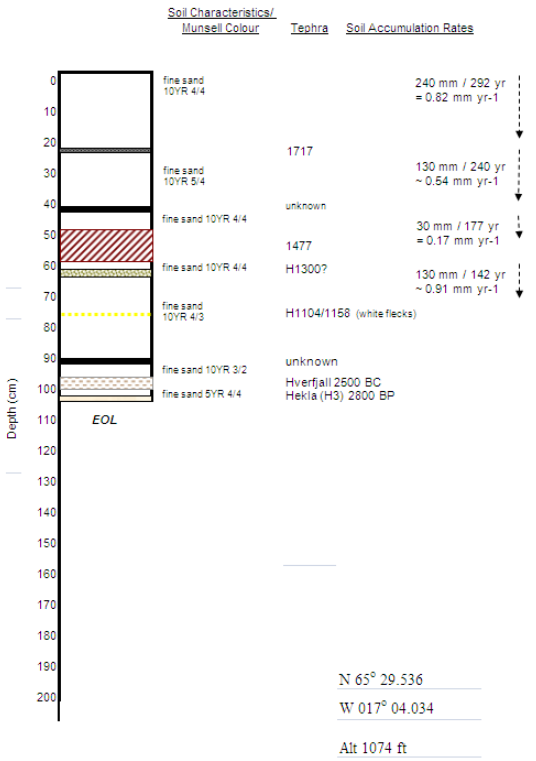




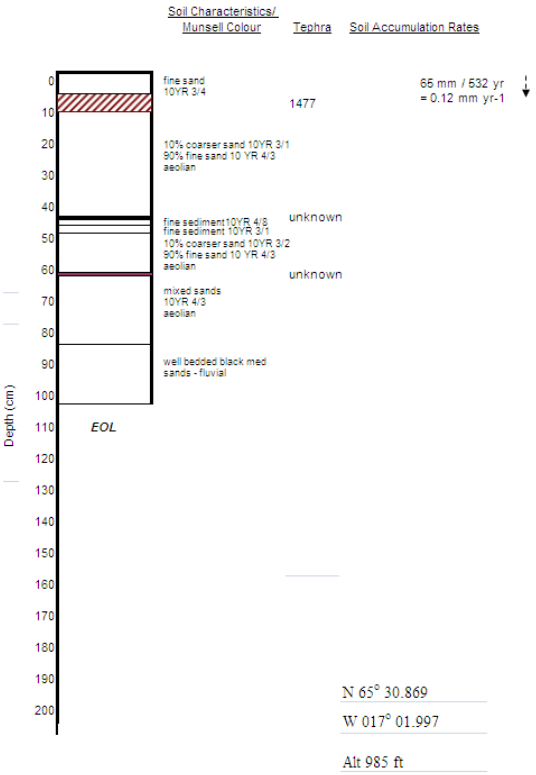
Profile 6 - Granaevátn Transect



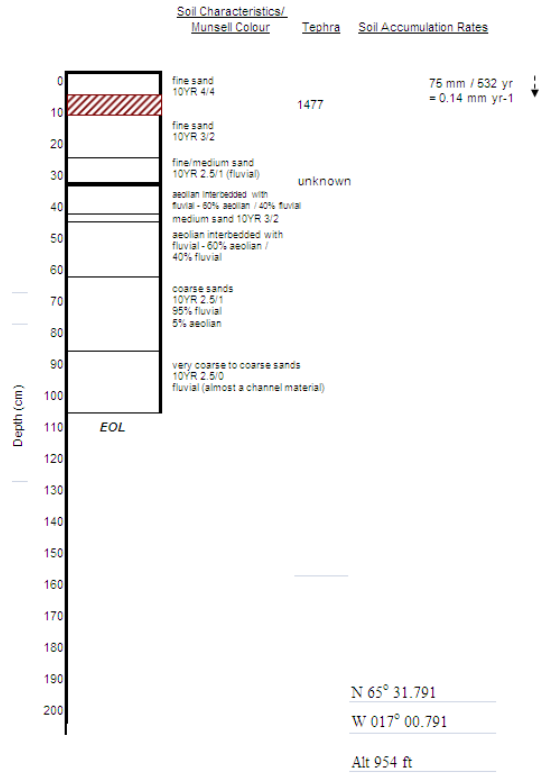
Profile 8 - Granaevátn Transect



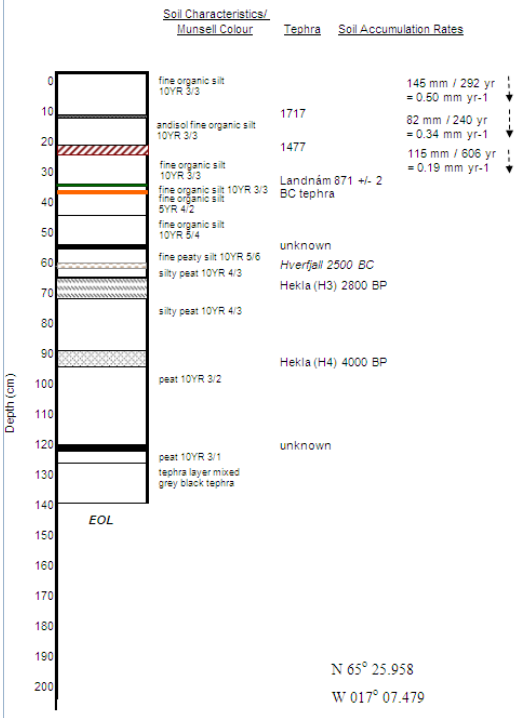
Profile 10 - Granaevátn Transect



