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The distribution of ash in Icelandic lake sediments and the relative importance of mixing and erosion processes

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ABSTRACT: During the Holocene the volcano Hekla explosively emitted highly silicic tephra on four occasions. The ash was widely dispersed by the wind. Distinctive light-coloured ash layers are now to be seen in the peats of Northern Iceland. Ash from the 1104 AD eruption was carried as far as Scandinavia. The most recent three tephra are preserved in the top 6 m of sediment in Lake Svinavatn. Chemical data from the sediment of Lake Svinavatn, which lies near the north coast of Iceland 170 km from Hekla, reveal the presence of silicic ash above the tephra visible to the naked eye. Unlike the vertical spread of ash in ocean sediment cores which results from biological mixing effects, the upwards spread of ash in the Svinavatn lake sediment cores appears to have been produced by erosion of ash from the lake catchment in the decades following the eruptions. The variations in concentrations of 11 elements, as determined by neutron activation analysis, can be explained by an exponentially decreasing input from catchment erosion. The additional input to each of the three Hekla ash layers was in the region of 3% of the ash which fell on the Svinavatn catchment.

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KEYWORDS: Lake sediments, mixing, tephra, neutron activation, erosion.

Introduction

The eruption history of the volcano Hekla has been elucidated through the careful assessment of written records and through tephrachronological studies, particularly of numerous Icelandic peat and soil sections (Thorarinsson, 1970). Silicic volcanic activity began 7000 years BP (tree-ring calibrated ages, 0 BP = 1950 AD) with an explosive rhyolitic eruption (H5). Other explosive eruptions followed, particularly at 4500 (H4), 2900 (H3) and 846 (H1) years BP. The ashes of all these eruptions are clearly preserved in peat sections to the north of Hekla and have allowed the dispersion of the ashes to be studied in detail (Larsen and Thorarinsson, 1977). The isopach thicknesses of the ashes at Svinavatn lake are 5cm, 3 cm and 2 cm for eruptions H4, H3 and H1 respectively (Larsen and Thorarinsson, 1977). Silicic tephra are relatively scarce in Northern Iceland, so the rhyolitic Hekla eruptions form the basis of a distinctive and clear tephrachronology.

Tephra preserved in lake sediments can be used to form the basis of very reliable chronologies and core correlations (e.g., Oldfield, et al., 1978). Less use has been made of the potential of volcanic ash falls as tracers for studying sedimentological and hydrological effects in lake basins and catchments. The stratigraphic variations within an ash layer preserved in a lake sediment record the effects of several sedimentation processes including catchment erosion, ash transport by water and wind, fluctuations in deposition patterns, bioturbation and mixings in addition to the volcanic characteristics of the source eruption. In a detailed study of the mineralogy and stratigraphy of ash layers in North Atlantic deep sea sediment, Ruddiman and Glover (1972) demonstrated the importance of mixing processes which they were able to attribute to bioturbation in the uppermost sediment.

In this paper we present the results of chemical analyses of the three Hekla tephras preserved in the sediments of Lake Svinavatn and of the more organic-rich sediments above and below the ash horizons. Neutron activation has formed the basis of the main chemical studies of the Svinavatn sediments, but X-ray fluorescence and electron microprobe work have also been carried out. Ash could have been incorporated into the organic-rich sediments stratigraphically adjacent to the three tephra layers either through (i) biological mixing processes or through (ii) resuspension and transportation of ash originally deposited in shallow waters, or through (iii) delayed catchment erosion and ash transportation by wind or by water. The aim of this paper, in addition to establishing a tephrachronology for the

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Svinavatn sediments, is to evaluate the relative importance of the above three processes in the Svinavatn basin and catchment in post ash-fall times.

The lake and catchment

Svinavatn (20°W 65°33'N) is a large (11.72 km^2) moraine-dammed lake situated in a plain 123 m above sea level at the head of Svinadalur valley (Fig. 1). Flat-topped basalt mountains rising steeply to 1000 m lie to the south-west of the lake, but otherwise the large catchment (229 km^2) is of generally low relief with widespread peatland vegetation. Four stream systems flow into the lake from the south. The rivers flow continuously following spring snow melt. The Laxa river after leaving the lake to the north meanders through peatlands from Svinavatn to Hunafjordur on the north coast. Peatland, arable fields and meadows comprise about 70% of the catchment, with the remainder being dry heath, screes and bare rock. *Carex chordorrhiza, C. nigra* and *C. panicea* are the commonest peatland species together with *Eleocharis* spp., *Equisetum* spp. and numerous bryophytes. Today there is no woodland in the catchment and much of the non-arable land is grazed by horses. The upland areas are rich in arctic-alpine species which include *Cassiope hypnoides, Loiseleuria procumbens* and *Veronica alpina*. Birch woodland would have dominated the catchment vegetation before the Landnam clearances which began around 870 AD (Einarsson, 1963).

