The Mobility and Re-Deposition of the Hekla 1991 Tephra, and the Effects of Wind and Snow

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Abstract

The eruption of Hekla in January 1991 was characterized by two short lived explosive phases of tephra production with a subsequent longer episode of lava production. A consequence of the timing of the eruption in the mid-winter, in combination with southeasterly winds during the explosive phases, was the deposition of tephra on the near continuous snow-fields northwards into the interior. During and immediately after the explosive phases heavy snow fall occurred, burying the tephra in a sandwich fashion.

The tephra was sampled at two lake basins 45 km northeast of Hekla in March and August 1991, and on the northern flanks of Hekla in August only. In both areas the fate of the tephra was investigated. In March, 60 samples of the more distal deposit were recovered from clusters of snow pits. Mass loading of the tephra was uneven in the extreme, varying by orders of magnitude across the area. Particle size distributions have been used, with limited success, to determine the effects of aeolian remobilization. The long-term fate of the tephra in these basins is unclear, although investigations in the summer demonstrate that wind is of far greater significance than fluvial and slope wash processes.

The proximal tephra on the flanks of Hekla was observed to have reduced the ablation rate of the underlying snow, preserving it well into the summer. The development of a polygonal ablation topography on the buried snow was observed and was shown to evolve continuously as ablation continued. The interaction of the wind with these tephra coated polygons led to a progressively more even tephra layer as the snow beds melted.

The implications of these observations are important in the local and regional distribution of tephra deposited on snow-fields. In Iceland such occurrences are frequent, owing to the persistence of snow, and caution should be exercised in considering the sampling strategies used when interpreting such layers.

Introduction

The most recent eruption of the Icelandic volcano Hekla commenced on the 17th January 1991, but received little media attention outside Iceland owing to its coincidence with the outbreak of the 'Gulf War' and the death of the Norwegian King, Olaf. The event was not insignificant, and ten minutes into the eruption, radar measurements showed the column to have reached a height of 11.5 km (SMITHSONIAN INST. 1991a). With ashfall reported along the northern coast of Iceland, some 300 km away, the initial explosive episode was the most productive. A second plume was observed on satellite

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images 6 hours after the onset of the eruption (SMITHSONIAN INST. 1991b) and in addition an ashfall of much reduced scale was registered 4 days later. Total tephra production was estimated at approximately 0.02 km^3 (LARSEN et al. 1992). This is about 1/3 of the volume of the 1970 and 1980/1981 tephras, making it the smallest of the four Hekla eruptions in the 20th century. The southeasterly winds deposited tephra in a relatively closed sector, owing to their strength and to the short duration of the explosive phase. This tephra was deposited on extensive snow-fields and rapidly buried during heavy snow storms. The tephra was sandwiched between the snow, affording possible protection from wind re-working, up to the spring thaw. The results obtained show the ineffectiveness of this protection; demonstrate the susceptibility of tephra to post-depositional movement; and suggest that the construction of mass loading isopach maps should not be undertaken without consideration of the timing (season) of the eruption. Such isopach maps (often based on less accurate layer thickness measurements, in place of mass loading) are extremely useful in directly determining the volume production of tephra following an eruption, and for estimating the explosivity of ancient eruptions from their tephra layers.

The fieldwork upon which this paper is founded was carried out in two sites to the north of Hekla and over two successive seasons. Although the further of the sites is no more than 45 km from the volcano, they shall be distinguished as the distal (*sensu lato*) and proximal sites.

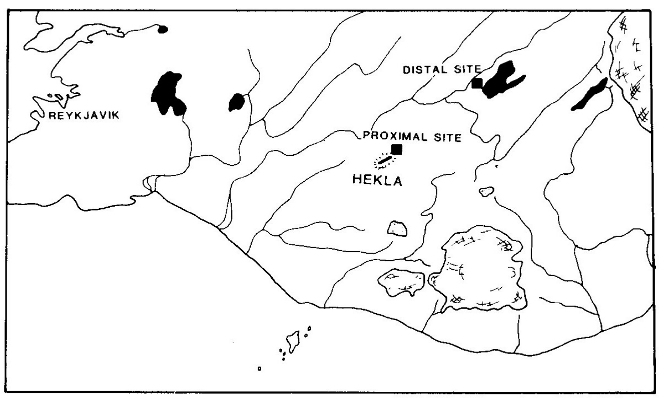

Fig. 1: The location of the proximal and distal sampling sites.

