Donald Ashburn, Martin P. Kirkbride and Andrew J. Dugmore

Post-Settlement Land Disturbance Indicated by Magnetic Susceptibility of Aeolian Soils at Seljaland

Abstract

Magnetic susceptibility variation within aeolian (wind-blown) sediments shows consistent patterns between seven sites around Seljaland, southern Iceland. The period before c. AD 870 is characterised by low-fluctuating values of magnetic susceptibility. The Norse Landnám, or settlement of Iceland, is understood to have begun in the late ninth century. Layers of volcanic ash, or tephra, settled out on the land surface from the atmosphere at c. AD 870 (the Landnám tephra) and again c. AD 920 (the Katla R tephra). Magnetic susceptibility values during this period are typically lower, and then increase in all profiles before levelling out into generally higher, but fluctuating readings. The timing of the stabilisation at higher values varies from c. AD 1100 to c. AD 1500, and is later in more rapidly-accumulating soils. The remarkable consistency of lowered magnetic susceptibility in the AD 870 – AD 920 period suggests a human-induced cause: increased organic input from the faeces of newly introduced farm animals and from decaying vegetation is one possibility, as this would 'dissolve' the magnetic signal. The subsequent rise in magnetic susceptibility values may, speculatively, be related to the increased concentration of relatively young iron-rich tephra in the soil deposits. Such a concentration would occur when sediment is reworked in a newly burnt landscape, cleared for grazing animals.

Introduction

Environmental magnetism works on the principle that everything, living or inanimate, is magnetic to some degree. Material properties such as grain size, mineral composition and concentration can be deduced from their magnetic properties (Thompson & Oldfield 1986, Walden *et al.* 1999). Volume magnetic susceptibility (χ) is a standard technique in the measurement of vertical profiles of aeolian or wind-blown soil (loess). In Iceland, the much thinner postglacial aeolian soils contain many distinctive tephra layers of known age (Þórarinsson 1944, 1954, 1958, 1961, 1967, 1975, Larsen & Þórarinsson 1977, Larsen *et al.* 1999), precluding the need for other correlation techniques and offering a powerful dating framework for the study of the spatial aspects of environmental change. In this respect, magnetic susceptibility is potentially a key indicator of change as it can reflect distinctive physical properties of the soil, which can assist in the interpretation of soil-forming and soil-modifying processes.

This short paper presents results from seven soil profiles around Seljaland, which were measured and sampled for magnetic susceptibility, using the tephrochronological framework of Dugmore & Erskine (1994) to provide the absolute time control against which changes in magnetic susceptibility can be compared. The purpose is to investigate whether changing land use and erosion rates following Norse settlement (Landnám c. AD 870) are associated with systematic patterns evident in the magnetic profiles. This association appears to be established. The introduction of agriculture to a previously natural landscape correlates well with magnetic susceptibility readings c. AD 870-920. The low susceptibility readings may be caused by the addition to the soil of both animal waste and decaying vegetation after initial land disturbance by domesticated animals – animals newly introduced to the landscape. In a number of profiles, low susceptibility readings begin before the c. AD 870 tephra was deposited. Above the c. AD 920 tephra, high magnetic susceptibility readings may have resulted from the early Norse practice of clearing woodland by fire, in order to create an environment suitable for grazing pastures.