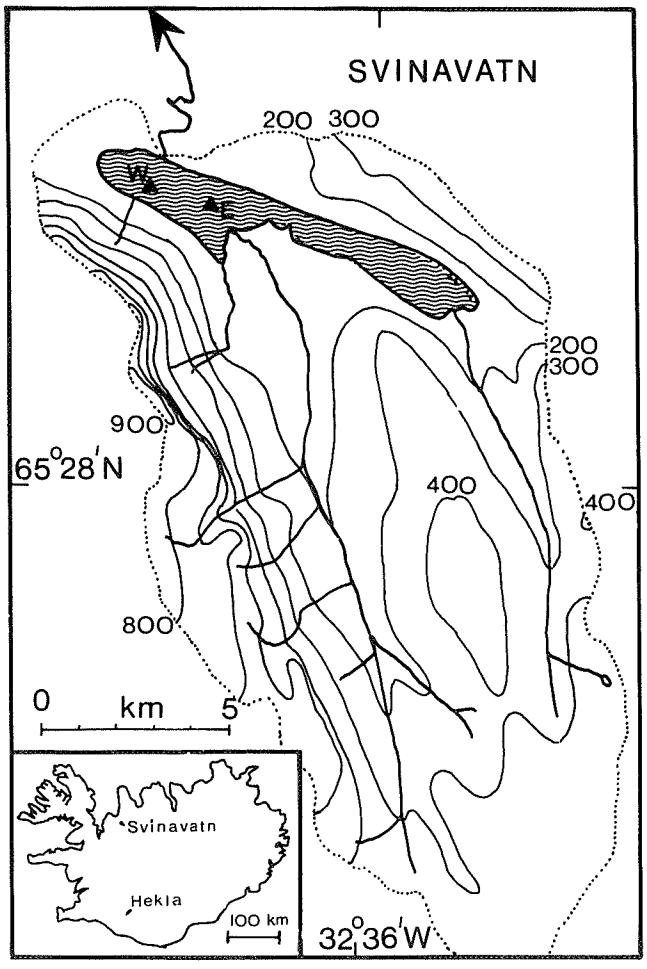


Figure 1 Location map for Svinavatn showing the main river systems. The edge of the catchment is dotted. Contours every 100 m. The two coring sites are marked by triangles.

Four cores up to 5.95 m in length were collected using a 6 m Mackereth corer at two sites, both near to the central axis of the lake (Fig. 1) on a flat bottom morphology. The eastern site, SVE, had a water depth of 30 m, the western site, SVW, 27 m. A single radiocarbon age determination of 4620 years BP (SRR-1776) from immediately below the oldest tephra in core SVE 1 confirms that the lowermost of the three SVE tephra is the 4500 year old H4.

Gudmundsson (1978) has studied the peat soils between Svinavatn and the coast. He found the three Hekla tephras, H4, H3 and H1 in all of his 26 peat-soil profiles and was able to use the tephra chronology to calculate average rates of peat accumulation. An increase in peat accumulation rate from 0.11 mm/year to 0.26 mm/year was deduced to have occurred around the time of the H1 eruption of 1104 AD. Mineral soils from Northern Iceland had previously been found (Gudbergsson, 1975) to have increased their accumulation rates from less than 0.08 mm/year before 874 AD to 0.5 mm/year between 1104 AD to the present. It has been suggested that the pronounced variations in mineral soil accumulation rate relate to either the changing flux of airborne volcanic ash being transported to Northern Iceland from the active volcanic zones, to climatic effects, or to the effects of wind erosion coupled with man's activity and the influences of his grazing livestock, particularly sheep, as discussed by Thorarinsson (1961; 1981). Gudmundsson (1978) explains the more rapid thickening of mineral soils in Northern Iceland as being caused by the more active transport by water and solifluction of aeolian material, which had originally settled on the hills. The mineral soils acted as collection sites which largely halted the transport of the aeolian material to the peats in the valley bottoms.

Instrumental neutron activition analysis of samples from Svinavatn

Eighty samples of approximately 0.1 g were weighed into polyethylene ampoules, and in view of the number were processed in five batches of sixteen samples. Each batch was irradiated for 6 hours in a flux of 3.6×10^{12}n cm^{-2} s^{-1} in the centre of the core of the reactor at East Kilbride together with a sample of the certified reference lake sediment SL-1, IAEA, Vienna. Approximately 4 days after irradiation each sample was counted for 30 minutes, 10 cm above an 80 cm^3 Ge (Li) detector with a resolution of 2.2. keV at 1,333 keV, and approximately 10 days after irradiation each sample was counted a second time for 1 hour, 1 cm above the same detector. The detector was controlled by an EGG-ORTEC data acquisition and analysis system with facilities for identification of photopeak energies and calculation of photopeak count rates. A representative spectrum from the second count is provided in Figure 2. Elemental concentrations in the samples were calculated by comparing the specific activities induced in them with the activities induced in the standard sediment (taking account of decay). Details of the indicator photopeaks and the accuracies attained (taking account of counting statistics and a 2% systematic (a priori) error) are provided in Table 1. The numerical data may be obtained from the authors.

Results

The concentrations of 11 elements were determined at 80 horizons in core SVE1 by neutron activation analysis. The results for the three tephra layers H4, H3 and H1 and for the