The Field Areas: Distal Site

In order to obtain undisturbed mass loading data it was vital to work in the field before the snow melt. Logistical factors, not the least being safety and accessibility, severely reduced the choice of sampling area. This choice was further reduced by the unusual warm spells in the early spring which led to the melting of snow below an altitude of 400 m. A lake catchment was required as the aim of the original research was to examine the lacustrine re-deposition of the 1991 tephra as an analog for the early Holocene Saksunarvatn Tephra (HUNT 1991, 1992). The selected area, Launöldur (*fig. 1, 2*), contains a lake (Launvötn) and lies some 45 km northeast of Hekla and 2.5 km west of Þórisvatn. The lake is unnamed on most topographic maps, but be recognized by its 'pear-shaped' outline and its three (ephemeral) inlet channels. The most southerly of these inlets drains a much smaller lake approximately 1 km away. The total catchment area is approximately 7 km^2 and ranges in elevation from ca 560 m to 620 m above sea level. The area consists of gently undulating hills dissected by several dry valleys. These reflect the high porosity of the bedrock, which is composed of interbedded hyaloclastites and tillites (JÓHANESSON & SÆMUNDSSON 1989), which are heavily fractured. The bedrock is mostly covered by a periglacial regolith, consisting of a wind-winnowed and frost-heaved pebble surface with underlying silty sands. The area is prone to high winds and is largely unvegetated, although occasionally certain species are encountered (most notably *Salix herbacea*, *Polygonum viviparum* and *Festuca vivipara*). Launvötn lies in a hydrologically closed basin and presumably owes its existence to the plugging effects of aeolian and fluvial sediments which have built up during the Holocene. The imperfect nature of this plugging explains the seasonal fluctuations in lake level which are known to occur (GUÐRÚN LARSEN pers. comm.).

Winter Sampling

During March and April 1991 a series of 21 snow pits were excavated in the area of Launvötn and 60 samples of black tephra were recovered from the snow and ice. The use of a measured template (250 cm^2) ensured that a constant area was sampled from each pit. Initially attempts were made to extract the debris from snow by rapid melting under a gas flame, but this proved time consuming and impractical. As an alternative approach the samples of the frozen debris-with-snow were bagged for later processing. This was made possible by the continuously sub-zero temperature, which prevented melting and subsequent leaking within the sample bags. Controlled thawing, draining and repacking of the tephra was carried out in Reykjavík, prior to transportation.

In the laboratory the samples were placed in a freezing unit for 24 hours prior to freeze-drying. The samples were then weighed and the results converted to mass loading figures (in kg m^{-2}). Mass loading was determined both for individual layers and, where multiple layers occurred, for complete pit sections. Bulk samples were then sieved at half phi (Ø) intervals for 20 minutes on an automatic shaker, and particle size distributions determined by weight. To encompass the entire population, sieve sizes ranged from -2.5 ∅ to +5.0 ∅. At the fine end of the size range it was assumed that the finer than +5.0 ∅ residue lay in the range +5.0 ∅ to +6.0 ∅. As the "fines" residue was generally less than 3.0% of the sample it is unlikely that this assumption has overly modified the results.

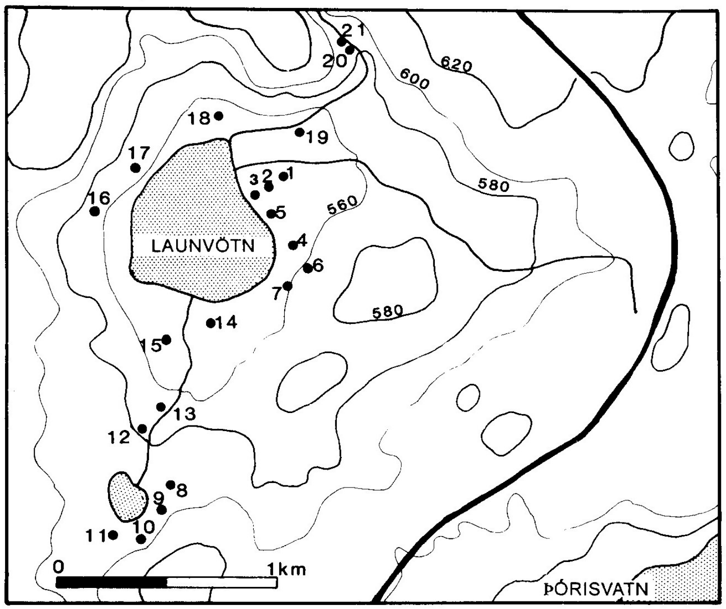

Fig. 2: The distal sampling site with locations of the winter snow pits (see *tab. 1* for mass loading values).