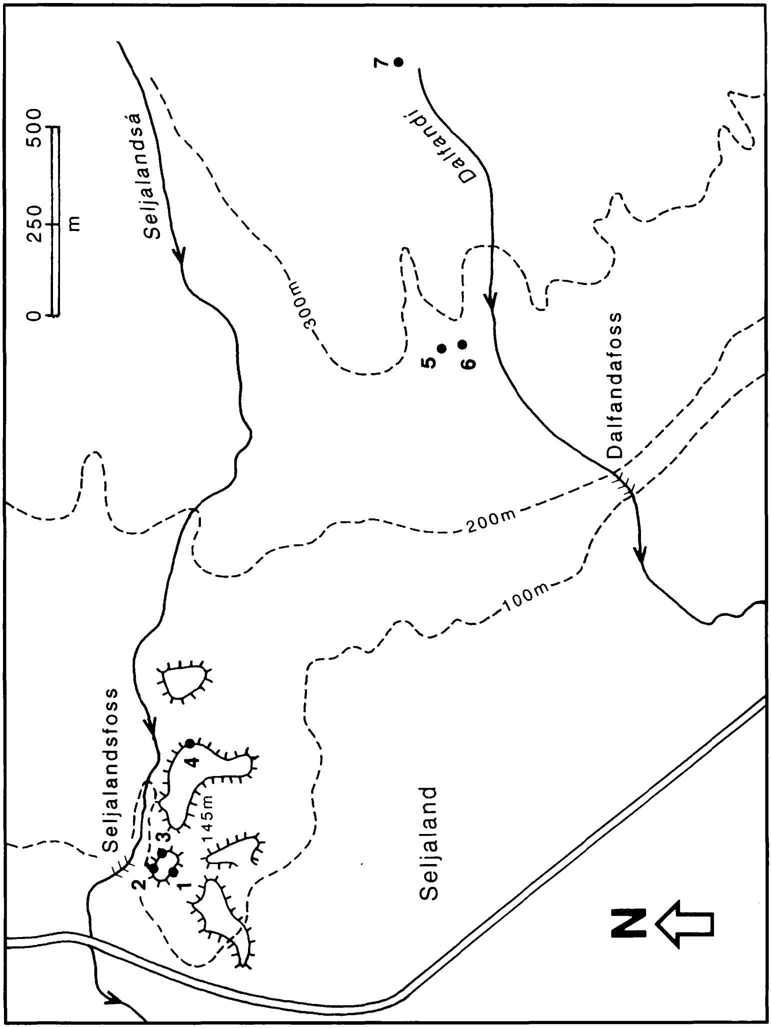

Figure 1. Location map showing the distribution of rofbards on Krosshóll (after Dugmore & Erskine 1994), and the location of Profiles 1 - 7.

Methods

Tephrochronology is used to provide a rigorous dating framework for the assessment of spatial change. Crucially, tephras give precise dating control within prehistory, notably the SILK YN tephra of c. AD 410 (Dugmore 1989, Larsen *et al.* 2001). The Norse colonisation of the ninth century is marked by the Landnám tephra, dated in the Greenland ice cores to AD 871±2 (Grönvald *et al.* 1995). Overlying this tephra and clearly separated by an intervening layer of wind-blown sediment is the Katla R tephra of c. AD 920 (Hafliðarson *et al.* 1992). These tephras effectively constrain the period of initial Norse settlement before the founding of the Althing in AD 930 and the establishment of the Icelandic Commonwealth. A key characteristic of the sequences in the study area is the high resolution of the record and the clear stratigraphic separation of layers closely spaced in age. Sediment accumulation through the historical period is effectively subdivided by the Hekla tephra of AD 1341, the Katla tephra of AD 1500, the Hekla tephra of AD 1510, the Katla tephra of AD 1755, the Eyjafjallajökull tephra of 1821, the Katla tephra of AD 1918 and the Hekla tephra of AD 1947 (Dugmore *et al.* 2000).

Seven soil profiles were recorded, profiles one to four at Krosshóll (200m altitude) and profiles five to seven at altitudes up to 400m on Seljalandsheiði, (Figure 1). In all cases profiles were dug to at least the Landnám layer, and where possible to the SILK YN layer. Profiles were measured to nearest centimetre and details of soil and tephra layer texture and colour were logged on a layer-by-layer basis. Key marker tephras were recorded according to the local tephra stratigraphy (Dugmore 1989, Dugmore & Buckland 1991, Dugmore & Erskine 1994, Larsen *et al.* 1999, 2001). The soil faces were cleaned with a plastic instrument to avoid magnetic contamination. Volume magnetic susceptibility measurements were taken on a centimetre scale from the profile surface to full depth, using a combination of the Bartington Instruments MS2 meter and MSF sensor. Readings were taken both from soil sediments and from tephra layers. Two sets of charts of magnetic susceptibility against depth were produced: one set with the tephra layers included, one set excluding tephra layers to allow calculation of background aeolian sedimentation rates. The sediments in profile 2 were comprehensively sampled for laboratory analyses of granulometry, mass specific magnetic susceptibility (χ), mass specific anhysteretic remanent magnetisation (χ_{arm}), and saturation isothermal remanent magnetisation (SIRM) (Walden *et al.* 1999). When subjected to statistical analysis, the above readings allow inferences to be made regarding mineral concentrations and composition. This paper will present charts of magnetic susceptibility against depth, and annual sediment accumulation rates for each of the seven profiles.

