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ABSTRACT. Evidence is provided from the joint application of tephrochronology and palynology in two Icelandic locations — the island of Papey off the east coast and Seljaland in the south. The Papey study relates to vegetation change around the time of volcanic ash deposition from the eruption of Katla in 1755. This produced various hypotheses concerning volcanic impacts and land-use activities, including changes in nutrient inputs, grazing activity, and climate. Similar data have been obtained from Seljaland, where a group of farms was affected by fall-out from the 1947 eruption of Hekla. The patterns of pollen-based vegetational change were similar at both locations, enabling a fuller exploration of floristic and anthropogenic responses to ash deposition. The Seljaland data are influenced by the known removal of livestock in order to guard against the effects of fluorosis. The resultant cessation of grazing was probably responsible for much of the vegetational change apparent in the pollen record, and this represents a credible recent analogue for processes that may have taken place in Papey in 1755.

Contents

Introduction

Tephras from Icelandic eruptions have been found in northern Europe, many hundreds of kilometres from their sources (Thorarinsson 1981a, 1981b; Dugmore and others 1995b). Glass shards are found stratified within peat and lake deposits, and can be identified to specific source areas, and sometimes to specific eruptions, by their geochemistry (Westgate and Gorton 1981; Dugmore and others 1995a; Turney and Lowe 2001). In addition to their role as chronostratigraphic markers, tephras may also be agents of environmental change. These impacts may be directly attributable to the tephra fall, or may be an indirect effect through, for example, chemical pollution or an effect on climate (for instance, Thorarinsson 1979; Mass and Portman 1989; Grattan 1994; Grattan and Charman 1994; Giles and others 1999; Sadler and Grattan 1999; Delmelle and others 2001). Direct impacts of macroscopic tephra deposits or pyroclastic flows, resulting in the destruction of towns such as Pompeii, Italy, and St Pierre, Martinique, are well documented (Sigurdsson and others 1982; Tanguy 1994; Scarth 1999; de Boer and Sanders 2002). Some indirect effects, such as the destruction of Icelandic domestic livestock by fluorosis following the Skaftáreldarhraun eruption of 1783–84 (Gunnlaugsson and others 1984), have also received much attention.

Modern studies of the effects of volcanic activity upon the flora have involved the development of vegetation on lava fields (Tagawa 1964; Friðriksson and others 1972; Beard 1976; Black and Mack 1986; Bjarnason 1991), as well as the patterns of vegetational recovery in tephra-cloaked areas beyond the lavas (Griggs 1922; Moral 1983; Moral and Wood 1988). The dumping of visible ('massive,' macroscopic) quantities of tephra upon the landscape close to the eruption source has a mechanical impact upon land surfaces, including the burial or partial burial of plants, the encouragement of erosion in freshly coated surfaces (Thorarinsson 1961), and the chemical 'scorching' of leaves (Wilcox 1959). Human dimensions of volcanic impact are also related to fall-out thickness, with suggestions that tephra deposits >100 mm in thickness trigger partial and/or permanent farm abandonment through their impacts on the vegetation (Thorarinsson 1967, 1979; Einarsson and others 1980).

In locations with tephra deposits of the order of one to several centimetres in thickness, however, it might be expected that the herbaceous flora would have the opportunity to survive light tephra fall (Eastwood and others 2002). Indeed, if either direct impact of gases (for example, CO_2 suffocation) or fluorosis kills grazing animals, or encourages their human managers to remove them from the area, a light tephra fall may benefit vegetation by reducing grazing pressures or providing nutrient inputs (Wilcox 1959). Land management prior to an eruption could play a crucial role in determining the sensitivity of vegetation communities to tephra deposition. Intensive grazing could produce short sward height, more susceptible to burial, and the higher sward heights produced by less intensive grazing (for example, in rangelands) would be less prone to vegetation burial.

At the distal scale (beyond Iceland), ash within deposits and visible to the naked eye would appear to have effected a vegetational response in the Faroe islands, as inferred from the pollen-analytical (palynological) evidence (Edwards and Craigie 1998). Farther afield, the microscopic dusting of tephra upon the Scottish landscape was more equivocal (Blackford and others 1992; Dodgshon and others 2000). Elsewhere, the lack of palynological resolution — especially as intimately associated with the tephra layers in peat and lake deposits — can make it difficult to evaluate historical ashfall–vegetation relationships.

The vegetation beyond the lava fields is a reflection of environmental conditions following the frequent volcanic eruptions experienced in Iceland and is vital to land-use practices and human history. References to detailed and potentially inter-related vegetational and human patterns and consequences of tephra deposition in Iceland are surprisingly sparse. This tephropalynological study seeks to examine the relationship between tephra deposition and the vegetational response of palynologically detectable taxa. This is pursued at two locations around the time of deposition of two historical tephras: those of Katla in AD 1755 (K-1755) and Hekla in AD 1947 (H-1947). It was hoped that knowledge of local conditions associated with the more recent eruption would furnish analogues of value in interpreting patterns found at the older site. The availability of documented accounts of volcanic impact to compare with the effects of a specific sub-fossil tephra layer is unusual in palaeoecology, and this is a particular strength of the present study. In addition, the complexity of the environmental factors involved has encouraged the utilisation of a multiple working hypothesis approach to the investigations.