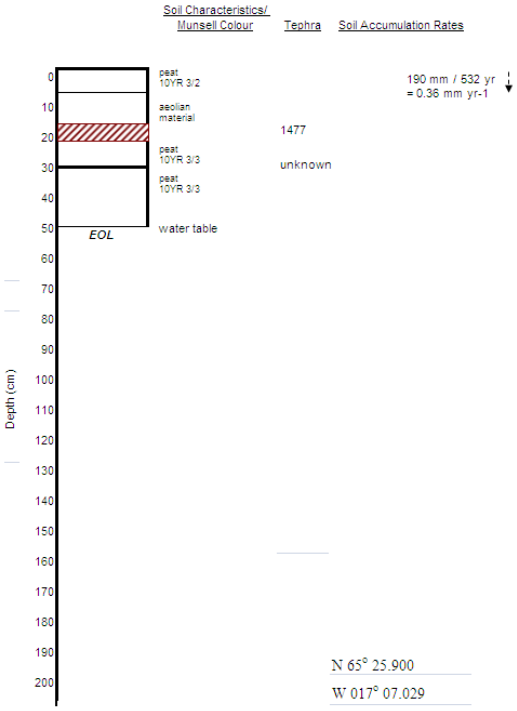
Profile 11 - Granaevátn Transect



Profile 13 - Cross Transect 1



Profile 14 - Cross Transect 1 ** not full profile **



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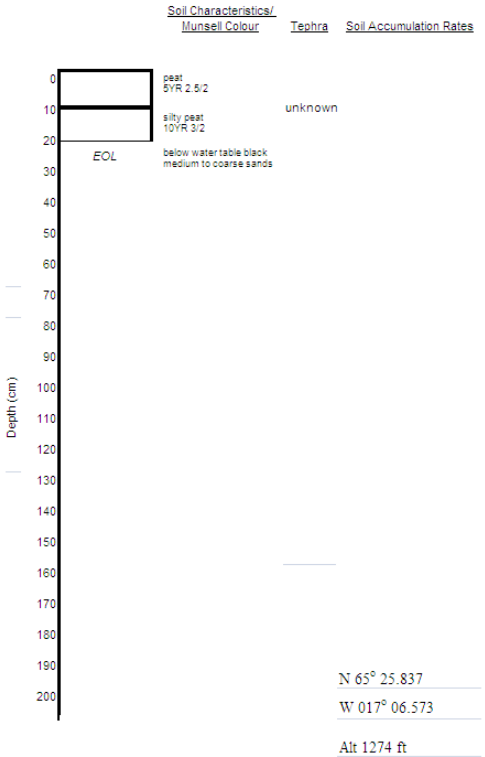