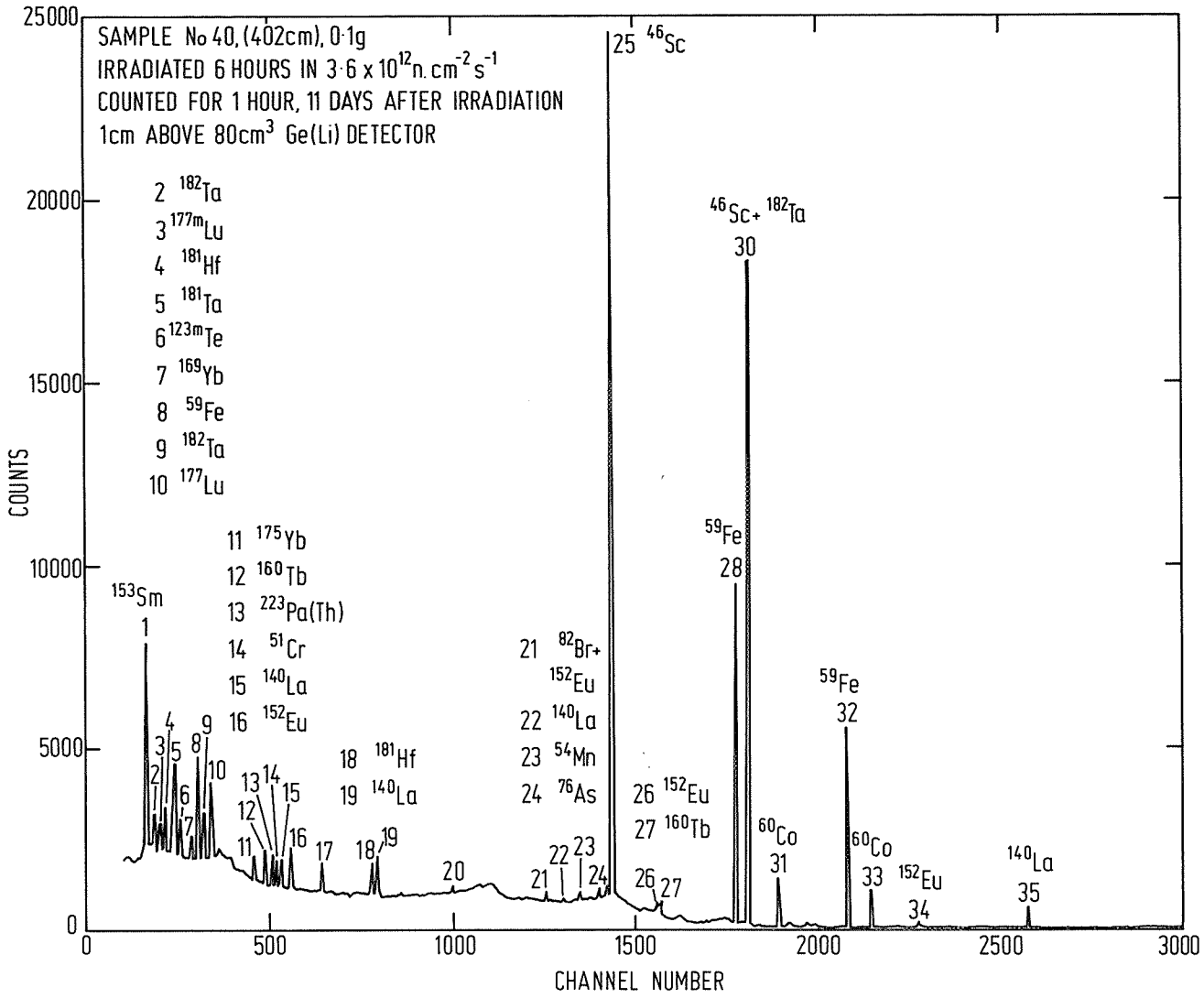


Figure 2 Activation spectrum of post-H4 Svinavatn sediment.

pre-tephra sediments are summarised in Table 2.

Representative profiles are shown in Figures 3 to 5. The composition of the ash of the tephra layers can be seen to be quite distinct from that of the normal pre-eruption organic-rich sediments.

Table 3 summarises major element concentrations, expressed as oxides and determined by X-ray fluorescence for pre-H4 and pre-H1 eruption sediments. The X-ray fluorescence iron and sodium results may be compared with the neutron activation data for these pre-eruption materials on conversion to oxide percentages. High iron and sodium concentrations are found by both methods for the pre-H1 sediments. Also tabulated in Table 3 are average oxide concentration values of 40 Svinavatn organic-rich sediment horizons and average results for tholeiite basalts from oceanic islands (Condie, 1982) and from the Skagi zone of Northern Iceland (Sigurdsson, et al. 1978). The X-ray fluorescence results show that compared with 'average' basalt (Taylor, 1964) the Svinavatn lake sediments are significantly richer in silica and noticeably depleted in magnesium and calcium, possibly reflecting input of more silicic materials from central volcanic materials (e.g., Carmichael, 1964) from the catchment.

The stratigraphic variation of the neutron activation results is illustrated in Figure 3, which shows the variation with depth of lanthanum and iron concentration. Lanthanum shows an increased concentration in the acidic ash bands while iron shows a decreased concentration. Similar increases are obtained in the acidic ashes for Hf, Th, Na and other rare earths, and reductions for Cr, Co and Sc. The lake sediments immediately overlying the Hekla tephra, at sediment depths between 412 and 400 cm, between 306 and 302 cm and between 112 and 108 cm can be seen to have intermediate iron and lanthanum concentrations. The well-defined sharp changes at

Table 1 Instrumental Neutron Activation Analysis of Samples from Svinavatn – Indicator Photopeaks and Accuracy

Isotope	Half-life	Eγ, keV	Accuracy, %
First count at 4 days decay			
^{24}Na	15.0 hours	1368	3
^{140}La	40.3 hours	1595	4
^{153}Sm	47.1 hours	103.2	3
Second count at 10 days decay			
^{46}Sc	83.9 days	1120	3
^{51}Cr	27.8 days	320	7
^{59}Fe	45.1 days	1291	3
^{60}Co	5.24 years	1333	4
^{152}Eu	12.2 years	1408	8
^{175}Yb	101 years	396	6
^{181}Hf	44.6 days	482	9
^{233}Pa*	27.2 days	312	8

* Indicator isotope for Th

Table 2 Neutron activation abundances, μg/g

Element	Average Pre-H4	Average Pre-H3	Average Pre-H1	Average of all 38 Pre-tephra samples	H4	H3	H1
	440-419 cm	322-311 cm	146-116 cm		413, 417.5 cm	307, 309 cm	114 cm
Co	30.2 μg/g	34.3 μg/g	31.2 μg/g	32.2 μg/g	6.94 μg/g	5.85 μg/g	5.34 μg/g
Cr	44.8	47.5	47.7	47.3	12.7	6.62	9.36
Eu	1.52	1.63	1.95	1.75	2.48	3.30	2.65
Yb	2.97	3.26	3.38	3.27	6.89	6.12	7.13
Fe	95 900	103 000	117 000	108 000	32 900	56 500	35 300
Na	9 600	11 100	12 200	11 300	32 700	38 000	35 000
La	18.1	20.8	22.3	20.9	66.7	73.6	73.1
Si	22.8	24.9	28.3	26.0	8.86	14.3	9.5
Sm	5.56	7.11	7.02	6.74	15.8	17.2	15.2
Hf	3.29	4.19	5.75	4.70	8.5	13.7	9.42
Tl	1.58	1.86	2.04	1.89	9.80	8.80	8.94