Sites and sampling contexts

Any site with a thin tephra deposit (for example, <50 mm thickness) and an associated pollen record could be used to evaluate aspects of tephropalynology pertinent to land-use activity. A site on Papey was selected because not only did it provide relevant data for this project, but it also had a wider cultural and environmental significance (Eldjarn 1989; Buckland and others 1995). In order to investigate matters further, a site at Seljaland was also selected. It was affected by tephra fall-out (with accumulations of about 10 mm in thickness) from the 1947 eruption of Hekla, which was studied in considerable detail at the time. Ethnographic data on the human consequences of the eruption exist, and sites survive in and around the farm complexes at Seljaland.

Hellisbjargi

This site is a peat basin on the small (2 km^2) island of Papey, which lies 9 km southeast of the town of Djúpivogur (Fig. 1). The basin lies 42 m north of an early Norse building, Tóft Undir Hellisbjargi, investigated archaeologically by Kristján Eldjárn (1989) (Fig. 2). A peat monolith was extracted and seen to contain three tephra layers. The upper dark grey layer, 10 mm in thickness, has now been assigned to K-1755 on the basis of electron microprobe analysis, and not Hekla-1766 as thought previously (Edwards and others 1994). The eruption began on 17 October 1755 and lasted approximately 120 days (Larsen 2000). Direct and indirect effects of this eruption led to significant population decline in Iceland (Vasey 1996). The Katla volcanic system is located beneath the Myrdalsjökull icecap, 260 km southwest of Papey.

Seljaland

The farm complexes of Seljaland lie close to the east bank of Markarfljót, and 12 km west of the edge of Eyjafjallajökull, in southern Iceland (Fig. 1). The farms are located in an area defined by upland to the north and east, and sandur to the south and west. Peaty deposits had accumulated in a series of basins, and a monolith was collected from a rising slope immediately beyond the infield area of farm 1, closest to the road (Fig. 3).

The historical tephra stratigraphy of the area is well known (Thorarinsson 1967, 1975; Haraldsson 1981; Dugmore 1989; Dugmore and Erskine 1994). Dominating the twentieth-century tephra record is the distinctive fall-out from Hekla in 1947 (coarse-grained pumices, grey, brown, and black in colour with fragments of red scoria and 10 mm in thickness in the monolith). The H-1947 eruption lasted from 29 March 1947 to 21 April 1948, but an estimated 86% of the volume of its tephra (and all the extensively dispersed component) fell in the first 24 hours in a cone-shaped sector projecting south of the fissure (Thorarinsson 1958). Hekla is located 45 km north-northeast of Seljaland. At the time of eruption in March 1947, the sheep and cattle were still stalled (Magnús Sigurjónsson, personal communication, 2002). They were kept indoors until late May–early June, by which time the tephra had mostly blown away, although pockets remained beyond this period. The horses, however, were moved to Landeyjar, an area to the west of Eyjafjallasveit.

Laboratory methods

Peat monoliths were sampled at contiguous intervals of 2–4 mm around the tephra layers and subjected to standard NaOH, HF, and acetolysis techniques for the concentration of pollen and spores (Faegri and Iversen 1989). Samples were embedded in silicone oil and a standard pollen and spore count of ≥ 500 total land pollen (TLP) was aimed at, with pollen type nomenclature adapted from Bennett (2002) and plant nomenclature