Results

The most significant finding was the consistent pattern of magnetic susceptibility readings through time in all of the profiles. The graphs of susceptibility against depth (Figures 2 and 3) show a three-stage pattern in volume susceptibility from AD 410 to the present. Stage 1, from prehistoric times to AD 870, is characterised by consistently low but variable readings. Because of lower sediment accumulation rates before AD 870, there is a proportionately greater amount of tephra layer thickness compared with silt layers, yet susceptibility remains low. Stage 2 comprises the interval between the Landnám tephra and AD 1100-1500, and is typified by steadily rising susceptibility readings in all cases. The timing of the transition from Stage 2 to 3 is variable, ranging from c. AD 1100 to AD 1500, yet most profiles show a distinct upper stage of high variable susceptibility that, in some profiles, reduces slightly during the 20th century.

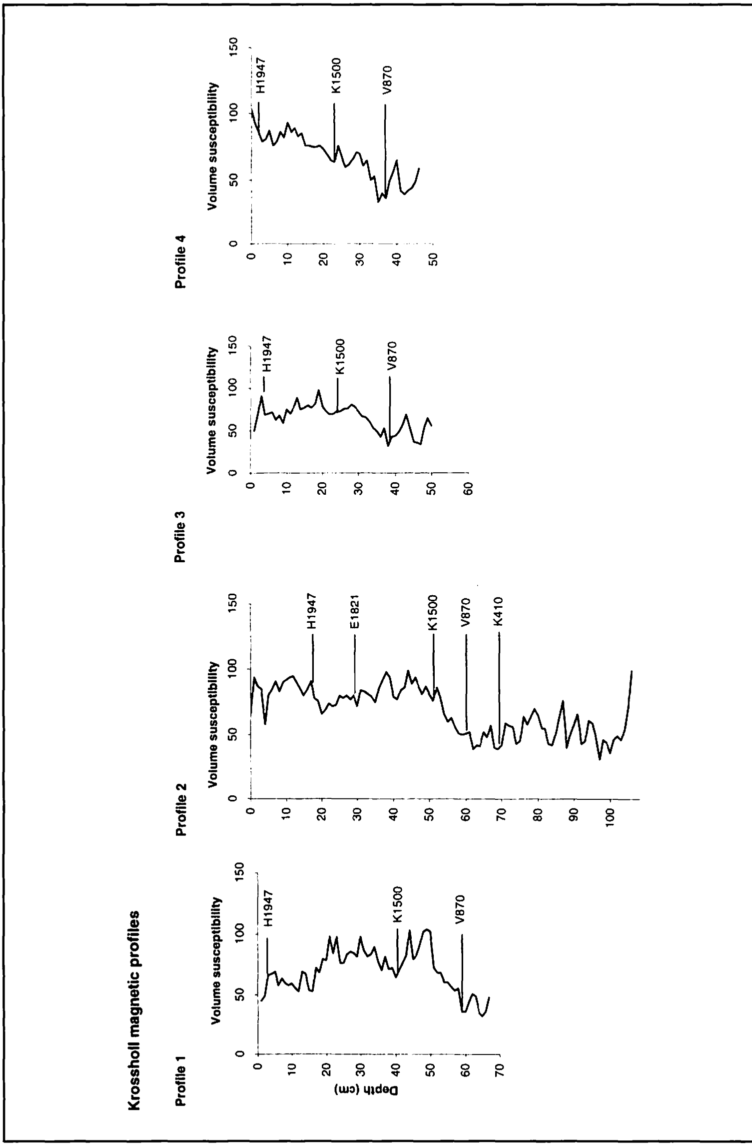

Figure 2. Magnetic susceptibility profiles from the Krosshóll site (see Figure 1 for locations), omitting tephra-layer spikes. Key tephra isochrones are marked.