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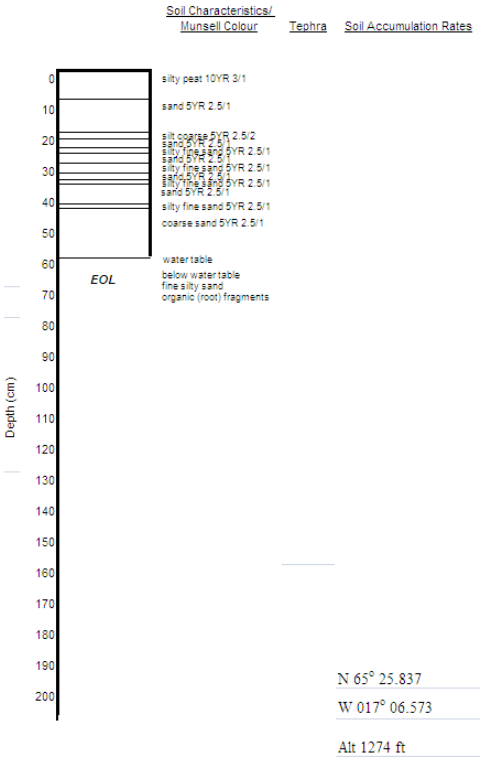

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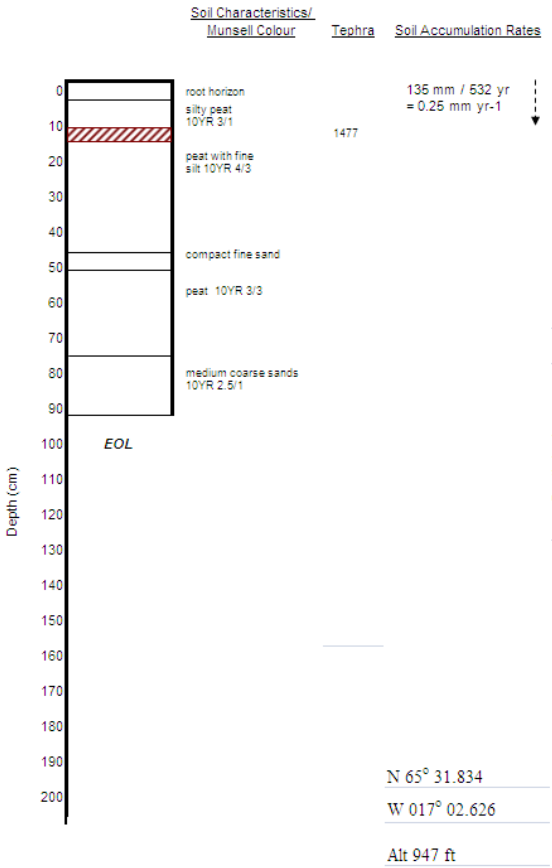