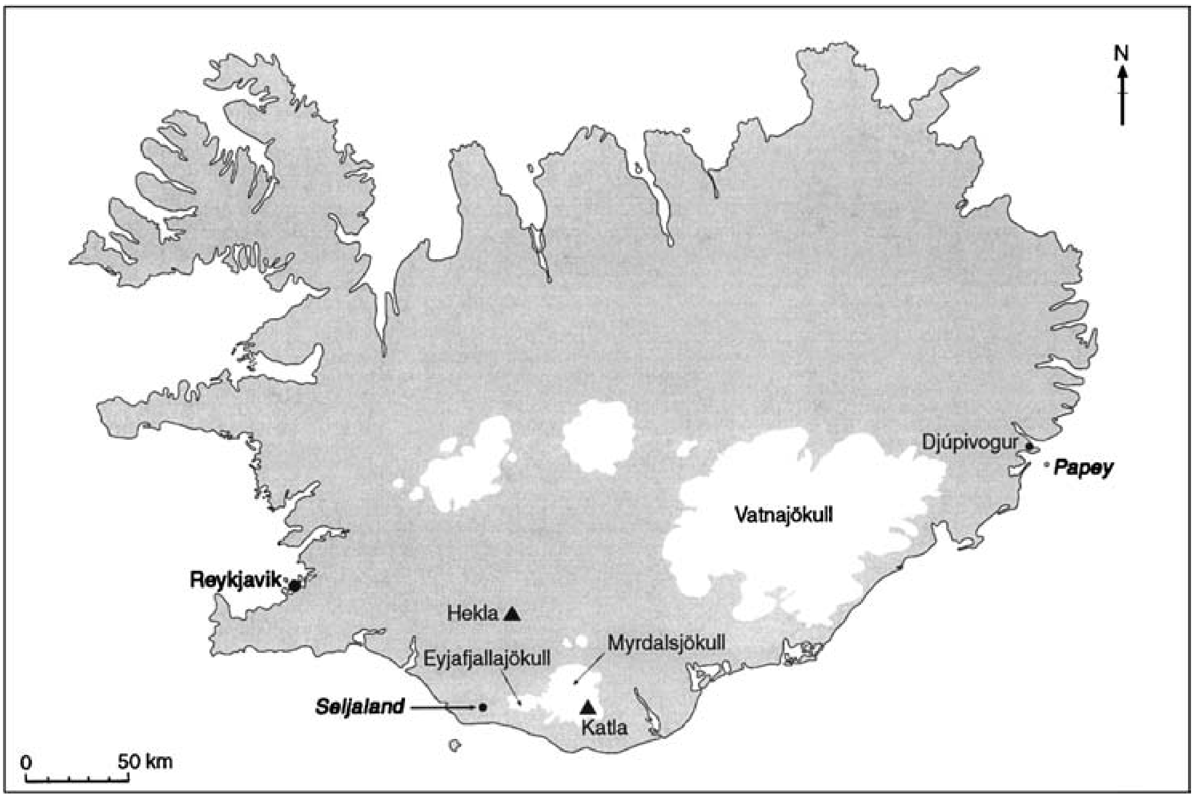

Fig. 1. Map of Iceland, showing locations mentioned in the text.

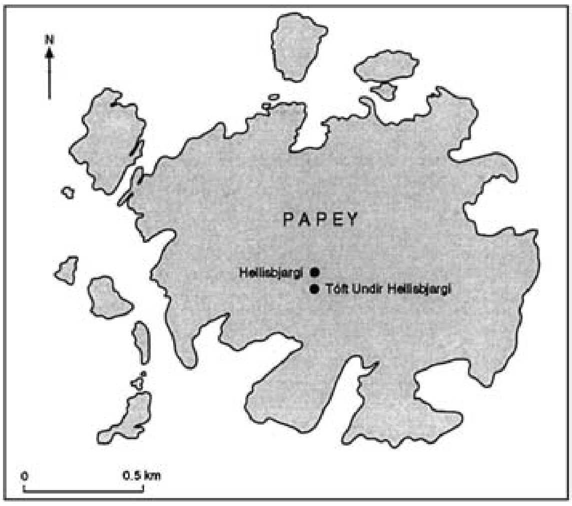

Fig. 2. Map of Papey, showing the location of the tephropalynological site at Hellisbjargi.

following Kristínsson (1987). Statistical calculations and pollen and spore diagrams (Figs 4–5) were produced with the computer programs TILIA and TILIA.GRAPH (Grimm 1991). It is assumed that *Pinus* (pine), *Alnus* (alder), *Quercus* (oak), and *Corylus avellana*-type (hazel) pollen are derived from long-distance aeolian transport (Hansom and Briggs 1989–90; Edwards and Craigie 1998), and their values were excluded from all computations although they are shown on the pollen diagrams.

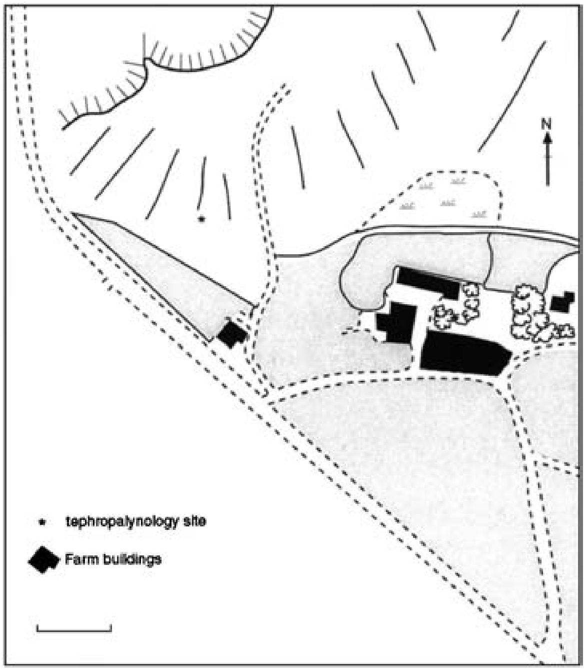

Fig. 3. Map of the farm area at Seljaland I, southern Iceland, showing the location of the tephropalynological site.

Tephra identification in both the south and east of Iceland is based on detailed regional stratigraphic frameworks. The 1947 eruption of Hekla and its tephra

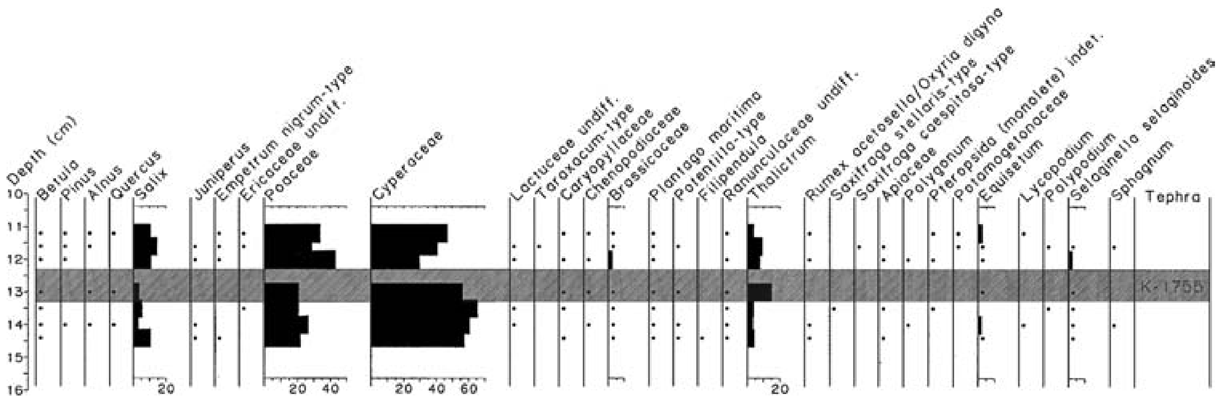

Fig. 4. Percentage pollen and spore diagram from Hellisbjargi.