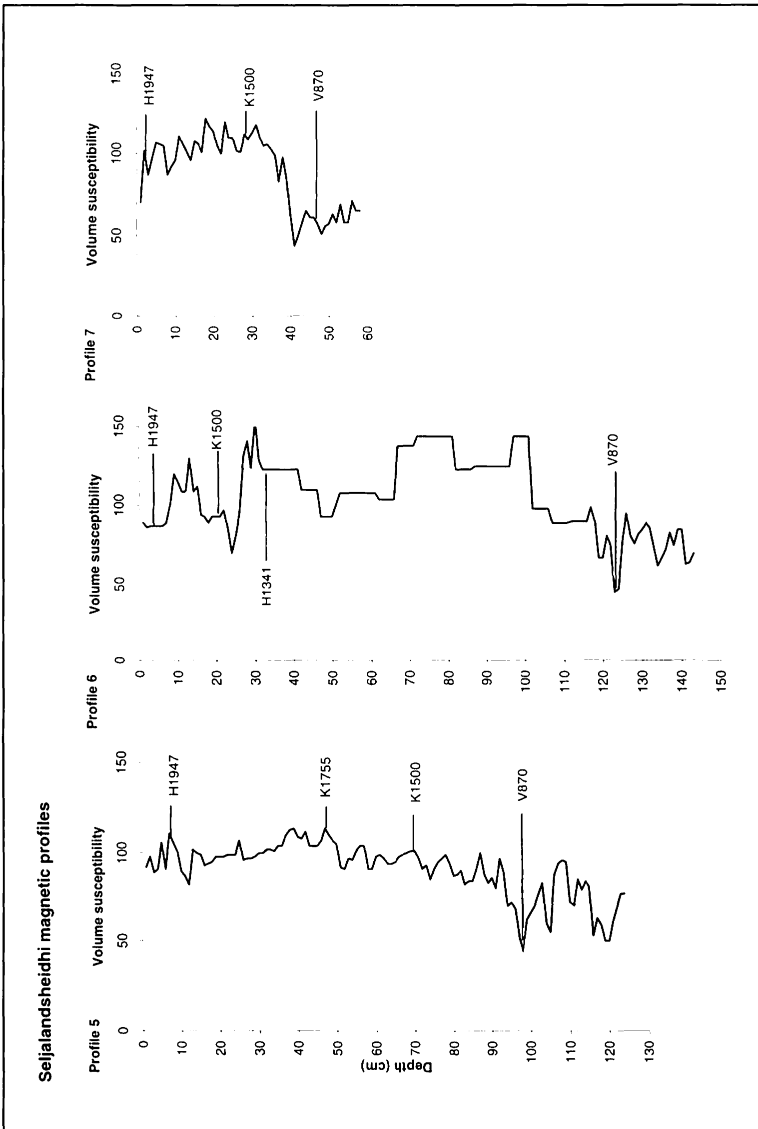

Figure 3. Magnetic susceptibility profiles for the Seljalandsheiði sites, omitting tephra-layer spikes. Key tephra isochrones are marked.

Perhaps the most striking consistency in the susceptibility readings is the association of the stage 1-2 transition with the Landnám tephra layer. In all profiles the susceptibility readings show low values between the Landnám and KR920 tephra layers, irrespective of the depths within the profile at which these layers are located. Furthermore, Dugmore and Erskine (1994) note a pale silt layer immediately below the Landnám tephra in the Krosshóll area. They observe this pale silt layer is similar to the post-Landnám sedimentary record of human impact upon the local environment. When the pale silt layer was sampled for magnetic susceptibility, consistently low values were obtained. Our study suggests the post-Landnám low susceptibility values may record a human impact upon the environment. Therefore the relationship between susceptibility values and the physical and chemical sedimentology of the deposits immediately below and above the Landnám tephra deserve further detailed investigation.

The possibility exists that the observed vertical variation in volume susceptibility in any profile is due to horizontal variability along a soil layer. To test whether vertical variation is more significant than layer-parallel horizontal variation, several silt beds adjacent to tephra layers were sampled horizontally over distances of up to 2m (a similar scale to vertical profiles). Layers were sampled from Stage 1 of the vertical profile (silts below and older than the Landnám tephra), from Stage 2 (adjacent to the KR920 tephra), and from Stage 3 (immediately above the H1510 and H1947 tephras). Lateral variations adjacent to H1510 and H1947 were measured in one pit each, adjacent to KR920 in four pits, and to the Landnám tephra in two pits.