Table 3 X-ray fluorescence abundances

	Pre-H1 146-116 cm	Pre-H4 440-419 cm	Average of 40 Svinavatn samples	Skagi region Fe-Ti-rich Tholeiite	Ocean Island Tholeiite
SiO_2	56.0%	62.0%	59.0%	47.9%	49.4%
Al_2O_3	12.8	9.6	11.5	13.7	13.9
Fe_{O3}	17.3	16.0	15.9	15.3	12.4
MgO	3.1	2.7	2.7	6.4	8.4
CaO	5.8	5.0	5.2	10.5	10.3
Na_2O	1.8	1.4	1.8	2.5	2.1
K_2O	0.4	0.4	0.5	0.4	0.4
TiO_2	2.4	2.0	2.1	3.3	2.5
MnO	0.52	0.34	0.42	0.27	–
ClO_3	0.46	0.52	0.44	0.33	–

the onset of tephra inputs indicate the absence of post-depositional mixing or resolution processes. The gradual trend back to pre-eruption values is most clearly displayed above the thick H4 ash. Thin dark basaltic ash horizons, in contrast with the light rhyolitic ashes can be seen to depress slightly the lanthanum concentrations for example at 293 cm depth.

Less pronounced chemical variations are found between the three pre-eruption compositions. For example in Figure 3 the average iron concentration can be seen to be higher prior to H1 than before H4. Similar small pre-eruption variations are found for the other elements (Table 1). Elemental changes in lake sediments have been reviewed by Engstrom and Wright (1984). They point out that iron variations are particularly difficult to interpret as changes can be produced by a range of independent environmental factors. Mackereth (1966) pointed out that both iron and manganese, on account of their solubility, could be transported to lakes in solution and that their supply could be controlled by pedological changes. The higher pre-H1 eruption values could be connected with settlement and the start of farming around this time through the removal of birch woodland and the subsequent deeper erosion of soil.

Some chemical differences are found between the three acidic tephra (Table 2). Thorarinsson (1967) noted that the chemistry of Hekla eruptions is a function of the time elapsed since the preceding eruption. Gradual changes in chemistry of the ash produced during the H3 eruption have also been documented by Larsen and Thorarinsson (1977).

Electron microprobe analyses of the major elements were performed on polished glass fragments from the Svinavatn tephra using energy dispersive techniques. The results of the studies are presented in Table 4. Crystal spectrometry was also tried in an attempt to determine certain trace element concentrations, but it was not successful. Glass particles were found in the bottom-most part of H4 and extracted for microprobe analysis. This tephra was mainly light grey in colour. The middle tephra, H3, was coarse but well sorted, fining upwards. It varied in colour from a light, whitish grey at the base through a light brown middle to a dark grey top. Elongated glass particles up to 0.6 mm long were found at its base. The uppermost tephra (H1) was light grey in colour with two pale brown laminated layers. Glass particles up to 0.03 mm in diameter and black particles up to 0.1 mm in diameter were found in it. Six glass particles from H1 and H3 and five from H4 were extracted, mounted and polished and then analysed using a 20 kV gun potential and a 6 nA probe current. Low percentage totals were obtained in the microprobe analyses (Table 4). The low totals partially resulted from H_20 not being detected in the microprobe technique. Sigvaldsson (1974) found H_20 ranged up to 2.7% in Hekla glass. However, even allowing for this the totals of the individual glass particles still fell short of 100% by between 2 and 8%. This further discrepancy probably resulted from the highly vesicular nature of the silicic Hekla glasses leading to scattering of the electron beam. We could probably have obtained higher totals by melting the glass before preparation for the probe work. Nevertheless the between-ash variations summarised in Table 4 aid in confirming the identification of the tephra and help in assessment of the accuracy of the other chemical methods. Observe for example how a high iron concentration for the middle ash, H3, is again found (Table 4) in the probe results.