was extensively studied both at the time and in succeeding decades (Thorarinsson 1967). The fall-out from Katla is also well known, with comprehensive assessments of both the complete historical record (Thorarinsson 1975) and detailed isopach maps of individual tephra layers (for example, Einarsson and others 1980; Thorarinsson 1981a; Larsen 2000; Larsen and others 2001). In order to validate the assignation of the Hellisbjargi tephra to K-1755, it was subjected to standard pretreatment and electron microprobe analysis (Dugmore and others 1995a). The results are detailed in Table 1 and shown graphically in Figure 6, where the data for two key components, TiO_2 and FeO, are contrasted with those for typical chemical distributions for the tephras originating in two other important volcanic complexes (Grímsvötn and Veiðivötn). The data from Papey are entirely consistent with the K-1755 tephra (TEPHRABASE 2002).

Discussion of results

Hellisbjargi

The pre-tephra pollen spectra are dominated by Poaceae (grasses), Cyperaceae (sedges), *Thalictrum alpinum* (alpine meadow-rue), and other open-land herbaceous taxa, together with *Salix* (willow) (Fig. 4). A distinct change in the pollen assemblage occurs coincident with the tephra horizon (or becomes evident immediately above it). Cyperaceae falls in abundance from 56 to 30% TLP, and Poaceae and *Salix* increase (from 21 to 43%, and 4 to 11%, respectively). *Thalictrum* exhibits a jump from 15% within the base of the tephra (from a preceeding level of 4%) and falls back to 8% immediately above the ash layer. While *Salix* percentages continue to rise, Poaceae falls after peat growth resumes, and Cyperaceae increases again. There is no obvious correspondence between the presence or absence of minor taxa either side of the K-1755 layer, although Brassicaceae (mustard family and including such taxa as *Capsella bursa-pastoris* (shepherd's purse), *Draba* spp. (whitlowgrass)), and *Selaginella selaginoides* (lesser clubmoss) expand slightly immediately above the tephra. The sampled increments of sediment probably cover a maximum period of approximately eight years each, based on straight-line extrapolation between the mire surface and the tephra horizon, although this is likely to be an overestimate as the mire surface may have been cut-over for fuel or bedding on more than one occasion.

The changes evident in the profile do not appear to be a consequence of autogenic changes to the vegetational communities within the pollen catchment area, as nothing similar occurs prior to this within the fully analyzed section, which covers perhaps a half-millennium or more (not shown here).

Unless the palynologically derived correlation between ash-fall and vegetation change is a coincidence,

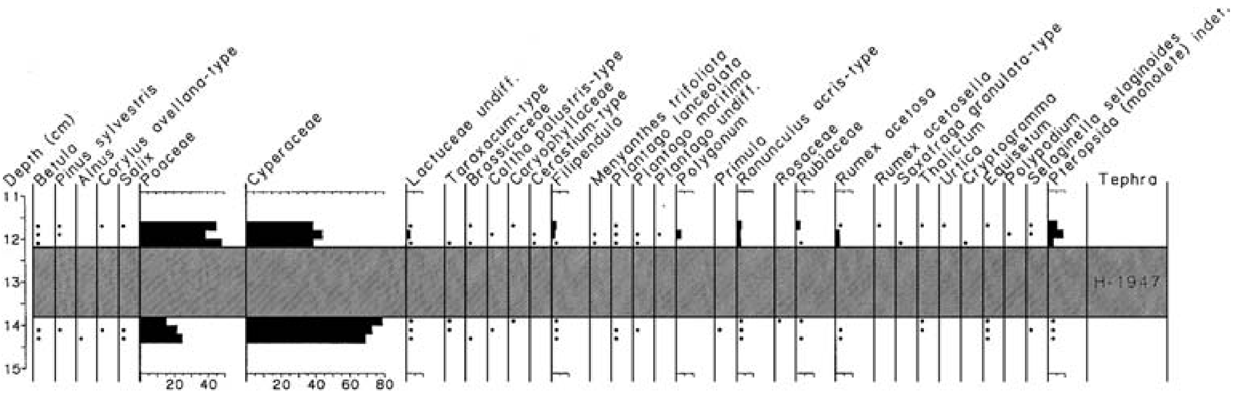

Fig. 5. Percentage pollen and spore diagram from Seljaland.