Results

In the field it was immediately apparent that conditions ideal to the in-snow protection of the tephra layers had not prevailed throughout the post-eruption period. Although a single discrete tephra layer (presumably the original horizon, and often with a central mm scale ice layer) was found in several pits (*fig. 3B*), in many others it had been replaced by up to five sharp or dispersed layers (*fig. 3C*). The similarity in particle size patterns (see later) between the basal layer in the multiple layer sections, and the single layer in other sections, suggests that they can be correlated. However the possibility that the multiple layers may represent complete removal and replacement of the single layer cannot be ruled out. The obvious conclusion that several phases of snow-melt had occurred was further supported by the presence of numerous ice layers within the granular snow between the tephra horizons. This indicates that the multiple layer examples did not arise as a result of a single storm event. Variability in tephra layering was paralleled by a variability in mass loading, a point well illustrated by the samples of a single discrete layer at either end of pit 4. Although the pit was less than 1 m^2 the mass loading across it varied by a factor of 4 (0.31 to 0.08 kg m^{-2}). This variability was conclusively demonstrated at pits 20 and 21, excavated through the tephra visible in section beneath the lip of a cornice (*fig. 3A*). In this unique locality it was possible to trace the behaviour of the layer over a distance of 9 m. With such localized variability in mass loading the proximal-distal relationship in both the loading and particle size were clearly of secondary importance as is indicated by the lack of spatial control on such data (*fig. 2, tab. 1*).

Fig. 3A: The cornice section (pits 20 and 21) showing lateral variability in thickness (mass loading) of the Hekla 1991 tephra. March 1991.

Particle Size Analysis

Moment statistics (McMANUS 1988, FRIEDMAN & JOHNSON 1982) were applied to the particle size distributions and used to numerically determine values for the mean, standard deviation, skewness and kurtosis of each distribution and to plot a variety of "environmental interpretation" graphs. For comparative purposes 4 generic classes were imposed on the data, grouping them on a stratigraphic basis - (1) single layers; (2) multiple layers, (basal part); (3) multiple layers, (non-basal parts); and (4) contaminated layers. The graphical inter-class comparisons (*fig. 4*) unfortunately demonstrate that the grain size characterization of a single sample is not sufficient to predict its class of origin. The graphs do demonstrate that by using real multiple data it is possible to distinguish between the artificially imposed classes. However discrete fields of data rarely occur, and the distinction is more often possible owing to differences in the spread of data. The greatest spread occurs in the contaminated class (*fig. 4E-H*); this is partly due to the presence of larger non-volcanic clasts. In both spread and absolute terms it is impossible to distinguish between the single layer and multiple layer (basal) classes (*fig. 4A*). The multiple layer (non-basal) class tends to have a larger spread of data, although smaller than the contaminated class (*fig. 4E*). Although these graphs are useful in comparing classes, their environmental significance should not be overstressed as their general usefulness has often been doubted (McMANUS 1988, FRIEDMAN & JOHNSON 1982).

Fig. 3B: An example of multiple tephra layers (pit 15).

Fig. 3C: An example of multiple tephra layers (pit 1).

Tab. 1: Mass loading data for the winter snow pits (distal site). Locations refer to fig. 2. [* represents contaminated layer; u=upper; m=middle; l=lower. Bold numerals indicate pit totals].

sample site	layer	mass loading (kg m^{-2})	sample site	layer	mass loading (kg m^{-2})
Pit 1	1*	0.1511	Pit 11	1	**0.3685**
	2*	0.2449			
	3*	1.1998	Pit 12	1	**0.5860**
	TOTAL	**1.5958**			
			Pit 13	1	0.0108
				2	1.6425
Pit 2	1*	0.1505		TOTAL	**1.6533**
Pit 3	1*	0.0381	Pit 14	1	0.0110
	2*	0.0045		2u	0.5184
	3*	0.6382		2m	0.2009
	4*	0.9838		2l	0.9555
	TOTAL	**1.6646**		TOTAL	**1.6858**
Pit 4a	1	**0.0752**	Pit 15	1	**1.1324**
Pit 4b	1	**0.3067**			
			Pit 16	1	**1.8836**
Pit 5	1*	**0.1171**			
			Pit 17	1	**0.8512**
Pit 6	1	**2.1379**			
			Pit 18	1	**0.9048**
Pit 7	1	1.0597			
	2u	0.1141	Pit 19	1u	0.1594
	2l	0.4361		1l	0.7913
	TOTAL	**1.6099**		TOTAL	**0.9507**
Pit 8	1	**0.2893**	Pit 20	1u	0.8621
				1l	2.0870
Pit 9	1	**0.2413**		TOTAL	**2.9491**
Pit 10	1	**0.2895**	Pit 21	1u	0.3073
				1m	2.1265
				1l	0.8544
				TOTAL	**3.2882**