The results (Figure 4) were subjected to a two-sample t-test, to test for differences between sample means. The test shows that the magnetic susceptibility of the silt layer immediately below the Landnám is indistinguishable between profiles 2 and 4. Similarly, silt layers close to KR920 are statistically indistinguishable across profiles 1, 2, 4 and 6. Grouping these samples and testing for difference between the two groups reveals that the silt layers of different age/stratigraphic level have different volume susceptibilities at the 0.01 significance level, supporting the separation of Stages 1 and 2 of the vertical sequence. Silt layers immediately above

H1510 and H1947, both in Stage 3 of the vertical sequence but separated by over 400 years, are magnetically indistinguishable from each other, but differ from all of the older layers at the 0.01 significance level. Thus, the observed pattern of a three-stage vertical variation in magnetic susceptibility has not arisen because of chance sampling of layers of high lateral magnetic variability, and the three-stage division is confirmed.

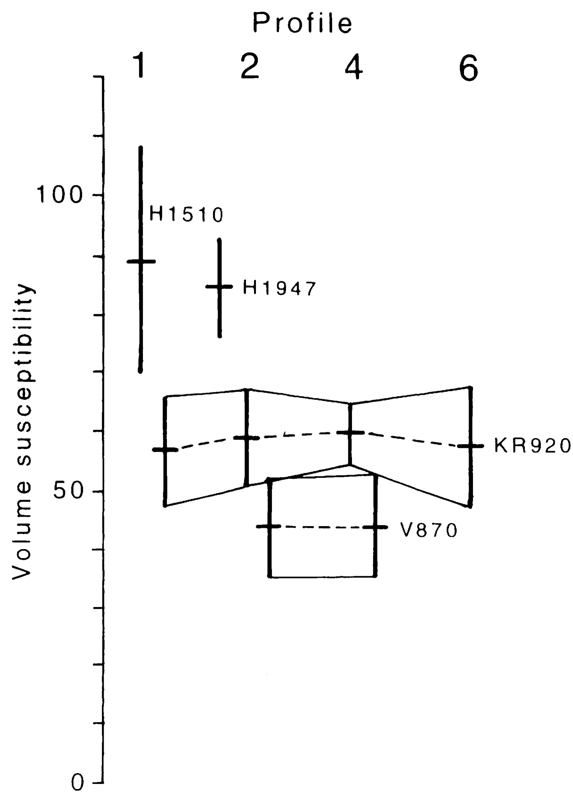

Figure 4. Means and standard deviations of magnetic susceptibility readings taken from silt layers adjacent to key tephra isochrones in profiles 1, 2, 4 and 6, demonstrating that up-profile variation greatly exceeds layer-parallel variation (see text for discussion).