Table 1. Electron microprobe analysis of Katla-1755 tephra from the Hellisbjargi core.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
	49.08	4.46	13.21	13.33	5.01	0.26	9.52	0.69	2.75	0.91	99.23
	47.61	4.59	13.09	14.05	5.15	0.27	9.84	0.59	3.42	0.92	99.53
	47.21	4.64	12.77	14.38	5.28	0.29	9.62	0.73	3.33	0.93	99.17
	46.93	4.72	12.80	14.80	5.17	0.32	9.47	0.74	3.47	0.94	99.36
	46.73	4.58	12.55	14.10	5.36	0.29	9.49	0.65	3.30	0.88	97.93
	46.67	4.59	12.72	14.07	5.36	0.26	9.70	0.73	3.29	0.91	98.31
	46.61	4.64	12.53	13.89	5.42	0.24	9.54	0.67	3.26	0.81	97.60
	46.52	4.67	12.53	13.96	5.29	0.25	9.52	0.69	3.42	0.81	97.65
	46.50	4.70	12.59	14.00	5.38	0.28	9.47	0.71	3.29	0.87	97.80
	46.40	4.87	12.58	15.09	5.10	0.29	9.49	0.75	3.40	0.93	98.88
Mean	47.03	4.65	12.74	14.17	5.25	0.27	9.57	0.70	3.29	0.89	98.55
Std Dev.	0.81	0.11	0.24	0.49	0.14	0.02	0.12	0.05	0.20	0.05	0.77

which seems unlikely given changes to be discussed below (and compare Edwards and Craigie 1998), then five hypotheses, at least, might be advanced to explain the pattern at Hellisbjargi:

Physical alteration of the plant growth environment

The arrival of a 10-mm thick tephra blanket might conceivably be expected to affect growing plants adversely through direct damage or impeded drainage. If ashfall was spread evenly over the eruption period, including during seasons of zero growth, then plant growth may have continued largely uninterrupted, with tephra being constantly washed to the ground from leaves and stems, thus minimising damage from chemical absorption. Vegetation should not be harmed by a porous tephra ground layer, which might also have facilitated drainage. A temporary reduction in ground wetness would favour grasses rather than sedges, although *Salix* (especially *S. phylicifolia*), like the sedges, might be expected to have a competitive advantage in damper conditions. In the absence of clear evidence to the contrary, it is difficult to see how the level of tephra deposition experienced at Hellisbjargi would have markedly affected plant growth and, if it did, why it should adversely affect Cyperaceae.

Chemical alteration of the plant growth environment

The potential toxic damage to plants from tephra deposition and associated acid precipitation, and the time

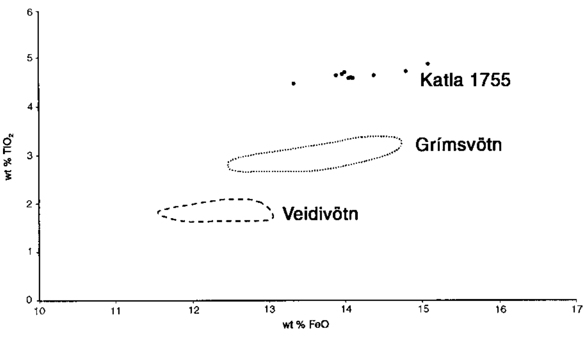

Fig. 6. Plot of microprobe data for TiO_2 and FeO from Hellisbjargi contrasted with typical chemical envelopes for tephras originating in the Grímsvötn and Veiðivötn volcanic complexes.

period during which it operates, is both variable (compare examples in Wilcox 1959; Cook and others 1981) or, in distal areas especially, largely unknown (compare Blackford and others 1992; Grattan and others 1999). Tephra may be washed continually from foliage, thus minimising chemical damage, and the same effects might also apply to soils temporarily benefiting from the nutrient inputs of trace elements contained in or on the tephra particles. The local substrates were probably already on the acid side of neutral and any additions to vegetation and soils may well have been deleterious, as acidic ecosystems have a low recovery potential from acid deposition (Skiba and others 1989; Smith and others 1993). Nevertheless, this is a topic that requires more research — especially in so far as it applies to more neutral areas of grazed land. Plants, the above-ground vegetative parts of which extended sufficiently proud of the ash layer, would probably have a good chance of long-term survival, although this might be expected to apply to many of the taxa seen in the pollen diagram.

In the absence of empirical data, the late Sigurður Thorarinsson (1979, and personal communication 1981) was of the opinion that in a high-precipitation environment, the tephra-blanket would have been subject to the removal of soluble bases by leaching. The ash layer would thereby represent a 'mulch,' providing nutrient enrichment for the period during which the supply of bases pertained. Did the infusion of nutrients at Hellisbjargi favour grasses rather than the more acidophilic sedges, and was the increase in *Thalictrum alpinum* within and above the base of the tephra layer a response to a temporary infusion of nutrients?

For the moment, and as far as Hellisbjargi is concerned, this hypothesis can be neither accepted nor refuted.

Reduction or cessation of grazing

An indirect effect of ashfall could involve a change in land use. Grazing lands may have been abandoned temporarily as livestock owners moved sheep and other animals to more sloping land (not a widespread feature on Papey), which would be subject to the erosional removal of tephra. Ash build-up would have been minimised and grasses and other nutritious herbs would still have grown. The attraction of this course of action may have been increased if farmers were aware of the dangers of fluorosis. This is a well-known effect of several volcanic eruptions in Iceland, whereby soluble fluorine is adsorbed onto tephra grains, ingested by grazing animals, leading to seizures, kidney and liver failure, and teeth and bone disintegration (Thorarinsson 1979; Óskarsson 1980). It is unknown whether fluorosis affected animal populations at this distance from the eruption source. Fluorine is highly mobile and can be rapidly flushed from the affected areas by rainfall. Maximum impacts occur during prolonged spells of dry weather. If ashfall, or the human fear of the consequences of tephra falls, affected grazing, this may have led to abandonment of the land. The eruption of Katla is known to have been followed by famine and a substantial human death toll between 1756 and 1758 (Vasey 1996).