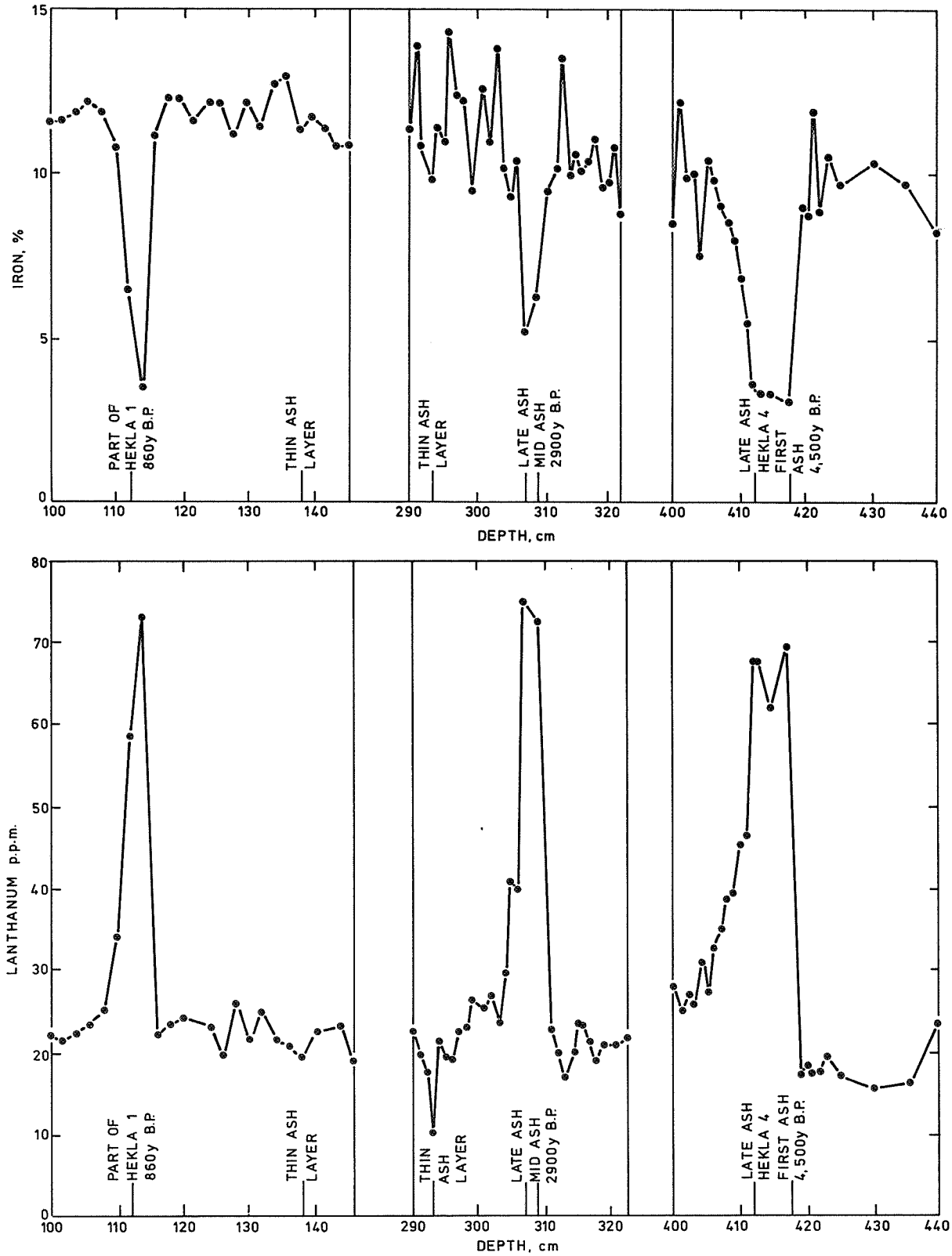


Figure 3 Lanthanum and iron concentration variations with depth in Svinavatn sediments. Lanthanum concentrations are high in all three acid Hekla tephras, whereas iron concentrations are reduced in the tephra. Thin basaltic tephras can be seen to reduce the lanthanum concentration (e.g., at 293 cm depth). The background level of iron, although scattered, can be seen to gradually decrease up the core.

Modelling

Quantitative modelling of the vertical concentration variation of chemical, mineralogical, faunal or isotopic species in sediments has tended to focus on the effects of biological mixing. Berger and Heath (1968) developed a simple 'box' mixing model. In the Berger and Heath approach it is assumed that fast mixing occurs down to a certain depth. So, in the absence of diagenetic alteration, the depositional record is locked into the sediment column when it is buried below the bioturbation mixing zone.

Ruddiman and Glover (1972) have studied the effect of the Berger and Heath mixing model on an impulse source such as an ashfall. The Berger and Heath mixing model would change an original thin ash band with sharp upper and lower