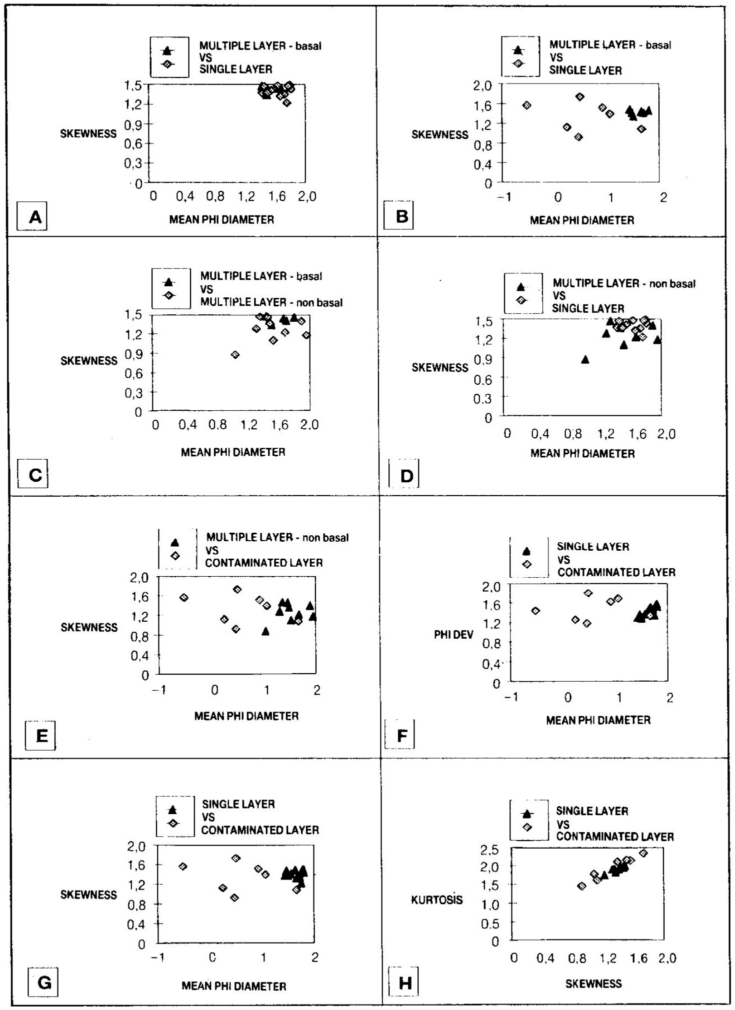

Fig. 4: Particle size distribution parameters (P.S.D.P.) graphs comparing the various classes imposed on the data (see text for discussion).

Discussion

Local irregularities in the thickness of certain Holocene tephra layers have been attributed to the original deposition of the tephra onto winter snow fields (ÞÓRARINSSON 1967, JÓHANNESSON 1981). Despite this, the re-depositional processes involved and their consequences for the preservation of tephras in the stratigraphic record have until now received little attention. Prior to the field work, it was mistakenly expected that the snow-burial of the 1991 tephra would have resulted in its protection from wind and slope-wash movement until final spring snow-melt. It was also assumed that slope-wash processes would be accelerated during the final melt resulting in the movement of tephra down slope towards the stream channels. ÞÓRARINSSON (1967), in his study of the historical eruptions of Hekla, envisaged a similar process to explain the absence of a tephra, since "... the volcano began to spout in mid-winter when the tephra doubtless fell on snow covered ground, and any fine, thin layer would have mostly been washed away in the spring thaw". Whilst slope-wash may generally play an important role in the post-depositional movement of tephras, it is clear that wind action on the 1991 tephra, prior to the spring thaw, is of greater significance, particularly in highland areas exposed to strong winds.