Whatever the underlying reason, the death or removal of animals would have meant a reduction or cessation of grazing. In such circumstances, Poaceae, *Thalictrum*, and *Salix* spp. might have thrived (or flowered). Their subsequent demise (or reduced flowering) might reflect a return to normal grazing, which would differentially favour Cyperaceae, for which percentages increase above the low level evident immediately above the tephra layer.

Climate change

Using records of sea-ice incidence as a proxy for annual mean temperatures, Bergthórsson (1969) and Ogilvie (1984, 1992) have shown, at least for northern and southern Iceland, that AD 1755 occurred during a marked interval of temperature depression, perhaps some 2°C cooler than present. Even if a temperature effect was exacerbated by volcanic activity (Mass and Portman 1989), this might be thought to favour sedges rather than grasses, unless it was also a period of lowered precipitation.

A combination of the above hypotheses

Another possibility is that any combination of the above hypotheses applied.

Seljaland

The pre- and post-tephra pollen contents of the Seljaland deposits differ markedly. The pollen of Cyperaceae is reduced (from 79 to 39% TLP) and that of Poaceae rises (from 15 to 48%). There are also small but distinctive increases in values for *Ranunculus acris*-type (meadow buttercup), *Rumex acetosa* (common sorrel), and Pteropsida (monolete) indet. (undifferentiated ferns) immediately above the tephra layer. It is difficult to see why these taxa exhibit improved representation, although they may be taller than other members of the flora, and hence could gain a competitive advantage immediately following tephra deposition.

The sampled increments of sediment probably cover a maximum period of approximately one year each, based on straight-line extrapolation between the mire surface and the tephra horizon. As was the case for Papey, this is likely to be an overestimate, as the mire surface may have been cut-over on more than one occasion.

The common feature of the Hellisbjargi and Seljaland pollen spectra is in the behaviour of Cyperaceae and Poaceae, indicating the suppression of sedges relative to grasses after tephra deposition. This pattern is also seen in the pollen concentration values (not reproduced here), suggesting a real change in the vegetation and not a statistical artefact of the mode of pollen depiction in the percentage diagrams. At first sight, and ignoring historical knowledge concerning Seljaland in 1947, this would allow a similar application of the hypotheses already raised for Hellisbjargi, namely the favouring of an explanation based on reduced grazing within the pollen catchment area, although a change in the chemical environment cannot be ruled out. Similarly, the mean temperatures over the North Atlantic around Iceland were also in decline in the latter half of the 1940s (Ogilvie and others 2000) and this is thought unlikely to favour the representation of grasses over sedges.

What is known from local knowledge, however, is that farmers at Seljaland kept sheep and cattle stalled and moved horses well away from the area in order to guard against the problems of fluorosis — Hekla, after all, is only 45 km distant, and tephra deposition would have begun within a matter of hours of the start of the eruption. Cattle and sheep grazing would have ceased for some two months at least, and horse grazing probably for longer. If it was for a major part of the growing season, this would not only provide grasses with an opportunity to flower, but with a chance to dominate the vegetation and palynological records for perhaps several years beyond this — and this may be evident in the Hellisbjargi diagram (Fig. 4). In addition, increased nutrient inputs to the soils at Seljaland may have boosted the productivity of grasses.

Conclusions

The results from Seljaland, benefiting from knowledge of local events following the eruption of Hekla in 1947, support a hypothesis of grazing cessation as at least part-explanation of changes in the pollen record. This provides an analogue for events at Hellisbjargi, and its acceptability is all the more credible because of the similarity in palynological patterns between the sites. Of course, had the animals died at either site, this would have had the same effect on the pollen records, and such a cause could still have applied to the Papey site after the Katla eruption of 1775. Uncertainty remains over the roles of chemical changes to the plant environment and explanations based on the existence of multiple causes.

The research to date shows the value of tephro-palynological approaches in exploring the connections between vegetational, wider environmental, and volcanic processes. Further work will be undertaken to develop the spatial potential of tephropalynology in Iceland and to investigare the potential provided by associated statistical approaches (compare Birks and Lotter 1994; Eastwood and others 2002). The Seljaland area contains a number of intact deposits that should enable a 'three-dimensional' analysis of the vegetational patterns via multiple cores from within and beyond the farmed areas. The H-1947 tephra deposit provides an isochrone that can link these deposits precisely.

Acknowledgements

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References

Beard, J.S. 1976. The process of plant succession on the Soufriére of St Vincent: observations in 1972. *Vegetatio* 31: 69–77.

Bennett, K.D. 2002. *Annotated catalogue of pollen and pteridophyte spore types of the British Isles.* http://www.kv.geo.uu.se/pc-intro.html

Bergthorsson, P. 1969. An estimate of drift ice and temperature in Iceland in 1000 years. *Jökull* 19: 94–101.

Birks, H.J.B., and A.F. Lotter. 1994. The impact of the Laacher See volcano (11,000 yr BP) on terrestrial vegetation and diatoms. *Journal of Paleolimnology* 11: 313–322.

Bjarnason, Á.H. 1991. Vegetation on lava fields in the Hekla area, Iceland. *Acta Phytogeographica Suecica* 77: 1–110.

Black, R.A., and R.N. Mack. 1986. Mount St Helens ash: recreating its effects on the steppe environment and ecophysiology. *Ecology* 67: 1289–1302.