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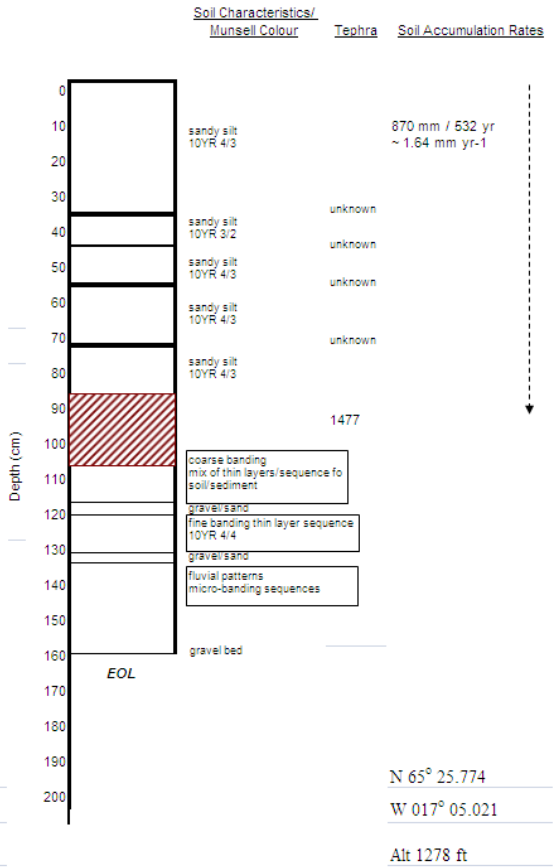

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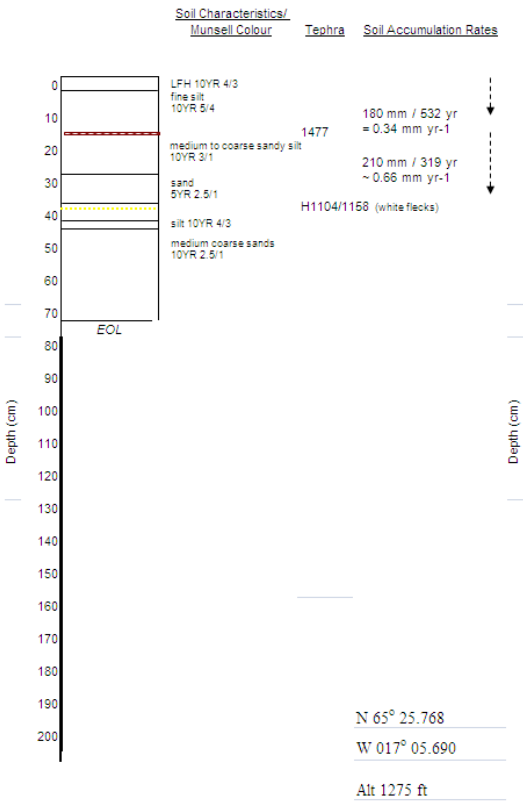

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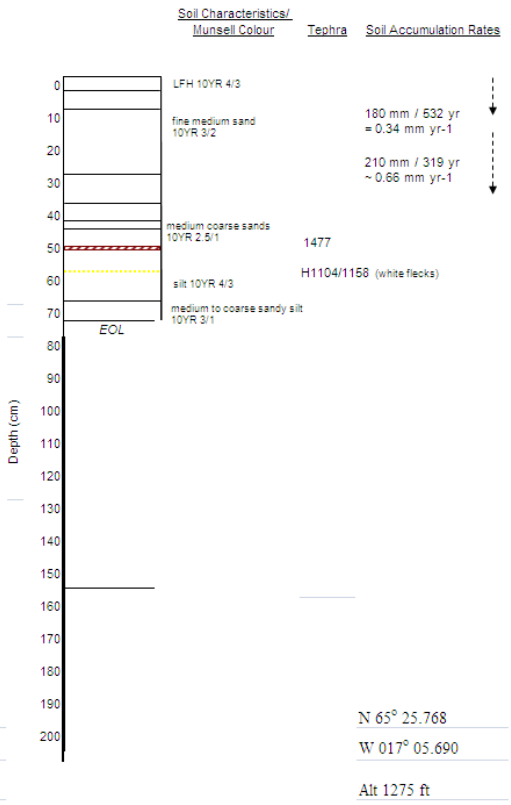

Appendix 2 – Pollen Sample