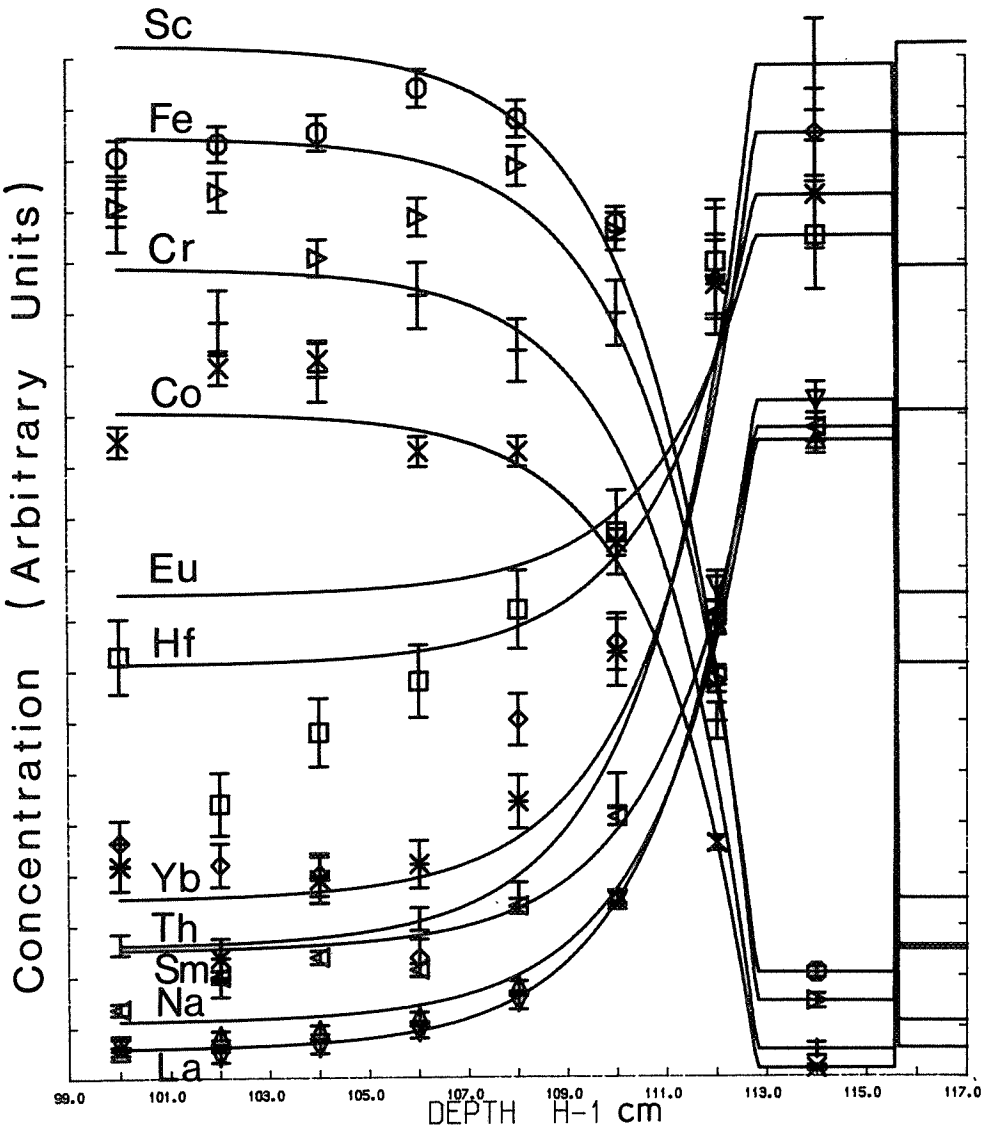


Figure 4 Concentration variation with depth in Svinavatn sediment for 11 elements through the H1 tephra layer. Curves model the variations in terms of an exponential change (m = 1.9 cm) from the concentrations in the H1 tephra to the pre-tephra background levels. Symbols as in Figure 5. Error bars indicate precision of laboratory counting.

Table 4 Energy dispersive microprobe abundances

	H1 Average of 6 glass particles		H3 Average of 6 glass particles		H4 Average of 5 glass particles	
	%	± sd	%	±	%	±
SiO_2	71.33	0.59	66.92	2.91	69.69	1.40
Al_2O_3	13.67	0.18	14.17	0.90	12.1	0.27
Fe_2O_3	3.16	0.07	5.27	1.82	1.95	0.08
MgO	–	–	0.49	–	–	–
CaO	1.97	0.06	3.00	0.90	1.28	0.16
Na_2O	2.55	0.50	2.57	0.66	3.50	0.38
K_2O	2.66	0.08	2.03	0.28	2.67	0.02
TiO_2	0.23	0.04	0.41	0.14	0.12	–
MnO	0.15	–	0.13	0.03	0.12	–
ClO_3	0.09	0.02	0.06	0.03	0.08	0.02
Total	95.81		95.05		91.51	

boundaries to a smeared record with a sharp bottom boundary and a long upper tail with an exponentially decreasing ash concentration. Such mixing would also significantly reduce the peak concentration and displace the peak concentration horizon down the sediment column by a distance equal to the mixing depth. In a detailed study Ruddiman and Glover compared their measurements of the vertical abundances of shards in ash layers in North Atlantic sediments with Berger and Heath mixing models of impulse sources. Ruddiman and Glover found more symmetric concentration variations than were predicted by the Berger and Heath equation with mixing both above and below the original layer giving rise to gradational upper and lower boundaries. They therefore inferred that complete mixing and homogenisation, as assumed in the Berger and Heath model, had not occurred in their North Atlantic sediments and furthermore that occasional deep burrows had moved material down below the main mixing layer. But Ruddiman and Glover concluded that biological mixing was the major process that had modified the form of the original ash layers in their marine deposits.

Guinasso and Schink (1975) have produced a time-dependent eddy diffusion mixing equation which more accurately models the types of vertical concentration variations found in marine sediments such as those observed in the study of Ruddiman and Glover. Guinasso and Schink presented a series of concentration variations that are to be found from their mixing equation for various combinations of mixing depths and mixing rates. The Berger and Heath model is a special case of the more general Guinasso and Schink mixing equation. By applying the diffusion model to abyssal sediments, maximum mixing depths of between 17 and 40 cm were deduced by Guinasso and Schink for microtektite distribution data and of up to 12 cm for plutonium data. In practice then, biological mixing of an impulse source leads to diffuse upper and lower boundaries with a reduction in peak concentration, downwards peak displacement and an overall shape similar to the symmetric gaussian curves of Ruddiman and Glover (1972) or the Guinasso and Schink (1975) equations.

The Svinavatn ashes have internal layering and sharp lower boundaries, and their peak concentrations have not been depressed. All these characteristics indicate that mixing has not been of particular importance in the Svinavatn sediments. The ashes do however have an exponentially decreasing upper tail giving them a pronounced asymmetric shape which can be well modelled by the Berger and Heath (1968) equation. The concentration of an element, P, a distance, L, above the tephra is taken to be related to the background concentration, P_b, and to the ash concentration, P_a, by

$$P = (P_a - P_b) \exp(-L/m) + P_b$$

where, following Berger and Heath (1968), the 'decay constant' m is the thickness of the mixing layer, or alternatively, in terms