Burial of the Tephra

In many respects it was fortuitous that the 2 months following the eruption were unusually warm and that samples were taken under conditions more representative of the end of season, when sporadic melt phases interspersed with periods of snow accumulation had already occurred. If the melt phases had not been so early in the season these more complex but normal conditions would not have been observed, and it is possible that the effects of the spring thaw would have been greatly overestimated during the summer return. However the snow pit excavations unequivocally demonstrate this complexity and indicate the importance of wind in the reworking of 'winter tephras'. The original tephra layer was buried by snow during or immediately after its deposition. In the cases where this layer was well-defined, its accumulation rate had exceeded that of the snow, whilst the tephra in the more dispersed (basal) layers had accumulated at rates less than or equal to the rate of snow accumulation. Field observations support this hypothesis, with the solid layers found in the flattest areas, and the dispersed layers in thicker snow drifts in the lee of slopes and ridges. Frequently multiple layers were found in the pits, with the basal layer usually the thickest. The layer(s) were found between 0.1 m and 1.5 m beneath the snow surface, with multiple layers spread over a range no greater than 30 cm. The occurrence of multiple layers was also greater in the thicker snow banks.

Particle Size Patterns

All samples analysed fall within fields analogous to the pyroclastic fall fields of WALKER (1971). The graphs of particle size distribution parameters (P.S.D.P.) (*fig. 4*) indicate no difference between the single layer and the basal multiple-layer groups suggesting that they were synchronous and represented the original depositional horizon. The tephra within all but the lowest of the multiple layers have been grouped together; it was not possible to correlate between them as variously 1, 2 or 3 additional layers were present. At several sites in the catchment, tephra was exposed at the snow surface; here the tephra cover was broken by linear furrows in the snow. It would seem that thawing and wind erosion were responsible for these patterns, and that the exposures acted as the source of the tephra in the multiple layers. The P.S.D.P. graphs show that the non-basal multiple layer class plots in the same region as the single layer and basal multiple layer classes, but occupies a greater range. This extended range is suggestive of a marginal trend towards a coarser grain-size (*fig. 4C, D*), and is possibly due to the winnowing of the source tephra, with long distance transport of the fines leaving the coarser residue to contribute locally to the multiple layers. The situation is clearer with the contaminated tephra layers. These were restricted to snow drifts in the lee of 2 large exposed ridges, with bedrock/regolith within 3 cm of the snow surface. During periods of snow melt the bedrock became exposed and in addition to the tephra, unconsolidated nonvolcaniclastic material was blown off the ridge onto the snow drift, where it was buried by later snow. These layers, clearly distinct on the P.S.D.P. graphs, had a greater range, and were coarse enough almost to define a distinct field (*fig. 4B, E, F, G*).

These distributions justify the imposition of the different layer classes (see earlier) which, although non-diagnostic, enable the speculative discussion of the processes responsible for the form of the tephras within the snow. All the layers demonstrate extreme variability of mass loading. This is most convincingly demonstrated with the basal/single layers, where correlation is more assured. Such irregularity can only arise by syn- and post-depositional wind action; the tephra behaves like snow with areas of erosion and of drift accumulation. This is consistent with JÓHANNESSON et al. (1981) who explain unevenness in the distribution of the Holocene Snæfellsjökull acidic tephras (Sn-1, -2 & -3) to be "due to the ash being piled into drifts by the wind; especially if .... the tephra was deposited on frozen or snow covered ground."

(Summary: From the snow pit samples and observations it is apparent that the interactions between tephra, wind and snow are extremely complex, even on the smallest scale. This will have a direct bearing on the post thaw distribution of the tephra.)

Summer Observations

In August a return visit to the catchments showed the effects of an unusually dry summer. The largest lake, Launvötn had contracted to about half its maximum area, with raised shorelines up to 4 m above the lake level. A small boat was carried to the lake and a 4 cm diameter Russian corer used to sample the surficial lake bed sediments. No trace of the 1991 tephra was observed in the 15-20 cm of sediment which could be sampled. At no point

was the water depth greater than 3.5 m, being mostly in the range 1.5 m to 2.0 m.

The tephra was found in the dry stream beds however, where it was most abundant in bedform troughs. At the mouths of these channels tephra and bedrock-derived sediments were found in irregular and uneven blankets. The largest of these was situated at the inlet from the upper lake, and had formed over a large area of level ground, prior to lake lowering. It was not possible to obtain data from this area owing to (1) the ubiquitous presence of incised and meandering channels formed as the lake retreated; and (2) the degree of aeolian activity, as illustrated by the numerous accumulations of tephra and locally-derived material as wind shadows in the lee of obstacles. The force of wind as an erosive agent in Iceland is considerable (ASHWELL 1966, 1972, BJARNARSON 1976, 1978, DUGMORE & BUCKLAND 1991, ÞÓRARINSSON 1961) and plays an important role in the mobility of the tephra during its immediate post-depositional history.