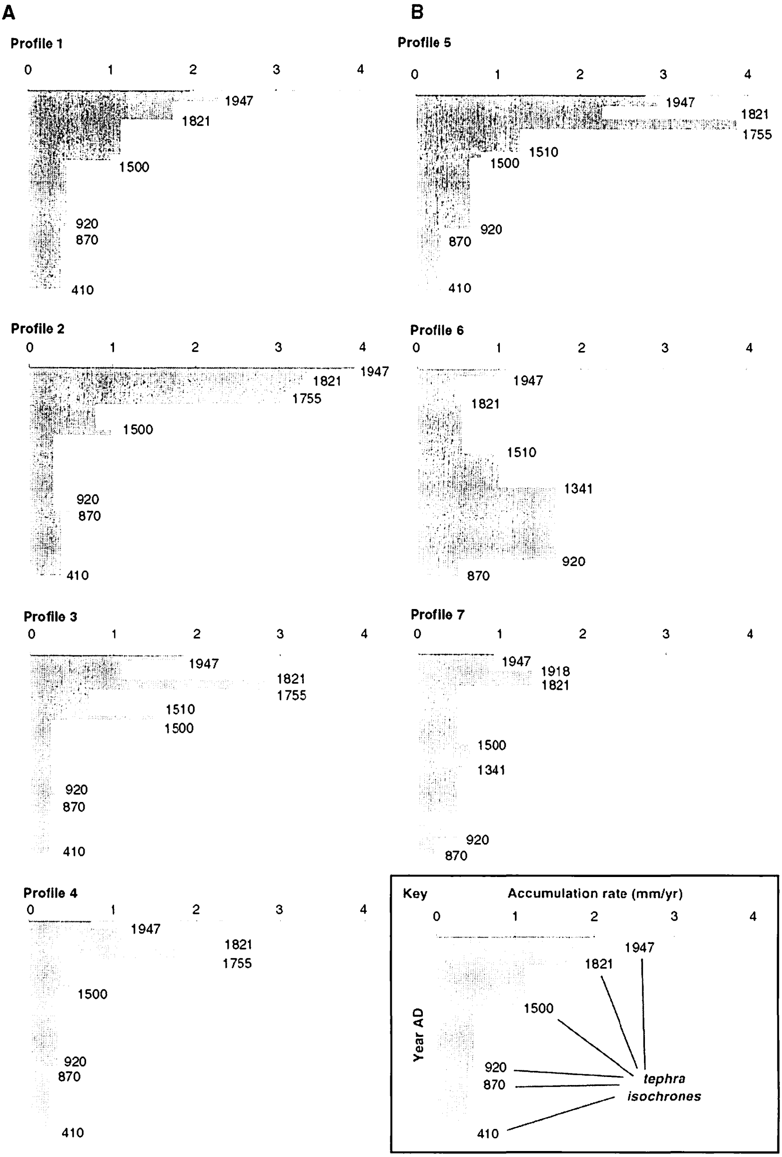

Figure 5. Sediment accumulation rates for the seven soil profiles, based on non-tephra sediment thicknesses divided by the time interval between adjacent tephra layers. A = Krosshóll profiles 1-4, B = Seljalandsheiði profiles 5-7.

With the exception of profile 6, which showed evidence of sediment re-working by slope wash, sediment accumulation rates (Figure 5) show consistency through space and time. Soil accumulation rates increase after settlement, most dramatically above the H1510 tephra, and in most profiles not until after the K1755 tephra. This pattern closely replicates the variations in sediment accumulation identified by earlier work (Dugmore & Erskine 1994).

Most profiles give a statistically significant relationship between magnetic susceptibility and sediment accumulation rate (Table 1), with correlation co-efficient >0.7 in four profiles. However, such an association must be treated cautiously due to lack of concrete evidence and is not taken to imply a direct causal relationship. Significant increases in soil accumulation commonly occur several centuries after the (Stage 2) rise in magnetic susceptibility, indicating separate influences.

Soil profile	R	Regression
1	0.33	$y = 7.71 \ln(x) + 61.02$
2	0.71	$y = 11.89 \ln(x) + 70.10$
3	0.74	$y = 11.31 \ln(x) + 68.27$
4	0.80	$y = 19.07 \ln(x) + 80.05$
5	0.78	$y = 14.69 \ln(x) + 86.82$
6	0.51	$y = 18.63 \ln(x) + 98.74$
7	0.60	$y = 21.76 \ln(x) + 106.87$
All data	0.46	$y = 12.02 \ln(x) + 9.84$

Table 1. Correlation and regression statistics for mean bulk susceptibility and sediment accumulation rate for layers of aeolian silt bounded by tephra isochrones.