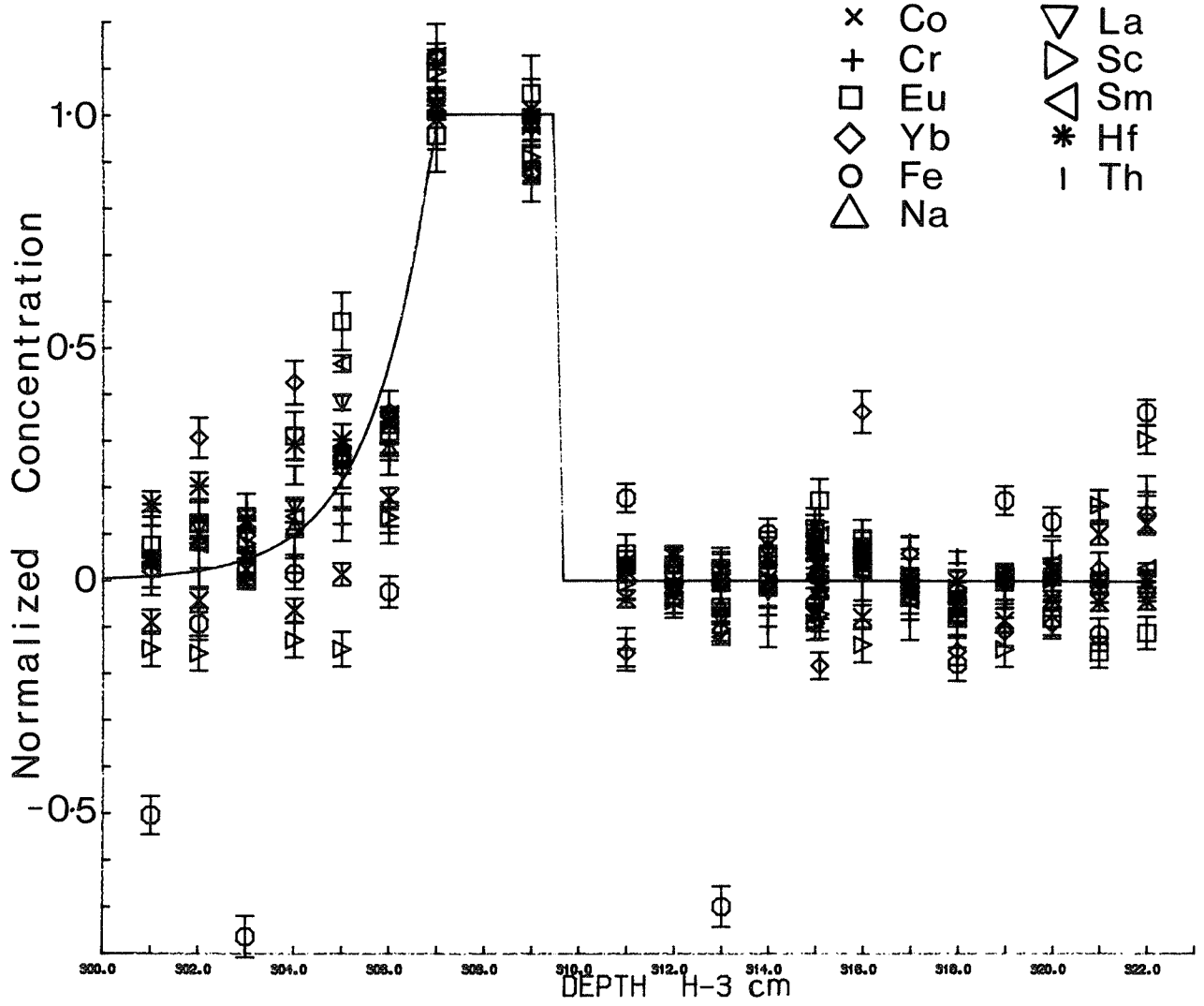


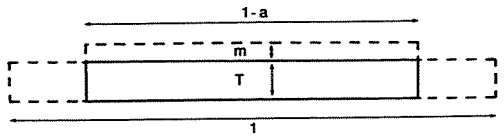
Figure 5 Normalised concentration variations with depth in Svinavatn sediment for 11 elements through the H3 tephra layer. The concentrations have been adjusted to make the average H3 tephra concentration one and to make the pre-H3 background level zero. The model curve is for the same exponential change for all 11 elements with a decay constant of m = 1.3 cm. Error bars as in Figure 4.

of the delivery of ash from the catchment to the lake, the 'decay constant' m is a measure of the total thickness of ash eroded from the catchment.

The chemistry of the Svinavatn sediments during and after Hekla eruptions is best modelled by taking individual pre-eruption sediment compositions and introducing the trace elements found in the ashes. Two examples of the results of these model calculations are shown in Figures 4 and 5.

In Figure 4 the fall in concentration in the elements Eu, Hf, Yb, Th, Sm, Na and La can be seen above the Hekla 1 ash as can the complementary increases in concentration of Sc, Fe, Cr and Co. The arbitrary scaling in concentration for each element allows the individual measurements, errors and model curves to be picked out. In Figure 5 the concentration data (in this case for Hekla 3) are presented on a normalised scale. This method of presentation emphasises how a single exponential fit has been derived for all 11 elements.

The exponential fit was simultaneously obtained for all the 11 chemical elements measured by the neutron activation studies using a weighted least squares formulation of the above equation. The relative weights were based on the percentage errors of Table 1. Best fits were found for m values of 4.8, 1.3 and 1.9 cm for tephra layers H4, H3 and H1 respectively.



T = Tephra thickness.
m = exponential 'decay constant'.

RESUSPENSION	CATCHMENT EROSION
a = Proportion of lake stripped of ash.	$\frac{1-a}{a}$ = Lake to catchment ratio.
Resuspended sediment = Redeposited sediment.	
$aT = (1-a)\,m$	Delivery ratio = $\frac{m}{T} \cdot \frac{(1-a)}{a}$
Hence $a = \frac{m}{m+T}$	

Figure 6 Diagram illustrating geometry of tephra before and after erosion and transportation for the two cases of (i) resuspension of lake material and (ii) catchment erosion. The dashed areas represent ash moved from its original deposition sites to new accumulation sites. The solid area represents ash deposited in the lake which has remained undisturbed. In the case of resuspension the proportion of the lakebed stripped of ash can be estimated from the tephra thickness, T, and the decay constant, m, calculated from the exponential decrease of ash in the organic-rich sediments above the tephra. In the case of catchment erosion the sediment delivery ratio can be estimated from T and m where a is the catchment area and 1-a the lake area.