The upper lake (max. depth - 0.5 m) also provided evidence of retreating shore levels and was investigated in the same way. The retreat evidence in this case was not of topographically defined raised beaches as at Launvötn, but of parallel strips of tephra some 1-3 m shorewards from the lake edge (*fig. 5*). These features are explained by a combination of wave action, rapid drops in lake level (during dry periods) and the shallowness of the lake. Near shore tephra on the lake bed tends to be moved landward when the on-shore wind is strong. The lowering of the lake therefore results in the abandonment of this tephra in raised strand lines. Similar strand lines or berms have been observed, defined by concentrations of fine grained sediment, around a fluctuating proglacial lake near Heinabergsjökull, Southeast Iceland (MATTHEW BENNETT pers. comm.). Observations of the lake level demonstrated a maximum shoreline retreat of 10 cm in 24 hours. It might be expected that these strandlines would preferen-

Fig. 5: Parallel berms or strandlines defined by the Hekla 1991 tephra, after lake contraction.

tially develop on down-wind shores; the inconsistent orientation of small tephra cones in the lee of raised matter (plants and pebbles) however, points to the local lack of a dominant wind direction and explains the near continuous nature of the strand lines on all but the northern shore. Tephra was generally not present on the lake bed.

Discussion

The lack of observations between the winter and summer field seasons creates difficulties in assessing the significance of the different processes which operate on the tephra during and after the spring thaw. The effects of wind, which are to be expected in unvegetated areas, are particularly well seen in the form of the raised shorelines and the wind shadow tephra accumulations. Tephra accumulation also occurs in the interstices between the frostheaved pebbles. Qualitative assessment of these accumulations suggests that there was a consistent down slope increase in interstitial tephra, indicating that slope wash effects have operated during the thaw, albeit of minor significance when compared to the effects of wind both before and after the thaw.

Although the instability of the 2 lakes in the Launöldur area prevented the tephra from accumulating on the lake bed, the observations made in the catchment are of wider interest, especially to those who are coring lakes in the unvegetated and windy highland areas which occupy a significant proportion of the Icelandic interior. The ease with which tephra can be mobilized in catchments such as these, both by wind and slope wash, indicates that the transport of tephra into lakes would be considerably greater than would be expected by analogy with vegetated lowland areas.

The Field Areas: Proximal Site

In August the proximal tephra immediately to the northeast of Hekla formed an extensive cover, with the exception of the exposed crests and ridges of the higher ground. In general, the tephra formed a smooth layer of even thickness, composed of pumiceous fragments in a size range of 1 cm - 10 cm in diameter. Above an altitude of ca 300 m, on sheltered slopes and hollows, the even tephra layer gave way to areas of polygonal hollows and ridges. These became more common with increasing altitude and excavation showed them to be indicative of underlying snow. The preservation of snow by debris (tephra) insulation is a common phenomenon (cf. DRIEDGER 1981, WILSON 1953, GUÐRÚN LARSEN pers. comm.). These features were particularly well-developed on the northeastern slopes of Hekla, where the usual route of ascent passes above the 1970 lava flow and the Skjólkvíahraun, about 4 km from the summit crater. They are commonly termed ablation polygons (RICHARDSON & HARPER 1957), ablation hollows (JAHN & KLAPA 1968, RHODES et al. 1987) or sun-cups (MATTHES 1934) and the ablation may be caused by turbulent heat transfer or solar radiation. These polygons are similar to those which develop ubiquitously in 'spring snow' at the side of dirt roads in much of Iceland (ÓSKAR KNUDSEN pers. comm.). An up-to-date view of current ideas is given by RHODES et al. (1987). The formation of this topography will be discussed in detail elsewhere (HUNT & LLOYD in prep.); it is its development and ultimate demise that is pertinent to the redistribution of tephra.