Discussion

The remarkably consistent occurrence of the onset of increasing magnetic susceptibility at Landnám is strongly suggestive of an anthropogenic or human-induced cause. The dominant pattern in prehistoric times was of a steady, generally low magnetic susceptibility signal and correspondingly low sediment accumulation rates. Most likely, post-Landnám increases in both sediment accumulation and magnetic susceptibility are related to land disturbance as agriculture was introduced to a previously natural landscape. Leaving aside the enigmatic 'early' data presented by Dugmore and Erskine (1994), Ahronson (*this volume*) and Smith and Ahronson (*this volume*), no significant human disturbance of the landscape occurred before AD 870 (Dugmore *et al.* 2000). Therefore, the principal influences on the prehistoric sequence of slowly accumulating soils are likely to have been tephra deposition and climatic variability. The figures calculated from the soil profiles show that annual sediment accumulation rates before settlement were 0.1 - 0.4 mm/yr, excluding airfall tephra layers. The correspondingly low magnetic susceptibility indicates a lower magnetic mineral detrital signal in the aeolian sediment record. In every one of the soil profiles, low magnetic susceptibility between AD 870 and 920 mark the settlement period. There are several possible reasons why the susceptibility readings fell in the decades immediately following settlement. Our favoured interpretation is the effect of the addition of organic matter from both animal waste and decaying vegetation after initial land disturbance by non-indigenous herbivores. Vegetation stress caused by the grazing of roots by introduced pigs, goats and sheep, and faeces from these animals would have increased the volume of detrital organic matter in the soil (Amorosi *et al.* 1997). One of the by-products of organic matter diagenesis in soils and peats is the dissolution of magnetic minerals (Williams 1990). This would be particularly marked in regions of high rainfall such as Seljaland. Williams argues that dissolution of ferrimagnetic minerals can induce refinement of magnetic mineral assemblages highlighted by declining SIRM/ARM ratios and a hardening of magnetic remanence. Later laboratory analysis from Seljaland profile 2 soil samples did show this ratio to decline at this point in the stratigraphy. So, for the initial Norse settlement period, the significant reduction in magnetic susceptibility could be attributed to increased vegetation and faecal inputs from grazing animals to the soils between AD 870 and 920.

The period following the initial Norse settlement shows a significant increase in both magnetic susceptibility and sediment accumulation rates, though increases in accumulation rate lag behind susceptibility increases by several centuries. The reasons for the increase in sediment accumulation rates have been shown to be initially due to overgrazing, and have been well documented (Dugmore & Erskine 1994, Dugmore *et al.* 2000). However, for susceptibility values to increase there is a requirement for an increase in the concentration of strongly magnetic particles accumulating in the sediments. Mechanisms which could bring this about include (1) transport of magnetic minerals from a strongly magnetic source; (2) preferential accumulation of more highly magnetic grains sorted more efficiently by size and density; and (3) the effect of the burning of soils with some organic content. Mechanism (1: *transport of magnetic minerals*) may have involved the exposure of ferromagnetic tephra layers in the shallow subsurface during the early stage of soil denudation. Surface susceptibility surveys on recently exposed soils close to the survey area showed that readings are three to four times higher than recorded in nearby vertical profiles. Local transport and redeposition of recently exposed sediment may account for elevated magnetic susceptibility in the profiles adjacent to these exposed soils. Mechanism (2: *preferential accumulation*) is more difficult to attribute to the influence of human settlement, but (3: *effect of the burning*) may be associated with the known use of fire by early Norse settlers to clear birch wood and create grazing pastures (Macniven *this volume*). Where surface temperatures are high, magnetic 'hotspots' of massively increased susceptibility are produced. Although any given area of soil may not have experienced direct burning, its upper horizons are likely to include significant dust fallout from burning (Smith 1999). The increase in susceptibility above the KR920 tephra may be due to re-working of tephra-rich soil by aeolian processes after the burning and grazing of surface vegetation. At Langanes (to the north-east of Seljaland), Mairs (*in prep*) collected data from tephra deposits that may record the loss of forest cover there by c. AD 920.

Conclusions

Our results demonstrate a clear relationship between the arrival of Norse farming methods around Seljaland and a systematic increase in the volume magnetic susceptibility of the soil. The increase continued for between two and six centuries after Landnám, but followed a short period of reduced volume susceptibility which we suggest may be a reflection of the addition to the soil surface of organic matter from the impact of grazing herbivores. Re-sedimentation of burnt soil may account for the raised susceptibilities after AD 920. Such burnt soil could result from early Norse settlers' use of fire to clear birch woodland, in order to transform the landscape into pastureland for grazing animals. These preliminary results indicate the need for a more comprehensive sampling regime in the Seljaland area in order to establish other magnetic properties within the soils of the Seljaland region.

Acknowledgements

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