Discussion

The chemical variations associated with the Svinavatn tephra layers and the pre- and post-eruption sediments follow a characteristic pattern for each tephra, viz.: (i) the lower boundaries of all three tephra are sharp (Fig. 3); (ii) the chemical compositions of the tephra all match with previously determined chemical compositions of the Hekla tephra H4, H3 and H1; and (iii) the upper boundary of each tephra is gradational with an exponentially decreasing ash content above the visible tephra. These features would not be found if biological mixing processes had been of importance in the Svinavatn sediments, as mixing would have given rise to gradational lower boundaries and diluted peak compositions in addition to exponential tails. Furthermore mixing processes, such as bioturbation by benthic invertebrates, would have destroyed thin laminations and narrow tephra observed at other depths in the cores. So rather than interpreting the above m values as mixing depths we take them to be a measure of the ash removed from other locations in the post-eruption period and transported to the coring site.

Transportation from the catchments, by wind or water, is one method by which ash could be incorporated into the sediments above the tephra. Another possible method is the resuspension and movement of ash within the lake. If the source of the post-eruption ash is from within the lake, for example through the resuspension of ash originally deposited in shallow water, then the thickness (T) of the visible tephra and the m values of the exponentially – decaying tails can be combined to estimate the proportion of the lake stripped of ash by resuspension (Fig. 6). The proportion, a, of the lake from which ash has been removed is given by the formula $a = m/(m + T)$. Table 5 gives the thicknesses of the visible tephra at the two Svinavatn coring sites as well as Larsen and Thorarinsson's isopach thicknesses in the Svinavatn region. We have chosen to use the tephra thicknesses at coring site E in our calculations, rather than Larson and Thorarinsson's isopach thicknesses, as this choice could reduce some of the influences of sediment focussing (Likens and Davis, 1975). The ratios of $m/(T + m)$ for H4, H3 and H1 are then estimates of the proportion of the lake area cleared of ash in the post-eruption periods. These proportions work out as 47%, 34% and 40% respectively. These proportions appear unrealistically high indicating that resuspension and redeposition of ash in the lake is unlikely to have been the dominant cause of the ash 'tails'.

If instead catchment erosion processes have been dominant in supplying the post-eruption ash then we can estimate the sediment delivery ratio for the Svinavatn catchment after each ash fall by comparing the volumes of ash in the visible tephra with that found in the ash tails above the tephra. Sediment delivery ratio is taken to be the ratio of the sediment yield to the available sediment. Taking the thicknesses, T, of the visible tephra at the coring site E as a measure of the available sediment, and the m values as estimates of the sediment yield, then sediment delivery ratio is given by multiplying the ratio m/T by the ratio of lake area to catchment area (1-a)/a as illustrated in Figure 6. For the H4, H3 and H1 tephra we get sediment delivery ratio estimates of 4%, 2.5% and 3% respectively when using a lake-to-catchment ratio of 1:20. If material has been blown into the lake from outside the catchment, or if resuspension has contributed significantly to the ash tails, then these delivery ratios will be overestimates.

By taking into account the rate of deposition of the lake sediments (Table 5) we can estimate the lengths of time for half of the post-eruption ashes, which are to be transported to the coring site E, to accumulate. The transportation times are approximately 36 years, 7 years and 8 years for the Hekla eruptions H4, H3 and H1 respectively. As the deposition rates of Table 5 may underestimate deposition rates immediately following the ash falls the above estimates of transportation times should be regarded as upper limits.

Conclusions

1. The Hekla tephra stratigraphy H4, H3 and H1 has been identified in the sediments of Lake Svinavatn.

Table 5 Svinadalur peat and lake sediment thicknesses and accumulation rates

Horizon	Age* (year BP)	Peat Isopach* Thickness (cm)	Accumulation† Rate (cm/year)	Lake Thickness (cm) core	core	Accumulation Rate (cm/year) core	core
Present	−29	–		E1	W4	E1	W4
			0.026			0.12	0.11
H1	846	2		2.8	1.8		
			0.012			0.10	0.08
H3	2900	3		2.5	1.6		
			0.011			0.07	0.04
H4	4500	5		5.5	5.3		
			–			>0.07	–
H5	7000	1		–	–		

* Hekla tephra layer ages and isopach thicknesses from Larsen and Thorarinsson (1977). Tree-ring calibrated ages: 0 BP = 1950 AD

† Peat accumulation rates from Gudmundsson (1978)

2. The Svinavatn lake sediment accumulation rates, like nearby peat accumulation rates (Table 5), increase only modestly after the start of farming in Iceland.
3. Neutron activation analysis allows changing acidic ash proportions to be accurately assessed in the Svinavatn sediments.
4. The time taken at Svinavatn for the transport of ash to the deposition sites in the lake was roughly exponentially related to the thickness of ash deposited.
5. The sediment delivery ratio to Lake Svinavatn after large ashfalls, as deduced from the proportion of ash lying above visible tephra layers in the lake cores, is estimated to be approximately 3%.
6. No evidence for biological mixing processes has been found in the Svinavatn sediments. Although some aspects of the Svinavatn pattern of ash content can theoretically be explained by homogeneous mixing models, the effects of erosion, transportation and redeposition provide a more likely explanation of the Svinavatn geochemical variations. In practical terms mixing appears to be of very minor significance compared with erosion and transportation processes at Svinavatn.

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