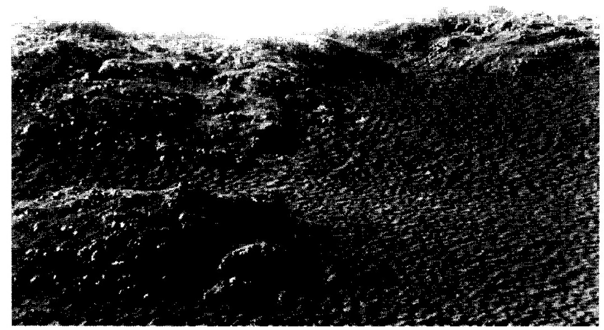

Fig. 6: The ablation topography at the proximal site (August 1991). On the steeper slopes the polygons become elongate downslope. Field of view is ca 150 m across.

Discussion

The site chosen for study was a north facing amphitheatre at an altitude of ca 720 m (*fig. 6*). On flat lying ground in the 'stage' of the amphitheatre an area (2.5 m x 1.5 m) of the ablation topography was cleared of tephra to reveal the snow surface (*figs. 7 A, B*). In addition to the surface irregularities the tephra cover was also variable; the depth of tephra in hollows continually exceeded the depth on the ridges (*fig. 8*). Gravitative settling, slope wash and wind movement can easily explain this distribution, which seems at odds with the tried and tested notion of thicker covers of debris providing greater insulation. These ideas can be reconciled if the topography is considered to be evolving dynamically. Support for this suggestion comes from observations made at the margins of the ablation topography. At many of these sites the snow gently thinned to onlap the bedrock and the amplitude of the ridges was reduced; the ridge-to-hollow differences in tephra thickness were also less. Near the very edge the removal of the tephra revealed a continuous ice layer exposed between mounds of snow. Where the underlying snow and ice ceased to be continuous the number of mounds decreased rapidly. These mounds were underlain by very thin ice, whereas the ground between them consisted of tephra in direct contact with the bed-rock. Where the ablation topography had completely retreated the tephra formed a uniform layer, without the thickness variations associated with the wasting snow. These observations can be explained by a simple model (fig. 9):

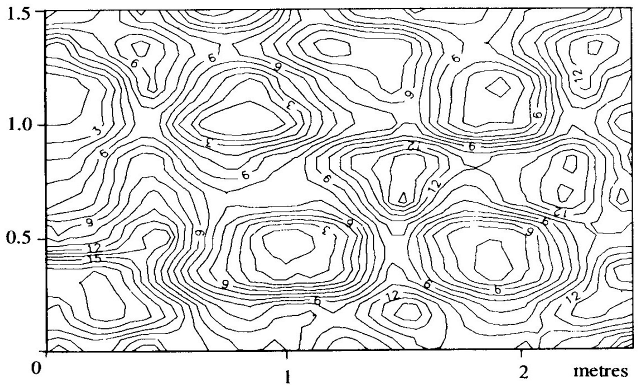

Fig. 7A: Contoured map of ablation topography on a level surface. Contour values record height above the lowest point. Polygons are up to 50 cm in diameter. The parallel stripes are an artifact of unequal sampling intervals on the X (every 5 cm) and Y (every 15 cm) axes.

Fig. 7B: The surface represented in *fig. 7A*. Note the thicker tephra cover above the hollows.

1) As the overlying snow melts, the sandwiched tephra layer becomes exposed. By some (unknown) mechanism ablation of the underlying snow results in the formation of polygonal hollows and ridges. The amplitude of these features initially increases with time (degree of ablation). This was illustrated earlier in the year at a more distal site, where the amplitude increased away from the edge of patches of overlying snow (GUÐRÚN LARSEN pers. comm.).
2) Tephra is moved (by wind and gravity) into the hollows. The hollows are therefore more effectively insulated, and ablation of the ridges proceeds relatively faster. Hollows therefore become ridges, and ridges, hollows. The tephra shifts to equilibriate with the new hollows and as the snow mass downwastes, the cycle of topographic inversion continues. A compressed resistant ice layer beneath the snow reduces the ablation rate when it forms the ablating surface, initially at the base of the hollows. Relative ablation of the ridges becomes even greater resulting in a reduction in the amplitude of the topography. The ridge-to-hollow differences in tephra cover also reduce.
3) At the edges of the ablation topography the isolated mounds (former ridges) gradually disappear. Hollows are no longer present and offer no sink for the tephra, which becomes smoothed by the wind to form an evenly distributed layer.

This simple model explains the field observations although it remains untested. The model predicts that such a topography is constantly changing, although the timescales involved are not clear. These predictions could be easily tested by accurate measurements of the topography (as in *fig. 7A*) repeated at regular intervals over an extended period.