Blackford, J.J., K.J. Edwards, A.J. Dugmore, G.T. Cook, and P.C. Buckland. 1992. Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in northern Scotland. *The Holocene* 2: 260–265.

Buckland, P.C., K.J. Edwards, J.J. Blackford, J.P. Dugmore, and G. Sveinbjarnardóttir. 1995. A question of Landnam: pollen, charcoal and insect studies on Papey, eastern Iceland. In: Butlin, R.A., and N. Roberts (editors). *Ecological relations in historical times: human impact and adaptation*. Oxford: Blackwell: 245–264.

Cook, R.J., J.C. Barron, R.I. Papendick, and G.J. Williams III. 1981. Impact on agriculture of the Mount St Helens eruptions. *Science* 211: 16–22.

de Boer, J.Z., and D.T. Sanders. 2002. *Volcanoes in human history: the far-reaching effects of major eruptions.* Princeton: Princeton University Press.

Delmelle, P., J. Stix, C.P.-A. Bourque, P.J. Baxter, J. Garcia-Alvarez, and J. Barquero. 2001. Dry deposition and heavy acid loading in the vicinity of Masaya volcano, a major sulfur and chlorine source in Nicaragua. *Environmental Science & Technology* 35: 1289–1293.

Dodgshon, R.A., D.D. Gilbertson, and J.P. Grattan. 2000. Endemic stress, farming communities and the influence of Icelandic volcanic eruptions in the Scottish Highlands. In: McGuire, W.G., D.R. Griffiths, P.L. Hancock, and I.S. Stewart (editors). *The archaeology of geological catastrophes.* London: Geological Society of London (Special publication 171): 267–280.

Dugmore, A. 1989. Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine* 105: 168–172.

Dugmore, A.J., and C.C. Erskine. 1994. Local and regional patterns of soil erosion in southern Iceland. *Münchener Geographische Abhandlungen* B12: 63–78.

Dugmore, A.J., G. Larsen, and A.J. Newton. 1995a. Seven tephra isochrones in Scotland. *The Holocene* 5: 257–266.

Dugmore, A.J., J.S. Shore, G.T. Cook, A.J. Newton, K.J. Edwards, and G. Larsen. 1995b. Radiocarbon dating tephra layers in Britain and Iceland. *Radiocarbon* 37: 379–388.

Eastwood, W.J., J. Tibby, N. Roberts, H.J.B. Birks, and H.F. Lamb. 2002. The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Gölhisar, southwest Turkey. *The Holocene* 12: 431–444.

Edwards, K.J., P.C. Buckland, J.J. Blackford, A.J. Dugmore, and J.P. Sadler. 1994. The impact of tephra: proximal and distal studies of Icelandic eruptions. *Münchener Geographische Abhandlungen* B12: 79–99.

Edwards, K.J., and R. Craigie. 1998. Palynological and vegetational changes associated with the deposition of Saksunarvatn ash in the Faroe islands. *Fróðskaparrit* 46: 245–258.

Einarsson, T., G. Larsen, and S. Thorarinsson. 1980. The Sólheimar tephra layer and the Katla eruption of c 1357 AD. *Acta Naturalia Islandica* 28: 1–24.

Eldjárn, K. 1989. Papey, Fornleifarannsóknir 1967–1981. Edited by G. Sveinbjarnardóttir. *Árbók Hins íslenzka Fornleifafélags* 35–188.

Faegri, K., and J. Iversen. 1989. *Textbook of pollen analysis.* Fourth edition. Chichester: John Wiley & Sons.

Friðriksson, S., B. Sveinbjörnsson, and S. Magnússon. 1972. Vegetation on Surtsey: summer 1970. *Surtsey Research in Progress Report* 6: 54–59.

Giles, T.M., R.M. Newnham, D.J. Lowe, and A.J. Munro. 1999. Impact of tephra fall and environmental change: a 1000 year record from Matakana Island, Bay of Plenty, North Island, New Zealand. In: Firth, C.R., and W.J. McGuire (editors). *Volcanoes in the Quaternary.* London: Geological Society of London (Special publication 161): 11–26.

Grattan, J.P. 1994. Land abandonment and Icelandic volcanic eruptions in the late second millennium BC. *Münchener Geographische Abhandlungen* B12: 111–132.

Grattan, J.P., and D.J. Charman. 1994. Non-climatic factors and the environmental impact of volcanic volatiles: implications of the Laki Fissure eruption of AD 1783. *The Holocene* 4: 101–106.

Grattan, J., D. Gilbertson, and D. Charman. 1999. Modelling the impact of Icelandic volcanic eruptions upon the prehistoric societies and environment of northern and western Britain. In: Firth, C.R., and W.J. Maguire (editors). *Volcanoes in the Quaternary.* London:

Geological Society of London (Special publication 161): 109–124.
Griggs, R.F. 1922. *The valley of ten thousand smokes*. Washington, DC: National Geographic Society.
Grimm, E.C. 1991. *TILIA and TILIA.GRAPH.* Springfield: Illinois State Museum.
Gunnlaugsson, G.A., G.M. Gudbersson, S. Thorarinsson, S. Rafnsson, and Th. Einarsson (editors). 1984. *Skaftáreldar 1783–1784.* Reykjavik: Ritgerdir og Heimildir: Mál og Menning.
Hansom, J.D., and D.J. Briggs. 1989–90. Pre-Landnam *Plantago lanceolata* in northwest Iceland. *Fróðskaparrit* 38–39: 69–75.
Haraldsson, H. 1981. The Markafljót sandur area, south Iceland. *Striae* 15: 1–58.
Kristínsson, H. 1987. *A guide to the flowering plants and ferns of Iceland.* Reykjavik: Örn og Örlygur.
Larsen, G. 2000. Holocene eruptions within the Katla volcanic system, south Iceland: characteristics and environmental impact. *Jökull* 49: 1–27.
Larsen, G., A.J. Newton, A.J. Dugmore, and E.G. Vilmundardóttir. 2001. Geochemistry, dispersal volumes and chronology of Holocene silicic tephra layers from the Katla volcanic system, Iceland. *Journal of Quaternary Science* 16: 119–132.
Mass, C.F., and D.A. Portman. 1989. Major volcanic eruptions and climate: a critical evaluation. *Journal of Climate* 2: 566–593.
Moral, R. del. 1983. Initial recovery of subalpine vegetation on Mount St. Helens. *American Midland Naturalist* 109: 72–80.
Moral, R. del, and D.M. Wood. 1988. Dynamics of herbaceous vegetation recovery on Mount St Helens, Washington, USA, after a volcanic eruption. *Vegetatio* 74: 11–27.
Ogilvie, A.E.J. 1984. The past climate and sea-ice record from Iceland, part I: data to AD 1780. *Climatic Change* 6: 131–152.
Ogilvie, A.E.J. 1992. Documentary evidence for changes in the climate of Iceland, AD 1500 to 1800. In: Bradley, R.S., and P.D. Jones (editors), *Climate since AD 1500.* London: Routledge: 92–117.
Ogilvie, A.E.J., L.K. Barlow, and A.E. Jennings. 2000. North Atlantic climate c AD 1000: Millennial reflections on the Viking discoveries of Iceland, Greenland and North America. *Weather* 55: 34–45.
Óskarsson, N. 1980. The interaction between volcanic gases and tephra: fluorine adhering to tephra of the 1970 Hekla eruption. *Journal of Volcanology and Geothermal Research* 8: 251–266.
Sadler, J.P., and J.P. Grattan. 1999. Volcanoes as agents of environmental change. *Global and Planetary Change* 21: 181–196.
Scarth, A. 1999. *Vulcan's fury: man against the volcano.* New Haven, CT: Yale University Press.
Sigurdsson, H., S. Cashdollar, and R.S.J. Sparks. 1982. The eruption of Vesuvius on AD 79: reconstruction from historical and volcanological evidence. *American Journal of Archaeology* 86: 39–51.
Skiba, U., M.S. Cresser, R.G. Derwent, and D.W. Futty. 1989. Peat acidification in Scotland. *Nature* 337: 68–69.
Smith, C.M.S., M.S. Cresser, and R.D.J. Mitchell. 1993. Sensitivity to acid deposition of dystrophic peat in Great Britain. *Ambio* 22: 22–26.
Tagawa, H. 1964. A study of the volcanic vegetation in Sakurajima, southwest Japan. I. Dynamics of vegetation. *Science at Kyushu University Series* E3: 165–228.
Tanguy, J.C. 1994. The 1902–05 eruptions of Montagne Pelée, Martinique: anatomy and retrospection. *Journal of Volcanology and Geothermal Research* 60: 87–107.
TEPHRABASE. 2002. http://www.geo.ed.ac.uk/tephrabase
Thorarinsson, S. 1958., The Öraefajökull eruption of 1362. *Acta Naturalia Islandica* 2: 1–99.
Thorarinsson, S. 1961. Uppblástur Íslandi í ljósi öskulagarannsókna (Wind erosion in Iceland. A tephrochronological study). *Ásrit Skógræktarfélags Íslands* 1961: 17–54.
Thorarinsson, S. 1967. *The eruptions of Hekla* 1947–1948. *I. The eruption of Hekla in historical times.* Reykjavik: Vísindifélag islendinga.
Thorarinsson, S. 1975. Katla og annall Kötlugosa (Katla and the annals of Katla tephras). *Árbók ferðafélags Íslands* 1975: 125–149.
Thorarinsson, S. 1979. On the damage caused by volcanic eruptions with special reference to tephra and gases. In: Sheets, P.D., and D.K. Grayson (editors). *Volcanic activity and human ecology.* London: Academic Press: 125–159.
Thorarinsson, S. 1981a. The application of tephrochronology in Iceland. In: Self, S., and R.S.J. Sparks (editors). *Tephra studies.* Dordrecht: Reidel: 95–102.
Thorarinsson, S. 1981b. Greetings from Iceland: ashfalls and volcanic aerosols in Scandinavia. *Geografiska Annaler* 63A: 109–118.
Turney, C.S.M., and J.J. Lowe. 2001. Tephrochronology. In: Last, W., and S.P. Smol (editors). *Tracking environmental changes in lake sediments: physical and chemical techniques.* Dordrecht: Kluwer Academic Publishers: 451–471.
Vasey, D.E. 1996. Population regulation, ecology and political economy in preindustrial Iceland. *American Ethnologist* 23: 366–392.
Westgate, J.A., and M.P. Gorton. 1981. Correlation techniques in tephra studies. In: Self, S., and R.S.J. Sparks (editors). *Tephra studies.* Dordrecht: Reidel: 73–94.
Wilcox, R.E. 1959. Some effects of recent volcanic ash falls, with especial reference to Alaska. *US Geological Survey Bulletin* 1028-N: 409–476.