Conclusions

The observations within this paper relate to the mobility of the Hekla 1991 tephra within less than a year of its deposition. Investigations of proximal and distal (*sensu lato*) deposits of the tephra have yielded surprisingly different results. The interaction between snow, wind and tephra on the proximal slopes of Hekla, has resulted in the smoothing of the tephra layer, through the development and decay of ablation polygons. The stability of this layer is likely to be short-lived; exposure to slope movement, rain, wind and ice will no doubt contribute to its disruption. The long-term significance of these results is therefore of little consequence to tephra stratigraphy. The distal tephra deposits and their susceptibility to syn- *and* post-depositional movement are of greater significance. Variations in the layering and mass loading of finer grained tephras deposited on snow indicate their susceptibility to re-mobilization by wind, both during primary deposition, and during *later* periods of snow melt. The unvegetated nature of the study area and its susceptibility to erosion by summer winds, reduced the *local* long-term significance of these observations. As the pre-Landnam vegetation cover in Iceland was far greater than present (BJARNARSON 1987), earlier tephras are more likely to have been deposited in vegetated areas. Although snow

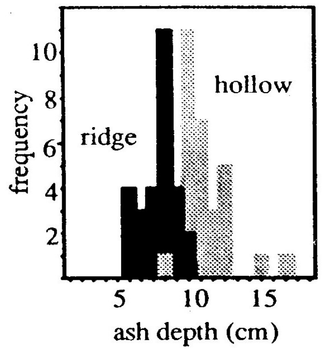

Fig. 8: The unequal tephra cover over the hollows and ridges (n=60).

drifting and consequently the degree of tephra irregularity may have been reduced in vegetated areas, post-thaw tephra layers should have been more protected in these circumstances and would therefore have been far more likely to record the winter mass loading irregularities which may have arisen. Such irregularities have been found in Holocene tephras (ÞÓRARINSSON 1967, JÓHANNESSON et al. 1981) and support these conclusions. The possibility of considerable and very localized variations in mass loading (or thickness) should therefore be considered in studies of older and far travelled tephras.

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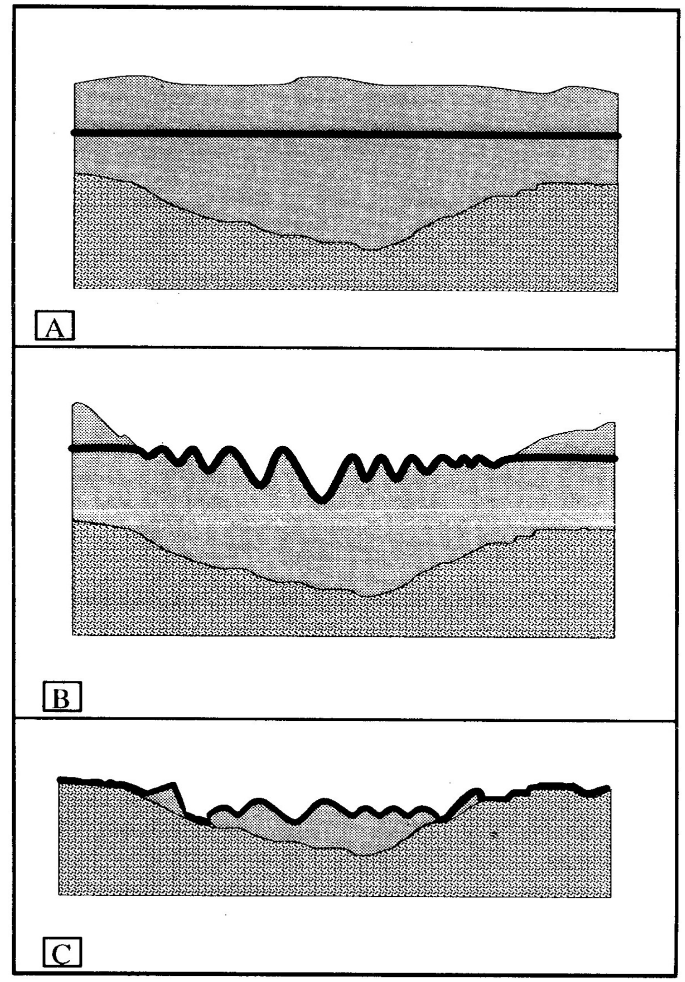

Fig. 9: A diagrammatic model for tephra movement and snow ablation at the proximal site. [Black represents tephra; stippled represents snow; and pattern, bedrock]. See text for full discussion.

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